Role of tropical intraseasonal oscillations in the South China Sea summer monsoon withdrawal in 2010

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Based on the ensemble empirical mode decomposition of low-level winds and outgoing longwave radiation, this paper analyzes the influence of tropical intraseasonal oscillations (ISOs) on one extremely late case of South China Sea (SCS) summer monsoon withdrawal (SMW). Compared to the climatological monsoon withdrawal of September 25, the South China Sea summer monsoon withdrawal in 2010 was delayed for approximately 1 month (October 26) and is the latest in the past 60 years. The quasi-biweekly oscillation (QBWO) and Madden-Julian oscillation (MJO) originating from the equatorial Indian Ocean propagate northeastward to the SCS. The accompanying circulation first induced a westerly burst event and prolonged the lifespan of the summer monsoon. After this transitory recovery, the circulation anomalies associated with the current propagation of ISOs into the SCS contributed to the large-scale circulation adjustment, leading to the shift of zonal wind (from westerlies to easterlies) and triggered the SCSSM withdrawal. This case study shows that, in addition to the well-studied impacts of ISOs on the monsoon onset and active/break cycle, the ISOs can also trigger the monsoon withdrawal.

KEYWORDS
Madden-Julian oscillation, quasi-biweekly oscillation, South China Sea, summer monsoon withdrawal, tropical intraseasonal oscillation

1 | INTRODUCTION

October 2010 witnessed the latest monsoon withdrawal over the South China Sea (SCS) and the heaviest autumn rainstorm on Hainan Island (located in the northern SCS) of the past 60 years (Figure 1a). According to the National Climate Center (NCC, 2016) of China Meteorological Administration, the South China Sea summer monsoon withdrawal (SCSSMW) in 2010 occurs in pentad 59 (fifth pentad of October), which is five pentads later than the climatology. Hainan Island experienced two sustained rainstorms (September 30 to October 9 and October 13 to 18; Figure 1b) that affected more than 2.5 million people and caused great economic losses (Cai et al., 2013; Qiao et al., 2015). Previous studies indicated that the tropical intraseasonal oscillations (ISOs), especially the quasi-biweekly oscillation (QBWO), have played important roles in these severe rainstorms (Jian and Zhang, 2013; Qiao et al., 2015; Wang et al., 2016; Li et al., 2017). Since Hainan Island is located in the northern SCS and these rainstorms occurred just before the SCSSMW, it is reasonable to question whether the ISOs affected the monsoon withdrawal in 2010 as well.

It is an established fact that the ISOs and the monsoon system are inherently linked. The seasonal march of monsoon circulation can strongly modulate the ISOs activities as manifested by, for example, the different behavior of ISOs in early and late summer (Yang et al., 2008; Hsu, 2012). The so called climatological ISOs are phase locked to the...
annual cycle and are very significant in the Asian monsoon region (Wang and Xu, 1997; Hsu, 2012). ISOs can not only trigger the monsoon onset (Wheeler and Hendon, 2004; Tong et al., 2009; Kajikawa and Wang, 2012; Lee et al., 2013) but can also modulate the active/break cycle of the rainy season (Ding and Chan, 2005; Mao and Chan, 2005; Hsu, 2012). However, it remains unclear if the ISOs affect the withdrawal of the monsoon as well. Previous studies concerning ISOs focus mainly on summer and winter seasons; however, the transition seasons (corresponding to monsoon onset/demise) are also very important and the ISOs often display strong seasonality and regionality (Yang et al., 2008; Hsu, 2012). However, it remains unclear if the ISOs affect the withdrawal of the monsoon as well. Previous studies concerning ISOs focus mainly on summer and winter seasons; however, the transition seasons (corresponding to monsoon onset/demise) are also very important and the ISOs often display strong seasonality and regionality (Yang et al., 2008; Hsu, 2012). Based on the case study of October 2010, we shall investigate the contribution of ISOs to this extremely late SCSSMW. The datasets and methods applied in this paper are described in Section 2. Section 3 investigates the influence of ISOs on the SCSSMW in 2010. The summary and discussions are presented in Section 4.

2 DATA AND METHODS

The datasets applied in this study includes: (a) European centre for medium-range weather forecasts interim reanalysis (ERA-interim reanalysis) data (Dee et al., 2011) with a resolution of 1° × 1°; (b) high quality climate data record of outgoing longwave radiation (OLR; Lee et al., 2014) from the National Oceanic and Atmospheric Administration with a resolution of 1° × 1°; (c) the pentad data of SCSSMW from the East Asian Monsoon Yearbook 2015 (NCC, 2016); and (d) the October rainfall at Haikou station (110.35°E, 20.03°N; province capital of Hainan Island).

The ensemble empirical mode decomposition (EEMD; Wu and Huang, 2009), which is an improvement of the empirical mode decomposition (Huang et al., 1998) designed for analyzing nonstationary and nonlinear time series, is used as an adaptive filter (without a priori determined basis) to obtain the QBWO and Madden-Julian oscillation (MJO) components. By using the EEMD, the problem of subjective selection of thresholds (for example: 10–20 days by Qiao et al. (2015) or 8–15 days by Li et al. (2017)) in other bandpass filters can be avoided. The Morlet wavelet (Torrence and Compo, 1998) is employed to analyze the spectrum characteristics and to define the statistically significant ISOs.

For the definition of SCSSMW, there are two criteria in NCC (2016): (a) steadily shifting zonal wind from westerlies to easterlies, and (b) the potential pseudo-equivalent temperature steadily less than 340 K, at 850 hPa in the key SCS region (110°–120°E, 10°–20°N; gray rectangle in Figure 3a). However, these criteria in NCC (2016) are subjective and it is more reasonable to define the monsoon withdrawal by some objective criteria (Lam et al., 2005; Zhang et al., 2014; Luo et al., 2017). One such definition has been proposed by Zhang et al. (2014), who used the same
monsoonal parameters as NCC (2016). Zhang et al. (2014) quantitatively defined the steady state as: (a) The state is maintained at least for three pentads and can be interrupted for no more than two pentads thereafter, or (b) The state is maintained for two pentads, and is then interrupted for one pentad but immediately returns to the state before interruption. In fact, most of the SCSSMW dates defined by the subjective monitor (NCC, 2016) are the same as those from objective criteria (Zhang et al., 2014), and their correlation is 0.74 for 1951–2012 (significant at 99.9% confidence level). For the case of 2010, both the NCC (2016) and Zhang et al. (2014) defined the monsoon withdrawal as pentad 59.

3 | INFLUENCE OF ISOs ON THE SCSSMW IN 2010

3.1 | The intraseasonal features of October 2010

Figure 1a shows the October rainfall at Haikou station and the SCSSMW pentad for 1951–2015 (NCC, 2016). Figure 1b shows the OLR and low-level winds averaged in 110°–120°E in 2010. The heavy convection in early-to-mid October corresponds to the heavy rainfall in Hainan. As documented in the introduction, the extreme autumn rainfall and the extremely late monsoon withdrawal in 2010 is worthy of investigation. Although there appear substantial easterlies after late-September (Figures 1b and 2a), the pseudo-equivalent temperature is still greater than 340 K (see the SCSSM monitoring in the NCC website, that is, http://cmdp.ncc-cma.net/Monitoring/EastAsian/p8ciu2010126.gif), indicating that the SCSSM has not yet ended. The two criteria in NCC (2016) and Zhang et al. (2014) were not both satisfied until late October, when the SCSSM finally ended.

Figure 2a shows the climatological mean and standard variation of 850 hPa zonal winds averaged in SCS. Climatologically, the transition of westerlies to easterlies occurs on September 25, which is very near to pentad 54 determined by the averaged withdrawal pentad of each year (Zhang et al., 2014; NCC, 2016). This climatological shift in zonal wind is mainly due to the westward intrusion of western North Pacific subtropical high. Other prominent changes during SCSSMW includes retreat of the monsoon trough/rain belt over the SCS, anomalous low-level anticyclone over the northern SCS, and deceleration of the upper-level tropical easterly stream (see Ha et al., 2018 for detail). The red curve in Figure 2a shows the 850 hPa zonal wind for 2010. The persistent change from westerly winds to easterly winds occurs on October 26 (at this time, the pseudo-equivalent temperature has shifted to less than 340 K). This result is also very close to pentad 59 and is approximately 1 month later than the mean monsoon withdrawal (Zhang et al., 2014; NCC, 2016).

To reveal the intraseasonal characteristics of zonal winds in Figure 2a, the wavelet spectrum is calculated and shown in Figure 2b. In October, the synoptic-scale (less than 1 week) oscillation and QBWO are very prominent and are significant at the 95% confidence level. Although the MJO with an approximate period of 30–60 days is also very strong in the wavelet spectrum, it does not pass the 95% significance test. The wavelet spectrum results of zonal winds over the large-scale SCS are in accordance with previous studies on several monsoonal parameters over Hainan Island, for example, Fourier spectrum for zonal winds (Jian and Zhang, 2013) and precipitation (Qiao et al., 2015), and wavelet spectrum for OLR (Wang et al., 2016) and rainfall (Li et al., 2017).

Figure 2c shows the EEMD filtered QBWO (blue curve) and MJO (red curve) component of 850 hPa zonal winds (green bar) during 2010. Since the mean periods for the third and fourth intrinsic mode function (Huang et al., 1998; Wu and Huang, 2009) are approximately 18 and 43 days, they are regarded as the QBWO and MJO components,
respectively. Although MJO is not significant in the wavelet spectrum, it cannot be ignored for the following reasons: First, Figure 2c shows that the amplitudes of QBWO and MJO were roughly equal (approximately 3 m/s) during October, indicating that both ISOs are important. Second, from September to November, the MJO component can...
explain approximately 36% of the total variance, which is greater than the QBWO component (approximately 21%). Third, the ISOs indices, such as real-time multivariate MJO index (RMM index) (Wheeler and Hendon, 2004) and boreal summer intraseasonal indices (Lee et al., 2013), show that the amplitude of MJO is very strong in October (not shown).

Fourth, previous studies on the sustained rainstorms over Hainan Island in October 2010 (Qiao et al., 2015; Wang et al., 2016) have also mentioned the modulation of MJO. Lastly, both the QBWO and MJO are in the transition phase of westerlies to easterlies in October 26 (day of monsoon withdrawal), suggesting that they may contribute to the monsoon withdrawal. Thus, in the analysis below we shall investigate the propagation of both QBWO and MJO, and their possible influence on the SCSSMW in 2010.

3.2 The propagation features of QBWO and MJO

Figure 3 displays the EEMD filtered QBWO component (the third intrinsic mode function) of OLR and winds at 850 hPa. On October 18 and 20 (Figure 3a,b), the SCSSMW in 2010 occurs in the transition phase (from westerlies to easterlies) and triggered the SCSSMW with the extremely late withdrawal by inducing the easterly/westerly shift. Previous studies also revealed that ISOs can be the trigger of the SCSSMW onset. For example, Tong et al. (2009) reported that, by inducing the large-scale easterly/westerly shift over the SCS, the MJO play an important role in trigger the monsoon onset. The case of October 2010 is very similar: the circulation anomalies associated with the current propagation of QBWO and MJO into the SCS contributed to the large-scale circulation adjustment (Figures 3 and 4), led to the shift of zonal wind (from westerlies to easterlies) and triggered the SCSSM withdrawal (Figure 2). Thus, it can be concluded that in 2010 the collaboration of two ISO modes, namely, the QBWO and MJO, contributed to the late withdrawal of SCSSM.

4 SUMMARY AND DISCUSSIONS

Based on the EEMD filtered low-level winds and OLR, this paper analyzes the contribution of ISOs to the extremely late SCSSMW in 2010, and some of the major findings are as follows:

1. In 2010, the summer monsoon withdrawal in the SCS occurred on October 26, which is about 1 week after the severe autumn rainstorm in Hainan Island and is approximately 1 month later than the climatological monsoon withdrawal.

2. The QBWO and MJO originating from the equatorial Indian Ocean propagated northeastward to the SCS, leading to a westerly burst event and prolonging the lifespan of the summer monsoon. The extremely late SCSSMW in 2010 occurs in the transition phase (from westerlies to easterlies) of QBWO and MJO.

3. The case study of 2010 shows that, in addition to the well-studied impacts of ISOs on the monsoon onset and active/break cycle, the ISOs can also trigger the monsoon withdrawal by inducing the easterly/westerly shift.
The above EEMD filtered QBWO and MJO have been verified by first-order bandpass filtering (Murakami, 1979; Qiao et al., 2015). Compared to previous work focusing on the influence of the QBWO on the local rainfall in Hainan Island during the early half of October 2010, this paper analyzes the contribution of ISOs (including MJO) to the large-scale circulation change (monsoon withdrawal) in the SCS during the late half of October 2010, which is a case study. The mechanism for the simultaneous arrival of QBWO and MJO, and the possible link to the La Niña background (Jian and Zhang, 2013; Qiao et al., 2015) remains unclear. The RMM index phase points for the SCSSMW dates suggest that statistically the MJO has a weak modulation effect on the SCSSMW (Hu et al., 2018), thus the impact of ISOs in other years needs further study. Syroka and Touni (2004) mentioned the intraseasonal variations accompanying the South Asian monsoon withdrawal, and Murakami et al. (1986) highlighted the role of low-frequency oscillations in determining the monsoon withdrawal in Australia. Thus the impacts of ISOs on monsoon withdrawal in other monsoon regions are also worthy of investigation.

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