Relationship between El Niño–Southern Oscillation and the Symmetry of the Hadley Circulation: Role of the Sea Surface Temperature Annual Cycle

Yi-Peng Guo and Zhe-Min Tan

Key Laboratory of Mesoscale Severe Weather/Ministry of Education, and School of Atmospheric Sciences, Nanjing University, Nanjing, China

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ABSTRACT

El Niño–Southern Oscillation (ENSO), which features an equatorial quasi-symmetric sea surface temperature anomaly (SSTA), is related to both the symmetric and asymmetric components of the Hadley circulation (HC) variability. However, the mechanisms for such a nonlinear HC–ENSO relationship are still unclear. Using 36-yr monthly reanalysis datasets, this study shows that the month-to-month HC variability is dominated by two principal modes, the asymmetric mode (AM) and symmetric mode (SM), both of which are highly correlated with ENSO variability. Furthermore, the relationship between the HC principal modes and the ENSO SSTA is modulated by the western Pacific SST annual cycle. When the zonal mean western Pacific SST peaks off (on) the equator, the ENSO SSTA leads to the AM (SM) of HC variability. This is because the zonal mean western Pacific SST peak provides a warmer background favorable for the SSTA to stimulate convection, indicating the important role of the combined effect of the SST annual cycle and the ENSO SSTA in affecting the HC variability. Importantly, the western Pacific SST annual cycle has no such modulation effect during central Pacific El Niño or La Niña events. The results have important implications for simulating and predicting the climatic impacts of ENSO and HC variability.

1. Introduction

The Hadley circulation (HC), which is a thermally driven meridional circulation in the tropics, plays an important role in balancing the atmospheric mass, energy, and angular momentum between the two hemispheres, as well as between the low and high latitudes (e.g., Held 2001; Kang et al. 2009; Schneider et al. 2010; Friedman et al. 2013). Thus, HC variation can significantly affect global climate variability (Lindzen 1994; Chang 1995; Hou 1998; Held 2001; Trenberth and Stepaniak 2003; Doos and Nilsson 2011). Hence, understanding HC variation and the underlying physical mechanisms is of great importance.

The originally proposed theoretical model depicts the HC as two cells symmetric about the equator, with a common rising branch near the equator (Hadley 1735), whereas subsequent analysis of radiosonde observations suggests that, for most of the year, especially the solstitial seasons, the HC is asymmetric about the equator (hereafter, asymmetric refers to equatorially asymmetric), with rising (descending) motion in the summer (winter) hemisphere (e.g., Oort and Rasmusson 1970; Newell et al. 1972; Peixoto and Oort 1992; Oort and Yienger 1996). Dima and Wallace (2003) further suggested that the annual cycle of the HC is dominated by two components: one is asymmetric about the equator and varies sinusoidally with the annual march, and the other one is a seasonally invariant pair of cells with common rising motion near the equator and subsidence in the subtropics. Later studies suggested that the year-to-year variability of the seasonal mean and annual mean HC is dominated by two principal modes: an equatorial asymmetric mode (AM) and an equatorial symmetric mode (SM) (Ma and Li 2008; Feng et al. 2013; Guo et al. 2016a,b). The AM is characterized by a single cell across the equator, which dominates the HC asymmetry, and the SM is characterized by a pair of cells located on the flanks of the equator with comparable strength but reversed directions, which dominates the HC symmetry. On interannual and even longer time scales, the AM and SM are the two major components dominating the HC variability.
The sea surface temperature anomalies (SSTAs) in the tropics are important to the HC variability. Theoretical work by Schneider and Lindzen (1977) suggested that the meridional tropical SST gradient can drive significant meridional circulation in the lower troposphere as well as moisture convergence, which can produce the HC ascending branch at the latitude of the SST maximum. Lindzen and Nigam (1987) used a simple one-layer model to reveal that the zonal mean low-level meridional flow, which represents the lower branch of the HC, is driven by the zonal mean meridional SST gradient. Additionally, the meridional gradient of the atmospheric heating is critical to the formation of the HC structure (Held and Hou 1980; Lindzen and Hou 1988; Hou and Lindzen 1992). Recent observational studies found a linear relationship between the symmetry of HC anomalies and that of the zonal mean SST: the zonal mean of the equatorial symmetric (asymmetric) SST can lead to equatorially symmetric (asymmetric) HC anomalies (Feng and Li 2013; Feng et al. 2016). Under such linear constraints, El Niño–Southern Oscillation (ENSO) turns out to be an important forcing for the SM owing to its equatorial asymmetry (Harrison and Larkin 1998; Harrison and Vecchi 1999; Vecchi and Harrison 2003, 2006). This counterintuitive finding implies that the symmetry of HC anomalies in response to the ENSO SSTAs may involve nonlinearity.

Previous studies have suggested that a southward shift of surface zonal wind is observed over the central Pacific in boreal winter and spring during ENSO events, and this zonal wind plays a role in terminating El Niño events owing to its equatorial asymmetry (Harrison 1987; Harrison and Larkin 1998; Harrison and Vecchi 1999; Vecchi and Harrison 2003, 2006). Later studies found that this southward shift of zonal wind during ENSO events indicates a nonlinear atmospheric interaction between ENSO and the SST annual cycle over the western Pacific (McGregor et al. 2012, 2013; Stuecker et al. 2013, 2015a,b; Zhang et al. 2015, 2016). Thus, the combination of two modes with different frequencies (annual cycle and interannual variability) can produce a nonlinear atmospheric response—that is, atmospheric circulation responds asymmetrically to the symmetric ENSO forcing. As the HC can also respond asymmetrically to the symmetric ENSO forcing, it is worth questioning whether such a nonlinear response is also related to the combined effect of the SST annual cycle and the ENSO SSTA. Previous studies have discussed the AM and SM based only on the year-to-year variability of the seasonal mean or annual mean HC, without including variability on the near-anual time scale (Ma and Li 2008; Feng et al. 2013; Guo et al. 2016a,b). Thus, the nonlinear relationship between HC symmetry and the ENSO SST is still unclear. However, such a nonlinear relationship is of great importance to our understanding of ENSO’s climatic impacts. To determine this nonlinear relationship, it is necessary to explore it based on the month-to-month variability because this approach does not filter out the near-anual variability induced by the interaction between the SST annual cycle and ENSO interannual variability.

The main purpose of this study is to investigate the principal modes of the month-to-month HC variability and their relationship with the tropical Pacific SST during ENSO events, with consideration of the SST annual cycle. The remainder of this paper is arranged as follows: Section 2 introduces the datasets and methods employed in this study. Section 3 explores the principal modes of the month-to-month variability of the HC. The statistical relationship between the HC principal modes and the ENSO variability is explored in section 4. Section 5 further discusses the underlying mechanisms. Conclusions and discussion are given in section 6.

2. Data and methods

a. Data

We used the monthly mean meridional winds, zonal winds, and vertical velocity from the European Centre for Medium-Range Weather Forecasts interim reanalysis (ERA-Interim) dataset for January 1979 to December 2014 (Dee et al. 2011). The dataset has a horizontal resolution of approximately 0.75° × 0.75° (longitude × latitude) with 60 vertical levels. We also used the monthly mean precipitation dataset (1979–2014) from the Global Precipitation Climatology Project (GPCP) on a 2.5° × 2.5° grid (Huffman et al. 2009) and the monthly mean SST dataset (1979–2014) from the Extended Reconstructed SST version 3b (ERSST v3b) reanalysis on a 2.0° × 2.0° grid (Smith et al. 2008). The precipitation and SST datasets were provided by the National Oceanic and Atmospheric Administration (NOAA) (http://www.esrl.noaa.gov/psd/).

b. Methods

According to the Climate Prediction Center’s definitions of ENSO’s warm and cold phases, which is a ±0.5-K threshold of the Niño-3.4 index (defined as the areal mean SSTA over the region 5°S–5°N, 120°–170°W), 10 El Niño events (1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03, 2004/05, 2006/07, 2009/10) and 7 La
The El Niño events (1983/84, 1988/89, 1995/96, 1998/99, 2005/06, 2007/08, 2010/11) were selected for composite analysis. The El Niño events could be further divided into two subtypes—eastern Pacific (EP) El Niño and central Pacific (CP) El Niño—according to their warming center locations (e.g., Ashok et al. 2007). The relative magnitudes of the Niño-3 index (defined as the areal mean SSTA over the region 5°S–5°N, 170°W–110°W) and the Niño-4 index (defined as the areal mean SSTA over the region 5°S–5°N, 160°E–150°W) are usually applied to identify EP and CP El Niño events (Kim et al. 2009; McPhaden et al. 2011; Zhang et al. 2015). Four EP El Niño events (1982/83, 1986/87, 1991/92, 1997/98) were identified with a Niño-3 index larger than the Niño-4 index, and the other six events (1987/88, 1994/95, 2002/03, 2004/05, 2006/07, 2009/10) were identified as CP El Niño events. It is worth noting that the 2006/07 El Niño event is recognized as EP type in McPhaden et al. (2011) or mixed type in Yu and Kim (2013) because of the different SST data or method employed. To reduce the uncertainty of the HC response to EP type El Niño, we categorized the 2006/07 El Niño event as CP type. Categorizing 2006/07 as an EP type will not change the main conclusion; however, it acts to slightly weaken the HC response.

The meridional mass streamfunction (MSF) was employed to depict the spatial structure of the HC. Positive (negative) values of the MSF denote clockwise (anticlockwise) meridional circulations. The MSF is derived from the zonal mean continuity equation and can be calculated by vertically integrating the zonal mean meridional wind (e.g., Oort and Yienger 1996). The monthly MSF anomalies with respect to the base period of 1979–2014 were analyzed in this study. The empirical orthogonal function (EOF) analysis was used to extract the principal modes of the HC variability. To obtain the ENSO combination mode, the surface zonal wind at 10 m was applied to the EOF analysis. This is slightly different from the approach used in previous studies, in which surface zonal and meridional wind anomalies at 10 m were combined for EOF analysis (McGregor et al. 2012; Stuecker et al. 2013, 2015a,b; Zhang et al. 2015, 2016). We also used composite and linear regression analysis to investigate the possible impacts of ENSO and the SST annual cycle on the HC’s principal modes. To take account of the effects of both the SST annual cycle and ENSO SSTA interannual variability, the monthly mean variables were all subjected to a 6–120-month bandpass Lanczos filter (Duchon 1979) to obtain the variability on near-annual to interannual time scales (Stuecker et al. 2013). The statistical significance of the results was estimated by using a two-tailed Student’s t test.

3. Principal modes of the month-to-month HC variability

Figure 1 shows the first two EOF modes and the corresponding principal components (PCs) of the monthly MSF anomalies during 1979–2014. The EOF-1 mode, which explains 31.3% of the total variance, exhibits a single cell across the equator. It is located between 10°S and 10°N with upward and downward branches on the flanks of the equator (Fig. 1a). The EOF-1 mode is named as the AM in this study owing to its equatorially asymmetric structure, and the corresponding PC-1 is defined as the AM index (AMI). The correlation coefficient between the AMI and Niño-3.4 index is 0.4, which is statistically significant at the 99% confidence level when taking account of the reduced effective degrees of freedom. It is also clear that there is a shift between the AMI and Niño-3.4 index time series (Fig. 1c). The correlation coefficient is 0.52 when the AMI is correlated with the Niño-3.4 index at a 3-month lag. These results imply that the AM has a lagged relationship with ENSO variability.

The EOF-2 mode explains 18.2% of the total variance and shows a pair of cells located on the flanks of the equator, with one common ascending branch within the equatorial belt and two descending branches in each hemisphere (Fig. 1b). The Southern Hemisphere cell is about 25% stronger than the Northern Hemisphere cell. Although the EOF-2 mode is not fully symmetric about the equator, for convenience it is still called the SM and the corresponding PC-2 is defined as the SM index (SMI). The correlation coefficient between the SMI and the Niño-3.4 index reaches 0.65, exceeding the 99% confidence level. This is consistent with a previous study that found that the equatorially symmetric ENSO SSTA tends to drive a symmetric HC anomaly (Feng and Li 2013), which corresponds to the SM. Based on the rule given by North et al. (1982), the AM and the SM can be statistically distinguished from the other eigenvectors, which means that the AM and SM are statistically independent modes.

Figure 2 shows a cross section of the anomalous meridional circulation and vertical velocity regressed upon the AMI and SMI, respectively. The AM is associated with strong upward motion at about 8°S in the Southern Hemisphere and downward motion at about 8°N in the Northern Hemisphere, and the cross-equatorial upper southerly and lower northerly wind anomalies, respectively (Fig. 2a). In contrast, the SM is characterized by strong upward motion in the equatorial belt around 2°N and downward motion in both hemispheres centered at about 14°S and 10°N, respectively (Fig. 2b). The results further highlight the different spatial structures of these two modes.
4. Statistical relationship between the HC principal modes and ENSO

Previous studies have suggested that the meridional shift in surface zonal wind during El Niño events is modulated by the SST annual cycle (McGregor et al. 2012, 2013). To investigate the possible modulation of HC anomalies by the SST annual cycle, we would first compare the spatial and temporal features of the surface wind variability associated with El Niño events and the HC principal modes.

a. Tropical Pacific surface wind variability related to ENSO and the HC principal modes

The surface wind variability over the tropical Pacific is largely driven by the ENSO SSTA. To obtain the dominant modes of the surface wind variability, an EOF
analysis was applied to the U10 anomalies over the equatorial Pacific region (10°S–10°N, 100°E–80°W) for 1979–2014. Vectors only show the winds exceeding the 95% confidence levels. The black dashed line indicates the equator. The values in the top-right corners indicate the explained variance for the EOF-1 and EOF-2 modes of the U10 variability, respectively.

In comparison, Fig. 4 shows the anomalies of surface winds and U10 regressed on the AMI and SMI, respectively. The surface wind pattern associated with the AMI captures a southward shift of the zonal wind anomalies, which is accompanied by the cross-equatorial meridional wind anomalies (Fig. 4a), while the pattern associated with the SMI captures large positive anomalies on the equator and anomalous convergence in the Pacific equatorial belt (Fig. 4b). It is interesting that the AMI-regressed surface wind pattern (Fig. 4a) is very similar to that of the C-mode (Fig. 3b), with a pattern correlation coefficient of 0.8, and the SMI-regressed surface wind pattern (Fig. 4b) resembles that associated with the EOF-1 mode of U10 variability (Fig. 3a), with a pattern correlation coefficient of 0.78. The correlation coefficient between the time series of U10_PC1 and SMI is 0.49 \((p < 0.05)\), and that between the C-mode index and AMI is 0.61 \((p < 0.05)\), both of which increase to 0.68 if the HC is confined within the Pacific region (100°E–80°W). This indicates that the main forcing for the AM and SM is in the Pacific region. These results indicate that the SM is driven by the typical SSTA of the ENSO mature phase, and the AM may be driven by the combined effect of ENSO variability and the SST annual cycle over the western Pacific. The following section further explores
the relationship between the HC principal modes and ENSO variability.

It is worth pointing out that the cross-equatorial meridional wind in response to the thermal forcing is nearly 4 times stronger than the equatorial symmetric meridional wind response (Feng et al. 2016), which means that the AM has larger variance than the SM. This is why the AM explains more variance than the SM, while the EOF-1 of U10 variability explains more variance than the ENSO C-mode.

The wind anomalies regressed upon the C-mode index and AMI are northeasterly over the western North Pacific and westerly over the southern central Pacific. The northeasterly (westerly) wind anomalies over the western North Pacific (southern central Pacific) can enhance (weaken) the original wind speed (Fig. 5), which cools (warms) the SST in the corresponding region. The SSTA pattern can in turn enhance the surface wind pattern, following a wind–evaporation–SST feedback (Xie et al. 2009).

b. Lead–lag relationship between the HC principal modes and ENSO variability

To further examine the relationship between the HC principal modes and ENSO variability, Fig. 6a shows the lead–lag correlation of the Niño-3.4 index with the U10 PC1 (triangle line), C-mode index (diamond line), SMI (circle line), and AMI (red dotted line), (b) Composite temporal evolutions of the Niño-3.4 index (solid black line), C-mode index (diamond line), U10 PC1 (triangle line), SMI (circle line), and AMI (red dotted line).

The contour intervals are $2 \times 10^{-3}$ Pa s$^{-1}$.
Given that the EP El Niño has stronger control over the surface wind meridional asymmetry than CP El Niño and La Niña events (McGregor et al. 2012; Zhang et al. 2015), the effect of EP type events on HC asymmetry is discussed independently. Figure 6b shows the composite temporal evolutions of the Niño-3.4 index, U10_PC1, C-mode index, AMI, and SMI based on the four EP El Niño events (1982/83, 1986/87, 1991/92, 1997/98). The notations ‘(0)’ and ‘(1)’ represent the months in the developing and decaying years of the EP El Niño events, respectively. The Niño-3.4 index, U10_PC1, and SMI reach their peak values simultaneously during December(0)–January(1), whereas the AMI and C-mode index reach their peak values in February(1)–March(1), which have an approximately 2- to 3-month lag with respect to the El Niño peak phase. The above results indicate that during an El Niño event, the SMI becomes the strongest at the El Niño’s peak phase, whereas the AM lags El Niño’s peak phase by several months. The physical mechanism for the above HC–ENSO relationship is investigated in the following section.

5. Physical mechanism

To illustrate how the SST annual cycle modulates the relationship between the HC principal modes and ENSO variability, Fig. 7 shows zonally averaged time–latitude sections of the composite evolutions of the SST, the SSTA, and the anomalous vertical velocity at 500 hPa over the longitudinal band of 140°E–130°W for the four EP El Niño events. The composite SSTA is symmetric about the equator, with the maximum SSTA on the equator throughout the EP El Niño events, while the total SST moves meridionally north and south following the annual cycle of solar insolation (Vecchi and Harrison 2003; Spencer 2004; Lengaigne et al. 2006; McGregor et al. 2012; Stuecker et al. 2013, 2015a,b; Zhang et al. 2015). The climatological SST provides the warm background state for the ENSO SSTA to trigger convection, and the dominant convection occurs in the region where the SSTA is positive and the SST is warmer than 28 K, which is an approximate threshold for convection occurrence (Gadgil et al. 1984; Graham and Barnett 1987).

From July(0) to September(0), the warmest SSTs are located in the Northern Hemisphere. A positive SSTA overlapped on a highly warmed background can excite the strongest convection at about 5°N and lead to an equatorially asymmetric HC anomaly (Fig. 8a). During October(0)–December(0), the SSTA on the equator is slightly lower than that on its flanks, but both the SST and the SSTA are symmetric about the equator; thus, the maximum convection occurs nearly on the equator, indicating an equatorially symmetric HC anomaly (Fig. 8b). During January(1)–April(1), the mean position of the warmest SST moves into the Southern Hemisphere, and hence the convection shifts southward to about 4°S, which also leads to an asymmetric HC anomaly but with the ascending branch in the Southern Hemisphere (Fig. 8c). The position of the maximum convection in January(1)–April(1) coincides with that of the AM’s upward
FIG. 8. Composite anomalies of the MSFs (contours; units: $10^9$ kg s$^{-1}$) and vertical velocity (shading; units: $10^{-3}$ Pa s$^{-1}$) during (a) July(0)–September(0), (b) October(0)–December(0), and (c) December(0)–April(1). Stippling indicates the values exceeding the 95% confidence level.
branch (Fig. 1a), which further confirms that the AM is driven by the combined effect of the climatological SST and the ENSO SSTA. The asymmetric HC anomaly and the maximum convection in January(1)–April(1) is much stronger than those in July(0)–September(0), which may be due to the warmer climatological background SST in the central Pacific Southern Hemisphere during January–April than its counterpart in the Northern Hemisphere during July–September (Fig. 5).

We also show the composite MSF anomalies based on the selected CP El Niño and La Niña events (Fig. 9). For both the CP El Niño and La Niña events, the HC anomalies show no asymmetric structure, even though the South Pacific convergence zone (SPCZ) warms during January(1)–April(1). During October(0)–December(0), the HC anomalies show SM-like structures for both the CP El Niño and La Niña events, but with reversed signs (Figs. 9b,e), which indicates that the CP El Niño and La Niña events only induce symmetric HC anomalies. The lack of an asymmetric HC response to CP El Niño events may be induced by the different spatial structure of the SSTA from that of the EP El Niño events, but it still needs further investigation to verify. For La Niña events, the wind anomalies increase the total wind speed, which limits the southward shift of the surface wind anomalies (McGregor et al. 2012, 2013).

Figure 10 shows the horizontal divergent wind anomalies at 200 hPa and precipitation anomalies during the three periods in the EP El Niño events. In July(0)–September(0), the SST in the central and eastern Pacific intertropical convergence zone is much higher than that in the Southern Hemisphere, as indicated by the 28-K SST isotherm (Fig. 10a). The northern side of the EP El Niño’s positive SSTA overlaps with the warm SST and triggers a convection
belt (denoted by precipitation anomalies) and off-equatorial divergence in the Northern Hemisphere (Fig. 10a), which indicates asymmetric HC anomalies (Fig. 8a). In October(0)–December(0), however, the SST is approximately symmetric about the equator, the convection induced by the SSTA is confined within the equatorial western Pacific, and the strongest divergence occurs on the equator (Fig. 10b), which leads to symmetric HC anomalies (Fig. 8b). In January(1)–April(1), the SST warms up in the SPCZ. The warm SPCZ combined with the positive ENSO SSTA to the south of the equator shifts the maximum convection southward to about 5°S over the central Pacific (150°W–180°), accompanied by strong divergence in the upper troposphere (Fig. 10c). The anomalous divergence is much stronger than that in the other two periods, which may be attributed to the combination of the large ENSO SSTA during this time of the year and the high climatological SST in the SPCZ, which leads to the high total SST (Fig. 7). Figure 10c also suggests that the asymmetric HC anomalies correspond to positive precipitation anomalies and upper-level divergence in the central Pacific Southern Hemisphere and negative precipitation anomalies and upper-level convergence in the western North Pacific. These results imply a low-level anticyclone over the western North Pacific stemming from the combined effect of the climatological SST and ENSO SSTA, as suggested by Stuecker et al. (2015a,b).

Furthermore, the vertical velocity at 500 hPa (W500) was regressed on the AMI and SMI, respectively (Fig. 11). The AM corresponds to enhanced upward motion over the southern central Pacific around 150°W, whereas the SM corresponds to enhanced upward motion on the equator around 180°. These anomalous vertical velocity patterns are in good agreement with the precipitation anomalies shown in Fig. 10. Comparing the W500 anomalous patterns to the climatological W500 and SST during the three periods (Figs. 5 and 11) further suggests that the AM is induced by the seasonal warming of the central Pacific in the Southern Hemisphere. As the SST seasonal variation matches well with that of the vertical velocity (Fig. 5), it can also be inferred that the precipitation induced by the warming SST in the Southern Hemisphere plays an important role in inducing the AM.

From a zonal mean perspective, Fig. 12 schematically summarizes how the SST and the ENSO SSTA combine to affect the formation of the AM and SM. During the whole ENSO cycle, the zonal mean SST is always quasi-symmetric about the equator, and peaks on the equator. However, in July(0)–September(0) and January(1)–April(1), the zonal mean SST peaks off the equator (Figs. 12a,c), providing a warmer background for the off-equatorial SSTA and triggering off-equatorial convection, which play an important role in affecting the AM formation (denoted by the cross-equatorial cell in Figs. 12a and 12c). In contrast, in the late autumn [October(0)–December(0)], the western Pacific SST is approximately symmetric about the equator. Although the equatorial SST is slightly smaller than that on its flanks, the ENSO SSTA peaks on the equator, which can drive a symmetric HC anomaly (Fig. 12b). The above results indicate that, although the ENSO SSTA exhibits an equatorial quasi-symmetric structure, it can induce both the formation of the AM and SM via a modulation of the SST annual cycle over the western Pacific.

6. Conclusions and discussion

We investigated the relationship between the HC month-to-month variability on near-annual to
interannual time scales and ENSO with consideration of the modulating effect of the SST annual cycle. The results show that the HC month-to-month variability on near-annual to interannual time scales is dominated by two principal modes, the AM and the SM, both of which are closely related to the ENSO SSTA in the tropical Pacific. The correlation patterns of the tropical Pacific SSTA with the AMI and SMI show different spatial structures: the former is asymmetric about the equator, while the latter is symmetric about the equator. Further analysis suggested that the western Pacific SST annual cycle plays an important role in modulating the HC–ENSO relationship, which is schematically summarized in Fig. 12. When the western Pacific SST peaks off the equator, the SSTA off-equatorial parts are more likely to trigger convections and leads to asymmetric HC anomalies because of a warmer background state off the equator (Figs. 12a,c); whereas, when the western Pacific SST is symmetric about the equator, such as in late autumn, convection tends to occur on the equator because both the background SST and the SSTA are symmetric about the equator (Fig. 12b). As previous studies suggested that the equatorially asymmetric SSTA is critical to the AM of the HC year-to-year variability (Feng et al. 2013; 2016), the possible impact of the asymmetric SSTA on the AM of the HC month-to-month variability was also evaluated. We defined an asymmetric SST index (ASSTI) as the difference of the areal mean SSTA between the western North Pacific (5°–15°N, 150°–170°E) and southern central Pacific (5°–15°S, 110°–160°W). The AMI is related to the ASSTI with a correlation coefficient of 0.47 (statistically significant at the 95% confidence level). This asymmetric SSTA may arise as a response to the forcing of the cross-equatorial wind following the wind–evaporation–SST feedback (Xie et al. 2009), which in turn enhances the cross-equatorial wind. The results in this study extend the current understanding of the HC–ENSO relationship, which may help to
FIG. 12. Schematic illustration of showing how the SST annual cycle modulates the impact of ENSO on the HC symmetry. The red shapes between 10°S and 10°N indicate the zonal mean SSTA associated with the EP El Niño events over the central Pacific. The blue lines indicate the zonal mean SST over the western Pacific. The solid black lines indicate the HC anomalies and the arrows on the black lines indicate the circulation direction. Note that the SSTA is constantly symmetric about the equator during an EP El Niño’s lifetime, while the annual cycle of the zonal mean SST over the western Pacific provides a symmetric (asymmetric) thermal background in (middle) October(0)–December(0) [(top) July(0)–September(0) and (bottom) January(1)–April(1)], which leads to the anomalous HC symmetry (asymmetry) in the corresponding period.
improve the predictions of the climatic impacts of both the HC and ENSO variability.

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