Contrasting Responses of the Hadley Circulation to Equatorially Asymmetric and Symmetric Meridional Sea Surface Temperature Structures

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ABSTRACT

The impacts of different meridional structures of tropical sea surface temperature (SST) on the Hadley circulation (HC) in the annual mean are investigated during the period 1948–2013. By decomposing the variations in SST and the HC into two components—that is, the equatorially asymmetric (SEA for SST, and HEA for HC) and the equatorially symmetric (SES for SST, and HES for HC) parts—it is shown that the long-term variability in SEA and SES captures well the temporal variations in equatorially asymmetric and symmetric variations in SST. The variation in HEA is closely linked to that of SEA, and the variation in HES is connected with that of SES. However, the response of HEA to a given amplitude variation in SEA is stronger (by ~5 times) than that of HES to the same amplitude variation in SES. This point is further verified by theoretical and numerical models, indicating that the meridional structure of SST plays a crucial role in determining the anomalies in HC. This result may explain why the principal mode of HC is dominated by an equatorially asymmetric mode in its long-term variability.

1. Introduction

The tropical Hadley circulation (HC) is defined as the zonal mean meridional mass circulation in the atmosphere bounded roughly by 30°S and 30°N. It is one of the most important and largest atmospheric circulations. The HC is mainly a thermally driven circulation, with warmer air rising in the tropics because of the release of
latent heat and colder air sinking in the subtropics in both hemispheres, generating a closed circulation in each hemisphere (Held and Hou 1980). This circulation is characterized by equatorward mass transport by the prevailing trade wind flow in the lower troposphere and poleward mass transport in the upper troposphere. The HC plays an essential role in the global climate system. It transports not only heat from the tropics to the subtropics and to high latitudes through extratropical eddies, but also momentum to the subtropics (Lindzen 1994; Hou 1998). Both heat and momentum transports have significant influences on the subtropical jet streams. Therefore, the HC has an important impact on global climate (Diaz and Bradley 2004; Feng et al. 2013).

In recent years there has been growing interest in the changes in the HC. Studies have focused on two key problems: one is the intensity of the HC, and the other is its meridional extent (Hu and Zhou 2009). Wielicki et al. (2002) and Chen et al. (2002) suggested that the annual mean HC intensified in the 1990s. Subsequently, the variations in the seasonal mean HC have been discussed in many studies. The variations in the HC during boreal winter [December–February (DJF)] have been extensively explored, and an obvious strengthening trend has been observed. For example, Quan et al. (2004) reported that the HC has strengthened since the 1950s. Similar results have been obtained in other studies for different datasets or periods (Hu et al. 2005; Mitas and Clement 2005; Ma and Li 2007, 2008). A similar intensifying trend is seen in boreal spring [March–May (MAM); Feng et al. (2013)]. In boreal summer [June–August (JJA)], the HC shows minor changes (e.g., Quan et al. 2004; Tanaka et al. 2004; Mitas and Clement 2006; Feng et al. 2011). With respect to the meridional extent of the HC, results from several recent studies (e.g., Fu et al. 2006; Hu and Fu 2007; Seidel and Randel 2007) suggest that the HC has expanded poleward since 1979, by 1.21°–5° latitude in different seasons and in different datasets (Hudson et al. 2006; Lu et al. 2007; Johanson and Fu 2009).

In addition to the strength and extent of the HC, its long-term variability has been investigated, as well as its relationship with sea surface temperature (SST) (e.g., Feng et al. 2011; Feng and Li 2013; Guo et al. 2016). In particular, the long-term variability in HC has been discussed using empirical orthogonal function (EOF) analysis to explore its spatiotemporal characteristics. For example, focusing on the seasonal cycle, Dima and Wallace (2003) found that the HC is dominated by two components with comparable mean-square amplitudes, one equatorially symmetric and the other equatorially asymmetric. The two modes vary sinusoidally with the seasonal cycle. As for the year-to-year variability in the seasonal mean HC, Ma and Li (2007, 2008) reported that the principal modes of boreal winter HC include an equatorially asymmetric and an equatorially symmetric mode; the two modes are connected to SST variations over the Indo-Pacific warm pool and tropical Pacific, respectively. Similar results have been reported for the long-term variability in the boreal summer HC (Feng et al. 2011; Sun and Zhou 2014). The equatorially asymmetric modes in boreal winter and summer mirror the climatological structure of the HC, as it is equatorially asymmetric in both boreal winter and summer. Further research by Feng et al. (2013) and Guo et al. (2016) showed that the first two principal modes of boreal spring and autumn [September–November (SON)] HC are an equatorially asymmetric and an equatorially symmetric mode. Their results indicate that inhomogeneous warming of SST over the tropical oceans contributes to the formation of the equatorially asymmetric mode (Feng et al. 2013; Li et al. 2013). These studies highlight the role of the SST meridional gradient in the variations of the HC, as seen in observations and numerical experiments; however, they do not explain why the equatorially asymmetric mode dominates the long-term variability of the HC.

In fact, theoretical and numerical studies have established that the meridional structure of tropical SST may change the strength and position of the ascending branch and convergence by adjusting the convergence process and thermal structure of the atmosphere (Schneider and Lindzen 1977; Rind and Rossow 1984). Theoretical work by Lindzen and Nigam (1987) indicates that meridionally inhomogeneous variations in SST lead to changes in the meridional gradient of SST, which in turn influence the boundary layer wind and vertical motion in the lower troposphere. Later work has also shown that convergence in the lower troposphere is sensitive to the meridional distribution of the heating profile (Lindzen and Hou 1988; Hou and Lindzen 1992). These studies indicate that the meridional distribution of tropical SST may have a considerable impact on the convergence in the lower troposphere. In previous studies, we also reported that the position of the anomalous ascending branch of the HC is linked to the meridional gradient of tropical SST (Feng et al. 2013; Feng and Li 2013).

Thus, it is clear that the meridional structure of SST is a key influence on the spatial structure of the HC. Moreover, it is found that the equatorially asymmetric mode dominates the variability of the HC in both long-term seasonal variations and its seasonal cycle, even in the transition seasons (i.e., boreal spring and autumn), when the HC is equatorially symmetric in the climatology. This suggests that the HC may respond differently
to different SST meridional structures. Therefore, the response of the HC to equatorially asymmetric thermal forcing may be greater than to equatorially symmetric forcing, thus contributing to the formation of the equatorially asymmetric mode of the HC. Understanding this issue would further our understanding of the variability of the HC and help us to assess the responses of the HC to different SST meridional structures. Here we focus on this issue by separating the variations in SST into two components, the equatorially asymmetric and symmetric, and examining their respective influences on the HC.

The remainder of this paper is organized as follows. The datasets, methodology, and models are described in section 2. Section 3 outlines the climatological features of the annual mean HC and zonal mean SST, as well as their principal modes. Section 4 demonstrates the responses of the HC to different SST meridional structures in reanalysis data, and section 5 shows the results from the theoretical and numerical models. Section 6 presents a simple theoretical deduction for the observation and model results. Finally, conclusions and a discussion are presented in section 7.

2. Datasets, methodology, and models

a. Datasets

The atmospheric fields are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), with 2.5° × 2.5° horizontal resolution. The two global SST reanalysis datasets are from the improved Extended Reconstructed SST (ERSST) on a 2° × 2° grid (Smith and Reynolds 2004), and the Met Office Hadley Centre Sea Ice and SST dataset (HadISST) gridded at 1° × 1° resolution (Rayner et al. 2003). We focus on the period from 1948 to 2013 and consider the annual mean.

b. Methodology

The HC is characterized by the mass streamfunction \( \psi \) of the mean meridional circulation. Clockwise circulation (the northern cell) is defined as positive and anticlockwise circulation (the southern cell) is defined as negative. Using pressure as the vertical coordinate, the conservation of mass requires

\[
\frac{1}{a \cos \phi} \frac{\partial u}{\partial \lambda} + \frac{1}{a \cos \phi} \frac{\partial (v \cos \phi)}{\partial \phi} + \frac{\partial \omega}{\partial p} = 0, \tag{1}
\]

zonally averaged around the entire globe. The first term in Eq. (1) goes to zero, giving

\[
\frac{1}{a} \frac{\partial [v]}{\partial \phi} + \frac{\partial [\omega]}{\partial p} = 0. \tag{2}
\]

Thus, we have

\[
[v] = \frac{g}{2\pi a \cos \phi} \frac{\partial \psi}{\partial p} \quad \text{and} \quad [\omega] = -\frac{g}{2\pi a^2 \cos \phi} \frac{\partial \psi}{\partial \phi}, \tag{3}
\]

where \([\psi]\) is the zonal mean meridional wind, \(a\) is the mean radius of Earth, \(\phi\) is latitude, \(g\) is gravitational acceleration, and \(p\) is pressure. The overbars and square brackets represent temporal and zonal averaging, respectively. Note that \([\omega]\) is an indirect variable and is obtained from zonal and meridional winds. Here, to reduce errors we integrate Eq. (3) involving the meridional wind from the top of the atmosphere, where it is assumed that \(\psi = 0\) and \(p = 0\), yielding

\[
\psi(\phi, p) = \frac{2\pi a \cos \phi}{g} \int_0^p [v(\phi, p)] \, dp. \tag{4}
\]

To examine the influence of the meridional structure of SST on the HC, we separate the variations in SST and HC into two components: the equatorially asymmetric and the equatorially symmetric parts. For the variations in SST, the equatorially asymmetric (i.e., SEA) and symmetric (i.e., SES) parts are, respectively, defined as

\[
\begin{align*}
\text{SEA}(j) &= \frac{\text{SST}(j) - \text{SST}(-j)}{2} \\
\text{SES}(j) &= \frac{\text{SST}(j) + \text{SST}(-j)}{2}.
\end{align*}
\tag{5}
\]

For the HC, since the MSF values in the two hemispheres are opposite, the equatorially asymmetric (i.e., HEA) and symmetric (i.e., HES) components are defined as follows:

\[
\begin{align*}
\text{HEA}(j) &= \frac{\text{MSF}(j) + \text{MSF}(-j)}{2} \\
\text{HES}(j) &= \frac{\text{MSF}(j) - \text{MSF}(-j)}{2},
\end{align*}
\tag{6}
\]

where \(j\) and \(-j\) are equatorially symmetric meridional positions. In addition, two SST indices defined by Feng and Li (2013), the meridional asymmetric SST index (MASI) and the meridional symmetric SST index (MSSI), are employed to further examine the meridional structure of tropical SST variations. The MASI and MSSI are defined as follows:

\[
\begin{align*}
\text{MASI} &= 0.5 \times \left[ \text{SSTA}_{(15^S-5^S)} + \text{SSTA}_{(15^N-15^N)} \right] \quad \text{and} \\
\text{MSSI} &= \text{SSTA}_{(15^S-5^S)} - \text{SSTA}_{(15^N-5^N)}. \tag{7}
\end{align*}
\]

The SSTA in the Eqs. (7) and (8) is for the SST anomalies removing the annual cycle, and the subscripts are
for the areal mean over the specified region. Note that to enable a direct comparison between the indices above and the decompositions, the sign of the MASI here is reversed compared with Feng and Li (2013). And we further simplify the MSSI to facilitate a direct comparison with the MASI.

The index of annual mean HC intensity (HCI) is defined as the maximum of the absolute value of the annual mean MSF between 30°S and 30°N (Oort and Yienger 1996). EOF analysis is employed to determine the principal mode of year-to-year variability of long-term annual mean MSF and the equatorially symmetric and asymmetric variabilities of the zonal mean SST and MSF. Regression and correlation methods are employed to detect the relationships between SST and the HC.

c. Models

Gill (1980) elucidated the responses of the tropical atmosphere to isolated equatorially symmetric heating in a resting atmosphere using linear shallow-water equations. Recently, Xing et al. (2014) explored the response of the atmosphere by adopting Gill’s model with detailed influences, including the location, strength, and extent of heating. Gill’s model is known to be a simple and useful theoretical model for exploring the response of the tropical atmosphere to a given distribution of heating in the tropics (e.g., Chao and Wang 1991; Ratnam et al. 2012). The steady-state version of the one-layer nondimensional equations following Gill (1980) may be written as follows:

\[ e \frac{1}{2} u \frac{\partial p}{\partial x} = -\frac{\partial p}{\partial x}, \]  
\[ e \frac{1}{2} v \frac{\partial p}{\partial y} = -\frac{\partial p}{\partial y}, \]  
\[ e p + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -Q, \quad \text{and} \]  
\[ w = ep + Q, \]  

where \((x, y)\) is nondimensional distance, with \(x\) and \(y\) representing eastward and northward distances from the equator, respectively; \((u, v)\) is proportional to horizontal velocity; \(p\) is proportional to the pressure perturbation; \(Q\) is proportional to the heating rate; \(w\) represents vertical velocity; and \(e\) is a decay factor.

The atmospheric general circulation model employed is the NCAR Community Atmospheric Model, version 5 (CAM5; Collins et al. 2006). This model is able to reproduce observed climate features (e.g., Feng and Li 2013) and serves as the atmospheric component of the Community Climate System Model (CCSM). The horizontal resolution is spectral T42 (approximately 2.8° × 2.8°), with 26 hybrid vertical levels (a complete description of this model version is available online at http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/ug5_0/ug.html).

3. Climatological features of the Hadley circulation and zonal mean SST

a. Hadley circulation

Figure 1 displays the climatological annual mean MSF and its first principal mode during the period 1948–2013. The contour interval is 0.015 × 10^{10} kg s^{-1}. (b) Principal mode of the annual mean HC during 1948–2013. Positive (negative) contours are shown as solid (dotted) lines. The contour interval is 0.015 × 10^{10} kg s^{-1}. (c) Time series of the principal mode of the annual mean HC (×10^{10} kg s^{-1}).
and a descending branch in the Northern Hemisphere. In contrast, the counterpart in the Southern Hemisphere is weak, with a descending branch positioned south of 30°S. The first principal mode here is similar to those observed in the seasonal long-term variations in the HC (Ma and Li 2008; Feng et al. 2011, 2013; Guo et al. 2016). Moreover, this mode has exhibited a significantly strengthened trend during the past six decades. The time series of this mode underwent a decadal transformation from negative to positive values during the late 1970s, which coincides with the timing of an interdecadal shift in tropical climate (e.g., Mantua et al. 1997; Xiao and Li 2007). The intensification of this mode is similar to the observed trend in the HCI, suggesting that intensification of the annual mean HC may be due to the variations in this mode. The strong correlation between these latter two factors ($r = 0.77$) supports this view.

The above result indicates that the year-to-year variability in long-term annual mean HC is dominated by an equatorially asymmetric mode that intensified during the period 1948–2013, and this variability contributes to the strengthening of the annual mean HC.

### b. Zonal mean SST

Figure 2 shows the distribution of the climatological annual zonal mean SST within the tropics and its first principal mode determined from the ERSST and HadISST data during 1948–2013. For the climatological mean, the zonal mean tropical SST shows two peaks symmetrically positioned about the equator. However, the peak value in the Northern Hemisphere is significantly larger than that in the Southern Hemisphere. This is in agreement with the average position of the annual mean intertropical convergence zone (An et al. 2015), to the north of the equator, as determined by the larger ocean area in the Southern Hemisphere. The first mode explains 88.6% (86.3%) of the total variance of the zonal mean SST variation based on ERSST (HadISST), representing the fundamental variability of zonal mean SST. This pattern shows a stronger value around the equator that decreases with latitude, resembling the proposed enhanced equatorial response (i.e., a stronger warming near the equator than in the subtropical Pacific) reported in Liu et al. (2005) and Xie et al. (2010). Although there is some inconsistency in amplitude between the two SST reanalyses, both show a consistent equatorially asymmetric structure, with larger values in the Southern Hemisphere; that is, the warming rate in the tropical Southern Hemisphere is higher than that in the Northern Hemisphere. The tendency here is different from that presented in Xie et al. (2010), which indicated a tendency for a greater warming in the northern subtropics than in the southern subtropics. Here, we focused on the global mean; however, only the Pacific is focused on in Xie et al. (2010). The principal component (PC) of this mode shows a clear upward trend, indicating significant warming in the tropical oceans; it also implies that the warming difference...
between the two tropical hemispheres has increased over time.

The HC is a thermally driven circulation, and its variations are closely linked to the underlying thermal structure. We therefore examine the possible linkage between the long-term variability of the annual mean HC and zonal mean SST. The correlation coefficient between the PCs of their first principal modes is 0.69, indicating that the tropical ocean warming is closely related to the long-term enhancement of the equatorially asymmetric modes.

4. Responses of the Hadley circulation to different meridional SST structures

We decompose the HC into two components, HEA and HES, as described in section 2b. Figure 3 shows their climatological spatial distribution and corresponding standard deviations. The climatological HEA (upper) extends from 30°S to 30°N, centered at the equator; its largest variability is around the equator. In contrast, the climatological HES contain two mirrored cells (below), with a combined ascending branch located at the equator and two descending branches positioned in the subtropics in each hemisphere. The HES is stronger than the HEA, but they have equivalent extent, while the variability of the HEA is much larger than that of the HES. In addition, the most variable parts of both the HEA and HES are located in the tropics, further indicating that the tropical Hadley circulation is the most prominent meridional circulation. These results show that the HEA and HES are distinct in both intensity and variability: the intensity of HES is larger, while the variability of HEA is larger. This point is consistent with the equatorial asymmetry of the first principal mode of the HC.

Figure 4 displays the meridional climatological distributions of zonal mean SST for the two components and their corresponding standard deviations. Although there is some disagreement between the two SST reanalyses (i.e., ERSST and HadISST), the spatial structures show consistent features. The amplitudes of SEA and SES are equivalent in the tropics. The variability is zero at the equator for the SEA and increases with increasing latitude. In contrast, the maximum variability of the SES is located around the equator and decreases with latitude.

We further examined the evolution of long-term variability in the HEA and HES. The principal modes as well as their corresponding time series are shown in Fig. 5. The first principal mode of SEA is similar to its climatological structure, with equatorial asymmetry, and explains 76.3% of the variance. The time series of this mode exhibits strong interdecadal variations and undergoes a decadal transformation from negative to positive values during the late 1970s. That is, the phase of the principal mode of the HEA changed at the same time as an interdecadal shift in tropical climate (e.g., Mantua et al. 1997; Xiao and Li 2007). Meanwhile, the first principal mode of HES is equatorially symmetric, with an explained variance of 63.5%, and the time series of this mode displays a long-term upward trend. The correlation coefficients of the PCs of the two modes and the climatology mean HC (HEA and HC, HES and HC) are 0.98 and 0.83, respectively. However, the correlation drops to −0.08 for the HES and HC when the linear trend is removed, while remaining at 0.98 for the HEA and HC, indicating that HES mainly represents
the long-term linear trend of the HC, while HEA refers to the interdecadal variations of the HC.

As for the zonal mean SST, the first principal mode of SEA is equatorially asymmetric (Fig. 6a), explaining 89.3% (88.2%) of the variance based on the ERSST (HadISST). The primary mode of SES explains 93.3% (92.1%) of the variance based on the ERSST (HadISST; Fig. 6b). The time series of the SEA primary mode shows strong interdecadal variability with no obvious trend (Fig. 6b), while the time series of the SES principal mode has an obvious intensifying trend (Fig. 6d). The correlation coefficients of the corresponding PCs are 0.71 (0.63) and 0.77 (0.69) for those of the HEA and SEA and HES and SES based on the ERSST (HadISST), respectively. The high correlations indicate that the variations in HEA are closely linked with the SEA, and the variations in HES are connected with the SES.

The time series of the SEA’s principal mode is also highly correlated with the MASI (correlation coefficient of 0.96; Fig. 7a), supporting the view that the MASI mainly represents the equatorially asymmetric variations in tropical SST. On the other hand, the time series of SES’s principal mode is associated with the MSSS (Fig. 7b), with a correlation coefficient of 0.99. These
results indicate that the MSSI and MASI perform well in capturing the equatorially symmetric and asymmetric variations in tropical SST.

What then are the corresponding vertical circulations associated with the variations in tropical SST? Fig. 8 shows the regression patterns of MASI and MSSI onto the meridional circulation. It is evident that the equatorially symmetric and asymmetric meridional circulation anomalies are connected with the MSSI and MASI, respectively. The equatorially asymmetric SST variation (i.e., MASI) is accompanied by an equatorially asymmetric meridional circulation (Fig. 8a), with the anomalous ascending branch to the south of the equator (Fig. 8c). Meanwhile, the symmetric SST variation (i.e., MSSI) is associated with the anomalous equatorially symmetric meridional circulation (Fig. 8b), with the anomalous ascending branch around the equator (Fig. 8d). On the other hand, although the variations of MSSI are generally associated with equatorial symmetric meridional circulation anomalies (Figs. 8b,d,f), the extent and intensity of the anomalous circulation accompanied with the MSSI in the two hemispheres show certain differences. The possible reasons are as follows: 1) The decompose method presented in this study is linear: that is, the MSSI and MASI are not orthogonal. This point implies that there may be some nonlinear process involving the relationship between the SST and HC. 2) Although the MSSI represents the equatorially symmetric variations of tropical SST, the factors influencing the MSSI may not be equatorially symmetric, which also may play a role in impacting the distribution of meridional circulation. Nevertheless, the result here further verifies that the equatorially asymmetric SST variations contribute to variations in the equatorially asymmetric HC, while the equatorially symmetric SST variations accompany the equatorially symmetric HC. What, therefore, are the possible differences in meridional circulation resulting from the differences in the meridional structure of the underlying SST?

To explore this issue, Fig. 9 shows scatterplots based on time series of the principal mode of HEA against SEA, as well as HES against SES. Besides the high linear correlations between the SEA and HEA, and between the SES and HES, we see that the responses of HEA to SEA and HES to SES are distinct. With ERSST data, the responses of HEA and HES to SST variations of equal amplitude in SEA and SES are significantly different, with coefficients of 24.84 and 4.30, respectively, a factor of roughly 5.8
between the response of the HEA to SEA and that of the HES to SES. Similar results are observed for the HadISST data (a factor of about 5.4). Although the exact values are slightly different, it is a consistent result that the response of HEA to SEA is ~5 times larger than that of HES to SES, even though the thermal forcings have the same magnitude. This may explain why the first principal mode of the HC is equatorially asymmetric: the response of the equatorially asymmetric circulation to underlying SST forces is much larger than that of the equatorially symmetric circulation, resulting in the equatorially asymmetric circulation dominating the variability of the HC.

5. Theoretical and numerical modeling

Results from the observational datasets indicate that the meridional structure of the underlying thermal forcing can result in very different induced responses of the HC. To further examine the influences of the meridional structure of the underlying SST forcing on the vertical circulation, we performed theoretical and numerical experiments.

a. Theoretical model

Gill’s model is used to investigate the responses of meridional circulation to the SST forcing. Considering
that the heating forcing source in the natural atmosphere often decays in strength from the center outwards and varies zonally (Jiang and Li 2011), the ideal heating source is calculated following Li et al. (2016):

\[
Q(x, y) = Q_1 + Q_2 = A_1g_1(x)e^{-\left(\frac{1}{R_1}\right)(x+d_1)^2} + A_2g_2(x)e^{-\left(\frac{1}{R_2}\right)(x+d_2)^2}
\]

and

\[
g_1(x) = \begin{cases} 
\cos k_1(x + l_1) & |x| \leq L_1 \quad \text{and} \quad k_1 = \pi/2L_1 \\
0 & |x| > L_1
\end{cases}
\]

\[
g_2(x) = \begin{cases} 
\cos k_2(x + l_2) & |x| \leq L_2 \quad \text{and} \quad k_2 = \pi/2L_2 \\
0 & |x| > L_2
\end{cases}
\]

Here, \(A_1\) and \(A_2\) represent bipolar heating intensities; \(R_1\) and \(R_2\) represent the meridional gradients of heating; \(d_1\) and \(d_2\) are meridional positions of the bipolar heating centers; \(d_1 > 0\) and \(d_2 > 0\) and \(d_1 < 0\) and \(d_2 < 0\) represent heating component centers located in the Southern and Northern Hemispheres, respectively; \(l_1\) and \(l_2\) are the zonal distances of the bipolar heating centers from the origin 0 (the intersection of the x and y axes); and \(2L_1\) and \(2L_2\) represent the zonal and meridional widths of heating sources. For equatorially symmetric heating, \(A_1 = 3.15, d_1 = 0, R_1 = 0.5, l_1 = 0, 2L_1 = 36,\) and \(A_2 = d_2 = R_2 = l_2 = 2L_2 = 0.\) For equatorially asymmetric heating, \(A_1 = 3.15, A_2 = -3.15, d_1 = -1.5, d_2 = 1.5, R_1 = R_2 = 0.5, l_1 = l_2 = 0,\) and \(2L_1 = 2L_2 = 36.\)

Two types of SST anomalies are constructed: one equatorially asymmetric and one equatorially symmetric (Fig. 10). Given that the intensity and meridional gradient of SST have important influences on the HC (e.g., Lindzen and Hou 1988; Chiang et al. 2001), the intensity of the underlying SST forcing and the meridional gradient centered on the equator are fixed so that the anomalies in meridional circulation are not contaminated by these parameters. The circulation anomalies are therefore mainly due to the differences in the meridional structure of the anomalous SST. The results show that equatorially asymmetric meridional circulation is associated with the equatorially asymmetric SST forcing, with anomalous ascent in the Southern Hemisphere and the circulation extending from 20°S to 20°N. In contrast, an equatorially symmetric meridional circulation is observed when the SST forcing is equatorially symmetric. The extent of this anomalous meridional circulation is smaller than in the equatorially asymmetric
case. The intensities of the two anomalous circulations are very different (with center values of 20 vs 4): the response of the meridional circulation to asymmetric SST forcing is about 5 times the response to the symmetric SST forcing. Note that the response difference shown here is insensitive to the shape of heating; the results based on the rectangular shape of heating show a similar result (figures not shown). This point indicates the responses from the equatorially asymmetric and symmetric structure are steady. The result here agrees well with the observations, further establishing the sensitivity of the response of the meridional vertical circulation to the meridional structure of the thermal forcing.

b. Numerical model

The CAM5 is employed to further examine the response of meridional circulation to the thermal meridional structure of SST. We use the aquaplanet version of CAM5. This is sufficient for our study, since the land area within the tropics (i.e., 20°S–20°N in this study) is small compared with the ocean. A control run was integrated for 8 yr and was used to derive a reference state. Two sets of sensitivity experiments were designed and integrated for 10 yr, with the last 8 yr of the integration used to construct an eight-member ensemble mean to reduce the uncertainties arising from varying initial conditions. To isolate and reproduce the impact of the SST meridional gradient and intensity on the associated circulation, the only difference between the two sets of sensitivity experiments is the SST meridional structure in the tropical oceans (see Fig. 11), as in the theoretical experiment. Note that the SST anomalies are identical to those used in the theoretical experiment. The prescribed profiles in the experiments are equatorially asymmetric and symmetric (Figs. 11a,c).

Figures 11b,d shows the ensemble-mean response of the MSF anomalies associated with the two sets of experiments. When forced with the equatorially asymmetric SST anomalies (see Fig. 11a), the observed anomalous equatorially asymmetric meridional circulation is well captured by the simulation (Fig. 11b). The convergence and rising branch lie to the south of the equator, with the descending branch in the Northern Hemisphere. With the equatorially symmetric SST forcing, we see anomalous convergence and a rising branch at the equator, with descent at 20° poleward in both hemispheres (Figs. 11b, d). These characteristics, in response to the different SST meridional structures, are similar to those seen in the observations. We also find that the anomalous meridional circulation induced by the asymmetric SST forcing is about 5 times stronger than that induced by the symmetric SST forcing (with center values of 20 vs 4). The consistency between the observations and model results further verifies the crucial impact of the meridional structure of SST on the meridional circulation, with the
influence of the equatorially asymmetric SST a factor of 5
larger than that of the equatorially symmetric forcing.

6. Theoretical explanations

The fundamental mechanism of the stronger response
of HEA to SEA can be further understood in the Gill
model, which can be used to investigate the importance
of rotation and the $\beta$ plane. In the simplest form without
rotation, the Gill model described in section 2 can be
reduced to the following form:

$$\varepsilon u = -\frac{\partial p}{\partial y} \quad \text{and} \quad \varepsilon p + \frac{\partial u}{\partial y} = -Q.$$ 

That is $(\partial^2 p/\partial y^2) - \varepsilon^2 p = -\varepsilon Q$. Given a waveform forc-
ing $Q = Q_0 e^{i\beta y}$, where $l$ represents the wavenumber in $y$
direction. We could get the solution $p = -(\varepsilon Q_0/\varepsilon^2 + \varepsilon^2) e^{i\beta y}$;
thus, the response function is $p/Q = \varepsilon(l^2 + \varepsilon^2)$. Namely,
the response amplitude depends on the spatial scale and
decreases with the spatial scale. Neglecting the $l = 0$ re-
response, which has a small projection into the symmetric
mode of forcing, an asymmetric mode has a small wave-
number $l = 1$, and the symmetric mode has $l = 2$, so the
ratio is about 4 if $\varepsilon$ is small, which is close to the observations
and model results.

On the other hand, the effect of the $\beta$ plane is further
examined based on the Gill model. We further cal-
culated the extreme value of zonally integrated meridi-
onal wind for the two kinds of modes [Eqs. (4.15) and
(5.7) in Gill (1980)]. For the equatorially symmetric
heating,

$$v = 4\varepsilon q_2(x) ye^{-\gamma^2/4} + yQ \quad \text{and} \quad Q = \cos k x \times e^{-\gamma^2/4},$$
we get that \( \int_{-\infty}^{\infty} v \, dx = (-y/3)(4L/\pi)e^{-y^2/4} \).

For the equatorially asymmetric, \( v = yQ + 6\sigma q_3(x)(y^2 - 1)e^{-y^2/4} \) and \( Q = \cos kx \times ye^{-y^2/4} \),

that is \( \int_{-\infty}^{\infty} v \, dx = [(6 - y^2)/5](4L/\pi)e^{-y^2/4} \). The definitions of \( q_2 \) and \( q_3 \) are the same as those described in Gill (1980). It is found that the extreme value for the equatorially asymmetric mode (when \( y = 1.41 \)) is \(-4\times\) that of the equatorially symmetric mode (when \( y = 1.41 \)). The quantity of the above deduction without rotation and considering the \( \beta \) plane indicates that the rotation may not be the main factor affecting the intensity of atmospheric response, but the effects of the \( \beta \) plane play roles in determining the different responses of HC to SST.

7. Discussion and conclusions

Using observational datasets for the past 66 yr, we investigated the influence of the meridional structure of SST on the HC, focusing on the annual mean response. By decomposing the long-term variations in SST and HC into two components, one equatorially asymmetric and one equatorially symmetric, we found that the equatorially asymmetric components of SST and HC (i.e., HEA and SEA) mainly reflect the interdecadal variations; in contrast, the equatorially symmetric parts (i.e., HES and SES) mainly represent the long-term linear trends. These results indicate that the equatorially asymmetric variations in HC are linked to the equatorially asymmetric variations in SST, while their equatorially asymmetric variations are closely correlated. However, the responses of the HEA and HES to SST forcing are very different: the response of the HEA to SEA is much bigger than that of the HES to SES. This result is further confirmed by both theoretical and numerical experiments. It has been reported that the principal mode of long-term variability of the HC is equatorially asymmetric, not only for boreal winter and summer (Ma and Li 2008; Feng et al. 2011), when the climatological structure of HC is equatorially asymmetric, but also for the boreal spring and autumn (Feng et al. 2013; Guo et al. 2016), when the climatological structure of the HC is equatorially symmetric. The present results provide a plausible explanation for this phenomenon, as disturbances of the same magnitude in SEA and SES are associated with different responses in the HC, and the response to SEA is about 5 times larger than that to SES, thereby contributing to the formation of the equatorially asymmetric mode.

In addition, previous studies have reported that the meridional distribution of heating plays an important role in inducing atmospheric anomalies. For example, Lindzen (1994) found that a larger meridional gradient of SST induces stronger atmospheric anomalies. In previous studies we have shown that the meridional gradient profile of tropical SST determines the location of anomalous atmospheric convergence (Feng et al. 2013; Feng and Li 2013). These studies gave a qualitative description of the importance of the meridional structure of SST for atmospheric circulation that was useful for better understanding the role of SST in impacting the atmosphere. In the present work, by decomposing the variations of SST into two components, we have quantitatively assessed the important role of SST meridional structure on the HC. Moreover, the effects of rotation and the \( \beta \) plane in impacting the contrast responses of HC to different SST meridional structures is further explored based on the Gill model. The theoretical deduction indicates that the cases without rotation and including the \( \beta \) plane both show equivalent quantity for different heating sources, suggesting the \( \beta \) plane plays a role in determining the contrast responses of HC to different SST meridional structures, whereas the role of rotation is limited. The results are helpful for understanding the important impact of the meridional structure of SST on atmospheric anomalies.

On the other hand, we found that the HC responds differently to different meridional structure in SST, and it is worth exploring further the reasons for the different responses. Are they due to internal ocean processes or to external processes involving air–sea interaction? In this study, we focused on the long-term variability in HC, but the HC is reported to be dominated by an equatorially asymmetric mode in the seasonal cycle (Dima and Wallace 2003). Thus, it would be interesting to further explore the responses of the HC to different SST meridional structures in the seasonal cycle, to discover whether a similar contrasting sensitivity is observed. Since the HC behaves differently during different seasons, such as greater interdecadal variability during boreal summer (Feng et al. 2011) and a close link to ENSO during boreal winter (Ma and Li 2007), it would also be interesting to further examine and compare the similarities and differences in the response of the HC to SST meridional structures in different seasons. Meanwhile, since the atmosphere–ocean system exhibits strong decadal variability in the late 1970s, it would be interesting to examine whether the response of the HC to different meridional structures of SST may also have some decadal variation. Do the background climate conditions play a role in determining the response of the atmosphere to SST? These questions remain unresolved and require further work.

Finally, our results highlight the important role of the meridional structure of SST in determining the
corresponding atmospheric circulations, and we conclude that the atmospheric response to a meridional distribution of SST can vary by more than a factor of 5. Therefore, the differences in the response of the HC to the meridional structure of SST may provide a useful criterion for assessing the output of coupled ocean–atmosphere general circulation models (CGCMs), while the sensitivity of the responses to climate change forcing can be assessed using CGCMs. Further work will investigate the application of the responses of the HC to different SST forcing using an ensemble of CGCM results. This appears to provide a useful “fingerprinting” technique for this specific aspect of climate change in the tropics.

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