Intraseasonal Oscillation of the South China Sea Summer Monsoon and Its Influence on Regionally Persistent Heavy Rain over Southern China

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ABSTRACT

The intraseasonal oscillation (ISO) in the South China Sea summer monsoon (SCSSM) and its influence on regionally persistent heavy rain (RPHR) over southern China are examined by using satellite outgoing long wave radiation, NCEP/NCAR reanalysis, and gridded rainfall station data in China from 1981 to 2010. The most important feature of the ISO in SCSSM, contributing to the modulation of RPHR, is found to be the fluctuation in the western Pacific subtropical high (WPSH), along with a close link to the Madden-Julian oscillation (MJO).

Southern China is divided into three regions by using rotated empirical orthogonal functions (REOFs) for intraseasonal rainfall, where the incidence rate of RPHR is closely linked to the intraseasonal variation in rainfall. It is found that SCSSM ISOs are the key systems controlling the intraseasonal variability in rainfall and can be described by the leading pair of empirical orthogonal functions (EOFs) for the 850-hPa zonal wind over the SCS and southern China. Composite analyses based on the principal components (PCs) of the EOFs indicate that the ISO process in SCSSM exhibits as the east-west oscillation of the WPSH, which is coupled with the northward-propagating MJO, creating alternating dry and wet phases over southern China with a period of 40 days. The wet phases provide stable and lasting circulation conditions that promote RPHR. However, differences in the ISO structures can be found when RPHR occurs in regions where the WPSH assumes different meridional positions. Further examination of the meridional-phase structure suggests an important role of northward-propagating ISO and regional air-sea interaction in the ISO process in SCSSM.

Key words: South China Sea summer monsoon (SCSSM), intraseasonal oscillation (ISO), southern China, regionally persistent heavy rain (RPHR)

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1. Introduction

Regionally persistent heavy rain (RPHR) (Bao, 2007) is one of the main types of disastrous weather. It is most likely to cause large-scale severe flooding and endangers the lives and property of the public. RPHR events in China are unpredictable and frequent. They have been responsible for many catastrophic floods in southern China, such as the floods that occurred in the Yangtze-Huai River valley in 1991 (Lu and Ding, 1996), South China in 2005 (Xiong et al., 2007), and the south of the Yangtze-Huai River in 2010 (Wang et al., 2010).

Considerable research effort has been devoted to defining and categorizing RPHR, as well as examining its causes (Tang et al., 2006; Bao, 2007; Min and Qian, 2008; Wu and Zhai, 2013). Given its central role in weather-related disasters, the prediction of RPHR has also received much attention; in recent years, with respect to extended range forecasts (ERFs) in partic-
ular. Atmospheric intraseasonal oscillation (ISO) is valuable for the ERF of rainfall due to its quasi-periodicity and identifiable time and spatial scales (Liang and Ding, 2012). Studies have shown that the summer rainy season of southern China exhibits large intraseasonal variability characterized by active phases with heavy rainfall interrupted by break phases with little rainfall (e.g., Li and Li, 1997; Chen et al., 2001; Yang and Li, 2003; Zhang et al., 2011). As the stability of large-scale circulation is essential for the persistence of rainstorms, ISO may also be a potential signal for ERFs of RPHR. A further understanding of the relationship between RPHR and ISO would be helpful for improving ERFs of persistent heavy rain (Chen et al., 2010, Chen and Wei, 2012). However, only a few case-study-based works have been published (e.g., Chen, 1988; Lu and Ding, 1996; Hong and Ren, 2013), and no one has comprehensively investigated (using long-term daily rainfall observations) the essential processes by which the ISO modulates RPHR.

The Asian summer monsoon (ASM) determines the rainy season in southern China. In addition, the intraseasonal behavior of the ASM is important because an uneven spatial and temporal distribution of monsoon rainfall may cause disasters, even if the seasonal mean is normal (Annamalai and Slingo, 2001). Therefore, the strong association between the activities of ISO and the Asian monsoon system is concerning. Yasunari (1979) was the first to examine the relationship between ISO and the Indian summer monsoon. Thereafter, the influence of ISO on the onset and active/break phases of the ASM has been successively reported (e.g., Yasunari, 1981; Lau and Chan, 1986; Wang and Xie, 1997; Wu et al., 1999; Annamalai and Sperber, 2005; Goswami, 2012). This influence is particularly important in the South China Sea (SCS) (Chen et al., 2000). Analyses (e.g., Mao and Chan, 2005) have indicated that the South China Sea summer monsoon (SCSSM) ISO is characterized by an alternation between the monsoon trough and the subtropical ridge that controls the position of the summer rainfall belt over southern China (Tao and Chen, 1987; Zhu et al., 2011). However, a comprehensive description of the characteristics of the RPHR-related ISO in SCSSM is still needed, including the origin, the three-dimensional structure and the relationship with RPHR.

The aim of this study is to explore the relationship between RPHR and ISO in SCSSM by examining the related data for a 30-yr period. The methods and the dataset are briefly introduced in Section 2. In Section 3, the results from rotated empirical orthogonal functions (REOFs) are used to describe the main spatial structures of intraseasonal rainfall, to identify the typical intraseasonal rainfall regions over southern China, and to investigate the relationship between intraseasonal rainfall and RPHR. In Section 4, key ISO systems affecting rainfall are identified by using regression and power spectrum analyses, the standing mode of the ISO in SCSSM is revealed by a pair of empirical orthogonal functions (EOFs) of the anomalous zonal wind at 850 hPa over the SCS and southern China, and evolution of the ISO in SCSSM is delineated through composite analyses of the 500-hPa geopotential height (H500), 850-hPa horizontal winds (wnd850), outgoing long wave radiation (OLR), and gridded station rainfall data. In Section 5, the relationship between the ISO in SCSSM and RPHR is interpreted based on the evolutionary processes of the ISO in SCSSM. To conclude, a summary and discussion are presented in Section 6.

2. Data and methods

The data used to describe the ISO life cycle include the daily average fields from the NCEP/NCAR reanalysis (Kalnay et al., 1996) and the interpolated daily values of the OLR from the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites (Liebmann and Smith, 1996) with a horizontal resolution of 2.5°. The above data for a 30-yr period from 1981 to 2010 are used.

For southern China (18°–35°N, 110°–125°E), with 537 points besides the default grids, daily precipitation observations derived from the gridded station data generated by the National Meteorological Information Center (NMIC) of China are used to obtain intraseasonal modes and composites of the precipita-
tion field. The data are taken on a 0.5° latitude × 0.5° longitude grid covering the period 1981–2010.

Daily climatological values are obtained for the 30-yr period (1981–2010). The anomalous fields are then obtained by removing the daily climatological values and the seasonal means for each individual year to eliminate the seasonal cycle. The anomaly fields created in this manner are denoted with a prime (e.g., U850′ and H500′). A 30–60-day Butterworth band-pass filter (Murakami, 1984; Lü et al., 1991) is performed on the anomaly fields to identify intraseasonal variability. We denote these 30–60-day components with an asterisk (e.g., OLR* and U850*).

The REOF method (Horel, 1981; Wei, 2007) involves rotating the principal components (PCs) of the EOF (Kutzbach, 1967); in particular, the orthogonal varimax method is used, resulting in a greater contribution to the total normalized variance. The REOF is less dependent on the domain of the analysis, making the PCs easier to interpret than with the EOF approach. To describe the main spatial structures of the intraseasonal rainfall over southern China, EOF analysis is first performed on the normalized 30–60-day band-pass filtered rainfall between 1 April and 30 September during 1981–2010, and then the first five EOFs are rotated. The number of rotating EOFs is determined by two factors (Wei, 2007): EOFs that explain 90% of the total variance and EOFs that are well separated from the remaining EOFs as explained by North et al. (1982) are rotated. Based on the spatial structure of the first three REOFs, three intraseasonal rainfall indices (IRIs) are constructed by averaging the 30–60-day filtered precipitation over the selected regions.

To identify the key regions where the intraseasonal variability of rainfall is influenced by the large-scale circulation, U850′ is regressed against the IRIs. The results show that the SCS is the key region and the SCSSM may be the main driving force for the intraseasonal variation of rainfall over southern China. An EOF analysis is then performed on the U850′ averaged at 0°–35°N, 110°–120°E for the period 15 days before to 135 days after the onset of the SCSSM in 1981–2010. Morlet wavelet analysis (Torrence and Compo, 1998) is performed on the PCs of leading EOFs to identify the dominant ISO modes; and this procedure is used to investigate the main modes of the ISO in SCSSM. In addition, the significance of the EOFs is determined by using the methods recommended by North et al. (1982). To describe the evolution of the ISO in SCSSM, the PCs of the leading EOF pair are used to identify the positive and negative events that contribute to the composite analysis on OLR*, wnd850*, and H500*. As indicated by Liang and Wu (2002), the dates of onset of the SCSSM from 1981 to 2010 are shown in Table 1.

3. Characteristics of the ISO of rainfall over southern China

3.1 Regional variability of the 30–60-day mode

The REOF analysis is performed on the precipitation field for a period of 5490 days (from 1 April to 30 September for 1981–2010) by using 537 points in space to determine the main areas where the intraseasonal variability occurs. Figure 1 shows the spatial structures of the first three REOFs that explain 54%
Fig. 1. (a–c) The first three REOF modes of the 30–60-day band-pass filtered precipitation over southern China from 1 April to 30 September of 1981–2010. Contours are drawn at 0.2 intervals. Negative anomalies are shaded. (d) A map of the three typical regions (R1, R2, and R3). The bold solid curve represents the Yangtze River.

of the total variance. The value attributed to the grid is the correlation coefficient for precipitation and the PC of the corresponding REOF. Therefore, the square of the grid value indicates the variance contribution of each corresponding REOF to the grid. REOF1 explains 23% of the total variance and has a dipole mode with opposite anomalies over the south of the Yangtze River and the mid-lower reaches of the Yangtze River. The main significant region for REOF2 is in South China. REOF3 mainly represents the variation over the Yangtze-Huai River basin. Southern China is divided into three typical regions, as shown in Fig. 1d: South China (R1), south of the Yangtze River (R2), and the Yangtze-Huai River basin (R3). The precise boundaries of the three regions are given in Table 2. Three IIRIs are defined by averaging the 30–60-day band-pass filtered precipitation of the three typical regions (Fig. 1d) from 1 April to 30 September of 1981–2010.
3.2 Relationship between intraseasonal rainfall and RPHR

ISO makes a stable large-scale circulation that promotes the persistence of rainstorms. To investigate the relationship between intraseasonal rainfall and RPHR, the RPHR events need to be first identified. As recommended by Tang et al. (2006) and Bao (2007), RPHR events are defined as areas with 120 grids in the horizontal range on a resolution of 0.5°, in which at least N grids record a rainfall accumulation that exceeds 100 mm in 3 days and have daily rainfall amounts greater than 25 mm. Taking into account the regional differences, we set N to 24, 28, and 30 in R1, R2, and R3, respectively. RPHR events that occur between April and September from 1981 to 2010 are identified in the three regions. As shown in Table 3, more than 80% of the RPHR events occur when the IRI is greater than one standard deviation (1SD). The phase and intensity of the intraseasonal rainfall is therefore clearly one of the most important factors associated with RPHR.

Table 2. Boundaries of the three regions of intraseasonal rainfall

|        | R1                          | R2                          | R3                          |
|--------|-----------------------------|-----------------------------|-----------------------------|
| Latitude | 21°–26°N                    | 26°–29°N                    | 29°–33°N                    |
| Longitude | 110°–120°E                  | 110°–122°E                  | 112°–122°E                  |

4. Structure of the ISO in SCSSM

4.1 Systems controlling the intraseasonal rainfall

To investigate the relationship between large-scale circulation and the intraseasonal rainfall of southern China, U850° is regressed against the three IRIs defined above from the onset day of the SCSSM to 30 September of 1981–2010. Statistical significance is strongest when the zonal wind lags or leads the rainfall index by approximately 20 days and when the zonal wind is synchronous with the rainfall indices. Figure 2 shows the sequence of regression coefficients obtained for the two above-mentioned situations. As shown by Figs. 2a, 2c, and 2e, when the zonal wind is synchronous with the rainfall, statistically significant zonal wind anomalies extend from the maritime continent to 35°N with a “− + −” pattern through the SCS. The precipitation areas fall between two statistically significant centers. When the wind leads or lags behind the rainfall by approximately 20 days (Figs. 2b, 2d, and 2f), the statistically significant zones are similar to those depicted in Figs. 2a, 2c, and 2e, though with reversed values. As shown in previous studies (e.g., Liang et al., 1999; Ding and Chan, 2005; Mao and Chan, 2005), the 850-hPa zonal wind in this region is directly related to the SCSSM. Power spectrum analysis is performed on the IRIs for the period 150 days before and after the onset of the SCSSM separately (Fig. 3). The results show that the 30–60-day mode becomes more significant after the onset of the SCSSM. Two hypotheses are thus proposed: (1) the intraseasonal rainfall in southern China is closely related to the SCSSM; (2) the subtropical large-scale circulation, which controls the intraseasonal rainfall, may be linked to the tropical system through the ISO processes in the SCS.

To investigate the main modes of the ISO processes in the SCSSM, EOF analysis is performed on U850°. Here, the SCS-southern China regionally averaged (110°–120°E) field is used. The composite analysis is conducted based on the different phases created by the PCs of the EOFs; ISO modes are identified by using the Morlet wavelet analysis.

4.2 EOF analysis results

The EOF analysis yields three prominent EOF modes; the first, second, and third modes explain 36%, 28%, and 16%, of the total variance respectively, while EOF4 explains only 7%. The results from the Morlet wavelet analysis of the PCs of the leading three EOFs are shown in Fig. 4. The 95% confidence level for the PCs is indicated by the thick contours in Figs. 4a, 4c,
Regression coefficients between U850° and the intraseasonal rainfall index for (a, b) South China, (c, d) the south of the Yangtze River, and (e, f) the Yangtze-Huai River basin, when (a, c, e) the rainfall index is synchronous with the wind and (b, d, f) the rainfall lags behind the wind by 20 days. Shaded areas indicate the values statistically significant at the 95% confidence level.

In Figs. 4b, 4d, and 4f, the solid line shows the global wavelet spectrum; the dashed curves show the 95% confidence level for the global wavelet spectrum. Most of the power of PC1 (Figs. 4a and 4b) and PC2 (Figs. 4c and 4d) are concentrated within the ISO band of days 30–60, although appreciable power can also be detected on the interannual scale. In contrast, PC3 contains little of the ISO signal because it is not dominated by the intraseasonal scale (Figs. 4e and 4f). Thus, the leading EOF pair represents the main mode of the ISO in SCSSM.

Figure 5a displays the structure of the first two EOF modes. EOF1 describes a situation whereby the low-level westerly winds control the SCS, while low-level easterlies extend to the south of the Yangtze River (22°–29°N). This mode corresponds to the significant correlation zones in Figs. 2c–f where U850° couples well with the intraseasonal rainfall over R2 and R3. The correlation coefficients between PC1 and the IRIs of R2 and R3 are −0.27 and −0.24, respectively; these correlations are all significant at the 99% confidence level. EOF2 is characterized by a crest to the north of the SCS and a peak near the Yangtze River (~30°N) that are in close quadrature with the crests and ridges of EOF1 and correspond to the significant correlation zones where the U850° couples well with the rainfall in R1 (Figs. 2a and 2b) and R3 (Figs. 2e and 2f). The correlation coefficient between PC2 and the IRI of R1 is −0.36.

The above analyses suggest that the structure of the leading EOF pair may represent the different ISO modes that affect the intraseasonal variation in rainfall over the different regions. Therefore, to describe the evolution of the ISO circulation, composite analyses of U850°*, OLR°*, and H500°* are performed based on the ISO phases determined using the 30–60-day...
Fig. 4. Morlet wavelet analysis of the PCs of the leading three EOFs. The contours in (a, c, e) denote the wavelet spectral coefficients. The thick contours enclose the regions with confidence levels greater than 95% for red or white noise. Thick long-solid curves indicate the cone of influence outside of which the edge effects become important. In (b, d, f), the solid line shows the global wavelet spectrum; the dashed curves show the 95% confidence levels for the global wavelet spectrum.

band-pass filtered PC1 and PC2 (PC1* and PC2*). As shown in Fig. 5b (where PC1* from 1991 is illustrated), the assignment of phases is relatively straightforward, as the index tends to oscillate in a sinusoidal manner (Eric and Dennis, 2000). The key event can be defined as occurring when the peak amplitude of PC* is greater than one standard deviation after the onset of the SCSSM (day 0); on average, this phenomenon occurs one or two times a year. Phase 5 represents the maximum positive amplitude classification of each event. Phases 1 and 9 are characterized by the largest negative amplitude before and after phase 5, respectively. Phases 3 and 7 represent the zero crossing point classifications; the other phases are distributed equidistantly between phases 1, 3, 7, and 9. A total of 66 and 49 life-cycles are selected from PC1* and
PC2*, respectively.

4.3 Composite analysis

Figure 6 provides details of phases 1–9 of the ISO in SCSSM as determined from PC1*. Growing negative OLR anomalies in the central Indian Ocean propagate eastward along the equator from phases 7 to 8 (when enhanced easterly wind anomalies appear near Indonesia) and are followed by positive OLR anomalies. Meanwhile, the western Pacific subtropical high (WPSH), represented by the positive H500* anomalies, begins to strengthen and expand westward. The zone of positive OLR anomalies and associated anomalous anticyclonic circulation (denoted as “AC” in Figs. 6b and 6c) is characterized by lasting northeastward movement from phases 7 to 9; this movement promotes the expansion of easterly winds from the SCS to the Bay of Bengal. During phase 9/1, the negative OLR anomalies enter the maritime continent, the WPSH positive anomaly peaks over the SCS, and the southwesterly anomalies to the north of the AC strengthen the transport of water vapor and the active rainfall in the region R2, as shown in Fig. 7a; these events define the wet phase of R2. The largest negative OLR anomalies and a cyclonic circulation anomaly (denoted as “C1” in the Figs. 6c and 6d) over the north of the equatorial Indian Ocean extend from the equator to 15°N and are characterized by a southeast-northwest orientation from phases 9/1 to 3; these characteristics are indicative of an emanation of Rossby waves (Jiang et al., 2004). At the same time, the WPSH weakens and retreats and is accompanied by a zone of negative OLR anomalies that propagates farther eastward and re-enhances over the equatorial western Pacific Ocean. Significant westerly wind anomalies appear near the maritime continent in phase 3 and begin to propagate northward over the SCS near 115°E and over the northwest of the equatorial western Pacific Ocean. The reinforcement of the northwestern propagation in the western Pacific is consistent with the phenomenon described in Fig. 4 of Wang and Xie (1997). This phenomenon indicates that the gravest meridional mode of moist Rossby waves is destabilized and modified by the easterly shear of the monsoon. From phases 3 to 4, C1 collapses when a new cyclonic circulation anomaly (denoted as “C2” in Figs. 6e–h) is established over
Fig. 6. Composite evolutions of $\text{U850}^*$ (vectors; m s$^{-1}$), $\text{OLR}^*$ (color shadings; W m$^{-2}$), and $\text{H500}^*$ (contours; dagpm) during an ISO cycle for PC1*. Panels (a–h) represent phases 1–9. Grid points where the wind anomalies are not significantly different from zero at the 95% confidence level according to Student's $t$-test are defaulted.

The convection peaks in phase 5 and the easterly wind anomalies to the north of C2 suppress convection and rainfall in the region south of the Yangtze River (Fig. 7b); these events define the dry phase of R2. At the same time, positive OLR anomalies are observed along most of the equatorial Indian Ocean and they propagate to the maritime continent region in phase 5. In phase 6, the westerly wind anomalies begin to weaken when the negative OLR anomalies move northeastward and are on the point of dissipating. This phenomenon brings another wet phase to the south of the Yangtze River and the easterly wind anomalies appear again over the southern SCS with the WPSH strengthening and expending westward in phase 7.

As shown by the composite life-cycle of PC1*, the negative OLR anomalies originate in the western and central equatorial Indian Ocean and propagate eastward along 5°N. Easterly winds are ahead of the convective center, with strong westerly winds at the wake.
The zone of negative OLR anomalies is amplified in the central Indian Ocean and divided into two parts: one part continues to move northward to the Bay of Bengal and peaks at phase 9/1 while the other part extends to the maritime continental region. This feature is likely similar to the Madden–Julian Oscillation (MJO) (Hendon and Salby, 1994). The 30-yr averaged correlation coefficient between the real-time multivariate MJO series 2 (RMM2) (Wheeler and Hendon, 2004) and PC1* is 0.5, while the correlation coefficient between the RMM1 and PC1* is 0.4 when PC1* lags RMM1 by 10 days. These correlation coefficients are all significant at the 99% confidence level. It is likely that the eastward propagation of the MJO across the tropical Indian Ocean and the maritime continent plays an important role in the ISO in SCSSM. However, this case also highlights features of the subtropical systems: in particular, the easterly wind anomalies ahead of the negative OLR move in a northward direction, precede the westward extension of the WPSH, and are associated with the anticyclone circulation over the central SCS that produces the wet phase to R2 (phases 7–9). The westerlies within and behind the eastward propagating convection and the anomalous cyclonic circulation within the re-enhanced convection over the western Pacific Ocean warm pool move in a northward direction and replace the anticyclone circulation over the central SCS that produces the dry phase to R2 (phases 3–5).

Similar processes are also seen in the composites of PC2* (Fig. 8). The tropical intraseasonal signal propagates eastward from the Indian Ocean to the maritime continent and interacts with the SCSSM systems in a manner similar to that seen in the composites of PC1*. The correlation between RMM1 and PC2* is 0.35. However, the associated cyclonic circulation begins to develop near the Indo-China Peninsula approximately five latitudes north of the region where the circulation begins in the composites of PC1*. Accordingly, the WPSH anomaly and the associated cyclonic/anticyclonic circulation anomalies occur approximately five latitudes further to the north in the peak phases than in PC1*. This results in the out-of-phase rainfall anomalies in R1 and R3 in Figs. 7c and 7d.
5. Relationship between the ISO in SCSSM and RPHR in different regions

5.1 Statistical relationship

As shown in Table 3, the 30–60-day intraseasonal variation in rainfall is strongly related to RPHR. Meanwhile, according to the analyses described in Section 4, the ISO in SCSSM causes an alternation between wet and dry phases in southern China with a period of approximately 40 days. Here, the statistical relationship between the ISO in SCSSM and RPHR is further investigated. Table 4 shows the total number of RPHR events and RPHR events that correspond to wet phases over the three typical regions from April to September. The wet phases for R1, R2, and R3 are represented by phase 9/1 of PC2*, phase 9/1 of PC1*, and phase 5 of PC2*, respectively. Over regions R1, R2, and R3, more than 70% of the RPHR events occur during the corresponding wet phases and less than 10% occur during the corresponding dry phases (figure omitted). This suggests that: 1) the stable and lasting circulation conditions created by the ISO of the SCSSM are necessary for RPHR over southern China; 2) the RPHR events in R2 are controlled by EOF1 of the ISO in SCSSM while the RPHR events in R1 and R3 are related to EOF2.

Table 4. The total number of RPHR events, the number of RPHR events that occur during the wet phases, and the total number of wet phases in the three regions

|                | R1 | R2 | R3 |
|----------------|----|----|----|
| Total number of RPHR events | 17 | 23 | 26 |
| RPHR events during wet phases  | 12 | 18 | 19 |
| Total number of wet phases     | 49 | 66 | 49 |

5.2 Affecting systems

Using results from the composite analysis, the meridional-vertical structures of wet phases are plotted in Fig. 9 to illustrate the conditions that promote RPHR and the differences in the wet phases in different regions. In Fig. 9a, the positive height anomaly, which is caused by the westward extension of the WPSH, ranges from the surface to 400 hPa along 20°N and coincides with the maximum descending motions (Fig. 9b). The meridional winds blow from the SCS to the land at the lower levels (below 400 hPa) and from the land to the SCS at the higher levels (above 300 hPa). A meridional circulation cell is established with ascending branches near the equator and 25°–30°N. The low-level convergence and the upper-tropospheric divergence (Fig. 9c) that coincides with the positive specific humidity anomaly at 25°–30°N are associated with this northern ascending branch (Fig. 9a). A reversed structure (figure omitted) in which the WPSH retreats to the east is found in the dry phases. This meridional-vertical structure of wet phases could contribute abundant water vapor, ascending motion, and time for the RPHR over R2; in contrast, large-scale rainfall would be suppressed during dry phases. This observation could be used to interpret the relationship between the ISO of the SCSSM and RPHR.

The position of the meridional circulation cells in the wet phase of R3 is distinctive from that observed in phase 9/1 of PC1*. In phase 5 of PC2*, as shown in Figs. 9d–f, the positive height anomaly center moves northward to 20°–25°N and the north ascending branch moves to 30°–35°N, coinciding with the baroclinic vorticity and divergence. This structure leads to the positive specific humidity anomaly at 30°–35°N and the positive rainfall anomaly at R3, as shown in Fig. 7d. For phase 9/1 of PC2*, as shown in Figs. 9g–i, the structure is reversed. The ascending branch and the positive specific humidity anomaly move to 20°–25°N, creating favorable conditions for RPHR in R1.

Interestingly, as shown in Figs. 9b and 9e, there is another meridional circulation cell in the south between the land and the tropical ocean in which the ascending branch (or the descending branch in Fig. 9h) is also very strong (Fig. 9b), even stronger than the north branch (Fig. 9e). The south ascending branches in Figs. 9b and 9e coincide with the negative OLR* centered over the maritime continent (Fig. 6c) and over the southern part of the SCS (Fig. 8b), while the descending branch in Fig. 9h coincides with the positive OLR* centered over the southern part of the SCS in Fig. 8a. In addition, as shown in Section 4.2, the correlations between PCs* and RMM1/RMM2 in-
Fig. 9. Meridional-vertical intraseasonal structures averaged over 110°E–120°E. (a–c) Phase 9/1 of PC1*; (d–f) phase 5 of PC2*; (g–i) phase 9/1 of PC2*. The specific humidity (contours; g kg\(^{-1}\)) and geopotential height (color shadings; dagpm) are plotted in (a, d, g); the meridional wind (contours; m s\(^{-1}\)) and vertical velocity (color shadings; hPa s\(^{-1}\)) are plotted in (b, e, h); the vorticity (contours; 10\(^{-6}\) s\(^{-1}\)) and divergence (color shadings; 10\(^{-6}\) s\(^{-1}\)) are plotted in (c, f, i). The vertical axis in all graphs represents pressure (hPa).

-8 -4 2 4 6 8
-1.5 -0.9 -0.3 0.3 0.9 1.5
-2.1 -1.5 -0.9 -0.3 0.3 0.9

Katherine et al. (2006) found that the onset of the SCSSM is modulated by the interactions of multi-scale systems in which the Kelvin wave generated by the MJO (Madden and Julian, 1994) propagating eastward may play a key role. While the ocean-to-atmosphere effect has been suggested to be important in SCSSM-related ISO (e.g., Wu, 2010; Roxy and Tanimoto, 2011), the dynamic processes of the internal atmosphere have also been recognized as dominant mechanisms (e.g., Jiang et al., 2004; Demott et al., 2013). We construct the meridional-phase structure of the composite ISO mode based on PC1*. As shown in Fig. 10, the contoured variable represents the geopotential height anomalies averaged from 500 to 1000 hPa; the colored variables represent the OLR in Fig. 10a and the skin temperature in Fig. 10b. The northward propagating OLR anomalies couple with the fluctuations in geopotential height anomalies between 10° and 30°N, indicating the importance of the northward propagation of ISO. The skin temperature anomaly centers between the geopotential height anomaly seesaws, indicating that the local air-sea interaction over
the SCS is also a key mechanism contributing to fluctuation in the WPSH. Mechanistic analysis is not the primary concern of the present paper; however, we do plan to make this a focus in future work.

According to the analysis described above, the east-west oscillation of the WPSH in the 30–60-day period causes an alternation in the meridional circulation that modulates the occurrence of RPHR, while the zonal position of the WPSH determines the regions where RPHR occurs. However, these favorable conditions are not sufficient, as the number of wet phases that feature RPHR is less than one-third of the total number of wet phases (Table 4). Therefore, other factors must be involved. In Fig. 9a, a strong negative height anomaly to the north of 30°N can be seen. The influence of the mid and high latitudes should be investigated. As shown in Fig. 11, the composite wet phases for the three regions are re-classified according to the exclusion (left column) and inclusion (right column) of the RPHR events. In Fig. 11b, a negative OLR* can be observed at the center of the south of the Yangtze River; however, this OLR* is not seen in Fig. 11a, indicating different convection conditions for the RPHR. Furthermore, the meridional high-latitude systems (including a lower-pressure center near Baikal Lake and an abnormal high-pressure center and anomalous anticyclonic circulation to the west of the Ural Mountains) are more active. This is similar to a blocking situation (Rex, 1950), which is one of the main phenomena involved in low frequency atmospheric variations (Gao et al., 1998). Blocking situations in East Asia have already been defined in detail and usually occur in three regions in the latitude range 40°–75°N (Tang, 1957; Li and Ding, 2004): the Ural Mountains (40°–75°E), Baikal Lake (80°–110°E), and Okhotsk region (130°–150°E). However, there is no clear definition for the intraseasonal variation of blocking situations; thus, we merely distinguish them from their location and intensity and denote them using double quotes (e.g., “Ural Mountain blocking”). The blocking situations can also be observed in Figs. 11d and 11f; however, when RPHR event occurs in different regions, the blocking situations are also different. As shown in Fig. 11d, the “Ural Mountain blocking” is replaced by the “Baikal Lake blocking”, and the “Okhotsk blocking” is very strong. This situation has been proved to be an important factor for RPHR in the Yangtze-Huai River basin (Ding, 1993; Bao, 2007). During the wet phase of RPHR for R1 (Fig. 11f), the northwest low-level winds (marked by the blue arrow) between the “Ural Mountain blocking” and the “Siberian low” move into North and Northeast China, and then shift southwestward at the south of a blocking high. This situation provides cold air for...
Fig. 11. The composite wet phases for the three typical regions re-classified according to the exclusion (left column) and inclusion (right column) of the RPHR events for (a, b) phase 9/1 of PC1*, (c, d) phase 5 of PC2*, and (e, f) phase 9/1 of PC2*. The variables are the same as those in Fig. 6.
RPHR. This finding shows that the mid- and high-latitude systems also play an important role in promoting RPHR over southern China during the wet phases created by the ISO in SCSSM; the low frequency variation of high-latitude systems, especially the blocking situations, may be out of step with the ISO in SCSSM. The role of these systems should be studied further.

6. Conclusions and discussion

In the present study, using observed gridded precipitation, OLR, and NCEP/NCAR reanalysis data from 1981 to 2010, the relationship between ISO and RPHR in southern China, the ISO process in SCSSM and its influence on RPHR are investigated.

Southern China can be divided into three typical regions based on the REOF modes of 30-60-day band-pass filtered rainfall. The IRI is defined as the average regional precipitation in each region. The RPHR events that occur in the typical regions are found to be strongly related to the intraseasonal variation in the rainfall; indeed, more than 80% of the RPHR events occur when the IRI is larger than one standard deviation.

The mapping of regression coefficients relating U850 to IRIs indicates that the SCSSM systems play an important role in regulating intraseasonal rainfall over southern China. EOF analysis is performed on the 850-hPa zonal wind, which is averaged over 110°-120°E, to represent the main mode of the SCSSM. Then, a pair of ISO modes of the SCSSM is identified by performing Morlet wavelet analysis on the leading PCs of EOF1 and EOF2. Composite analyses based on PC1 and PC2 reveal the following evolution processes of the ISO in SCSSM: the accompanying eastward-propagating MJO and the east-west oscillation of the WPSH produce alternating dry and wet phases over southern China. These alternating periods last approximately 40 days and modulate the intraseasonal variation in the rainfall. EOF1 of the 850-hPa zonal wind over the SCS and southern China mainly represents the ISO mode controlling the intraseasonal rainfall south of the Yangtze River, while EOF2 leads to the intraseasonal out-of-phase rainfall over South China and the Yangtze-Huai River basin.

The RPHR is found to be closely related to the ISO in SCSSM. In the three typical regions, more than 70% of RPHR events occur during wet phases from April to September. During wet phases, moisture-rich air is transported to southern China at lower levels by the southwestward flow to the north of the WPSH. The unstable lower atmosphere coincides with an upper-tropospheric divergence and a low-level positive vorticity center that promotes heavy rainfall. The structures of ISO systems are reversed during dry phases, suppressing the rainfall over the corresponding regions. The region of RPHR is determined by the zonal position of the WPSH.

The meridional-phase structure of the composite ISO modes indicates that the northward-propagating ISO and local air-sea interactions over the SCS are two key factors that promote the fluctuations in the geopotential height anomaly. However, we did not investigate potential mechanisms behind these phenomena, as such a topic is not the primary focus of the present work, and additional numerical simulations would be needed to identify the dominant mechanism. Coupling between the ISO in SCSSM and the mid- and high-latitude systems, especially blocking situations, also play important roles in promoting the occurrence of RPHR over southern China during wet phases, and should be studied further.

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