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ORIGINAL PAPER

Role of SST meridional structure in coupling the Kelvin and Rossby waves of the intraseasonal oscillation

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Abstract The intraseasonal oscillation (ISO) is one of the most important modes of the tropical atmosphere, which influences global livelihood of hundreds of millions of people. The meridional structure of sea surface temperature (SST) has been found to be important for the ISO simulation in general circulation models (GCMs). Using a theoretical frictional skeleton model for the ISO, we investigate the effects of different SST structures on the ISO in this study. The model results show that the observed Madden-Julian oscillation (MJO), boreal summer ISO (BSISO) and quasi-biweekly oscillation can be simulated in this model with different SST structures. The Ekman pumping of the boundary layer associated with equatorially trapped SST favors the growth of eastward propagating Kelvin waves and prefers the fast eastward propagating signal. A broad SST provides a strong instability source for the Rossby waves, which will slow down the MJO. In the boreal summer, the high SST center in the off-equatorial region can trigger strong off-equatorial moisture pumping from the boundary layer, which enhances the Rossby waves and can simulate the northwest-southeast tilted rain band associated with the BSISO. When the Rossby component overwhelms the Kelvin component, the low-frequency westward component of the BSISO and the higher-frequency quasi-biweekly oscillation can be simulated.

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1 Introduction

The intraseasonal oscillation (ISO) is one of the most important modes of the tropical atmosphere (Zhang 2005). It is composed of the Madden-Julian oscillation (MJO) in the boreal winter (Madden and Julian 1971, 1972, 1994) and the boreal summer ISO (BSISO) in the boreal summer (Yasunari 1979; Krishnamurti and Subrahmanyam 1982; Wang et al. 2009). Although trapped in the tropical Eastern Hemisphere, the ISO affects the monsoon regions directly via global teleconnection. Current general circulation models (GCMs), however, cannot simulate the ISO well (Kim et al. 2008). Many studies have been carried out to improve the ISO simulation in the GCMs (Fu and Wang 2009; Li et al. 2009; Maloney et al. 2010).

In a recent study (Kang et al. 2013), the role of sea surface temperature (SST) meridional structure in the MJO simulation has been discussed in an aqua-planet GCM. The meridional scale of the SST was found to be a key for simulating the MJO, and the GCM experiment with a broad SST meridional scale produced slowly eastward propagating signals related to the MJO, and that with a narrow SST meridional scale simulated fast eastward propagating signals associated with the moist Kelvin waves. Although a simple discussion was provided to help understand the model results, this simple theory of SST meridional scale mainly represents the moist Kelvin waves, not the MJO and the BSISO. To understand the role of the

SST meridional structure on the ISO, we need a new theoretical model.

In the observations, the MJO features an equatorially trapped, slowly eastward propagating, planetary-scale baroclinic circulation cell in the Eastern Hemisphere (Knutson and Weickmann 1987; Wang and Rui 1990; Hendon and Salby 1994; Maloney and Hartmann 1998; Kiladis et al. 2005). In the boreal summer, the BSISO exhibits significant northward/northeastward propagation over the Indian Ocean (Yasunari 1979; Krishnamurti and Subrahmanyam 1982; Lau and Chan 1986; Annamalai and Sperber 2005; Wang et al. 2005) or northward/northwestward propagation over the western North Pacific (Murakami 1984; Kemball-Cook and Wang 2001). Vertical shear (Wang and Xie 1997), convective momentum transfer (Kang et al. 2010), and beta-drift (Boos and Kuang 2010) may contribute to this northward propagation.

In terms of physics, the MJO comprises equatorial Kelvin waves and Rossby waves and exhibits a quadrupole vortex horizontal structure when the MJO convection is located over the equatorial Indian Ocean and the western Pacific Ocean (Rui and Wang 1990; Hendon and Salby 1994). Furthermore, a phase lag is observed between the leading planetary boundary layer (PBL) moisture convergence and the mid-tropospheric counterparts (Hendon and Salby 1994; Hsu and Li 2012). These observations suggest that the MJO is a coupled system of tropical Kelvin and Rossby waves led by PBL moisture convergence. The BSISO can also be seen as a coupled system (Wang and Xie 1997).

Coupling of Rossby waves and Kelvin waves of the ISO can be represented by the theoretical frictional skeleton model of the MJO (Liu and Wang 2012b). We extend their work to study how different SST meridional structures control the ISO type. The frictional skeleton model of the ISO is summarized in Section 2. We discuss the roles of different SST meridional structures in Section 3 and summarize the results and discuss future work as well as the limitations of this study in Section 4.

2 The frictional ISO skeleton model

2.1 The model equations

To understand the essential dynamics of the ISO, we need to include two theories, the wave dynamics (Wang 1988; Wang and Rui 1990) and the thermodynamics of moisture processes (Sobel and Maloney 2012, 2013). The first theory neglects the moisture processes and only cares about the frictional wave dynamics, while the second theory neglects the wave dynamics so the instability is only caused by thermodynamics.

By coupling wave dynamics and moisture processes, Majda and Stechmann (Majda and Stechmann 2009) built a neutral skeleton model for the ISO, which was developed into a frictional skeleton model for the ISO by Liu and Wang (Liu and Wang 2012b). In the frictional skeleton model, the effects of synoptic wave activity (Wang and Liu 2011; Liu et al. 2012; Liu and Wang 2012c, 2013a) are parameterized as an oscillator in the temperature and moisture equations, which drives the ISO skeleton. An assumption was made: the temporal tendency of wave activity a is determined by moisture anomaly q, i.e., $a_t = \Gamma \overline{\boldsymbol{q}}$, where Γ is a constant of proportionality; it means that positive lower-tropospheric moisture anomaly favors the growth of synoptic-scale wave activity. The moisture convergence of the PBL provides an instability source for the free troposphere (Wang 1988); therefore, the steady PBL model of Li and Wang (Li and Wang 1994) is used to couple with the neutral skeleton model of Majda and Stechmann (Majda and Stechmann 2009). Taking C=50 $m{\cdot}s^{-1}$ (the lowest internal gravity wave speed) as the reference speed and the characteristic temporal and spatial scales as $\sqrt{1/C\beta} = 8.5\ h$ and $\sqrt{C/\beta} = 1,500\ km$, respectively, where β represents the leading-order curvature effect of the Earth at the equator; the non-dimensional frictional skeleton model can be written as (Liu and Wang 2012b):

$$
\begin{aligned}
&u_t - yv + p_x = 0,\\
&yu + p_y = 0,\\
&p_t + u_x + v_y = -a,\\
&q_t + \widetilde{Q}\left(u_x + v_y\right) = -a + r_b(\theta_s - 9.18)w_b,\\
&\alpha_t = \Gamma \overline{a} q,
\end{aligned}
\tag{1}
$$

where u and v are zonal (x) and meridional (y) velocities, respectively, and p is pressure. The magnitude of non-dimensional vertical gradient of the background moisture $\widetilde{Q}$ is taken as 0.9, a standard value for low-frequency motions (Yano and Emanuel 1991; Frierson et al. 2004). Γ=1.5 (≈ 0.3 $K^{-1}{\cdot}day^{-1}$ in dimensional units), while $\Gamma \overline{a}$≈0.03 acts as a dynamic growth/decay rate of the wave activity envelope, in response to moisture anomaly. The standard PBL coefficient is r_b=0.06. θ_s is the SST. The Ekman pumping of the PBL, w_b, is

$$
w_b = \frac{H_b}{H_T}\left(d_1 \nabla^2 p + d_2 p_x + d_3 p_y\right),
\tag{2}
$$

where $d_1 = E/(E^2+y^2)$, $d_2 = -(E^2-y^2)/(E^2+y^2)^2$, and $d_3 = -2Ey/(E^2+y^2)^2$. The boundary layer depth H_b=1 km, and troposphere depth scale is H_T=16/π=5.1 km (Majda and Biello 2004). Friction of the PBL, E, is selected to represent a damping of one third of a day, and its non-dimensional value is 1.1.

2.2 Eigenvalue problem and the Rossby/Kelvin component

The frictional skeleton model of Eqs. (1) and (2) is a linear system, so it can be readily solved as an eigenvalue problem. For the zonally propagating plane waves, the structure of $e^{i(kx-\sigma t)}$ is assumed first, where k is wavenumber and σ is frequency. The phase speed and growth rate are defined by $\mathrm{Re}(\sigma)/k$ and $\mathrm{Im}(\sigma)$, respectively. Following the work of Liu and Wang (Liu and Wang 2012b), when only keeping the lowest N meridional modes of each variable for the meridional expansion of parabolic cylinder functions, the frictional skeleton model can be projected on to the $\sigma-k$ space, which gives us a linear matrix of (5° N×5° N) for the five variables in Eq. (1). Here, N = 1 represents the lowest equatorially trapped mode. The frequency and eigenvectors are calculated through the matrix inversion corresponding to each wavenumber. Because of the longwave approximation, only the Kelvin and Rossby waves are kept in Eq. (1). The Rossby and Kelvin waves, for the lowest meridional modes, can be studied by using N = 3, and sensitive experiments showed that a higher N does not affect the results qualitatively.

Following the work of Kang et al. (Kang et al. 2013), we use the ratio of the wave activity magnitude between the off-equatorial region (15°–25° N) and equatorial region (5°S–5° N) to represent the ratio between Rossby and Kelvin components. The simplest structure of the SST can be represented by $\exp(-((y-y_0)/y_L)^2)$, where y_0 is the center latitude of the maximum SST. The SST decreases from its center with an e-fold scale of y_L. In the observation (Kang et al. 2013), this value is about $y_L=30^o$.

3 Roles of different SST structures

3.1 Neutral modes

The skeleton model with or without the PBL can capture three important features of the MJO (Majda and Stechmann 2009; Liu and Wang 2012b), namely, (i) the peculiar dispersion relation of $d\sigma/dk\approx 0$, (ii) the slow phase speed of ~5 m/s, and (iii) the horizontal quadrupole vortex structure. In their studies, only the first meridional mode, the equatorially trapped mode associated with the observed wave activity, was included. In order to study the roles of SST meridional structures, we include all first three modes. Without the frictional boundary layer, this model still simulates the peculiar dispersion relation and phase speed of the MJO over the uniform SST (Fig. 1a, b), while it only captures the Kelvin-wave-like structure and has no quadrupole vortex structure (Fig. 2a). In the observation, the background moisture field associated with the SST is equatorially trapped, and the observed SST has a meridional structure with an e-fold scale of $y_L=30^o$ (Kang et al. 2013). With this equatorially trapped SST, the solution of this model still stays in the MJO spectrum domain (Fig. 1a), and it also captures the quadrupole vortex structure of the MJO (Fig. 2b).

3.2 Role of meridional scale of the SST structure

The Ekman pumping of the PBL can transfer additional moisture to the stable troposphere to sustain the growth of the MJO (Liu and Wang 2012b). Here, we study the role of SST with different meridional scales by changing parameter y_L, since larger y_L represents broader SST structure (Fig. 3). For a narrow SST with $y_L<20^o$, the most unstable mode stays in the planetary eastward propagating domain (Fig. 3b), because the equatorially trapped Ekman pumping has the largest projection on the planetary moist Kelvin waves and favors the growth of the longest Kelvin waves (Liu and Wang 2012b). This fast growing Kelvin component dominates (Fig. 3c) and causes the MJO to propagate eastward fast (Fig. 3a). For the westward propagating modes, the equatorially trapped Ekman pumping damps the Kelvin component. The model also has small projection on the Rossby waves to support the growth of the Rossby component; thus, this model presents damped westward modes.

When the SST becomes broader with larger y_L, the Rossby component becomes stronger for both eastward and westward modes (Fig. 3c), because the off-equatorial Ekman pumping associated with broad SST enhances the Rossby waves (Fig. 2b). As a result, the stronger Rossby component will suppress the Kelvin component. For the eastward modes, the increasing Rossby component will drag the system and slow down the MJO, which is consistent with the results of Kang et al. (Kang et al. 2013), in which the GCM with broader SST simulated slower eastward propagating modes. For the westward modes, the increasing Rossby component leads the coupled system to propagate westward faster (Fig. 2a).

3.3 Role of off-equatorial SST

In the monsoon region, the off-equatorial monsoon trough usually provides enough moisture for the growth of the BSISO (Liu and Wang 2012a, 2014). For simplicity, we assume that this off-equatorial moisture be determined by asymmetric SST, which can be represented by $y_0>0$ in this model. Following the observation (Kang et al. 2013), the SST has a meridional e-fold scale of 30°. When the SST is equatorially trapped, the frictional skeleton model presents the most unstable, planetary, eastward propagating mode, which stays in the MJO domain (Fig. 4a). This mode is dominated by the eastward propagating Kelvin component (Fig. 4c), which is consistent with the results of Liu and Wang (Liu and Wang 2012b).

When the summer season arrives, the SST center moves northward and the Rossby component increases for both

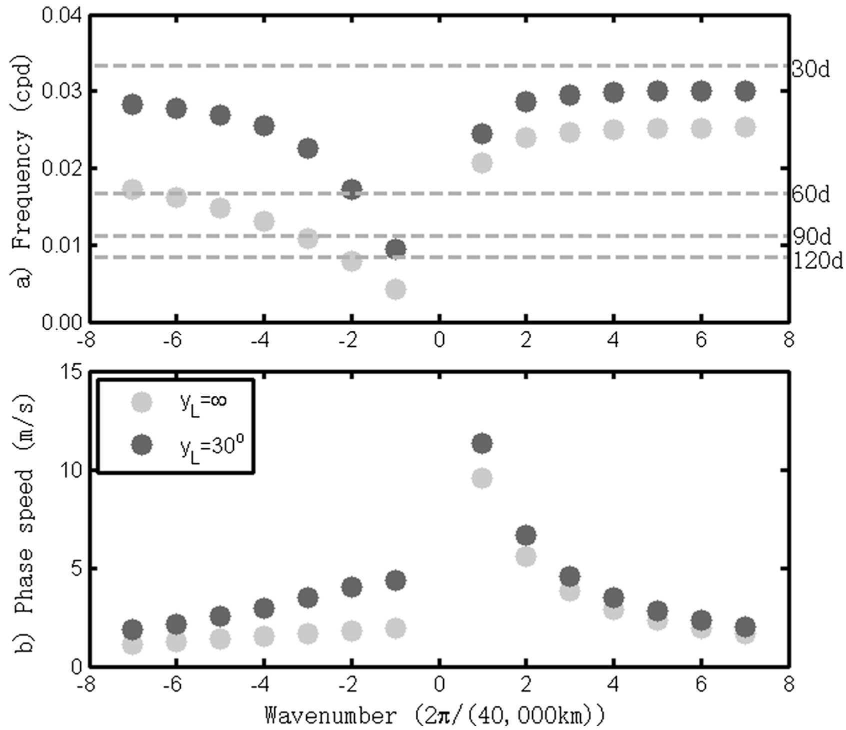

Fig. 1 Results from the neutral skeleton model. Shown are the frequency (**a**) and phase speed (**b**) as functions of wavenumber for low-frequency modes. *Gray* and *black dots* denote the neutral modes for the uniform SST ($y_L=\infty$) and equatorially trapped SST ($y_L=30^o$), respectively

eastward and westward modes (Fig. 4c). The most unstable mode also changes from the eastward mode to the westward mode (Fig. 4b). For the unstable eastward propagating mode, the northwest-southeast tilted rain band associated with the BSISO, observed over the Indian Ocean (Yasunari 1979; Krishnamurti and Subrahmanyam 1982; Lau and Chan 1986; Annamalai and Sperber 2005; Wang et al. 2009), is simulated (Fig. 5a), because the equatorial Kelvin waves lead the off-equatorial Rossby waves and cause this tilted rain band. The instability, as well as the period of the eastward modes, decreases as the SST center moves northward (Fig. 4b), because the colder equatorial SST increases the static instability and induces faster Kelvin waves.

For the westward modes, the off-equatorial wave activity suppresses the equatorially trapped waves (Fig. 4c) and can obtain enough moisture from the PBL. The westward

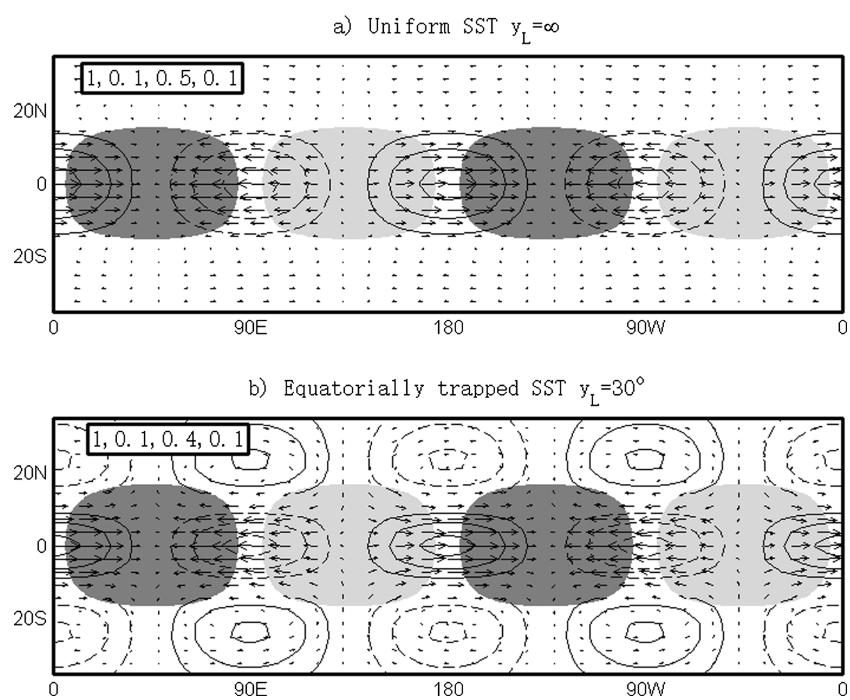

Fig. 2 Eigenvectors for eastward wavenumber 2 shown in Fig. 1. Normalized velocity (*vector*) and wave activity (*shading*) with lower-tropospheric pressure (*contour*) of the experiments with **a** uniform SST and **b** equatorially trapped SST are plotted for the eastward propagating wavenumber 2. Solid (*dashed*) contours are for positive (negative) values. Contour interval is one fifth of the magnitude, and zero contours are not drawn. *Dark* (*light*) *gray shading* is for positive (negative) value. Only wave activity above one fifth of the magnitude is shaded. The four values in the parentheses in each panel denote the magnitudes of zonal wind, meridional wind, wave activity, and pressure anomalies, respectively

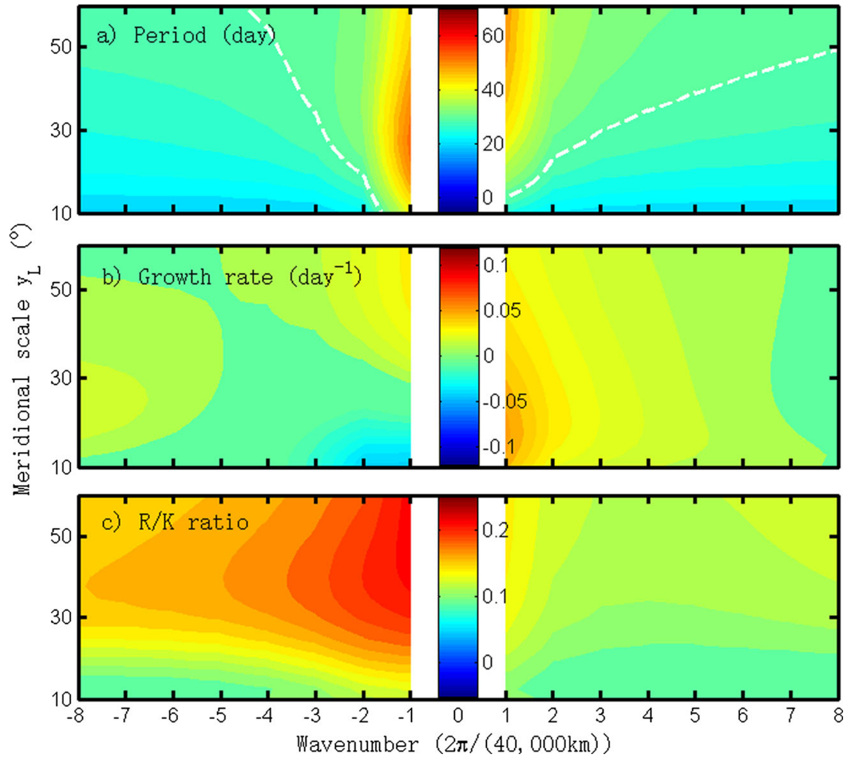

Fig. 3 Role of meridional scale of SST in the frictional skeleton model. Shown are the simulated period (**a**), growth rate (**b**), and Rossby/Kelvin ratio (**c**) as functions of wavenumber and meridional scale of SST. *White dashed line* denotes the period of 30 days

propagating component of the BSISO, observed over the western North Pacific (Murakami 1984; Kemball-Cook and Wang 2001; Wang et al. 2009), is simulated (Fig. 5b), which is controlled by the planetary-scale Rossby waves. The short Rossby waves simulated in this model has a short period of about 2 weeks (Fig. 4a), which may explain the quasi-biweekly oscillation observed over the Indo-western North Pacific region (Kikuchi and Wang 2009).

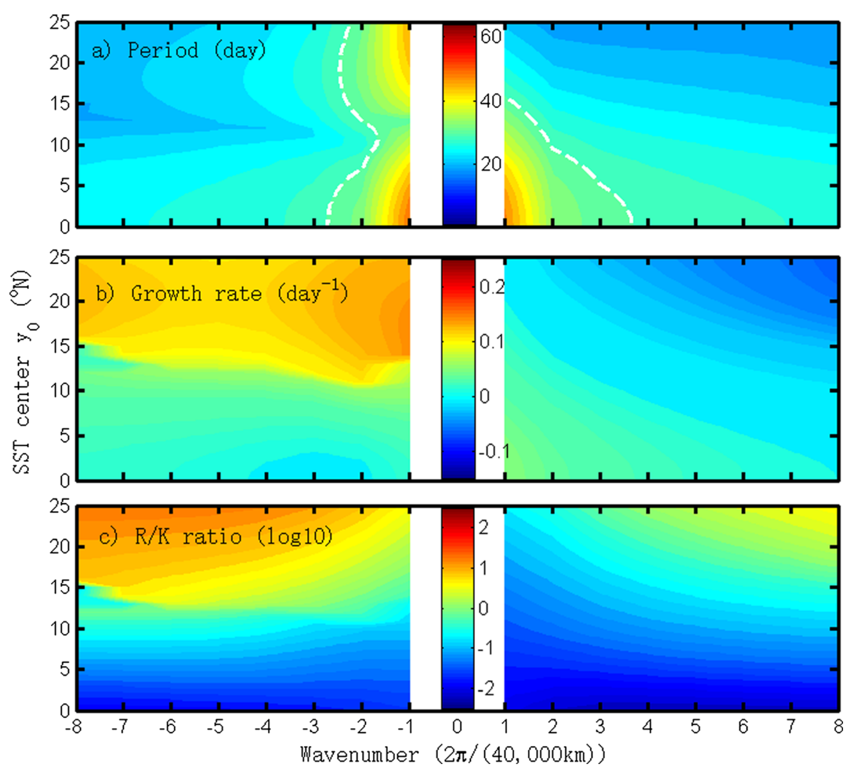

Fig. 4 Role of off-equatorial SST in the frictional skeleton model. Shown are the simulated period (**a**), growth rate (**b**), and log10 of Rossby/Kelvin ratio (**c**) as functions of wavenumber and latitude of the SST center. *White dashed line* denotes the period of 30 days

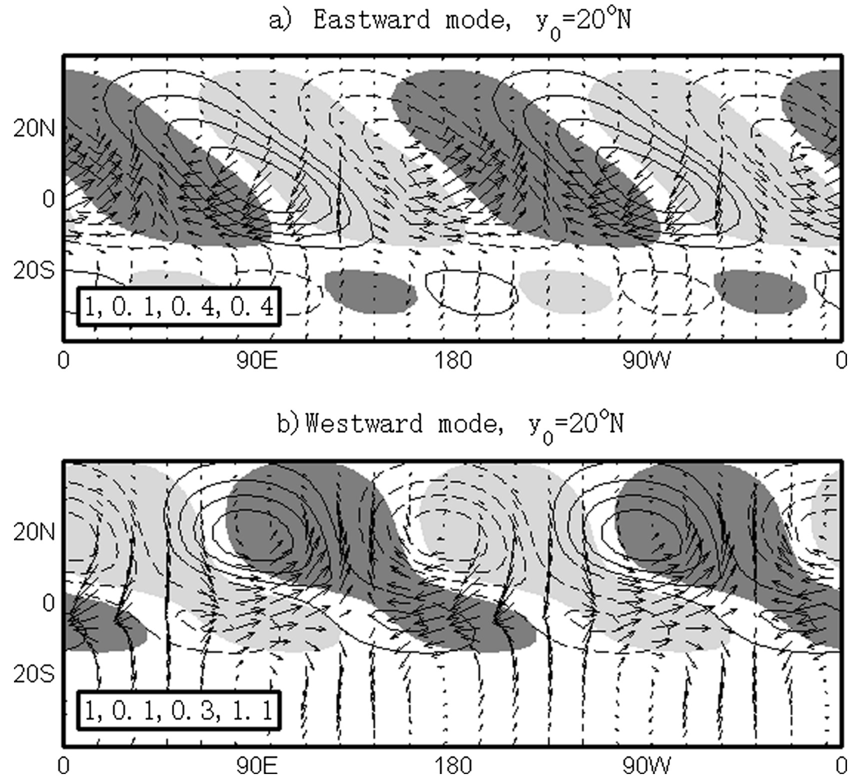

Fig. 5 Horizontal structures of two different unstable modes of wavenumber two. Same as Fig. 2, except for velocity (*vector*) and wave activity (*shading*) with lower-tropospheric moisture (contour) of **a** eastward mode and **b** westward mode with SST center at 20° N

4 Concluding remarks

This theoretical work demonstrates the important roles of the coupling of Rossby and Kelvin waves in determining the ISO type: different meridional SST structures control relative strengths of the Kelvin and Rossby components of the coupling system, which will determine the direction and speed of the propagation of the most unstable modes. Narrow equatorially trapped SST favors the growth of fast eastward propagating Kelvin waves, while broad SST provides enough moisture for the growth of Rossby waves and the model presents a slowly eastward propagating mode associated with the MJO, which explains why the GCMs with narrow SST only simulated the fast eastward propagating signal related to the moist Kelvin waves (Kang et al. 2013). The location of the maximum SST is important for the simulation of the BSISO. The maximum SST centered in off-equatorial region provides enough moisture for the Rossby waves, which couple with the equatorial Kelvin waves to form the northwest-southeast tilted rain band of the BSISO (Fig. 5a). Without the role of vertical shear (Wang and Xie 1997; Jiang et al. 2004), convective momentum transfer (Kang et al. 2010), and beta-drift (Boos and Kuang 2010), the northward propagation of the BSISO cannot be produced in this model. When Rossby component suppresses the Kelvin component when the maximum SST is centered in the monsoon region, the westward propagating Rossby waves provide an explanation for the westward propagating component of the BSISO and the quasi-biweekly oscillation.

This linear instability analysis suggests that the SST meridional structure is important for the GCMs to simulate the ISO. These theoretical results, however, are based on the linear system, while nonlinear processes are important in the GCMs. The linear model is also parameter-dependent; for example, the solution with smaller precipitation parameter $\Gamma<1$ is always in the MJO domain whether the SST meridional structure is narrow or broad, though the model with broader SST still simulates slower eastward propagating mode. Thus, the roles of different SST meridional structures on the ISO simulation need to be further studied using GCMs.

In this work, we neglected the zonal variation of the SST. The zonal variation of the SST associated with warm SST over the warm pool region and cold SST over the eastern Pacific may also have important impacts on the ISO. The zonal variation of the SST, however, cannot be calculated as an eigenvalue problem in this model. The meridional propagation of the BSISO is also important, which cannot be solved as an eigenvalue problem. These call for a study as an initial condition problem. The air-sea interaction (Liu and Wang 2013b) and multi-scale interaction (Majda and Biello 2004; Wang and Liu 2011) of the ISO may be different for different SST structures, these also need to be investigated using the frictional skeleton model.

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