Mechanisms of Northward-Propagating Intraseasonal Oscillation over the South China Sea during the Pre-Monsoon Period

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ABSTRACT

In the present study, the spatiotemporal structures of the northward-propagating intraseasonal oscillation (ISO) over the South China Sea (SCS) in the premonsoon period are analyzed by using the TropFlux air–sea flux and the JRA-55 reanalysis datasets. It is found that the SCS ISO is significant in the premonsoon season with a strong component of the northward propagation and that the mean state is different from that of summertime. Moreover, there are similar structures to those of a boreal summer ISO event except for the perturbation vorticity with no obvious phase leading. An internal atmospheric dynamics mechanism is proposed to understand the cause of the northward propagation of the ISO during the premonsoon period based on the spatial and temporal structures of the ISOs. The key process associated with this mechanism is the barotropic vorticity advection by the mean barotropic southerly winds, and the main barotropic vorticity around the convection center can be induced by the vertical advection of the mean vorticity. Low-level moisture convergence caused by anomalous flow is a supplementary mechanism to drive the ISOs northward during the premonsoon period, particularly over the northern SCS. In this mechanism, the SST-induced wind anomalies play a more important role than the convection-induced wind anomalies. The summer monsoon circulation has not built up during the premonsoon period, and thus the vertical wind shear effect and the barotropic vorticity effect associated with the meridional advection of baroclinic vorticity are not essential to cause the northward propagation of the ISOs over the SCS.

1. Introduction

The South China Sea (SCS) has a special geographic location that joins three Asian monsoon subsystems: the subtropical East Asian monsoon, the tropical Indian monsoon, and the western North Pacific (WNP) monsoon. With the earliest onset date in April (Zheng et al. 2011a; Luo and Lin 2017), SCS summer monsoon (SCSSM) outbreaks occur relatively earlier than other subsystems of the Asian summer monsoon (Wang and Lin 2002). With the onset of the SCSSM, the atmospheric circulation over SCS undergoes significant adjustments, shifting from a winter-type circulation to a summer-type one (as shown in Fig. 1). Figure 1a shows a climatological outbreak of the SCSSM in May. With the onset of the SCSSM, in the SCS the positive meridional

gradient of surface moisture, vertical easterly shear, and baroclinic northerly get enhanced suddenly and reach the maximum in the mature period (June–August) of the SCSSM (Figs. 1b–d). During the decaying period of the SCSSM, the associated circulations weaken (Figs. 1b–d) gradually.

While some previous researchers regard the SCSSM as a part of the East Asian summer monsoon (Zhu et al. 1986; Ding 1992), others link it to the tropical WNP monsoon (Murakami and Matsumoto 1994; Wang 1994; Zheng et al. 2007b) since it is a typical tropical monsoon. Figure 2a shows the precipitation averaged from June to August. While the rainbelt in the SCS is linked with the WNP rainbelt (Fig. 2a), the circulation characteristics of the SCSSM are quite different from those of the WNP summer monsoon (Fig. 2b). Therefore, Zheng et al. (2013) pointed out that the SCSSM and the WNP summer monsoon are different monsoon systems. Figure 2b indeed shows that the circulation characteristics of the SCSSM are similar to those in the tropical Indian monsoon rather than in the WNP monsoon. Because of

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FIG. 1. Mean state of April–October over the SCS: (a) precipitation (mm day^{-1}), (b) meridional gradient of the specific humidity ($\text{g kg}^{-1} \text{ degree}^{-1}$), (c) vertical wind shear (200–850-hPa zonal winds; m s^{-1}), and (d) differences of meridional winds between 200 and 850 hPa ($200 - 850 \text{ hPa; m s}^{-1}$).

the SCSMS's unique characteristics in geographic location and relation to other monsoon subsystems, the greater emphasis has been on SCSSM research, especially after the SCS Monsoon Experiment (SCSMEX) in 1998 (Lau et al. 2000; Ding et al. 2004). Over the SCS, the mean vorticity and wind have different seasonal cycles as shown in Figs. 2c and 2d. While the mean vorticity in the upper-level troposphere shows a negative value over the SCS almost throughout January to December, the upper-tropospheric meridional wind changes from a southerly to a northerly flow in May (Fig. 2c). It is implied that the center of an upper-tropospheric anticyclone shifts from the east of the SCS to the west in that time. The mean vorticity in the lower troposphere has a different seasonal cycle with a sign change over the SCS from a negative one to a positive in May, whereas the lower-tropospheric southerly appears in April. That implies that the west side of a lower-tropospheric anticyclone is still located in the SCS in April. Moreover, sea surface temperature (SST) has a great difference in the SCS before and after the summer monsoon onset. During the premonsoon period, warm SST in the SCS develops fast, while the SST is maintained above 29°C .

The SCSSM has prominent climate variability on intraseasonal to geological time scales (Wang et al. 2009). The intraseasonal variability in the SCS is greatly significant during boreal summer (Kemball-Cook and Wang 2001). The SCS intraseasonal oscillations (ISOs) usually include two periods of 10–20 and 30–60 days (Mao and Chan 2005) and impact the precipitation over southern China with a northward or northwestward movement (Chen et al. 2015; Li et al. 2015; Gao et al. 2016; Zheng and Huang 2018). The mechanisms for northward propagation of the ISO mainly include feedbacks from land surface heat fluxes (Webster and

Holton 1982), convection-moist stability interaction (Goswami and Shukla 1984), air–sea interaction (Kemball-Cook and Wang 2001), vertical easterly wind shear (Wang and Xie 1997; Jiang et al. 2004; Drbohlav and Wang 2005), vorticity advection effect associated with baroclinic vorticity and baroclinic mean meridional wind (Bellon and Sobel 2008), convective momentum transport (Kang et al. 2010; Liu et al. 2015), and the beta shift (Boos and Kuang 2010). The moisture advection in the planetary boundary layer (PBL) and barotropic vorticity effect are found to be the dominant mechanisms for the northward propagation of ISO (DeMott et al. 2013), which are mainly attributed to the mean state of the atmospheric circulation.

The previous studies were focused on the ISOs and their northward propagation commonly in the mature period of summer monsoon (June–August). But we know the rainy season in southern China begins in April and should be impacted, at least partially, by the tropical systems from the SCS. Thus, in this study, we aim to analyze the 30–60-day ISOs in the SCS during the pre-onset period of the SCSSM, and then to find the possible mechanisms for the northward propagation of them. The next section describes the datasets and methods used in this study. The northward-propagating ISOs over the SCS are examined in section 3. A detailed discussion about the propagation mechanisms is presented in section 4, followed by the conclusions from this study.

2. Data and analysis method

a. Data

In this study, the daily three-dimensional winds, water vapor, geopotential height, air temperature, vorticity,

FIG. 2. Summer mean state of (a) precipitation (mm day⁻¹), (b) 850-hPa horizontal winds over the SCS (m s⁻¹), the seasonal cycle of meridional wind (areas with southerly flow are shaded, m s⁻¹) and vorticity (contour, 1 s⁻¹) at (c) 200 and (d) 850 hPa, and (e) SST in the SCSSM region (105°–120°E).

and divergence are from the Japanese 55-Year Reanalysis (JRA-55; Kobayashi et al. 2015) with $1.25^\circ \times 1.25^\circ$ grids. The other datasets include the Global Precipitation Climatology Project (GPCP) satellite-derived infrared (IR) GOES precipitation index (GPI) daily rainfall estimates at 1° spatial resolution (Huffman et al. 2001) and the TropFlux data, which provide daily surface latent heat flux, sensible heat flux, shortwave radiation, surface wind speed at 10 m, specific humidity at 2 m, and sea surface temperature (SST) (Kumar et al. 2012) on $1^\circ \times 1^\circ$ grids. Note that positive values of latent heat flux, sensible heat flux, and shortwave radiation indicate energy transfers from the atmosphere to ocean.

FIG. 3. Space-time power spectra of the 105°–120°E zonal mean precipitation anomalies at 0°–30°N in March and April 1997–2016.

b. Analysis method

A space-time power spectrum analysis (Hayashi 1982) is applied to the SCS precipitation of the premonsoon (Fig. 3). One can see that the ISO is significant in the premonsoon season with a strong component of the northward propagation. Moreover, we find that the SCS ISO mainly includes two periods of 20–30 and 30–60 days in the premonsoon season. The period of the high-frequency ISO is different from that in the monsoon season (10–20 days; Mao and Chan 2005). In this work, we focus on the 30–60-day ISO and its propagation in the premonsoon period. For convenience, all data are interpolated into $1^\circ \times 1^\circ$ spatial resolution as the GPI daily precipitation. Moreover, all data except for climatological variations were filtered by 30–60-day bandpass filters. The climatological mean is from 1981 to 2010. ISOs are identified by maximum filtered precipitation anomalies averaged over the longitudes 105°–120°E. A Hovmöller diagram is introduced to understand the propagation of ISOs and the relationship between the convection and other variations. The latitude and day with maximum zonally averaged precipitation anomalies were chosen as the reference latitude (zero latitude) and reference day (zero day); they cover 10° N/S latitude of the reference latitude and 10 days before and after the reference day. Furthermore, a composite analysis referenced to the convection center is used in this study.

3. The intraseasonal oscillation over the SCS

Over the SCS (105°–120°E), a northward-propagating component of ISOs is also found in the premonsoon period (Fig. 4). These northward-propagating ISOs can reach as far north as around 30°N, the Yangtze River basin. The big difference from the ISOs in the mature period of the SCSSM is that the convection is relative weaker in the premonsoon period. However, the ISOs in the premonsoon season link close to the onset of the summer monsoon (Wu et al. 1999; Zhou and Chan 2005; Zhou and Murtugudde

FIG. 4. The 30–60-day-filtered daily precipitation (mm day^{-1}) averaged over the SCS (105° – 120°E) for April–October of 1997–2016. Major northward-propagating ISOs in the premonsoon period are marked by red solid lines, and the time marked by a triangle means the SCSSM onset date.

2014; Shao et al. 2015; H. Wang et al. 2018) and impact the persistent extreme precipitation in the first rainy season over South China (Hu et al. 2014). Therefore, it is worth studying the ISOs and the propagations in the premonsoon season although they are relatively weaker than those in the monsoon season. Since the mean state of the atmospheric circulation is different in April and May (Fig. 2c and 2d), we just select the ISO events in April and the northward-propagating ISOs of 2001, 2004, 2005, 2007, 2009, and 2015 are not chosen in this work, even if they occur in the premonsoon period.

Besides the independent northward propagating ISOs, we also find some northward propagating ISOs related to the eastward propagating MJO (e.g., 2002, 2006, 2010–14; Figs. 4 and 5). In early summer (May–July), the origin of the northward propagating ISO can also be from the eastward propagating MJO (Fig. 5 in Li and Wang 2005), and the key factor driving the MJO movement northward is the equatorial asymmetry of a

thermal equator that induces more PBL divergence and precipitation appearing to the north of the equator (Li 2014). But in the premonsoon period (e.g., April), the mean state of the precipitation is still a winter-type one that is a main rainfall belt at and south of the equator in the SCSSM longitudes (Fig. 1a). That is almost consistent with the pattern of mean SST in April (Fig. 2e).

To reveal the meridional and vertical structure of the ISO, we take a composite approach by selecting 14 evident northward propagation cases (marked by red lines in Fig. 4). We do a composite test by using a statistic:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{(n_1 - 1)\sigma_1^2 + (n_2 - 1)\sigma_2^2}{n_1 + n_2 - 2} \left(\frac{1}{n_1} + \frac{1}{n_2} \right)}},$$

where $\bar{x}_1$ and $\bar{x}_2$ denote the means of ISOs with and without a northward propagation, respectively, n denotes

FIG. 5. The 30–60-day-filtered daily precipitation (mm day^{-1}) averaged over the equator (10°S – 10°N) for April–October of 1997–2016. The region between the two red dashed lines denotes the longitudes of the SCSSM.

the number of samples, and σ is the standard deviation. The statistic t obeys the t distribution with a degree of freedom $n_1 + n_2 - 2$, and $|t| > t_{95}$ means the difference between $\bar{x}_1$ and $\bar{x}_2$ is significant exceeding the 95% confidence level. It is worth noting that the difference between the mean of northward-propagating ISOs and climatology is not robust (figure not shown). That is because 14 northward-propagating ISOs are chosen for composites that contribute most to the 20-yr climatological mean (14/20). Figure 3 indeed shows an evident northward propagation of 30–60-day ISOs during the premonsoon period of 1997–2016. Therefore, in this study, we do not choose the statistic constructed as

$$t = \frac{\bar{x} - x_c}{\sigma} \sqrt{n},$$

where $\bar{x}$ is the composite and x_c is the 20-yr mean of 1997–2016 by the 30–60-day filtered variables.

Figure 6 shows the meridional–vertical structure of the composite northward-propagating ISO from the JRA-55 reanalysis. It is indicated that maximum vertical motion occurs at 400–300 hPa and coincides with the convection center (Fig. 6a). Associated with this maximum ascending motion are the low-level convergence and the upper-tropospheric divergence (Fig. 6d). It is worth noting that the convergence in the PBL tends to lead the convection by around 2° . And a maximum center of the low-level specific humidity appears about 4° to the north of the convection center (Fig. 6e). The geopotential height and temperature fields also show a significant asymmetry relative to the maximum convection (Figs. 6c and 6f). The ISO structures in the premonsoon period are similar to those in the SCSSM season (figure not shown) except the vorticity. In the SCSSM season, a positive center of the barotropic vorticity, associated with the northward-propagating ISO,

FIG. 6. Meridional-vertical structures of the northward-propagating ISOs over the SCS based on the ISO center in the premonsoon period marked in Fig. 3: (a) vertical velocity (Pa s^{-1}), (b) vorticity (s^{-1}), (c) geopotential height (gpm), (d) divergence (s^{-1}), (e) specific humidity (g kg^{-1}), and (f) air temperature (K) from JRA-55. All variables are after 30–60-day filtering. The positive (negative) value of the x axis means the distance to the north (south) of the convection center. The vertical axis is the pressure (hPa). The two shaded areas indicate the composite anomalies exceeding 90% and 95% confidence levels.

is generally located a few degrees north of the convection center, while a negative one appears to the south [similar to the ISO structures over the South Asian monsoon shown in Jiang et al. (2004)]. In comparison, one can find in the premonsoon period a positive vorticity center with an equivalent barotropic structure located at the convection center exactly. This is accompanied by the northward tilting of the positive low-level vorticity.

4. Mechanisms for the northward propagation

a. The air–sea interactions

As in Fig. 7, one-dimensional composites were conducted for various variables. Figure 7a shows that precipitation anomalies are roughly symmetric relative to the ISO center (corresponding to zero latitude in Fig. 7), where the maximum precipitation is located, while the convergence center (vertical mean between 1000 and 700 hPa) shown in Fig. 7b is located around 2° north of the convection center, which favors the ISOs moving northward. To reveal the causes of the phase leading of

the PBL convergence to the convection, we first examine the possible ocean–atmosphere interaction.

Warm SST anomalies (SSTAs) usually transfer the energy from the ocean to atmosphere by sensible heat flux. Thus the destabilized atmosphere would induce low-level convergence and the ISOs tend to move northward (Kemball-Cook and Wang 2001; Hsu et al. 2004). Figure 7c indeed shows that warm SSTAs appear a few degrees north of the precipitation maximum. However, the sensible heat flux anomalies are roughly symmetric relative to the reference latitude (Fig. 7h), which is not consistent with the pattern of SSTAs. This is due to the contribution from the surface air temperature anomalies, with the minimum around zero latitude (Fig. 6f; this also can be seen from the air temperature anomalies at 2 m in TropFlux dataset, which is not shown). The negative surface air temperature anomaly in the convective center would be attributed to the reduced solar radiation (Fig. 7e) and rainfall-induced cooling (Fig. 7a). Furthermore, the differences of the surface air temperature anomalies and SSTAs (not shown) have a similar distribution in comparison with the sensible heat flux anomalies. It implies

FIG. 7. Composites of the northward-propagating ISOs over the SCS based on the ISO center marked in Fig. 3 for (a) precipitation (mm day^{-1}), (b) surface divergence (10^{-6} s^{-1}), (c) SST ($^{\circ}\text{C}$), (d) SST tendency ($^{\circ}\text{C day}^{-1}$), (e) surface solar radiation (W m^{-2}), (f) surface wind speed (m s^{-1}), (g) surface latent heat flux (W m^{-2}), and (h) surface sensible heat flux (W m^{-2}). The positive (negative) value of the x axis means the distance to the north (south) of the convection center. The red lines indicate the composite anomalies exceeding 95% confidence levels.

that, in the premonsoon period, the changes in sensible heat flux are controlled by changes in surface air temperature rather than those in SST. Thus, the mechanism involving changes in sensible heat flux should not induce the northward-propagating ISOs over the SCS in the premonsoon period.

Larger precipitation anomalies are accompanied by more cloudiness, which prevents more solar radiation to the surface ground. So the meridional distribution of net surface solar radiation coincides with those of the precipitation anomalies (Fig. 7e). Moreover, the net surface solar radiation exhibits a much larger change, with a maximum around 12 W m^{-2} , than the changes in surface latent heat flux (Fig. 7g), sensible heat flux (Fig. 7h), and longwave radiation (figure not shown), especially around the convection. However, one can see from Fig. 7d that the maximum SST tendency is located about 6° north of the precipitation maximum, which is different from the changes in surface solar radiation or net surface heat flux (figure not shown), especially around the convection center. This implies that the SST tendency is not controlled by net surface solar radiation over the SCS in the premonsoon period; however, ocean processes, such as heat transport via subsurface entrainment (Duvel and Vialard 2007; Bellon and Sobel

2008), might play an important role, at least near the convection center. Thus, the cloud-radiation effect is not a dominant factor for the northward propagation of ISOs in the SCS region in the premonsoon period.

From Fig. 7g, it can be seen that the pattern of surface latent heat flux is similar to those of SST (Fig. 7c) and surface wind speed (Fig. 7f). This implies that the changes in latent heat flux are controlled by both the SSTAs and the surface wind speed. In Fig. 7g, the main upward latent heat flux anomalies (negative value) are located north of the maximum precipitation anomalies. This implies that the air–sea interaction associated with surface latent heat flux plays a role, to some extent, in the northward propagation of the ISOs over the SCS, although it should not be a dominant factor because the main upward latent heat flux anomalies are too far away from the convection center.

Besides, SST gradients could also induce low-level convergence (Lindzen and Nigam 1987; Back and Bretherton 2009; Roxy and Tanimoto 2012; T. Wang et al. 2018), which then favors the ISOs propagating northward. However, Fig. 7c shows that the meridional distribution of SSTAs might induce the PBL convergence much farther north of the convection center, which is not consistent with the distribution of the low-level

FIG. 8. Hovmöller diagrams of 30–60-day-filtered variables with 350 hPa vertical velocity (Pa s^{-1}) shaded. (a) SST (contour; $^{\circ}\text{C}$), low-level convergence center (red cross; s^{-1}), and negative surface geopotential height (green dot; gpm), (b) surface sensible heat flux (contour; W m^{-2}) and upward surface latent heat flux (red dot; W m^{-2}), (c) surface zonal wind (contour; m s^{-1}) and positive surface wind speed (red cross; m s^{-1}), and (d) surface solar radiation (contour; W m^{-2}) and positive SST tendency (open circle; $^{\circ}\text{C day}^{-1}$). The positive (negative) value of the x axis means the day after (before) the precipitation maximum. Only the composite anomalies exceeding 95% confidence levels are displayed.

convergence as shown in Fig. 7b. Thus, the SST gradient should not be a key factor here to drive ISOs northward, but it could affect northward-propagating ISOs by creating a favorable condition with a convergence north of the ISO center.

To clearly illustrate the phase relationship, we display Hovmöller diagrams of anomalies of different variables exceeding 95% statistical significant level. Figure 8a shows, on the 30–60-day time scale, that the PBL convergence center and associated negative surface geopotential height anomalies lead the convection. The maximum SSTA center also leads the convection, but occurring much earlier and much farther north of the ISO center. Thus, the SST gradient should not be a dominant factor here. From Fig. 8b, one can see that the sensible heat flux anomalies and the convection are roughly in phase, whereas the latent heat flux anomalies are almost out of phase to the convection. Thus, the mechanism involving changes in sensible heat flux should not induce the northward-propagating ISOs here. While the changes in latent heat flux should be mainly attributed to the surface wind speed anomalies (shown in Fig. 8c), the SSTAs have a supplementary contribution (Fig. 8a). Because the upward latent heat flux anomalies lead convection center too much in time

and space, the associated air–sea interaction should not be a dominant factor, although it does create a favorable condition for ISOs propagating northward. Figure 8d shows that the solar radiation anomalies and the convection are nearly out of phase. By contrast, more solar radiation appears south of the ISO precipitation maximum with a main positive SST tendency. This implies that the cloud-radiation effect is not a mechanism for the northward propagation of ISOs in the SCS region in the premonsoon period. The results from the Hovmöller diagram (see Fig. 8) are consistent with the discussion above.

b. The barotropic vorticity effect

Here, the barotropic vorticity effect denote mechanisms that would induce positive barotropic vorticity north of the ISO precipitation maximum, such as the vertical wind shear mechanism (Wang and Xie 1997; Jiang et al. 2004; Drbohlav and Wang 2005) and the mechanism associated with meridional advection of baroclinic vorticity in the free atmosphere (Bellon and Sobel 2008). In Fig. 9a, the main positive barotropic vorticity (defined as vertical mean between 850 and 100 hPa) tendency is located north of the maximum precipitation anomalies, and the pattern is similar to that

FIG. 9. As in Fig. 7, but for (a) barotropic vorticity tendency ($10^{-6} \text{ s}^{-1} \text{ day}^{-1}$), (b) barotropic vorticity tendency associated with vertical wind shear ($10^{-6} \text{ s}^{-1} \text{ day}^{-1}$), (c) vorticity advection by mean flow ($10^{-6} \text{ s}^{-1} \text{ day}^{-1}$), (d) surface moisture advection ($\text{g kg}^{-1} \text{ day}^{-1}$), (e) surface meridional wind (m s^{-1}), and (f) meridional gradient of surface specific humidity ($\text{g kg}^{-1} \text{ degree}^{-1}$).

of convergence (Fig. 7b), implying that the free atmosphere barotropic vorticity would induce convergence in the PBL via a Coriolis effect, and then drive ISOs northward. The daily data used in this work include, at least partially, the phase relationship between the barotropic vorticity and the PBL convergence. Therefore, Fig. 6a shows a tilting of the maximum vertical velocity axis with a PBL ascending flow ahead of the convection center. We next examine the internal atmospheric dynamics mechanisms associated with the barotropic vorticity effect.

In the summer monsoon season, mean easterly vertical wind shear could induce a horizontal vorticity with a southward direction, and then a positive barotropic vorticity is generated north of the ISO center via the twisting effect that is associated with meridional gradient of vertical velocity. Thus, PBL moisture convergence due to the free atmosphere barotropic vorticity should favor ISOs moving northward. Figure 1c shows that a strong easterly vertical wind shear covers the entire SCS from the end of May to September, so the vertical wind shear effect (Wang and Xie 1997; Jiang et al. 2004; Drbohlav and Wang 2005) could be an important mechanism for the northward propagation of ISOs during the monsoon season. In the premonsoon period, however, there is mean westerly vertical wind shear instead (Fig. 1c), which has a negative contribution to the northward propagation as shown in Fig. 9b because of main negative tendency of barotropic vorticity induced and located north of the convection center. This implies that the vertical wind shear effect might

be not favorable to the northward propagation of ISOs over the SCS during the premonsoon period.

Bellon and Sobel (2008) proposed a mechanism that is meridional advection of baroclinic vorticity via mean baroclinic meridional winds. In this mechanism, the mean meridional baroclinic flow is a key factor to induce positive barotropic vorticity north of the convection center. Figure 1d shows mean meridional baroclinic flow averaged over 105° – 120°E that is consistent with the mechanism of the meridional advection of vorticity in Bellon and Sobel (2008), especially during the summer monsoon season. During the premonsoon period, there appear dominantly mean baroclinic meridional winds with the northerly and southerly winds in the lower and upper troposphere between the equator and 10°N , which reverse sign between 10° and 20°N . Because of the pattern of mean baroclinic meridional winds, two peaks of vorticity tendency appear south and north of the maximum precipitation anomalies, respectively (Fig. 9c). This implies that the meridional advection of baroclinic vorticity should not be a factor to make ISOs propagate northward over the SCS in the premonsoon period.

In this study, we propose another mechanism associated with meridional advection of barotropic vorticity. During the premonsoon period, the west sides of the upper-tropospheric high (Fig. 10a) and the western Pacific subtropical high (Fig. 10b) are located in the SCS, which leads to a mean barotropic southerly wind. The strong vertical gradient of the mean vorticity (Fig. 10c) results in a main barotropic vorticity appearing around the convection center (as shown in Fig. 6b) through the

FIG. 10. April mean stream field at (a) 200 and (b) 850 hPa, (c) vertical profile of the mean vorticity averaged in the SCSSM region denoted by red dashed line box in Figs. 8a and 8b, and (d) vertical advection by ω at the convection center shown in Fig. 6a.

vertical advection (Fig. 10d). On the other hand, although the convection would induce a baroclinic vorticity around the convection, it is relatively weaker in the premonsoon period. Thus, we can see that a positive barotropic vorticity appears in the convection center (Fig. 10b). By the mean barotropic southerly winds, a positive barotropic vorticity may be generated to the north of the convection center (Fig. 9c). As a result, the convection tends to move northward.

Figure 11 shows the Hovmöller diagrams of anomalies of different variables associated with the internal atmospheric dynamics (only the composite anomalies exceeding 95% confidence levels are displayed). From Fig. 11a, one can see that the barotropic vorticity and the convection center are almost in phase, which is greatly different from the phase relationship in summer monsoon season (e.g., Jiang et al. 2004; Chou and Hsueh 2010; Zheng and Huang 2018). But the positive barotropic vorticity tendency indeed leads the convection. It implies that the barotropic vorticity effect should play an important role in the northward propagation of the ISOs over the SCS during the premonsoon period. In Fig. 11b, the negative barotropic vorticity tendency induced by the vertical wind shear leads the convection (Fig. 9b) and should be not favorable to the northward propagation of ISOs. The positive barotropic vorticity tendency by the meridional advection of baroclinic vorticity occurs both south and north of the ISO precipitation maximum (Fig. 11c), which implies that the

barotropic vorticity effect associated with the advection of anomalous baroclinic vorticity via mean baroclinic meridional winds should not induce the northward-propagating ISOs. However, the positive barotropic vorticity tendency induced by the meridional advection of barotropic vorticity evidently leads the convection (Fig. 11c) and has a similar pattern to the positive barotropic vorticity tendency in Fig. 11a. This implies that the changes in positive barotropic vorticity are mainly controlled by the advection of anomalous barotropic vorticity via mean barotropic meridional winds.

c. The moisture advection effect

Low-level moisture convergence induced by horizontal winds is a possible mechanism to drive the ISOs northward. Figure 9d shows a positive moisture advection north of the maximum precipitation anomalies. These anomalies are dominated by anomalous flow and mean water vapor, not mean flow and anomalous water vapor. Figure 1b shows the surface meridional gradient of the mean moisture averaged over 105°–120°E. During the premonsoon period, the meridional gradient of the mean specific humidity is negative roughly over the entire SCS, whereas in the summer monsoon period the meridional gradient of the mean moisture is positive over the SCS region, and the ISO convective heating excites a northerly wind to the north and a southerly wind to the south of the convection center. This would result in a positive center of the anomalous moist to the

FIG. 11. As in Fig. 8, but for (a) barotropic vorticity tendency (contour; $10^{-6} \text{ s}^{-1} \text{ day}^{-1}$) and positive barotropic vorticity (red cross; s^{-1}), (b) barotropic vorticity tendency associated with vertical wind shear (contour; $10^{-6} \text{ s}^{-1} \text{ day}^{-1}$), (c) barotropic vorticity tendency induced by the advection of barotropic vorticity (contour; $10^{-6} \text{ s}^{-1} \text{ day}^{-1}$) and positive barotropic vorticity tendency induced by the advection of baroclinic vorticity (red cross; $10^{-6} \text{ s}^{-1} \text{ day}^{-1}$), and (d) moisture advection by mean flow (contour; $\text{g kg}^{-1} \text{ day}^{-1}$) and positive moisture advection by anomalous wind (open circle; $\text{g kg}^{-1} \text{ day}^{-1}$).

north of the convection center and a negative one to the south (figure not shown), which is similar to the processes over the Indian summer monsoon region shown in Jiang et al. (2004). By contrast, during the premonsoon period, a positive moisture tendency by anomalous flow and mean water vapor appear north of the maximum precipitation anomalies rather than south of it (Fig. 9d) because the perturbation wind has a northward flow over the entire domain (Fig. 9e). In response to the convective heating, the anomalous wind has a southward flow to the north of the convection center, while the V -wind anomalies are southerly (Fig. 9e). This implies that the SST gradient has a greater contribution to the V -wind anomalies at and north of the convection center (Roxy and Tanimoto 2012; T. Wang et al. 2018). On the other hand, the response to the convective heating has a northward flow to the south of the convection center, which should contribute more to the V -wind anomalies because of the small SST gradient south of the convection center. So the domain-averaged perturbation wind is southerly (Fig. 9e). Figures 7c and 8a show a phase relationship of SSTAs to the ISO precipitation maximum. Main warm SSTAs indeed lead the convection center, but the former are found much farther away (more than 5°) from the latter. While the upward latent heat flux anomalies and low-level

divergence induced by SSTAs are not dominant factors here, moisture advection by the SST-induced southerly (Lindzen and Nigam 1987; T. Wang et al. 2018) may be a factor for ISOs propagating northward. We note that a positive or small negative meridional gradient of the mean specific humidity occurring in the southern SCS might weaken the contribution of this mechanism to the northward-propagating ISOs, particularly between the equator and 10°N . As a result, for moisture advection by anomalous winds, the time-leads to the convection just occur north of the ISO center (Fig. 11d).

5. Summary and discussion

In southern China, the rainy season begins in April when the SCSSM does not break out. While persistent rainfalls in southern China should be influenced by both the tropical and subtropical systems (Zheng et al. 2007a; Zheng and Huang 2018), the tropical ISOs usually impact the precipitation over southern China with a northward or northwestward movement (Chen et al. 2015; Li et al. 2015; Gao et al. 2016). During the premonsoon period, dominant mechanisms of the northward propagation of the ISOs are different from those in the summer monsoon season due to different mean state of circulation and moisture. The major

FIG. 12. Schematic diagram for the mechanism of meridional advection of barotropic vorticity. During the premonsoon period, (a) the mean state of circulation shows a barotropic southerly and the strong vertical gradient of the mean vorticity. (b) The latter results in a main barotropic vorticity appearing around the convection center through the vertical advection. (c) Thus, with the advection by the mean flow, a positive barotropic vorticity may be generated to the north of the convection center, leading to (d) a barotropic divergence in situ, which further leads to a boundary layer convergence and thus a northward propagation of the convection.

findings made in this study are summarized and discussed as follows.

- 1) During the premonsoon period, the vertical wind shear effect (Wang and Xie 1997; Jiang et al. 2004; Drbohlav and Wang 2005) and the barotropic vorticity effect associated with the meridional advection of baroclinic vorticity (Bellon and Sobel 2008) are not essential to cause the northward propagation of the ISOs over the SCS, which is different from the mechanisms in the summer monsoon season since the mean state of circulation is different.
- 2) In the present study, we propose a mechanism associated with meridional advection of barotropic vorticity that should play an important role in northward propagation of the ISOs over the SCS during the premonsoon period. Figure 12 shows a schematic diagram illustrating how the meridional advection of barotropic vorticity leads to the northward propagation of the ISO convection. During the premonsoon period, the mean state of circulation shows that the west sides of the upper-tropospheric high (Fig. 8a) and the western Pacific subtropical high (Fig. 8b) in the upper and lower troposphere are located in the SCS, which leads to a mean barotropic southerly wind (Fig. 12a), while the strong vertical gradient of the mean vorticity (Fig. 8c) results in a main barotropic vorticity appearing around the convection center through the vertical advection (Fig. 12b). Thus, a positive barotropic vorticity may be generated to the north of the convection center (Figs. 7a and 12c). A barotropic divergence (Fig. 12d), due to the positive barotropic vorticity, leads further to a convergence in the PBL (Figs. 5b and 12d). This favors the convection moving northward.
- 3) During the premonsoon period, low-level moisture convergence induced by anomalous flow is a supplementary mechanism to drive the ISOs northward. In this mechanism, the SST-induced wind anomalies should play more important role (Roxy and Tanimoto 2012; T. Wang et al. 2018) in the northward propagation of ISO than the convection-induced

TABLE 1. Comparisons of the northward propagating ISO over the SCS in premonsoon period and in the monsoon season.

	Premonsoon period (April)	Monsoon season
Mean states	Weak precipitation (Fig. 1a) Positive differences of meridional and zonal winds between 200 and 850 hPa (Figs. 1c and 1d) Negative meridional gradient of the specific humidity (Fig. 1b) Southerly both in the upper and lower troposphere (Figs. 2c and 2d)	Strong precipitation (Figs. 1a and 2a). Negative differences of meridional and zonal winds between 200 and 850 hPa (Figs. 1c and 1d) Positive meridional gradient of the specific humidity (Fig. 1b) Southerly in the lower troposphere and northerly in the upper troposphere (Figs. 2b–d)
Structure	Barotropic vorticity over the convection center (Fig. 6b)	Barotropic vorticity ahead of the convection center (Zheng and Huang 2018)
Main mechanisms	Barotropic vorticity advection (Fig. 12) PBL moisture advection by anomalous wind (Figs. 6e and 9d)	Baroclinic vorticity advection (Zheng and Huang 2018) PBL moisture advection by mean flow (Zheng et al. 2011b; Zheng and Huang 2018) and vertical wind shear effect (Zheng et al. 2011b; Zheng and Huang 2018)

wind anomalies because the negative mean meridional gradient of surface moisture appears to the north of the convection center. It is worth noting that the mechanism might have a weak or negative contribution to the northward-propagating ISOs between the equator and 10°N where a positive or small negative meridional gradient of the mean specific humidity occurs.

To clearly compare the northward propagating ISO over the SCS in the premonsoon period and in the monsoon season, the main associated features are listed in Table 1.

There are no obvious northward-propagating ISOs before April (not shown). So the first branch of the northward-propagating ISO over the SCS generally occurs in April as we have selected the cases (Fig. 4), which is consistent with Li et al. (2013). In their work, both the vorticity and lower convergence are in phase with the convection center related to the first branch northward-propagating ISOs in the Bay of Bengal, while the lower convergence has a phase leading over the SCS. This implies there are different mechanisms for the northward-propagating ISO over the SCS in the premonsoon period. Li et al. (2013) attribute the northward propagation of premonsoon ISO to the meridional asymmetry of the background convective instability and the zonal moisture advection by anomalous U wind. In this study, we proposed a new mechanism associated with meridional advection of barotropic vorticity. This mechanism provides a precondition such that around the convection center a main positive barotropic vorticity (as shown in Fig. 6b) results from the strong vertical gradient of the mean vorticity by vertical advection during the premonsoon period. In fact, the positive barotropic vorticity could also occur in the convection center during the mature period of the summer monsoon

(e.g., Figs. 7b and 8b in Jiang et al. 2004; Fig. 11b in Zheng and Huang 2018). However, the mean baroclinic meridional winds in the monsoon season highlight the contribution of the advection of the baroclinic vorticity (Bellon and Sobel 2008) and meanwhile suppress that of the barotropic vorticity.

There are some cases of southward propagation not only in the premonsoon period but also in the monsoon season (Fig. 4). There is no clear evidence showing the connection between the southward and northward propagations, while a persistent extreme precipitation would be triggered when they meet together (Hu et al. 2014; Zheng and Huang 2018). Both the northward and southward propagations of the ISOs are mainly attributed to the mean state of atmosphere (e.g., mean moisture distribution and mean atmospheric circulation) (Zheng and Huang 2018). But the features of the mean moisture and atmospheric circulation driving the ISOs northward and southward are quite different. Generally, the northward propagation of ISOs is related to the easterly vertical shear, meridional monsoon circulation, and positive meridional gradient of the surface moisture, while the southward propagation is almost related to a contrary mean state.

Previous studies have shown that PBL horizontal moisture advection plays an important role in northward propagation of the ISOs during the summer monsoon season (Jiang et al. 2004). In this mechanism, the perturbation wind has a southward flow to the north and a northward flow to the south of the convection center due to the ISO convective heating. But in the premonsoon period, the wind anomalies north of the convection center are controlled by the SST gradient (Figs. 7c and 9e) since the response to the convective heating is a northerly flow. Thus, during the premonsoon period, the SST gradient should have an indirect effect on the northward propagation of ISOs besides the direct effect

such that the induced convergence, despite occurring much farther north of the ISO center, does create a favorable condition for ISOs propagating northward.

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