10–30-Day Subseasonal Features Associated with Multiple and Isolated Persistent Rainfall Events over South China

BIN ZHENG,a,b AILAN LIN,a,b AND YANYAN HUANG,a,b

a Guangzhou Institute of Tropical and Marine Meteorology, China Meteorological Administration, Guangzhou, China
b Guangdong Provincial Key Laboratory of Regional Numerical Weather Prediction, Guangzhou, China

(Manuscript received 17 September 2022, in final form 24 November 2022)

ABSTRACT: In this study, persistent rainfall (PR) over South China (SC) is divided into two types. One type occurs multiple times in succession [defined as multiple PR (MPR)]; another type represents isolated PR (IPR), for which no new PR occurs for 10 days after the previous PR. The spatiotemporal structures of the 10–30-day intraseasonal oscillations (ISOs) associated with the two types of PR are compared and analyzed. The results reveal that the low-level moisture and air temperature perturbations always have a leading phase relative to the anomalous precipitation. In addition, the positive low-level moisture tendency appears in the MPR ending phase, whereas that in the IPR is close to zero. This difference results in convective development after the MPR ending phase, though not after the IPR. The moisture budget shows that the difference in moisture tendency between MPR and IPR is mainly due to meridional advection, including advections by the mean meridional flow across the perturbation moisture gradient and by the perturbation meridional flow across the mean moisture gradient. For the former, the difference is attributed to the perturbation moisture gradients, while the mean moisture gradients are responsible for the difference of the latter. Furthermore, an essential cause of the difference is the influence of higher-latitude disturbances that affect the IPR more significantly than the MPR. Two associated mechanisms are proposed. One is the perturbation stacking effect, and the other is the effect of angular momentum conservation. By contrast, the low-level temperature anomalies are not the key factor causing the difference between MPR and IPR.

SIGNIFICANCE STATEMENT: The persistent rainfall over South China sometimes occurs multiple times in succession, though most are in isolation. We want to understand the structures of the related 10–30-day ISOs and then find the possible cause of why convection develops after the ending stage of the multiple persistent rainfall events but not after the isolated rainfall events. We reveal that the effect of higher-latitude disturbances is an essential factor for the development of the two types of persistent rainfall over South China, with two proposed mechanisms of the perturbation stacking effect and angular momentum conservation. This is helpful for predicting persistent rainfall over South China. Future work should examine the findings by numerical experiments with a climate model.

KEYWORDS: Advection; Rainfall; Angular momentum; Extreme events; Moisture/moisture budget; Intraseasonal variability

1. Introduction

Persistent rainfall (PR) is a main meteorological disaster that occurs during the flood season and severely affects the safety of people’s lives and property by causing floods, landslides, and mudslides. In the context of climate change, global persistent precipitation has increased significantly (Du et al. 2019). This increasing trend of PR is also found in China and is reflected mainly in the frequency and intensity of these occurrences (Chen and Zhai 2013).

PR in mainland China mainly occurs in southern China and is closely linked to the intraseasonal oscillation (ISO) (Ren et al. 2013; Li et al. 2015; Hui and Fang 2016a,b; Wang et al. 2017; Zheng and Huang 2018). Therefore, Gao et al. (2016) introduced a regional ISO index to monitor the PR in South China (SC). Generally, the ISOs include high-frequency (HF) and low-frequency (LF) oscillations with periods of 10–20 (or 10–30) and 30–60 days, respectively (Mao and Chan 2005; Krishnamurthy and Shukla 2007; Li et al. 2015; Hui and Fang 2016a,b; Li et al. 2018; Zheng and Huang 2019). The HF-ISO, namely, the quasi-biweekly (QBW) oscillation (QBWO), is one of the major systems that affect tropical and subtropical weather and climate. For example, the QBW mode plays a significant role in extreme weather events over East Asia via variations in atmospheric circulation and propagation of convection (Wang et al. 2013; Gui and Yang 2020; Zhu et al. 2020). In SC, PR is generally associated with atmospheric circulation and moisture processes on multiple time scales (Fang et al. 2012; Hong and Ren 2013; Li et al. 2014; Li and Zhou 2015; Li et al. 2015), while the QBW mode has the most remarkable contribution (Li et al. 2015; Zheng and Huang 2018; Zheng et al. 2021).

The dominant structure of the QBW mode associated with PR over SC is a northwest–southeast-oriented wave train, with a low-level cyclonic anomaly and a high-level anticyclonic anomaly over the convection center, in which the QBW disturbances move northwestward from near the tropical western North Pacific (WNP; Li et al. 2015; Wang and Chen 2017; Li et al.
Tropical northwestern-propagating QBW disturbances can be understood in terms of moist equatorial Rossby waves (e.g., Chatterjee and Goswami 2004; Kikuchi and Wang 2009) or mixed Rossby–gravity waves (e.g., Mao and Chan 2005) in the presence of monsoon mean flow and convective coupling. In addition, the effects of higher-latitude disturbances may be important for the PR events over SC (Fang et al. 2012; Li et al. 2015; Zheng and Huang 2018; Cheng et al. 2020; Zheng et al. 2021).

The extratropical QBW mode connects with upstream extratropical Rossby wave trains and propagates primarily eastward and equatorward (Kikuchi and Wang 2009). The QBWO is often defined as a 10–20-day oscillation (e.g., Mao and Chan 2005; Wen et al. 2010; Li et al. 2015; Li and Zhou 2015), but other bands, such as 8–25 days (Wang et al. 2012) and 10–30 days (Qian et al. 2019), were also selected. According to Li et al. (2018), the spectral band of the South China Sea–WNP QBWO is not fixed at 10–20 days; it has been lengthening for many years. Moreover, the results in the QBWO study are not sensitive to whether we choose 10–20 days or the broader 12–30 days for QBW filtering (Kikuchi and Wang 2009).

In this study, to include the main QBWO periods from 1961 to 2017, we chose a band of 10–30 days. This paper refers to the 10–30-day oscillation as HF-ISO to avoid confusion with the 10–20-day QBWO.

In addition to the HF-ISO, the LF-ISO effects on the PR over SC have also been noted in previous studies. Here, the LF-ISO includes the northward-propagating LF-ISO and the eastward-propagating Madden–Julian oscillation (Madden and Julian 1971, 1972). The former can directly affect the PR over SC via northward propagation (e.g., Li et al. 2015; Zheng et al. 2020), which is explained by many mechanisms (e.g., vertical easterly wind shear; Wang and Xie 1997; Jiang et al. 2004; Drbohlav and Wang 2005; baroclinic vorticity advection; Bellon and Sobel 2008; barotropic vorticity advection: Zheng and Huang 2019; Zheng et al. 2019; and feedback from underlying surface heat fluxes: Webster and Holton 1982; Webster 1983; Gyoswami and Shukla 1984; Kemball-Cook and Wang 2001; Zheng et al. 2020, etc.). The Madden–Julian oscillation influences the PR in SC by modulating the WNP tropical high (Bai et al. 2013; Lin et al. 2015) or the South China Sea summer monsoon onset (Lin et al. 2016; Li et al. 2019) when convection shifts eastward to the Maritime Continent and the equatorial western Pacific. The mechanism of eastward propagation is attributed to the moisture mode theory (Hsu and Li 2012; Sobel et al. 2014; Adames et al. 2016; Jiang 2017; Jiang et al. 2018; Wang and Li 2020a,b), which is widely accepted. Very recently, Zheng et al. (2022) pointed out that on the intraseasonal time scale, the HF variation (10–30 days) of rainfall over SC has a much larger variance than the LF variation (30–60 days). Therefore, this study focuses on the regional PR processes related to HF-ISO.

In addition, sea surface temperature (SST) forcing plays an important role in China rainfall on interannual and larger time scales (Yuan et al. 2008; Feng et al. 2011; Chen et al. 2017), and even the interannual variability in boreal summer ISOs can be significantly affected by ENSO (e.g., Lin and Li 2008) and the Indian Ocean dipole or basin mode (e.g., Lin et al. 2011). Nevertheless, the contribution of SST forcing to the ISO process generally does not exceed 20% (e.g., Gao et al. 2019; Li et al. 2020). It implies that the internal atmospheric dynamics, which are the focus of this study, are essential to the ISO processes.

Typically, the previous studies did not distinguish between multiple PR (MPR) and isolated PR (IPR). Therefore, the differences in the physical characteristics of MPR and IPR are not clear, especially at the ending stages, and understanding why the subsequent convection develops or does not develop is difficult. Thus, in this study, we aim to analyze the structures of the HF-ISOS related to MPR and IPR over SC and then find the possible cause of why convection can develop after the ending stage of MPR and not develop at that of IPR. The next section describes the datasets and methods used in this study. The structures of the HF-ISOS related to MPR and IPR over SC are presented in section 3. The cause of differences in convective development after the end of PR is discussed in detail in section 4. Finally, a summary and discussion are provided in section 5.

2. Data and analysis method

a. Data

The data used in this study include the daily precipitation from the China Meteorological Administration (CMA) surface stations in China with 2407 sites (the locations of the 2407 sites are shown in Fig. 1) for the period 1 January 1961–31 December 2017. Based on the source precipitation observations from the 2407 sites that have been quality controlled (e.g., excluding invalid data, revising incorrect data), a standard normal homogeneity test method is applied to correct the inhomogeneous series (Alexandersson 1986; Wang et al. 2012). The other data include the daily three-dimensional winds, specific humidity, and air temperature from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) with 2.5° × 2.5° grids for the period 1 January 1961–31 December 2017 and the outgoing longwave radiation (OLR) daily data (Schreck et al. 2018) from NOAA’s National Centers for Environmental Information with 1° × 1° grids for the period 1 January 1979–31 December 2017. For convenience, all the variations from the NCEP–NCAR reanalysis data are interpolated to a 1° × 1° spatial resolution.

b. Definition of regional PR

Following Lin et al. (2020), a PR event in this study is defined when the regional precipitation meets the given conditions for 3 consecutive days or more. The given conditions include the ratio of the number of stations with precipitation larger than 50 mm to the total number of stations in the region greater than or equal to 4%, and regional average precipitation exceeding 1.5 times the standard deviation (std). In this study, the SC region is 107°–120°E, 21°–26°N (see the box in Fig. 1); 267 regional PR events occur within it. Since we are interested in the intraseasonal persistent rainfall, we chose PR events related to HF-ISO by using the following criterion: the regional mean 10–30-day filtering precipitation is greater
than 0.5 times the std and lasts for 4 days or more; at the same time, the PR process is at least 3 days in this period. Thus, we obtain 220 PR events over SC. This implies that most PRs over SC, with a proportion of 220/267, are related to HF-ISO.

c. Phase identification

Based on an understanding of ISO, the ISO process is usually divided into eight (Lee et al. 2013; Karmakar et al. 2017) or four phases (Hsu et al. 2011). For example, Karmakar et al. (2017) used the first PC of a particular ISO mode and estimated the amplitude and phase angle, then divided the phase plane into eight equal intervals. Hsu et al. (2011) divided ISO into four phases with 1 std as the threshold. PR is not completely equal to ISO. Thus, the phase of a PR event is not fully in accordance with an ISO process. The composite results based on the SC PR maximum and minimum show a larger amplitude in the positive phase than in the negative phase. Considering the phase asymmetry, we
divide the HF-ISOs related to the SC PR into five phases with 1 std (red dashed line in Fig. 2a) in the positive phase and −0.75 std (blue dashed line in Fig. 2a) in the negative phase as the threshold (Zheng et al. 2022). That is, the suppressed phase and developing phase appear before the peak precipitation with values less than −0.75 std and between −0.75 and 1 std, respectively; an active phase is the period when the 10–30-day filtering precipitation is greater than 1 std; and the decaying phase and ending phase appear in the period after the peak precipitation when the ISO precipitation is between −0.75 and 1 std and less than −0.75 std, respectively (as shown in Fig. 2a). Based on the threshold, some HF-ISO processes associated with PR events are missing the suppressed phase, ending phase or even both phases (e.g., a PR case in 2016, as shown in Fig. 2b). In this study, only PR events that were significant in all five phases were selected. Thus, 195 PR cases were obtained.

d. Other methods

To obtain the 10–30-day intraseasonal component, a bandpass filter is applied to the daily data. The synoptic-scale and LF components are derived from the deviation from the 11-day running mean and the 31-day running mean, respectively. The climatological mean is from 1981 to 2010. In this study, the SC region extends from 21° to 26°N and from 107° to 120°E. The day with the minimum precipitation in the ending phase averaged over SC was chosen as the reference day (zero day) for composite analysis. Furthermore, moisture balance analysis is also employed in this study.

3. Structures of the 10–30-day ISOs related to MPR and IPR over SC

PR often occurs in isolation over SC, that is, IPR, defined as no new PR occurring for 10 days after the ending phase. Thus, we obtain 134 IPR cases from 1961 to 2017, accounting for approximately 70% of the total (134/195). The composite 10–30-day SC precipitation is shown in Fig. 2d based on the reference day when the precipitation anomaly reaches a minimum after the extreme wet phase. From Fig. 2d, we can see that there is a precipitation maximum on the sixth day before the extreme dry phase. Furthermore, convection does not develop after the negative phase, and the positive precipitation anomaly is ridiculously small, much less than the 1 std. Composite 10–30-day OLR is shown in Figs. 3d–f. Corresponding to the precipitation maximum before the negative phase (−6 days), there is a convection (OLR negative anomaly) center over SC, and a suppressed convection (OLR positive anomaly) center to the south (Fig. 3d). Weak convection appears over the Maritime Continent to the south of the suppressed convection center. On the reference day (0 day), the suppressed convection moved northward and controlled SC, while the budding convection on the Maritime Continent propagated northward to approximately 10°N and developed to a certain extent. On the sixth day of the reference day (+6 days), the weak convection moved to SC and did not develop into PR.

In addition, PR sometimes occurs multiple times in succession. When a new PR occurs within 10 days after the ending phase, the previous PR is called MPR. This type of PR accounted for slightly over 30% of the total (61/195). One can
see from Fig. 2c that there are two peaks with values exceeding 1 std; that is, after the minimum precipitation, there is a new convection development that reaches a certain intensity (more than 1 std). Similar to the IPR results, the convection related to MPR moves northward from the equator to SC; however, another developing convection propagates northward to SC and is strengthened to a comparable intensity relative to the previous PR (Figs. 3a–c). Thus, a new PR occurs shortly after the previous PR.

To understand the PR processes over SC, horizontal and vertical structures of the associated 10–30-day ISO are analyzed. Figures 4 and 5 show 850-hPa 10–30-day ISO vorticity
and horizontal winds related to MPR and IPR, respectively. One can see from Figs. 4 and 5 that more significant anomalies of vorticity and wind appear in the suppressed, active, and ending phases (referred to as phase 1, phase 3, and phase 5) than in the developing and decaying phases (referred to as phase 2 and phase 4). For the MPR over SC, phase 3 is characterized by a strong positive vorticity and a cyclonic flow at lower level in SC, with a strong negative vorticity and a low-level anticyclonic flow to the southeast of SC (Fig. 4c). The wind and vorticity anomalies during phase 1 and phase 5 are almost the same pattern that is out of phase to those in phase 1 (Figs. 4a,c,e). Phase 2 and phase 4 are the transition periods of phase 1 to phase 3 and then to phase 5 (Figs. 4b,d). Since the ISO precipitation is so small, the associated anomalies are evidently weak in phase 2 and phase 4 (Figs. 4b,d), especially over SC. In the postending period (defined as 5 days after phase 5), the low-level vorticity and wind anomalies, with a greater strength, have a similar pattern to those in phase 2 (Figs. 4b,f). For the IPR over SC, the low-level wind and vorticity anomalies have similar patterns to those of MPR from phase 1 to phase 5, while the anomalies during the postending phase are weaker than those in phase 2 (Figs. 5b,d), which contrasts MPR. Additionally, the upper anomalies have almost the same patterns as those at the lower level, but with an opposite sign (figure not shown). This implies that the PR over SC is characterized by an obvious baroclinic structure.

Figures 6 and 7 show the anomalous water vapor at the 925-hPa level based on different phases of MPR and IPR, respectively. A northwest–southeast-oriented wave train pattern is also reflected in the low-level moisture anomalies associated with MPR and IPR. Different from the circulation anomaly, there is an obvious positive moisture anomaly in SC in phase 2 of PR (Figs. 6b and 7b). Since low-level moisture plays a key role in convective instability over SC (Zheng et al. 2020), a positive anomaly of water vapor in phase 2 is favorable to the development of PR in phase 3. In addition, a significant positive anomaly of moisture appeared over SC during the postending period of MPR (Fig. 6f), favoring a new PR, while no significant moisture anomaly for IPR (Fig. 7f) to develop a new PR.

Overall, the 10–30-day mode related to PR over SC is characterized by a northwest–southeast-oriented wave train pattern with a significant baroclinic vertical structure. In addition, the 10–30-day mode has a significant feature of northwestward propagation as shown in Figs. 4–7. These features are consistent with Li et al. (2015). Moreover, a positive moisture anomaly plays a key role in developing a PR.

Figures 8 and 9 show a vertical structure of the 10–30-day mode related to MPR and IPR. From Fig. 8, one can see that vertical velocity, vorticity, divergence, moisture, high-level temperature, and low-level temperature tendency are in phase with the precipitation anomalies for MPR, while low-level moisture and temperature are ahead of the precipitation anomalies, which is due to the radiative forcing. A shortwave radiation minimum corresponds to the precipitation maximum, and thus a minimum of low-level temperature tendency, leading to a subsequent low-level temperature minimum (Figs. 8e,f).

For IPR, there are similar vertical structures relative to those in MPR (Fig. 9). The difference between MPR and IPR appears in the postending phase when the anomalies of almost all variables in MPR are much larger than those in IPR, except for temperature. The low-level temperature anomaly in the postending phase of IPR is even greater than that in MPR. This implies that the low-level temperature anomaly is not a key factor for the development of PR over SC.
4. Moisture budget in the ending phase (phase 5)

As mentioned above, the positive moisture anomaly over SC in the postending phase plays an important role in developing new PR. Therefore, the positive moisture anomaly in the postending phase of MPR is more significant than that in IPR. From Fig. 10a, we can see that there is a positive moisture tendency in phase 5 of MPR, while that in IPR is close to zero, as shown in Fig. 10b. To consider the scale interactions, we separated the anomalous fields
into four components: the mean state, the LF (>30 days), HF-ISO (10–30 days), and synoptic scale (<10 days),

\[ A = \bar{A} + \tilde{A} + A' + A''. \quad (1) \]

where an overbar denotes the mean state, a tilde overbar denotes the LF component, a prime denotes the HF-ISO field, and a double prime denotes the synoptic-scale field. Thus, for a good approximation, \((\partial q/\partial t)'\) can be written as...

**Fig. 9.** As in Fig. 8, but for IPR.

**Fig. 10.** The 925-hPa moisture budget in phase 5 of (a) MPR and (b) IPR, and (c) the differences (IPR minus MPR).
Fig. 11. Relative roles of the terms to the effects of the mean state in phase 5 of (a) MPR and (b) IPR, and (c) the differences (IPR minus MPR).

\[
\frac{\partial q}{\partial t} \approx -\frac{(u \partial q_y)}{\partial y} - \frac{(v \partial q_x)}{\partial x}
- \frac{(\bar{u} \partial q_y)}{\partial y} - \frac{(\bar{v} \partial q_x)}{\partial x}
- \frac{(\pi \partial q_y)}{\partial y} - \frac{(\nu \partial q_x)}{\partial x}
- \frac{\partial q_y}{\partial y}
- \frac{(Q_s)}{L}.
\]

where \( q \) is the specific humidity, \( u \) is the zonal wind, \( v \) is the meridional wind, \( \omega \) is the vertical pressure velocity, \( Q_s \) is the atmospheric apparent moisture sink, \( L \) is the latent heat of condensation, HH represents the eddy terms, HL denotes the interaction terms between low frequency and synoptic scale, LL denotes the low-frequency contributions, MS represents the mean state contributions, WQ is the vertical advection term, and OP is the latent heat term. One can see from Fig. 10a that the moisture tendency in phase 5 of MPR is mainly attributed to the terms MS, HH, and OP, while the positive moisture tendency in IPR is mainly contributed by the terms HH and OP as shown in Fig. 10b. The difference in the moisture tendency between IPR and MPR, however, is only due to the MS contribution (Fig. 10c).

Why is the effect of MS on the low-level moisture different? Next, we examined the relative roles of each term of MS (Fig. 11). From Fig. 11a, one can see that the meridional advection plays a key role in the term MS in phase 5 of MPR, and the advection term by the mean zonal flow \( -[(\bar{u} \partial q_y) / \partial y] \) has a modest contribution. For IPR, the term MS, with an opposite sign to that in MPR, is also due to the contribution of meridional advection (Fig. 11b). From Fig. 12c, we can see that the MS difference in phase 5 between MPR and IPR is induced by meridional advection, including advectons by the mean meridional flow across the perturbation moisture gradient and by the perturbation meridional flow across the mean moisture gradient.

**a. Effect of the mean meridional flow**

Figure 12 shows a negative meridional gradient of the moisture anomaly in phase 5 of MPR over SC and a positive gradient in IPR. PR over SC mainly occurs in the rainy season from April to September when the mean meridional flow over SC is southerly. Thus, positive meridional moisture advection occurs in phase 5 of MPR, and a negative advection occurs in IPR. This is consistent with Figs. 11a and 11b. Comparing Fig. 6e and Fig. 7e, we can see that the center of the negative moisture anomaly in phase 5 of MPR is located to the north of that of IPR, resulting in a difference in the meridional gradient of low-level water vapor between MPR and IPR, as shown in Fig. 12. Figure 7 shows that a positive moisture anomaly moves southward from higher latitudes during phase 3 throughout phase 5, so the center of the northward-propagating moisture anomaly, with a negative extreme, is prohibited in the southern part of SC during phase 5 of IPR. By contrast, the southward propagation in the MPR is not significant (Fig. 6). To show the propagation characteristics more clearly, a finite-domain (10.5°–40.5°N along SC) wavenumber–frequency analysis (e.g., Teng and Wang 2003; Lin and Li 2008; Lin et al. 2011; Zheng and Huang 2019) is
applied to transform the OLR field from a space–time domain to a wavenumber–frequency domain as shown in Fig. 13. The wavenumber–frequency analysis extends from the traditional temporal power spectrum analysis to the spatiotemporal power spectrum analysis. In this study, wavenumber 1 corresponds to a wavelength of 30° in latitude, and negative wavenumber corresponds to a southward-propagating component, since phase velocity is equal to wavelength multiplied by frequency. From Fig. 13, one can see that the northward-propagating 10–30-day OLR anomaly is a dominant mode for both MPR and IPR, while the southward-propagating component is indeed more significant in IPR than in MPR.

b. Effect of the mean meridional moisture gradient

From Fig. 14, we can see that the MPR events occur in April–October, with most occurring in May–August (the monsoon season), when the mean meridional gradient of the 925-hPa moisture is positive over SC. By contrast, IPR events occur from March to December, including the monsoon season and the nonmonsoon season, when the mean meridional gradient of low-level moisture is negative over SC, with a larger contribution coming from the nonmonsoon season. In response to a negative convective heating in phase 5, the perturbation wind is northerly over SC as shown in Figs. 4e and 5e. Thus, a positive moisture advection by the HF-ISO wind appears in phase 5 of MPR and a negative advection for IPR, as shown in Fig. 11.

Even during May–August (the monsoon season), the moisture advection by the anomalous meridional wind in phase 5 of IPR is much smaller than that in MPR, although they both have the same mean meridional moisture gradient over SC (figure not shown). This situation is due to the effect of higher
latitudes, as mentioned above. Hence, the vorticity and wind anomalies in phase 5 of IPR have a center to the south of those in MPR (Figs. 4 and 5). As a result, the anomalous northerly over SC is weaker in IPR than in MPR, leading to a relatively small moisture advection by the perturbation wind in IPR, although with the same mean moisture gradient.

5. Mechanisms of interaction in low and middle latitudes

As mentioned above, due to the influence from higher latitudes, the perturbation pattern over SC in the ending phase is different between MPR and IPR, which leads to differences in the development of low-level water vapor and PR. We tried to understand the mid–low-latitude interaction processes from the following two aspects:

\[ \text{FIG. 14. Climatological-mean meridional gradient of 925-hPa moisture (open circles; g kg}^{-1}\text{ per degree). The red horizontal line denotes the April–October mean, and the blue horizontal line denotes the March–December mean. Red and blue vertical lines represent the times of all MPR and IPR events from 1961 to 2017, respectively.} \]

\[ \text{FIG. 15. Regressed 925-hPa moisture (g kg}^{-1}\text{) in phase 5 on the anomalous OLR averaged over SC (open circles), on the anomalous OLR averaged over northern SC (107°–120°E, 32°–40°N, closed circles), and on both (red line) for (a) MPR and (b) IPR. Red and blue text represent the SC meridional gradient of regressed low-level moisture on both convection anomalies (red line) in the MPR and IPR ending phase, respectively.} \]

**a. Perturbation stacking effect**

Since SC is evidently affected by higher-latitude southward-propagating perturbations during the IPR period, in addition to the local disturbance source in SC, there was also a disturbance source to the north of SC. The two perturbations are superimposed together, leading to a different pattern of perturbation moisture between MPR and IPR. As shown in Fig. 15a, for MPR, the regressed moisture on SC convection has a similar pattern to that on both SC convection and northern convection because of the weak influence of higher latitudes in this period. For IPR, the regressed moisture on only the SC convection is similar to that for MPR, whereas the regressed moisture on both disturbance sources has a large change over SC, from negative gradients to positive gradients,
which is almost the same as Fig. 12b. This implies that the perturbation stacking effect does play an important role in the development of MPR and IPR over SC.

b. Effect of angular momentum conservation

As mentioned above, because of the effect from the higher latitudes, the vorticity and wind anomalies in phase 5 of IPR have a center to the south of those in MPR. This can be explained by the conservation of angular momentum. Note that the angular momentum here refers to the absolute angular momentum with the vertical axis. The equation of conservation of angular momentum can be written as

\[ v_\theta R + R^2 \Omega \sin \varphi = \text{constant}, \]

where \( v_\theta \) is the tangential velocity, \( R \) is the radius, \( \Omega \) is the angular velocity of Earth’s rotation, and \( \varphi \) is the latitude. For a simple case, we take \( R \) as a constant; thus, changes in tangential velocity \( v_\theta \) will cause changes in the latitude \( \varphi \) of the vortex. Though the mean meridional gradient of low-level moisture is same during the monsoon season (as shown in Fig. 14), the disturbance meridional flow is different between MPR and IPR due to the effect of angular momentum conservation, which lead to the difference between MPR and IPR in the advection of the mean moisture by the anomalous meridional wind during May–August (figure not shown). In phase 5 of the MPR, an anticyclonic anomaly appears over SC (Fig. 4e and schematic in Fig. 16a). Therefore, the advection of the background moisture by the perturbation northerly leads to the development of MPR. In the case of IPR, the influence from the north increases \( v_\theta \) and then the anticyclone shifts southward (as shown in Fig. 16b). As a result, the anomalous northerly over SC is weaker in IPR than in MPR (Fig. 16c), leading to a relatively small moisture advection by the perturbation wind in IPR, although with the same mean moisture gradient.

6. Summary and discussion

In SC, the rainy season begins in April and ends in September or even October when PR often occurs several times. PR in SC is closely linked to the ISO (Li et al. 2015; Wang et al. 2017; Zheng and Huang 2018). In this study, the PRs over SC with a 10–30-day subseasonal feature are divided into two types. One type occurs multiple times in succession (MPR); another type is
isolated PR (IPR) with no new PR occurring for 10 days after the previous PR ended. The major findings of this study are summarized and discussed as follows.

1) There are similar structures between MPR and IPR with a northwest-southeast-oriented wave train pattern and a significant baroclinic vertical structure on the 10–30-day time scale. The northward-propagating component is a dominant mode for both MPR and IPR, while the southward-propagating component is more significant in IPR than in MPR.

2) The positive low-level moisture tendency appears in the MPR ending phase, which favors convective development after the MPR ending phase. The low-level moisture tendency in the IPR ending phase is close to zero, which results in no new PR developing after the previous convection. The difference in moisture tendency between MPR and IPR is mainly due to the meridional advections of the mean fields.

3) The essential cause for the development of MPR and IPR is the meridional gradient difference of the low-level perturbation moisture and wind, which results from the interaction in the low and middle latitudes. Two associated mechanisms, the perturbation stacking effect and the effect of angular momentum conservation, are proposed in this study.

4) Since MPR and IPR have similar low-level temperature changes, it implies that the low-level temperature anomalies are not the key factor causing the difference between MPR and IPR.

In this study, the HF-ISO process related to the PR over SC is divided into 5 phases, which is different from previous studies (e.g., Hsu et al. 2011; Lee et al. 2013; Karmakar et al. 2017). For the MPR, a new PR will develop after the ending phase; thus, the ending phase is equal to the suppressed phase and the HF-ISO process related to the MPR can be described with four phases as in Hsu et al. (2011). In contrast, the IPR has no new PR occurring after the ending phase. Thus, the phase of an IPR event is not fully in accordance with an ISO process in previous studies (e.g., Hsu et al. 2011; Lee et al. 2013; Karmakar et al. 2017). It is helpful for the prediction of PR over SC to understand the differences of the ending phase of the MPR and IPR and the possible causes.

Generally, the effect of HF-ISO disturbances from higher latitudes plays a key role in the PR over the lower reach of the Yangtze River basin (LYRB). For example, Yang et al. (2010) revealed that the biweekly mode of the LYRB PR is initiated by a midlatitude jet stream vorticity anomaly moving southeastward. In contrast, we found that the northward-propagating ISO is a dominant mode for the PR over SC (Fig. 13). This implies that the PR over SC is mainly affected by tropical disturbances. Here, the tropical disturbances refer to the tropical ISOs, which affect the PR over SC through northward or northward propagation (e.g., Li et al. 2015; Zheng et al. 2020). It is worth noting that the 10–30-day HF-ISO disturbances are concerned in this study. Nevertheless, disturbances from higher latitudes sometimes affect the PR over SC with the tropical ISO (e.g., Zheng and Huang 2018). Very recently, Cheng et al. (2020) reported that the PR over SC is affected by three kinds of ISOs, including the southward-propagating ISO, the northward-propagating ISO, and the northwestward-propagating ISO. In the present study, we found that the higher-latitude disturbances have a great influence on the meridional distribution of HF-ISO in SC, although most of the higher-latitude disturbances will not directly affect the PR over SC (Figs. 3–8). The different meridional disturbances are favorable to the MPR and IPR over SC.

Previous studies have shown that the vorticity anomaly plays an important role in the ISOs related to the PR (e.g., Hong and Ren 2013; Li et al. 2014; Hong et al. 2015; Zheng and Huang 2018, 2019; Zheng et al. 2019). In the developing and active phases, the moisture convergence, corresponding to the positive vorticity anomaly in the planetary boundary layer (PBL), favors a PR over SC (Figs. 9b,c and 10b,c). However, during the ending phase, the induced moisture divergence in the PBL has a negative contribution to the positive moisture tendency as shown in Figs. 11a and 11b. It implies that anomalous vorticity in the ending phase favors an IPR event rather than an MPR event.

Acknowledgments. This work is supported by the National Key R&D Program of China (Grant 2018YFC1505801) and the Guangdong Basic and Applied Basic Research Foundation (Grants 2021A1515011399, 2022A1515011870).

Data availability statement. The daily precipitation data of surface stations in China are provided by National Climate Center (NCC), China Meteorological Administration (CMA), the NCEP–NCAR reanalysis data were obtained from ftp://ftp.cdc.noaa.gov/, and the OLR data were obtained from https://www.ncdc.noaa.gov/cdr/atmospheric/outgoing-longwave-radiation-daily.

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