Asymmetric Boreal Summer Intraseasonal Oscillation Events over the Western North Pacific and Their Impacts on East Asian Precipitation

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ABSTRACT: The boreal summer intraseasonal oscillation (BSISO) is the most prominent tropical subseasonal signature. Due to the restriction of methodology used to extract BSISO, most of the previous studies ignored its asymmetry. This study reexamines the BSISO events over the western North Pacific (WNP) for 1985–2010 with a hierarchical cluster analysis. Two categories of BSISO events are classified, the long-period (20–60 day) and short-period (10–20 day) events. The long-period BSISO events manifest as a northward-propagating mode with a significant phase asymmetry characterized by a fast development, but a slow decay of the intraseasonal convection. The phase asymmetry is found to be determined by the BSISO-induced amplitude-asymmetric sea surface temperature (SST) anomalies, in which the suppressed convection-induced positive SST anomalies are stronger than the active convection-induced negative ones. Such amplitude-asymmetric SST anomalies result from the nonlinear relationship between convection and surface downward shortwave radiation flux anomalies caused by the cloud transmission effect. The stronger positive SST anomalies—induced turbulence flux anomalies act as a negative feedback onto the atmosphere, making the transition from the convection suppressed phase to the active phase earlier and faster. The fast-developing convection tends to cause a fast northeastward retreat of the preceding enhanced western North Pacific subtropical high. Accordingly, the middle and lower reaches of Yangtze River valley experience a rapid reversal from the increased precipitation to the decreased. The asymmetric BSISO events over WNP and their impacts revealed in this study would provide a new potential for subseasonal-to-seasonal forecast of the East Asian summer monsoon precipitation.

KEYWORDS: Atmosphere-ocean interaction; Intraseasonal variability; Subseasonal variability; Tropical variability

1. Introduction

Subseasonal-to-seasonal (S2S) forecasts that bridge the gap between weather forecasts and seasonal climate prediction have attracted more and more attention in recent years. Forecasts of this time scale are particularly important to reduce the economic losses and casualties caused by extreme or persistent weather events. At present, it is still a challenging issue to forecast with the time scale from 2 weeks to 3 months, that is, the weather–seasonal climate prediction gap (Hendon et al. 2000; Molteni et al. 2007; Neena et al. 2014; Li and Robertson 2015). Improving the S2S forecast skill is an urgent need for the development of meteorological services, and also a current international trend (Vitart et al. 2012; Hoskins 2013; Mariotti et al. 2018).

Intraseasonal oscillation (ISO) is the major source of the S2S predictability. As one of the main components of tropical climate system variability, ISO exhibits significant seasonal variations (Wang and Rui 1990; Madden and Julian 1994; Salby and Hendon 1994; Zhang and Dong 2004). The tropical ISO is characterized by equatorially trapped eastward-propagating convective variability, known as the Madden–Julian oscillation (MJO) in boreal winter (Madden and Julian 1994). In boreal summer, the tropical ISO has farther-north variability centers and more complex propagation characteristics, which is called the boreal summer intraseasonal oscillation (BSISO) (Wang and Xie 1997; Lawrence and Webster 2002; Jiang et al. 2004; Li 2014). The BSISO over the western North Pacific (WNP) plays a crucial role in the evolution of East Asian summer monsoon (EASM) and associated rain belt by changing the large-scale circulation and moisture supply, and also has a high correlation with the extreme weather/climate events in East Asia (Lau and Chan 1986; Chen and Chen 1995; Wu and Wang 2001; Lee et al. 2013; Zhu et al. 2003; Mao et al. 2010; Ren et al. 2013; Li et al. 2015a,b; Gao et al. 2016; Hsu et al. 2017; Chen and Zhai 2017). It provides a physical foundation for the S2S prediction of EASM-related precipitation and atmospheric circulation (Waliser et al. 2003; Wang et al. 2009; Lee et al. 2010; Fu et al. 2013; Lin 2013). An in-depth understanding of the evolution characteristics and propagation mechanism of the BSISO over WNP is of great significance for diagnosing and predicting the intraseasonal climate variability in East Asia.

It is necessary to extract the BSISO signals in practical research. The time-scale-based bandpass filtering of relevant meteorological variables is an informative method (Hong and Ren 2013; Truong and Tuan 2019). Due to the need to understand the spatial pattern and temporal evolution, single or multivariate empirical orthogonal function (EOF) analyses on convection, precipitation, and wind field have become a conventional methodology (Zhu et al. 2003; Mao et al. 2010; Jiang...
et al. 2011; Kikuchi et al. 2012; Lee et al. 2013; Ren et al. 2020). Lee et al. (2013) defined two real-time multivariate indices (BSISO1 and BSISO2) for two BSISO modes through a multivariate EOF (MV-EOF) analysis on the daily outgoing longwave radiation (OLR) and zonal wind at 850 hPa over the Asian summer monsoon region. The first mode represented by BSISO1 indicates a northward and northeastward-propagating mode with the convection anomalies originating from the equatorial Indian Ocean (IO) with a time scale of 30–60 days. This mode is also associated with the eastward-propagating component along the equator like MJO in winter. The other mode represented by BSISO2 indicates a 10–30-day northwestward-propagating mode with convection anomalies propagating northwestward from IO and the Philippine Sea, respectively. These two modes describe the major parts of spatiotemporal variations of BSISO and explain the ISO variabilities over the Asian summer monsoon region to a great extent. Therefore, they have been widely used in recent studies (J. Li et al. 2015; Hsu et al. 2016; Chen and Zhai 2017; Hsu et al. 2017; Lee et al. 2017; Diao et al. 2018).

However, just as Lee et al. (2013) pointed out, the third and fourth principal components (PCs) of their MV-EOF decomposition, which are defined as BSISO2 have different leading periods, respectively. A power spectra analysis shows that the leading period is around 30 days for PC3 and 10–20 days for PC4. Defining BSISO2 by these two PCs for the follow-up analysis may yield confusion. In addition, the northward-propagating signals of convection anomalies over WNP, which may remarkably affect the East Asian climate are split into two indices. On the other hand, using self-organizing map (SOM), Chu et al. (2017) found nonlinearity and asymmetry existing in the convection oscillation. The stationary dipole pattern over the eastern IO and the Philippine Sea at phase 1 and phase 5 occurs more frequently and lasts longer than in other phases. The propagating mode at phase 3 and phase 7 shows an obvious asymmetry in convective activity over the eastern IO, which manifests as slow growing but fast decaying. However, the evolution of the convection anomalies over WNP obtained in the previous studies is generally considered to be symmetric (Hsu and Weng 2001; Tsou et al. 2005; Chen et al. 2015; Wang et al. 2018; Ren et al. 2018). In fact, by a preinvestigation, we found a considerable number of asymmetric intraseasonal oscillations of convection over WNP, with the convection weakening process slower than its strengthening process. It is worth asking why this asymmetric evolution of BSISO over WNP was not revealed in the previous studies. We speculate that the bandpass filtering of data with a narrower range of time scales used may impair the oscillation asymmetry. Also, just as Oettli et al. (2014) indicated, the results of EOF analysis are constrained by both orthogonality and linearity. Thus, the asymmetric BSISO over WNP needs to be clearly identified, and a new objective method rather than filtering or EOF decomposition is required to achieve this goal.

The air–sea interaction process’s importance in the propagation of BSISO has been pointed out by a variety of previous studies (Wang and Xie 1998; Fu and Wang 2004; Chou and Hsueh 2010; Hsu and Li 2011; Hsu et al. 2011; Wang et al. 2018). Associated with BSISO and its northward propagation, the atmosphere can force the ocean by altering solar radiation and air–sea turbulent exchange (Kemball-Cook and Wang 2001). A near-quadrature phase relationship was found between sea surface temperature (SST) and convection anomalies (Vecchi and Harrison 2002; Chou and Hsueh 2010; Wang et al. 2018), with cold (warm) SST anomalies lagging (leading) active convection by about 1/4 life cycle, and spatially locating between the dry and wet phases of intraseasonal convection anomalies. The ocean can feedback onto the atmosphere by changing air–sea turbulence flux, atmospheric stability, and convergence/divergence in the boundary layer (Lindzen and Nigam 1987; Chen and Chen 1995; Hendon and Glick 1997; Shinoda et al. 1998; Kemball-Cook and Wang 2001; Agudelo et al. 2006; Rajendran and Kitoh 2006; Roxy and Tanimoto 2007; Sobel et al. 2008; Back and Bretherton 2009; DeMott et al. 2013; Chen et al. 2015; Wang et al. 2018). The oceanic feedback process is relatively slow compared with the atmospheric process. It can be speculated that the phase asymmetry in asymmetric BSISO events is attributed to a positive ocean feedback process that slows down the decay of convection anomalies, or a negative ocean feedback process that accelerates development of convection anomalies. The spatiotemporal variations of SST accompanying the asymmetric BSISO and the role of air–sea interaction processes in the formation of asymmetric convection anomalies need to be further explored.

In this study, we propose to use a hierarchical cluster analysis to classify the BSISO events over WNP and then reveal their asymmetry features. The detailed processes of air–sea interaction and the impacts of the asymmetric BSISO events on the East Asian climate are further investigated. The rest of the paper is structured as follows. Section 2 introduces the reanalysis datasets and methods used in this study. Detailed procedures of the hierarchical clustering are also described in this section. Classification of the BSISO events and their spatiotemporal evolution characteristics especially the asymmetry features are presented in section 3. Section 4 analyzes the SST anomalies associated with the convection anomalies and the oceanic feedback through air–sea turbulent exchange. The BSISO-related precipitation anomaly pattern and the accompanying large-scale anomalous circulation and moisture supply are examined in section 5. Section 6 is devoted to conclusions and discussion.

2. Data and method

The National Oceanic and Atmospheric Administration (NOAA) daily OLR data on a 2.5° × 2.5° grid are used to depict the convective signal of BSISO (Liebmann and Smith 1996). To analyze evolution of the radiation distribution, large-scale circulation, and moisture change, the Climate Forecast System Reanalysis (CFSR) data including daily averaged surface longwave and shortwave radiation flux, zonal and meridional winds, specific humidity, and geopotential height at a 2.5° × 2.5° resolution are utilized (Saha et al. 2010). The daily 1° × 1° indexes from the Objectively Analyzed Air–Sea Heat Flux (OAFlux) (Yu and Weller 2007) are obtained, including SST, sensible heat flux (SHF), latent heat flux (LHF), 10 m wind speed (ws), 2 m air temperature (Ts), and 2 m air specific
humidity ($q_a$). The upper-layer oceanic elements including temperature, density, mixed layer depth, meridional and zonal velocity, and wind stress are used from the Simple Ocean Data Assimilation (SODA) version 3.3.1 daily data on 1° × 1° grid (Carton et al. 2018) for further SST tendency budget. The rainfall data are taken from the Climate Prediction Center (CPC) Global Unified Precipitation data at 0.5° spatial resolution (Xie et al. 2007; Chen et al. 2008a,b). The analyzed period for all datasets is 26 years spanning from 1985 to 2010 in order to match up the time range of CFSR dataset and to guarantee reliability. All the original datasets have been pre-processed by removing climatological annual cycle and yearly summer seasonal mean and then doing 5-day moving average (hereafter called the raw pentad anomaly).

A cluster analysis is made to achieve the aim of extracting BSISO signals objectively. There are two kinds of main clustering algorithms named partitioning and hierarchical methods, respectively, in the actual processing of grid data. The partitioning method divides the data into $k$ mutual exclusive groups. To obtain $k$ clusters, $k$ objects (called representative objects) are selected in a dataset. Each remaining object is assigned to the nearest representative object to find the corresponding cluster. The average distance from the representative object to all other objects in the same cluster is minimized and as far away as possible from objects in other clusters. It should be noted that the selection of $k$ is artificial. The disadvantages of this algorithm are the predetermined $k$ and the random selection of initial representative objects. Instead of constructing a single partition containing $k$ clusters, the hierarchical method investigates data over different scales of distance at the same time. This algorithm does not need to manually specify the number of partitions, that is, the $k$ value. The abovementioned SOM method used to reveal the nonlinearity and asymmetry of BSISO over the eastern IO is just based on the principle of the hierarchical algorithm (Chu et al. 2017).

The hierarchical clustering is used in this study to classify the BSISO events over WNP. The detailed procedure for the cluster analysis is as follows. The first step is to choose the objects of cluster analysis. To remove the influence of synoptic-scale noises and long-term interannual or interdecadal signals without impairing the original characteristics of data themselves, a wider 10–90-day bandpass filtering is applied. It should be emphasized that the bandpass filtering is applied only in this step for extracting the BSISO events. Once the events are identified through the cluster analysis, their original characteristics are explored with the raw pentad anomalies mentioned earlier. A daily time series is obtained by averaging the 10–90-day filtered OLR anomalies spatially over WNP, a target region that is marked by a black box in Fig. 1a, and then it is normalized by its standard deviation. A BSISO event is defined when the regional average OLR changes from positive to negative value. The duration between the first zero point to the left and right of this transition point is called the life cycle. The BSISO events should meet two criteria: Its life cycle is longer than 10 days and the difference between the maximum and the minimum normalized OLR anomalies is greater than 1. For such a definition, 101 BSISO events are identified for the summers of 1985–2010. The life cycle data are defined to be a set of objects. The
second step is to compute the Euclidean distance between every other alternate object, which is calculated as the root-mean-square value. The third step is to construct the cluster hierarchy using a linkage function named average. A smaller average Euclidean distance means a better correlation and being easier to group together for two clusters. The agglomeration process starts when all objects are separated, and then two clusters are merged in each step until only one is left. The final step confirms which distance scale to cut the hierarchical tree to get the most appropriate final classification in the application.

3. Classification of BSISO events and their phase asymmetry

Figure 1a shows the boreal summer intraseasonal variabilities and corresponding summertime climatological patterns of large-scale circulation for 1985–2010. Large intraseasonal variabilities are observed over the Arabian Sea, the Bay of Bengal, and WNP from the standard deviation distribution of 10–90-day filtered OLR anomalies. With a view to the tropical East Asian summer monsoon area, a target region (7.5°–22.5°N, 110°–135°E) in WNP where the intraseasonal convection is the most active is selected. The climatological low-level horizontal winds (vectors in Fig. 1a) over the target region are mainly northeastward with large meridional components. A wavelet analysis that is performed on the time series of the averaged OLR anomalies over the target region (Fig. 1b) exhibits two significant leading periods around 10–20 and 20–60 days, respectively.

By applying the hierarchical cluster analysis to the life cycle data of 101 BSISO events identified, we can classify those convection events. The visualization result is presented by the dendrogram in Fig. 1c. It can be seen that the 101 BSISO events are divided into three types based on a distance scale of over 15. From the corresponding histogram of life cycle data (Fig. 1d), a single event belong to the third category has an extreme long life cycle of 56 days. The composite raw pentad OLR anomalies for the combination of type 3 and type 1 events are almost the same as the type 1 events alone (figure is not shown). Therefore, the third type of this individual BSISO extreme event is excluded from subsequent studies. The BSISO events over WNP can be classified into two categories: 45 long-period events and 55 short-period events. The average life cycles of the long-period events and the short-period events are 36 and 16 days, respectively, which is consistent with the wavelet analysis result.

Figure 2a shows the time series of composite raw pentad OLR anomalies averaged over the target region in WNP for long- and short-period BSISO events, in which day 0 is set to be the transition of convection from a suppression phase to an active phase. Spatial average of composite raw pentad OLR anomalies at day 0 is almost zero over the WNP target region. To diagnose the state of convection events conveniently, a composite BSISO event is divided into eight phases. Phase 1 represents the start point of an event when the convection suppression is to begin, phase 3 the timing when the convection suppression reaches the maximum, phase 5 the timing at day 0 for the transition of convection from a suppression phase to an active phase, and phase 7 the timing when the active convection reaches the maximum. Accordingly, phases 2, 4, 6, and 8 indicate those time points when the convection anomalies are respectively in between. With these definitions, days −20, −12.5, −5, −2.5, 0, +2.5, +5, and +12.5 are used for phases 1 to 8 of the long-period BSISO events, while days −8, −6, −4, −2, 0, +2, +4, and +6 are for those of the short-period BSISO events. It is noted that the time intervals between any two adjacent phases for the long-period BSISO events are not uniform, which indicates a phase asymmetry, while those for the short-period BSISO events are uniform under the same phase definition criteria.

During the oscillation of a composite long-period BSISO event (red line in Fig. 2a), it takes 15 days (from phase 1 to phase 3) for the development of convection suppression from zero to the maximum but only 5 days for its decaying (from phase 3 to phase 5), while it takes only 5 days for convection enhancement (from phase 5 to phase 7) but 15 days for its weakening (from phases 7 through phase 8 and back to phase 1). This result manifests a phase asymmetry for the long-period BSISO events in which the intraseasonal convections are featured by a rapid development, but a slow decay. To confirm whether the bandpass filtering before composite analysis can change this feature, Fig. 2b shows the composite OLR anomalies filtered on different time scales. It can be clearly seen that a wider 10–90-day bandpass filtering does not change the phase asymmetry of the long-period events (red solid line in Fig. 2b). However, a narrower 20–60-day bandpass filtering obviously impairs the decaying (developing) rate of suppressed (active)
convections and weakens the amplitude of convection anomalies at the same time (red dashed line in Fig. 2b). Therefore, using a narrower 20–60-day bandpass filtering to extract BSISO signals in the previous studies brought a consequence of ignoring the asymmetry of BSISO.

The evolution of composite raw pentad OLR anomalies for two types of BSISO events as a sequence of eight phases are illustrated in Fig. 3. For the long-period events, during the development phases of suppressed convections (from phase 1 to phase 3, Figs. 3a–c), positive OLR anomalies gradually strengthen from the western equatorial Pacific and propagate northward to the WNP target region. It takes 15 days for the positive OLR anomalies to develop from zero to the maximum, while only 5 days to decline from the maximum to zero. The active convections on the south side begin to develop and intensify also in these 5 days (from phase 3 to phase 5, Figs. 3c–e). Negative OLR anomalies develop and move fast from the western equatorial Pacific to the WNP target region (from phase 5 to phase 7, Figs. 3e–g) and then weaken slowly (from phase 7 through phase 8 and back to phase 1, Figs. 3g,h,a). Thus, during the whole oscillation, the development (weakening) of active (suppressed) convection anomalies. Such an asymmetry of the life cycle of long-period BSISO events.

The evolution of composite raw pentad OLR anomalies for the short-period BSISO events exhibits typical harmonic characteristics (blue line in Fig. 2a). The enhancement and suppression of convection take about the same duration of 4 days. In other words, the growth rate of convection development is the same as that of decay, and there is no phase asymmetry in the short-period BSISO events. As a result, even a narrower 10–20-day bandpass filtering does not significantly change the phase and amplitude of the convection oscillation (dashed blue line in Fig. 2b).

Composite raw pentad OLR anomalies for two types of the BSISO events as a sequence of eight phases are illustrated in Fig. 3. For the long-period events, during the development phases of suppressed convections (from phase 1 to phase 3, Figs. 3a–c), positive OLR anomalies gradually strengthen from the western equatorial Pacific and propagate northward to the WNP target region. It takes 15 days for the positive OLR anomalies to develop from zero to the maximum, while only 5 days to decline from the maximum to zero. The active convections on the south side begin to develop and intensify also in these 5 days (from phase 3 to phase 5, Figs. 3c–e). Negative OLR anomalies develop and move fast from the western equatorial Pacific to the WNP target region (from phase 5 to phase 7, Figs. 3e–g) and then weaken slowly (from phase 7 through phase 8 and back to phase 1, Figs. 3g,h,a). Thus, during the whole oscillation, the development (weakening) of active (suppressed) convection anomalies. Such an asymmetry of the
long-period BSISO events also reflects in their northward propagation.

Different from the long-period BSISO events, the life cycles of the short-period BSISO events are shorter and they exhibit a northwestward propagation feature. As shown in Figs. 3i–3p, the convection anomalies develop from the tropical Pacific to the east of the Maritime Continent (MC) and strengthen near 15°N, eventually dying out over the South China Sea (SCS).

To illustrate the propagating characteristics more intuitively, the sections of composite raw anomalies along propagation direction are shown in Fig. 4. Periodic oscillations and northward (northwestward) propagation of the organized OLR anomalies for the long-period (short-period) events can be clearly observed, in which the northern boundary of the movement is about 25°N (20°N). It also manifests the characteristic of the fast development and the slow decay in the long life cycle of convection anomalies.

4. Air–sea interaction processes in asymmetric BSISO events

a. Amplitude-asymmetric SST anomalies caused by atmospheric forcing

To explore the change of SST anomalies in long- and short-period BSISO events, Fig. 5 shows the composite SST anomalies averaged over the WNP target region. It can be seen in Fig. 5a that the SST anomalies has a near-quadrature phase relationship with the convection anomalies for the long-period, asymmetric BSISO events, which is consistent with the result of previous studies (Vecchi and Harrison 2002; Chou and Hsueh 2010; Wang et al. 2018). It is worth noting that there is no phase asymmetry but an obvious amplitude asymmetry in the SST anomalies, which exhibit that the amplitude of positive SST anomalies is significantly larger than that of negative SST anomalies. The amplitude-asymmetric feature can also be seen in the spatial distributions of SST anomalies for long-period BSISO events in Fig. 6. With the development and northward propagation of suppressed convection anomalies (Figs. 3a–c), the SST anomalies are reversed from the negative maximum values to positive values (from phase 1 to phase 3, Figs. 6a–c). During the rapid decay of suppressed convection anomalies from phase 3 to phase 5, the positive SST anomalies continue to develop and reach the maximum values (Fig. 6c) that is strikingly larger than the negative peak over the WNP target region (Fig. 6a). The SST anomalies during the fast development and the slow weakening of active convection anomalies (from phases 5 to phase 8 and back to phase 1, Figs. 6e–h,a) exhibit a mirrored phase characteristics of the first half cycle. The short-period BSISO events...
feature very small, accompanied SST anomalies (green bar in Fig. 5b) and weak air–sea coupling, which will not be examined in the subsequent studies on air–sea interaction processes.

A SST tendency budget equation is used to quantitatively investigate the cause of the amplitude-asymmetric SST anomalies (Li et al. 2002; Wang et al. 2012; Zhang et al. 2020):

$$\frac{\partial T'}{\partial t} = -\mathbf{V} \cdot \nabla T' - \left( w_e \frac{\partial}{\partial z} \right) + \left( \frac{Q}{\rho_w c_w H} \right),$$  

where the prime denotes the raw pentad anomaly, $\mathbf{V}$ is the horizontal gradient operator, $\mathbf{V}$ the horizontal wind vector, $w_e$ the Ekman pumping speed calculated from the sea surface wind stress $\tau$ from Eq. (2), $f$ the Coriolis parameter, $Q$ the surface net downward heat flux, $\rho_w$ the water density, $c_w$ the specific heat capacity of seawater, and $H$ the mixed layer depth. The three terms on the right-hand side of Eq. (1) represent horizontal advection, vertical entrainment, and heat exchange at the air–sea interface, respectively. In terms of Eq. (1), the SST tendency budget over the WNP region is analyzed and its contributions from different processes are illustrated in Figs. 7a–c. Overall, as seen in Fig. 7a, the surface net downward heat flux anomalies (black line) have the largest contribution to the total SST tendency anomalies (black dotted line), while the contributions from anomalous Ekman pumping and horizontal temperature advection are very small (not shown). The surface net downward heat flux anomalies are the difference between the net downward radiation flux anomalies and the upward turbulence sensible and latent heat flux anomalies. It can be seen in Fig. 7b that the net downward radiation flux anomalies (black line in Fig. 7b) that induce SST anomalies have an amplitude asymmetry. After further decomposition, it can be found that the surface downward shortwave radiation flux anomalies (black dotted line in Fig. 7c) are the dominant components of the net downward radiation flux anomalies and have an obvious amplitude asymmetry. Figure 8 demonstrate spatial distributions of the surface downward shortwave radiation flux anomalies at two extreme phases of the suppressed (phase 3) and active (phase 7) convection anomalies (Figs. 8a,b) and their sum representing their asymmetric components (Fig. 8c). It can be seen that there exist considerable positive asymmetric anomalies at the WNP target region, indicating that the increased downward shortwave radiation flux anomalies at the suppressed convection phase are larger in amplitude than the decreased downward shortwave radiation flux anomalies at the active convection phase. It is the key factor for the formation of the amplitude-asymmetric SST anomalies.

![Fig. 5. Temporal evolutions of composite raw OLR anomalies (gray bars) and SST anomalies (green bars) spatially averaged over the WNP target region for (a) long-period and (b) short-period BSISO events.](image1)

![Fig. 6. Spatial distributions of composite raw pentad SST anomalies at eight phases (P1–P8) of long-period BSISO events. The black dots indicate those SST anomalies exceeding the 95% confidence level (Student’s t test). The black box represents the WNP target region.](image2)
The amplitude-asymmetric downward shortwave radiation flux anomalies can be related to the nonlinear effect in the transmission of clouds to solar radiation. In the less cloud circumstance, which can be represented by negative cloud anomalies for the suppressed convection, most of the incoming solar radiation can reach the surface with less intercepting and reflecting, resulting in a warmer SST. On the contrary, positive cloud anomalies for the active convection tend to prevent the solar radiation from reaching the surface, resulting in a cold SST. However, due to the nonnegligible transmission effect of clouds (Neiburger 1949; Liou 2002), the blocked solar radiation flux reduces, thus increasing the solar radiation reaching the surface. Therefore, the amplitude-asymmetric surface downward shortwave radiation flux anomalies occur and generate the amplitude-asymmetric SST anomalies. A scatter diagram for the relationship between the OLR anomalies and the surface downward shortwave radiation flux anomalies during the summers of 1985–2010; red dashed lines denote the prediction bounds across the extrapolated fit range at the 99% confidence level.

b. Oceanic feedback onto the atmosphere through air–sea turbulence fluxes

The near-quadrature phase relationship between region-averaged SST anomalies and OLR anomalies shown in Fig. 5a suggests the existence of oceanic feedback onto the atmosphere. From the perspective of surface turbulent flux exchange, the
feedback process of positive SST anomalies during the rapid development phase of convection anomalies is analyzed. The LHF and SHF are calculated and decomposed using the bulk algorithm (Liu et al. 1979; Yu and Weller 2007):

\[
\text{LHF}' = \left[ \rho L_c c_e q_s \left( T_s - q_s \right) \right]' = \left[ \rho L_c c_e \Delta q \right]' + \left[ \rho L_c c_e U \Delta q' + U' \Delta q \right] + \left[ (U' \Delta q')' \right],
\]

\[
\text{SHF}' = \left[ \rho C_p c_h (T_s - T_a) \right]' = \left[ \rho C_p c_h U' \Delta T \right]' + \left[ \rho C_p c_h U' \Delta T' + (U' \Delta T')' \right].
\]

where the overbar and the prime denote the climatological mean and the raw pentad anomaly, respectively, \( \rho \) is the air density, \( c_e \) and \( c_h \) are the turbulent exchange coefficients of LHF and SHF, respectively, \( C_p \) is the specific heat capacity, \( L_c \) is the latent heat of evaporation, \( U \) is the wind speed at 10 m above the sea surface, \( q_s \) and \( q_a \) (\( T_s \) and \( T_a \)) are the specific humidity (temperature) at the sea surface and the 2 m height in the atmosphere; \( \Delta q \) and \( \Delta T \) are the specific humidity and temperature differences between the sea surface and near-surface air, respectively. The coefficients are calculated from the known LHF, SHF, \( U, \Delta q \), and \( \Delta T \). The variables are written in the form of the climatological mean plus raw pentad anomaly to decompose LHF and SHF anomalies. Then three components are obtained: \( \rho L_c c_e U' \Delta q \) and \( \rho C_p c_h U' \Delta T \) related to the air–air temperature differences of specific humidity (temperature), \( \rho L_c c_e U' \Delta q \) and \( \rho C_p c_h U' \Delta T \) related to the surface wind speed anomalies, and the nonlinear term, which is found to be much smaller than the first two terms after calculation and neglected in the following study.

The averaged LHF and SHF anomalies and their components over the WNP target region are illustrated in Fig. 9. Both the LHF and SHF anomalies follow the change of the OLR anomalies, but the transition times of these two are ahead of the latter. The wind speed–related components dominated by the atmosphere show a good negative correlation with the OLR anomalies. Suppressed (active) convection anomalies tend to weaken (enhance) surface wind speed anomalies, thereby weakening (enhancing) upward LHF and SHF anomalies. The sea–air specific humidity difference–related term \( \rho L_c c_e U' \Delta q \) changes in phase with the SST anomalies, and the sea–air temperature difference–related term \( \rho C_p c_h U' \Delta T \) lags the SST anomalies. Therefore, the sea surface specific humidity (temperature) anomalies dominate the variation of the sea–air specific humidity (temperature) differences rather than the atmospheric specific humidity (temperature) anomalies. Due to the strong positive SST anomalies around the transition phase of convection anomalies, the positive sea–air specific humidity (temperature) difference anomalies (black line in Fig. 9a and black line in Fig. 9b) directly lead to the earlier transition of LHF (SHF) anomalies (black square marked line in Fig. 9a and black hollow circle marked line in Fig. 9b), indicating the existence of oceanic feedback during the rapid development phase of convection anomalies.

A detailed expression of oceanic feedback can be seen in Fig. 10, which shows the spatial distributions of the LHF (SHF) anomalies and the sea–air specific humidity (temperature) difference anomalies from phase 4 to phase 6. The sea–air specific humidity (temperature) difference anomalies over the WNP target region at phase 4 are positive (Figs. 10d,l), but the LHF (SHF) anomalies are still negative due to the greater contribution of the negative wind speed anomalies (Figs. 10a,g). However, at the transition time point of the asymmetric BSISO events, the positive sea–air specific humidity (temperature) difference anomalies (Figs. 10e,k) reverse the signs of the LHF (SHF) anomalies from negative values to positive ones (Figs. 10b,h), so the positive SST anomalies begin to feedback onto the atmosphere, which is conducive to the development of active convection anomalies. The positive contribution of the sea–air specific humidity (temperature) difference anomalies still exist at phase 6 (Figs. 10f). Combined with the regional average curves and spatial distributions of LHF and SHF anomalies and their components, it can be concluded that the oceanic feedback indicated by the turbulent flux exchange starts from the positive SST anomalies reaching maximum intensity and plays a negative feedback role in the transition of convection anomalies from the suppressed phase to the active phase, making the time point and process of transition earlier and faster, which is the most notable manifestation of the phase asymmetric BSISO events.

5. Impact of the asymmetric BSISO events on East Asian precipitation

Previous studies have pointed out that the BSISO over WNP can significantly affect the East Asian summer monsoon and
associated rainfall. How the phase asymmetry of the long-period BSISO events can affect East Asian precipitation is one of the major concerns in this study. The spatial distribution of standard deviation of composite raw pentad precipitation anomalies for the long-period BSISO events during day 20 (Fig. 12a) exhibits several land regions with obvious intraseasonal variabilities, Indo-China Peninsula (ICP), Maritime Continent (MC), coastal South China (CSC), and the middle and lower reaches of Yangtze River valley (MLYRV).

Composite precipitation anomalies at eight phases of a composite long-period BSISO event are shown in Fig. 11. At phase 3, the maximum positive OLR anomalies (suppressed convection) are located over CSC, ICP, and the northern part of MC (Fig. 11c) where there exist significant negative rainfall anomalies. North of the positive OLR anomalies, there exist considerable positive precipitation anomalies over MLYRV. During the 15 days from phase 1 to phase 3 (Figs. 11a–c), the positive precipitation anomalies slowly propagate northward from the
northern MC to MLYRV. Meanwhile, the negative precipitation anomalies keep the pace with the enhancement and northward shift of the positive OLR anomalies. During the 5 days from phase 3 to phase 5 when the positive OLR anomalies over WNP are rapidly weakened (Figs. 11c–e) and the negative OLR anomalies over the equatorial region begin to develop, the areas of negative precipitation anomalies rapidly shrink from the ICP–CSC–MC region to the CSC and northern MC region, and the precipitation anomalies over the ICP–south-central MC region even turn from negative values to positive ones. The increased precipitations over MLYRV and its south area also weaken quickly. During the 5 days from the transition phase (i.e., phase 5) to phase 7 (Figs. 11e–g), the negative OLR anomalies over WNP increase and shift northward. Correspondingly, the precipitation anomalies over MLYRV rapidly turn to be negative and reach the maximum, and the negative precipitation anomalies over CSC sustain but reduce in intensity while the positive precipitation anomalies over ICP–MC increase to the peak. Impact of the long-period BSISO events on the East Asian precipitation can reach about 35°N, while the northward propagation of the convection anomalies only reaches about 25°N. A tripole pattern of precipitation anomalies develops and moves northward along with slow enhancement and northward propagation of the suppressed convections.

In the phase asymmetric evolution of the long-period BSISO events, a 10-day rapid development of the convection anomalies over WNP from the maximum positive OLR anomalies to the maximum negative OLR anomalies causes a rapid switch of a negative extremum and a positive extremum of the precipitation anomalies over MLYRV and the persistent negative precipitation anomalies over CSC, while a slow decay of the convection anomalies over WNP corresponds to a slow establishment and final extinction of precipitation anomalies. The synergistic variation of precipitation and convection anomalies can also be seen from their spatial means over the key regions (Fig. 12b). The peak of positive precipitation anomalies gradually shifts from CSC to MLYRV in the slow developing stage of suppressed convection anomalies (Fig. 12b, from day 20 to day 5), corresponding to the enhancement and northward propagation of the positive precipitation anomalies seen in the spatial distributions (Figs. 11a–e). The transition of the positive-to-negative extremum over MLYRV and the maintenance of the negative precipitation anomalies over CSC in the rapid developing stage of active convection anomalies can also be seen in the regional mean curve (Fig. 12b, from day 20 to day 5). The positive precipitation anomalies over CSC persist for about 15 days in the slow decay (development) phase of active (suppressed) convection anomalies (Fig. 12b, from day 20 to day 5 and from day 5 to day 20).
With the aim of exploring the variations of large-scale circulation and moisture supply arising from the intraseasonal convection anomalies to explain the change of precipitation anomalies, composite 1000–850 hPa integrated moisture flux anomalies and their convergences at eight phases of the long-period BSISO events are shown in Fig. 13, in which the composite western North Pacific subtropical high (WNPSH) at 500 hPa indicated by the contours of 5860 and 5880 gpm is superimposed. The composite WNPSH is calculated by adding the climatological mean to the raw pentad anomaly. As shown, for the long-period BSISO events, during the developing stage of suppressed convection anomalies (from phase 1 to phase 3, Figs. 13a–c), the associated anticyclonic moisture circulation anomalies originating from the western equatorial Pacific enhance slowly and propagate northward to the ICP–CSC–MC region and then reach the maximum intensity. The northward movement of the suppressed convection anomalies coupling with the local anticyclonic circulation anomalies leads to a northwestward stretch of WNPSH at 500 hPa. The WNPSH ridge is defined as the position where the zonal wind at 500 hPa is zero and its meridional gradient is greater than zero within the range of 100°–150°E. The average latitude of the WNPSH ridge line migrates northward from 20° to 22.5°N and its western ridge point extends from 117.5° to 107.5°E (Figs. 14a,b, from day −20 to day −5). Along with the northwestward extension of WNPSH, the southwesterly water vapor transport anomalies on the northwest flank of the WNPSH main body gradually shift from the northern MC to CSC, and finally to MLYRV. The moisture convergence anomalies experience the same propagation path. Abundant moisture supply and low-level convergence provide favorable conditions for increased precipitation in those regions.

During the rapid weakening of suppressed convection anomalies and quick enhancement of active convection anomalies,
The boreal summer intraseasonal oscillation (BSISO) is the most prominent summertime subseasonal signature over the tropical Indian Ocean and western Pacific, especially over the western North Pacific (WNP), which has a considerable impact on the East Asian summer monsoon circulation and precipitation. Due to the restriction in methodology to extract the BSISO signals with EOF or bandpass filtering analyses, most of the previous studies ignored the asymmetry or nonlinearity of BSISO, which had been recognized by some of the studies on the BSISO over the equatorial Indian Ocean (Oettli et al. 2014; Chu et al. 2017). This study examines asymmetric BSISO events over WNP and their influences on the East Asian summer monsoon circulation and precipitation. A hierarchical cluster analysis is used to objectively classify the BSISO events over WNP with raw pentad OLR anomalies, and then the characteristics of those classified events, especially those asymmetric events and their impacts on the East Asian summer precipitation at different phases of those events, are identified with raw pentad anomalies of OLR, wind, precipitation, and other meteorological elements by composite analyses. The atmospheric forcing and oceanic feedback in the asymmetric events are also preliminarily investigated.

One hundred and one strong BSISO events that are defined with the OLR anomalies averaged over the WNP target region are identified for the summers of 1996 and 2002. After excluding an individual extreme event, the 100 BSISO events are classified by hierarchical clustering into two categories: 45 long-period versus 55 short-period events. The mean life cycle is 20–60 days for the long-period BSISO events, which...
manifest as a northward propagation mode in convection anomalies with an obvious phase asymmetry. Such an asymmetry is characterized by a fast development of the intraseasonal convection from the most suppressed phase to the most active phase within 10 days, but a slow decay of the convection with a opposite phase evolution, i.e., from the most active phase to the most suppressed phase, within nearly 30 days. The suppressed convection anomalies slowly intensify from the western equatorial Pacific and propagate northward, reaching the maximum value over the WNP target region 15 days later. In the following 5 days, the suppressed convection anomalies weaken rapidly and the active convection anomalies on the south side begin to develop. Like a mirror image of the suppressed convection anomalies phase, the active convection anomalies increase rapidly and reach the maximum intensity in the WNP target region 5 days, while it takes 15 days to decay. In the long-period BSISO events, the convection anomalies develop rapidly and decay slowly, which is different from the slow-growing and fast-decaying convective activity found over the eastern Indian Ocean (Chu et al. 2017).

Consistent with previous studies, there is a quasi-quadrature phase relationship between the convection anomalies and their accompanied SST anomalies in asymmetric BSISO events, with the SST anomalies lagging the OLR anomalies by about a quarter of cycle. What is noteworthy is that the amplitude of positive SST anomalies is significantly larger than that of negative SST anomalies. Based on the diagnosis analysis of the SST tendency anomalies and the decomposition of the surface net heat flux, it is found that the amplitude-asymmetric surface downward shortwave radiation flux anomalies are responsible for the amplitude asymmetry of the SST anomalies. The transmission of convection anomalies–induced cloud anomalies to solar radiation makes the increment of surface downward shortwave radiation flux anomalies during the suppressed convection phase greater than the decrement during the active convection phase, which, in turn, results in the asymmetric amplitude of SST anomalies.

The feedback of stronger warm SST anomalies onto the evolution of convection anomalies is investigated from the perspective of surface turbulence flux. Compared with OLR anomalies, the earlier transitions of the latent and sensible heat flux anomalies indicate the existence of oceanic feedback. The earlier transitions of the latent (sensible) heat flux anomalies are caused by the sea–air specific humidity (temperature) difference anomalies, which are dominated by the SST anomalies. When the positive SST anomalies reach the strongest intensity, the positive sea–air specific humidity (temperature) difference anomalies make the latent (sensible) heat flux anomalies no longer dominated by the wind speed anomalies, and the direction of the latent (sensible) heat flux anomalies turns from the downward to the upward, realizing the negative feedback of the ocean onto the atmosphere, and making the convection anomalies transition earlier and faster. It is the amplitude-asymmetric SST anomalies that bring out the phase asymmetry of the convection anomalies.

Along the propagation path of the main body of convection anomalies, the descending (ascending) motion and moisture divergence (convergence) resulted from anomalous anticyclonic (cyclonic) circulation accompanied with suppressed (active) convection anomalies directly lead to the negative (positive) precipitation anomalies over underlying land or sea area. Consequently, in the long-period BSISO events, the variations of precipitation anomalies in the ICP–MC region follow those of OLR anomalies. The precipitation anomalies in SCS, which is on the north side of the ICP–MC region slightly lag those in the ICP–MC region.

In the East Asian region beyond the north limit of the convection propagation, the BSISO events affect the precipitation anomalies mainly by modulating the movement of WNPSH and the associated moisture transport through the accompanied large-scale circulation anomalies. In the long-period BSISO events, a northward propagation of the anticyclonic moisture circulation anomalies at the suppressed convection development stage make WNPSH extend westward
and shift northward slowly. The slow intensifying and northward shifting of moisture transport caused by the southwest wind anomalies on the northwestern flank of the anomalous WNPSH lead to the occurrence of positive precipitation anomalies, which then propagate to MLYRV and reach maximum value there. The weakening and dissipation of the anticyclonic moisture circulation anomalies and the strengthening and northward propagation of the cyclonic moisture circulation anomalies result in a rapid eastward retreat and northward migration of WNPSH at the fast-development stage of active convection anomalies. The rapid reversal of the anomalous wind and associated moisture supply makes the precipitation anomalies over MLYRV experience a rapid transition from the positive to the negative. A schematic diagram shown in Fig. 15 summarizes above mentioned processes of the asymmetric long-period BSISO events over WNP and their influences on the East Asian precipitation, with composite anomalies of OLR, SST, precipitation and associated anomalous large-scale circulation patterns at key phases. The short-period BSISO events act as a northwestward propagation mode with a mean life cycle of 10–20 days. For these events, the convection anomalies originate from the eastern MC and move northwestern until dying over the Bay of Bengal. The development and decay rate of convection anomalies are the same, suggesting no phase asymmetry in the short-period BSISO events.

The phase asymmetry in the long-period BSISO events over WNP and its impact on the East Asian precipitation revealed in this study would provide a new potential for extended-range forecasts of the East Asian summer monsoon. One of the future studies will be on the dynamical mechanism responsible for the phase asymmetry of asymmetric BSISO events more in depth. As mentioned before, atmospheric stability and convergence/divergence in the boundary layer are also approaches of oceanic feedback. Whether and how these processes can play a crucial role in the formation of phase asymmetry is worth examining in future studies.

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Data availability statement. The interpolated daily OLR data are provided by the NOAA/OAR/ESRL/PSC, from their website at https://psl.noaa.gov/data/gridded/data.olr.dr.interp.html. The CFSR data were provided by Research Data Archive at the National Center for Atmospheric Research and are available at https://doi.org/10.5065/D69K4873. The OAFlux data can be downloaded at ftp://ftp.whoi.edu/pub/science/oaflux/data_v3/. The 3D upper-layer oceanic dynamic and thermal elements data from SODA3 version 3.3.1 can be downloaded at https://www2.atmos.umd.edu/~ocean/index_files/soda3.3.1_mn_download.htm. The CPC Unified Gauge-Based Analysis of Global Daily Precipitation data are available at https://climatedataguide.ucar.edu/climate-data/cpc-unified-gauge-based-analysis-global-daily-precipitation.

REFERENCES


Mao, J., Z. Sun, and G. Wu, 2010: 20–50-day oscillation of summer Yangtze rainfall in response to intraseasonal variations in the subtropical high over the western North Pacific and


