Subseasonal variation of winter rainfall anomalies over South China during the mature phase of super El Niño events

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1. Introduction

The winter rainfall over South China usually becomes greater-than-normal during the mature phase of El Niño (from November to the succeeding February). The enhanced winter rainfall over South China was particularly notable during the 1982/83, 1997/98 and 2015/16 super El Niño events. The anomaly of seasonal-accumulated winter rainfall in South China is 278, 132, and 107 mm in super El Niño years, normal El Niño years, and neutral years, respectively. However, the rainfall amount is not exactly proportional to the intensity of super El Niño events. Although the strongest rainfall anomaly appeared in the winter of 2015/16 with the maximum Niño3.4 index, the weakest positive anomaly of the South China rainfall occurred in the winter of 1997/98, when the Niño3.4 index was comparable to that in 1982/83 (Figure 1). In the seasonal-mean field, the El Niño-enhanced western North Pacific subtropical high (WNPSH), with low-level southwesterly flow and warm moisture flux, is critical for the South China rainfall anomaly (e.g., Zhang, Sumi, and Kimoto 1996; Wang, Wu, and Fu 2000; Zhang and Sumi 2002). However, the winter WNPSH index (defined as by the National Climate Center (Mu et al. 2001)) also does not correspond to the intensity of super El Niño events (Figure 1). Therefore, the nonlinear relationship between the rainfall amount, the WNPSH strength and the El Niño intensity could increase the uncertainty in the seasonal prediction of the abnormal South China winter rainfall. Since the noise of seasonal prediction could transform into the subseasonal signal, we need to further investigate the intraseasonal variation of South China winter rainfall in these years for understanding the above paradox. The Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972, 1994; Zhang 2005), as an important factor of the South China winter rainfall anomaly (e.g., Barlow et al. 2005; Jeong et al. 2008; He, Lin, and Wu, 2011), shows no explicit
correspondence to the El Niño intensity in boreal winter (Figure 1), suggesting a complexity of the intraseasonal variation of South China winter rainfall.

In the present study, we analyze the atmospheric ISOs and reveal their impacts on the South China rainfall anomaly during the winter season. Since previous studies have paid attention to the subseasonal variation of the WNPSH in the lower layer (Zhang et al. 2015), we focus on the ISOs in the upper-level atmosphere (Yang, Wang, and Qing 2010; Miao, Wen, and Zhang 2017) to explain why the positive anomalies of South China winter rainfall show distinct fluctuation during the three super El Niño events. The datasets include daily NOAA SST data (Reynolds et al. 2007), MJO index (Wheeler and Hendon 2004), and the daily in-situ observed rainfall in South China (20.15°–31°N, 105°–123°E) of 506 stations provided by the National Meteorological Information Center, China Meteorological Administration) and the NCEP-DOE Reanalysis with a horizontal resolution of 2.5°×2.5° (Kanamitsu et al. 2002). Here, the ISOs are defined as the 5–120-day components of the daily anomaly obtained by the popular method (Myers and Waliser 2003; Mao and Chen 2005; Lee et al. 2013).

2. Isos of the South China winter rainfall
The intraseasonal anomalies of South China winter rainfall are spatially coherent in each boreal winter, which is verified by the first leading empirical orthogonal function (EOF1) mode (figure not shown) for each case. The first principle component (PC1) is significantly correlated to the ISO of area-averaged South China rainfall anomaly in each winter. Thus, we can treat the PC1 as the ISO index of the South China winter rainfall.

The above-normal rainfall in South China is mainly contributed by the cluster of heavy rainfall events, which successively appear in the positive phase of the ISO index (Figures 2(a,c,e)). The number of rainfall clusters (i.e. the wet phase of ISO) varies from five to eight in the three winters. The frequency of rainfall clusters is highest during the winter of 1997/98, but relatively lower in the cases of 1982/83 and 2015/16. However, the stronger positive anomaly of seasonal-accumulated rainfall does not take place in the winter of 1997/98 as expected (Figures 1 and 2(c)); instead, it appears in the other two years with the relatively lower-frequency rainfall clusters. Therefore, the rainfall amount is not directly proportional to the frequency of rainfall clusters in boreal winter of the super El Niño events. Wavelet analysis (Torrence and Compo 1998) suggests that the periods of the South China rainfall ISO are distinct among the three winters (Figures 2(b,d,f)). The 10–20- and 20–50-day ISOs are robust during the winter of 1982/83 and 2015/16, while the latter becomes weaker in the winter of 1997/98. Thus, even though the above-normal rainfall events mostly take place in the wet phase of 10–20-day ISO, the extreme rainfall events (>10 mm d⁻¹) occur when the 20–50-day ISO becomes pronounced, such as the cases of 1982/83 and 2015/16.

3. Case-by-case comparison
Generally, the two ISOs with different periods alternately emerge in the successive rainfall events during the three winters, and thus we can divide the ISOs into the 10–20- and 20–50-day components by Lanczos band-pass filtering.

In the case of 1982/83, the heavy rainfall events mostly occur when the wet phases of the two ISOs arrive in South China together, such as in the late November of 1982, as well as the early January and February of 1983 (Figure 3(a)). In particular, during the wet phase of the 10–20-day ISO, the wave activity flux (Takaya and Nakamura 2001) exhibits a ‘V’ curve pattern, indicating an eastward propagating wave train along with a series of zonally oriented anomalies of 200hPa stream function and divergence (Figure 3(b)). Four centers of anomalous

Figure 1. Seasonal-accumulated above-normal rainfall anomaly averaged in South China, along with the Niño3.4, western north Pacific subtropical high (WNPSH) and MJO intensity indices during boreal winter (November to the succeeding February) of the 1982/83, 1997/98, and 2015/16 El Niño events.
circulation are located between 20°N and 30°N, where the upper-level subtropical westerly jet prevails in boreal winter (Schiemann, Lüthi, and Schär 2008). The wave train propagates southeastward to the west but north-eastward to the east of the Tibetan Plateau, respectively. Thus, South China is beneath an upper-level divergence anomaly between the abnormal cyclonic and anticyclonic circulation in the northeastward branch of the wave train. According to the conservation of mass theorem, the divergence anomaly in the upper troposphere could enhance the ascending motion and the low-level convergence to induce the rainfall events in South China. In the wet phase of the 20–50-day ISO, a northeastward propagating wave train is observed at 200 hPa to the east of the Tibetan Plateau, along with a southeastward propagating one to the west (Figure 3(c)). They are possibly related to the cold wave activity around Lake Baikal during boreal winter (Yang and Li 2016). Furthermore, three centers of anomalous circulation embedded in the 20–50-day wave trains are close to the activity nodes in the 10–20-day ISO (Figure 3(c)). Thus, the in-phase superimposition of the 10–20- and 20–50-day ISO could enhance the upper-level pumping effect over South China and facilitate the local persistent heavy rainfall events in the winter of 1982/83. When the two eastward propagating wave trains repeatedly pass through South China, successive rainfall events take place in-situ during the boreal winter of 1982/83 (Figures 3(b,c)). Compared with the 20–50-day wave train, the 10–20-day one travels at double the speed with a varied amplitude (Figure 3(d)). Also, the extreme heavy rainfall clusters occur when these two wave trains arrive in South China together, especially for the first three heavy rainfall cluster events.

Figure 2. Time series of the daily rainfall anomalies over South China (histogram; units: mm d⁻¹) and their corresponding ISOs (red dotted curve; units: mm d⁻¹) during the (a) 1982/83, (c) 1997/98 and (e) 2015/16 El Niño events, respectively. Panels (b, d, f) show the wavelet power spectrum of ISOs during the 1982/83, 1997/98 and 2015/16 El Niño events, respectively. ‘DOG’ (derivative of Gaussian) is used as the mother wavelet, where the shading in the black lines indicates the values exceeding the 95% confidence level for a red-noise process, and the red dashed line denotes the cone of influence.
In the case of 1997/98, the effects of the 10–20-day ISO on the heavy rainfall clusters become more prominent, whereas the influences of the 20–50-day ISO are reduced in contrast to the case of 1982/83 (Figure 4(a)). The anomalous circulation in the wet phase of the 10–20-day ISO embeds in a 200 hPa wave train, whose negative node with evident divergence drifts off the westerly jet and moves onto the South China Sea (Figure 4(b)). In the meantime, the 20–50-day ISO is much weaker in this winter than its counterpart in 1982/83 (Figures 2(b,d)), presenting a loose structure of the eastward propagating wave train to the south of 40°N at 200 hPa (Figure 4(c)). Instead, an eastward propagating wave train emerges in the higher latitudes between 40° and 60°N. The absence of phase-locking between the 10–20- and 20–50-day wave train may weaken the anomalies of resonance divergence over South China and further attenuate the local heavy rainfall clusters. Figure 4(d) shows that the heavy rainfall clusters in the winter of 1997/98 almost occur beneath the anomalies of upper-level divergence in the eastward propagating 10–20-day ISO, rather than the 20–50-day ISO as in 1982/83 (Figure 3(d)). Therefore, the above-normal anomaly of seasonal-accumulated

Figure 3. Time series of the daily rainfall anomalies over South China (histogram; units: mm d$^{-1}$), the 10–20-day (blue curve) and 20–50-day (red curve) filtered PC1 in 1982/83. Phase 7 of the (b) 10–20-day and (c) 20–50-day low-frequency streamfunction (contours; units: 106 m$^2$ s$^{-1}$); solid and dashed lines represent the positive and negative values, respectively), divergence (shading; units: 10$^{-5}$ m s$^{-2}$) and wave activity flux (vectors; units: m$^2$ s$^{-2}$) at 200 hPa in winter 1982/83. Here, according to the ISO rainfall indices (a), each active–inactive cycle is divided into eight phases. Phase 1 represented a transition from an active to inactive period, while phase 5 is a transition from an inactive to active phase period. Phases 3 and 7 are the peaks of the inactive and active period, respectively. Phases 2, 4, 6, and 8 occur at the time when the oscillation reaches half its maximum or minimum value. The red rectangle shows the South China region defined in this study. (d) Time–longitude cross section of the 10–20-day low-frequency divergence (shading; units: 10$^{-5}$ m s$^{-2}$) and the 20–50-day low-frequency divergence (contours; units 10$^{-5}$ m s$^{-2}$) at 200 hPa averaged between 20°N and 30°N in 1982/83.
rainfall becomes less in South China during the winter of 1997/98 due to the weaker influence of 20–50-day ISO.

During the winter of 2015/16, we can see that the maximum positive anomaly of seasonal-accumulated South China rainfall constitutes five heavy rainfall events (Figures 1 and 2(e)). Generally, they take place from November 2015 to late January 2016, when both 10–20- and 20–50-day ISOs are significant (Figure 2(f)), suggesting the joint effect of two ISOs (Figure 5(a)). The upper-level wave trains associated with the 10–20-day ISO in 2015/16 resemble those in 1982/83 but have stronger active centers (Figures 3(b) and 5(b)). The upper-level divergence and its resultant pumping effect over South China are sandwiched by the centers of the anomalous cyclone and anticyclone in the wave train during the wet phase of the ISO (Figure 5(b)). In the 20–50-day ISO, except for a weak cyclonic anomaly over the east periphery of the Tibetan Plateau, the anomalous circulation surrounding South China is similar as the situation in 1982/83 (El Niño). In addition, there are seven and five cycles of the 10–20- and 20–50-day ISO events in the winter of 2015/16, respectively (Figure 5(d)), and the top three extreme heavy rainfall
clusters occur when the wet phase of the two ISOs simultaneously reach South China (Figures 5(a,d)). This is indicative of their collaboration to the more above-normal rainfall in this winter.

4. Summary and discussion

In the present study we analyze the influences of ISO on the winter rainfall anomaly in South China during the 1982/83, 1997/98 and 2015/16 super El Niño events. Our results suggest that the intraseasonal variation of the South China winter rainfall is spatially coherent, but the periods and features of its associated atmospheric ISO are distinct during the three winters. In 1982/83 and 2015/16, when the seasonal-accumulated winter rainfall was much above-normal in South China, there were stronger 10–20- and 20–50-day ISOs. In the upper troposphere, the two ISOs are characterized by eastward propagating wave trains along the subtropical westerly jet, with pronounced abnormal divergence and convergence at 200-hPa between 20°N and 30°N. When the wave trains with different speed concurrently pass through South China, the in-phase superimposition of the anomalous upper-level divergences enhances the ascending motion, thereby resulting in the heavy rainfall clusters. The positive seasonal-accumulated rainfall in South China is contributed by
successive heavy rainfall events, which embed in the wet phases of the 10–20- and 20–50-day ISOs. However, the 20–50-day ISO becomes relative weaker in the winter of 1997/98. Although the effect of 10–20-day ISO alone could cause the higher-frequency rainfall events, the weaker 20–50-day ISO prevents the persistent extreme rainfall clusters and weakens the positive anomaly of the accumulated winter rainfall in South China. As a result, the joint effects of the 10–20- and 20–50-day ISOs are critical for the larger amount of above-normal rainfall over South China during the mature phase of the super El Niño events of 1982/83 and 2015/16.

The weaker 20–50-day ISO during winter of 1997/98 may be attributable to the adverse conformation between the position of the wave source and the horizontal structure of basic flow. In the winter of 1982/83 and 2015/16, the 20–50-day ISO located to the south of 40°N embeds in the abnormal zonal wind, which facilitates the eastward and northeastward propagation of the ISO into South China (Figures 3(c) and 5(c)). Whereas, the 20–50-day ISO in the winter of 1997/98 comes into the Asian continent between 40°N and 60°N (Figure 4c), where the meridional gradient of the abnormal zonal wind may prevent its southward intrusion. Meanwhile, the waveguide anomaly in the mid–high latitudes benefits the eastward propagation of the 20–50-day ISO to the north of 40°N. However, the details about this question require further investigation.

The wave train of the 10–20-day ISO is possibly an intrinsic mode with an eastward energy dispersion, and coincides with the subtropical jet over the southern Eurasian continent (Blackmon, Lee, and Wallace, 1984; Kushnir and Wallace 1989; Hsu 1996). This wave train is also detected in boreal spring (Pan, Miao, and Wu, 2012). Although the 20–50-day ISO resembles the MJQ periodicity (Yao, Lin, and Wu 2015), here it is more correlated with the intraseasonal variation of the East Asian trough. However, what caused the 20–50-day ISO of the East Asian trough during the winter of 1982/83 and 2015/16 is still an open question.

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