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Role of the 10–20-Day Oscillation in Sustained Rainstorms over Hainan, China in October 2010

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ABSTRACT

Hainan, an island province of China in the northern South China Sea, experienced two sustained rainstorms in October 2010, which were the most severe autumn rainstorms of the past 60 years. From August to October 2010, the most dominant signal of Hainan rainfall was the 10–20-day oscillation. This paper examines the roles of the 10–20-day oscillation in the convective activity and atmospheric circulation during the rainstorms of October 2010 over Hainan. During both rainstorms, Hainan was near the center of convective activity and under the influence of a lower-troposphere cyclonic circulation. The convective center was initiated in the west-central tropical Indian Ocean several days prior to the rainstorm in Hainan. The convective center first propagated eastward to the maritime continent, accompanied by the cyclonic circulation, and then moved northward to the northern South China Sea and South China, causing the rainstorms over Hainan. In addition, the westward propagation of convection from the tropical western Pacific to the southern South China Sea, as well as the propagation farther northward, intensified the convective activity over the northern South China Sea and South China during the first rainstorm.

Key words: convective activity, propagation characteristics, tropical Indian Ocean, western Pacific

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1. Introduction

Hainan is an island off the southern coast of China, located at roughly (18°N, 110°E) in the northern South China Sea. The rainy season in Hainan is mainly from May to October. In October 2010, Hainan experienced unusually sustained rainstorms, which were the most severe during the past 60 years. Around 2 500 000 people were affected by these storms, and direct economic losses amounted to 3 billion Yuan, approximately $500 million. Thus, it is of great importance to investigate the possible causes of such sustained rainstorms in order to better understand the variability of rainfall over the Hainan region.

As shown by previous studies, rainstorms over southern China bear a close relationship with intraseasonal oscillation (Shi and Ding, 2000; Lin et al., 2007). Intraseasonal oscillation, including the 30–60-day oscillation and 10–20-day oscillation (nearly identical to the quasi-biweekly oscillation, the 12–24-day oscillation), is considered to be one of the most significant signals influencing tropical circulation and rainfall. Although the 30–60-day oscillation has received a lot of attention since the Madden–Julian Oscillation (MJO) was discovered (Madden and Julian, 1971, 1972), an increasing amount of research has focused on the 10–20-day oscillation.

Many studies have emphasized the importance of intraseasonal oscillation over the South China Sea (Fukutomi and Yasunari, 1999; Kajikawa and Yasunari, 2005; Mao and Chan, 2005; Zhou and Chan, 2005; Tong et al., 2009; Wu, 2010). In most years, the 10–20-day oscillation is one of the two major intraseasonal modes that modulate the behavior of the South China Sea summer monsoon (Mao and Chan, 2005). On the 10–20-day timescale, rainfall activities over the South China Sea have a larger interannual variation than those over the Bay of Bengal and the Arabian Sea (Kajikawa and Yasunari, 2005). Enhanced convection occurs in conjunction with well-organized cyclonic circulation anomalies over the South China Sea (Fukutomi and Yasunari, 1999). In addition, there are significant 10–20-day oscillations in the East Asian monsoon region, the western Pacific, the Indochina Peninsula, and around Sumatra (Fukutomi and Yasunari, 2002; Ren and Huang, 2002; Ko and Hsu, 2006; Yokoi et al., 2007; Wen and Zhang, 2008).

Convection and circulation changes over the South China Sea are closely related to the propagation of the 10–20-day oscillation from the tropical Indian Ocean and the western

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Pacific. Associated with the onset of the summer monsoon in the South China Sea, strong convection centers exist mainly in three regions: the tropical Indian Ocean, the equatorial South China Sea–Kalimantan, and the tropical western Pacific (Yuan and Chen, 2012). The subseasonal variability that affects the onset of the South China Sea summer monsoon starts over the equatorial western Pacific, propagates northward to the Philippine Sea, and then moves westward to the South China Sea (Wu, 2010). The northwestward propagation of the 10–20-day mode is associated with a weakening of the subtropical high over the western Pacific, which induces the establishment of the South China Sea summer monsoon (Zhou and Chan, 2005). Kikuchi and Wang (2009) described in detail the quasi-biweekly oscillation from a global perspective in terms of its initiation, movement, development, and dissipation. In boreal summer, there is a strong convective activity signal associated with the quasi-biweekly oscillation in the western North Pacific, South China Sea, southeast Indian Ocean, and the Gulf of Mexico.

The 10–20-day mode of global precipitation was investigated by Chen et al. (1995) using satellite data from the Goddard Laboratory for Atmospheres for the period 1979–80. The structure and propagation characteristics of 10–20-day oscillations over different regions were explored, such as the Asian–Australian monsoon region, East Asia, and the Indochina Peninsula (Lau et al., 1988; Chen et al., 1995; Yokoi et al., 2007). There have also been a few studies on the 10–20-day oscillation of rainfall in China. Over the middle and lower reaches of the Yangtze River, the 10–20-day oscillation has been found to have a greater amplitude than the 30–60-day oscillation in summer for both flood and drought years (Wang and Ding, 2008). The interannual variability of the Mei-yu 10–20-day oscillation over the Yangtze–Huaihe River Valley and its relationship with atmospheric circulation and sea surface temperature have also been studied (Yin et al., 2011). Other studies have shown that precipitation over South China during the flood season is closely linked to the significant 10–20-day oscillation (Tong et al., 2007; Xin et al., 2007; Ji et al., 2010). For example, rainfall during the flood season in the Xijiang River Valley of South China mainly exhibits 10–20-day oscillations; one of the possible causes of the 10–20-day oscillation in rainstorms in this region is the convergence over the valley between low-frequency zonal winds propagating northward from the south and those going westward from the northwest Pacific (Ji et al., 2011).

The 10–20-day oscillation has also been found to be significant during fall. Based on daily First GARP (Global Atmospheric Research Program) Global Experiment IIIb and outgoing longwave radiation data, Chen and Chen (1993) found a transition in the regime of variation in precipitation time from a domination by the 12–24-day mode in the spring of 1979 to a domination by the 30–60-day mode in summer, and a return to the 12–24-day mode in fall. The 10–20-day variation over the coastal regions of northern and central Vietnam has been found to be active during August–November (Yokoi et al., 2007). Recently, Feng et al. (2013) investigated the year-to-year variations in September–October rainfall over Hainan, China, for the period 1965–2010. The large variability in wet years was attributed to contributions of tropical cyclones and intraseasonal oscillations (ISOs). The rainfall showed large intraseasonal variations with periods of 10–20 and 30–60 days during September–October in the wet years.

The aforementioned studies have revealed an important role of the 10–20-day oscillation on the convection, atmospheric circulation, and rainfall over many regions. From August to October 2010, the 10–20-day oscillation is also a dominant signal of Hainan rainfall. The underlying mechanisms of rainstorms over Hainan in October 2010 may be quite different from those of other rainstorms in two respects. First, Hainan is an island in the northern South China Sea, and so the circulation and convection influencing Hainan rainfall are quite different from those over South China, to the north. Second, previous studies (Wang and Ding, 2008; Ji et al., 2010; Yin et al., 2011) focused mainly on rainfall in boreal summer over South China and the Yangtze–Huaihe River Valley, but in this case the storms occurred in October in Hainan. There have been few studies on the 10–20-day oscillation in boreal autumn. In this paper, we investigate the characteristics of Hainan rainfall from August to October 2010, and explore the characteristics and propagation of the 10–20-day oscillation of convective activity together with atmospheric circulation and their influence on the sustained rainstorms of October 2010 over Hainan. The data and methodology are introduced in section 2. In section 3, the characteristics of the Hainan rainstorms in October 2010 are examined. In section 4, the anomalous patterns of circulation and convection in October 2010 are explored. In section 5, the propagation of the 10–20-day oscillations of convection and circulation is investigated. Finally, a conclusion and discussion are given in section 6.

2. Data and methodology

The present study uses daily rain gauge data from 18 stations in Hainan Province, China, for the period of August to October 2010, and monthly precipitation data from Haikou for 1951–2010. The ERA-Interim Reanalysis daily data used in this study were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) Data Server, with a horizontal resolution of $1.5^{\circ} \times 1.5^{\circ}$, for the period 1979–2010, including zonal wind, meridional wind, and vertical p-velocity. This ERA-Interim dataset is significantly better than ERA-40; it is supplemented by observational data for later years from the ECMWF's operational archive and has more advances in data assimilation than ERA-40 (Simmons et al., 2007; Dee et al., 2011). Daily outgoing longwave radiation (OLR) data for the period of August to October 2010 and monthly OLR data for 1974–2010 with $2.5^{\circ} \times 2.5^{\circ}$ grid spacing were derived from the National Oceanic and Atmospheric Administration (NOAA)/Office of Oceanic and Atmospheric Research (OAR)/Earth System Research Laboratory (ESRL) Physical Sciences Division (Liebmann and Smith, 1996). First-order band-pass filtering was applied to extract the 10–20-day components (Murakami, 1979).

3. Characteristics of the rainstorms in Hainan in October 2010

Figure 1a shows the time series of the regional mean daily rainfall over Hainan Province, China, from August to October 2010. There are two peaks during this period, both in October. The first peak occurs from 30 September to 9 October and has a maximum value of 160 mm, and the second peak occurs from 13 October to 18 October and has a maximum value of 108 mm. This indicates that Hainan experienced two sustained rainstorms in October 2010, and the stronger rainstorm occurred in early October. Figure 1b shows the time series of monthly precipitation anomalies in October in Haikou, the capital of Hainan Province, with respect to the 1951–2010 average. During the last four Octobers, rainfall anomalies in Haikou have remained positive, indicating a relatively wet period. In 2010, the rainfall anomaly reached 998 mm, the most rainfall in October for 1951–2010. Compared with the climatological mean precipitation of 215 mm in October during this period, the anomalous precipitation in 2010 increased by 464%. The two rainstorms in October 2010 were therefore of greater intensity than any storms in the last 60 years, and it is of paramount importance to investigate the main characteristics of these storms and the possible mechanisms underpinning them.

In order to understand the synoptic systems that induced the sustained rainstorms over Hainan, we examine the infrared radiation cloud images from China's geostationary meteorological satellite, FY2D. On 29 September (Fig. 2a), a tropical convergence belt appeared along 10°N from the tropical Indian Ocean to the tropical western Pacific, in which several tropical depressions could be clearly seen. On 30 September (Fig. 2b), the tropical depressions strengthened and moved northward to the north-central South China Sea. On 3 October (Fig. 2c), the tropical depressions combined and moved farther north over the South China Sea. The center of this combined tropical depression was right over Hainan and induced the severe rainstorm there in early October. Early on the morning of 12 October (Fig. 2d), remarkable convective disturbances existed along the southeast coast of the Indochina Peninsula, accompanied by a tropical convergence belt that extended from the tropical Indian Ocean to the tropical western Pacific. Several hours later (Fig. 2e), the convective disturbances on the southeast coast of Indochina enlarged rapidly and moved northward. On 16 October (Fig. 2f), the tropical depression arrived in Hainan and induced the second rainstorm there. As discussed by Ko and Hsu (2006), the moving track of the tropical depression may have been affected by the 10–20-day oscillation of the convection and circulation.

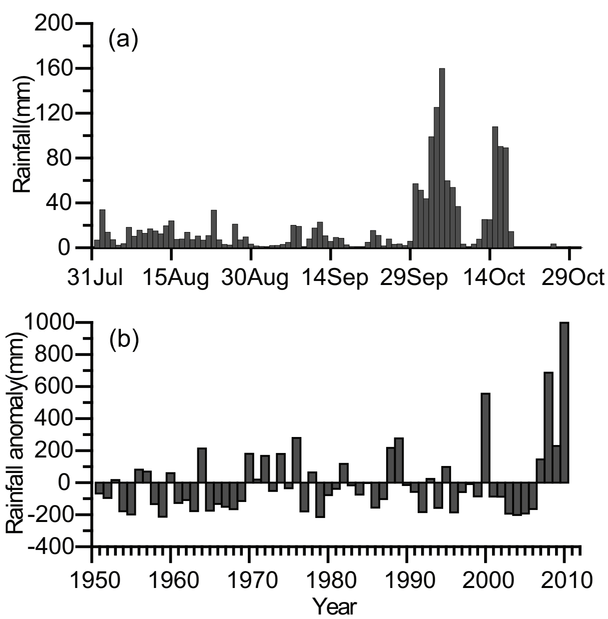

Fig. 1. Time series of (a) regional mean daily rainfall (units: mm) over Hainan, China, from August to October 2010, and (b) monthly precipitation anomalies (units: mm) in October in Haikou with respect to the 1951–2010 average.

To further understand the temporal characteristics of the two rainstorms, power spectrum analysis was applied to examine the dominant periodicity of the daily rainfall over Hainan from August to October 2010. The most outstanding signal was the 10–20-day oscillation, which passed the significance test of $\alpha = 0.05$ (Fig. 3), in contrast to the 30–60-day oscillation, which did not pass this test. The 10–20-day oscillation of precipitation could be considered as the main contributor to the two sustained rainstorms over Hainan. This could also be shown in the comparison of the 10–20-day oscillation and the 30–60-day oscillation of OLR at (18°N, 110°E), which will be explained in section 5.

4. Anomalous circulation and convection patterns in October 2010

In this section, we discuss the atmospheric circulation and convection in order to identify the possible causes of the rainstorms over Hainan in October 2010. Figure 4 shows the climatological mean wind fields and OLR and their anomalies in October 2010. In the climatological mean wind fields at the middle and low levels (Fig. 4a), the major feature is a cyclonic circulation over the South China Sea and the western North Pacific, and an anticyclonic circulation over southern China. Correspondingly, a large ascending area appears over the South China Sea and the western North Pacific, and a descending area appears over southern China. Hainan, located at the southern edge of the anticyclonic circulation, is subject to strong northeasterly wind with very weak vertical motion. In the anomalous wind fields for October 2010 (Fig. 4b), the westerly and easterly winds converge into the southerly wind around the Philippines and the South China Sea. A notable cyclonic circulation appears over southern China and

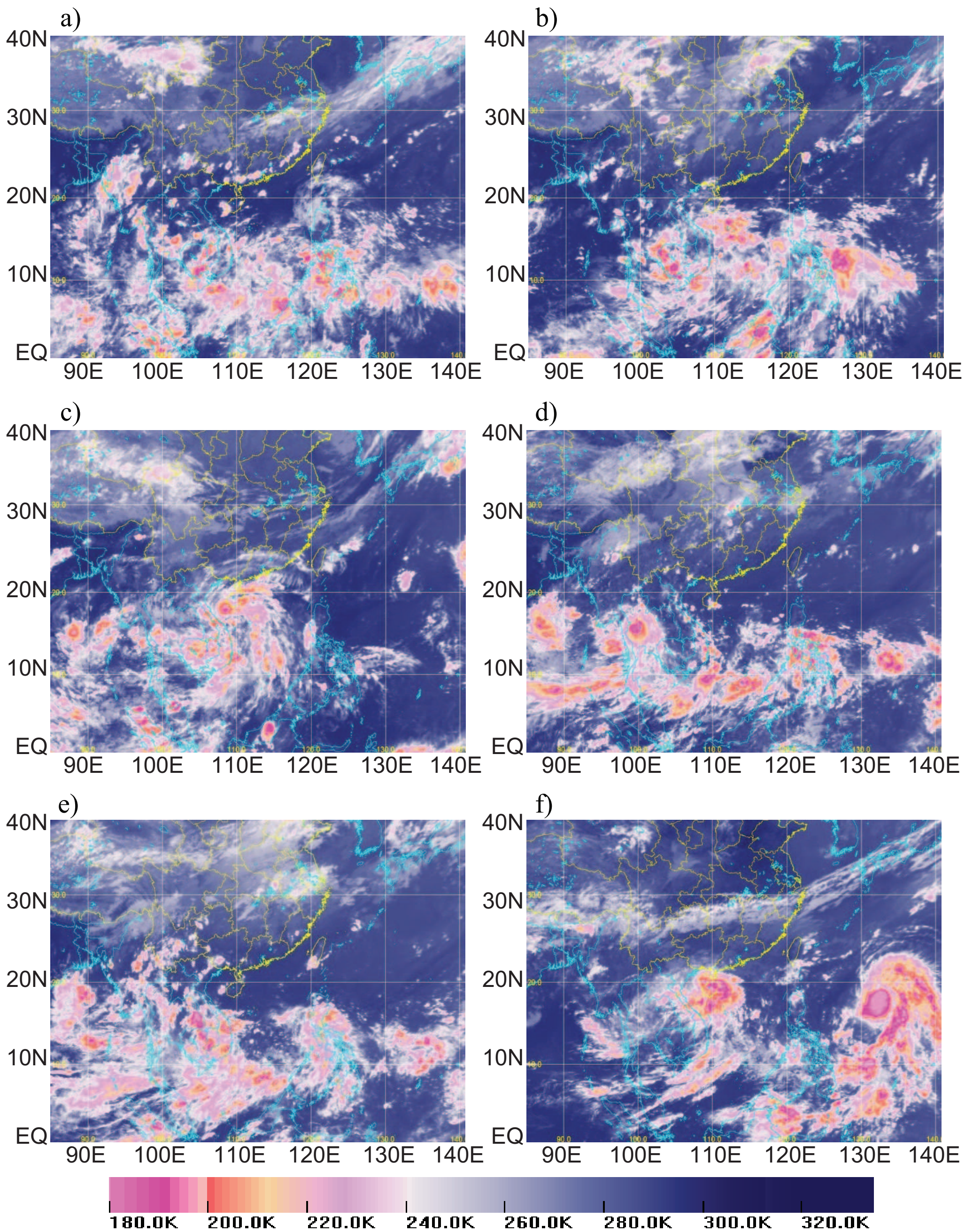

Fig. 2. Infrared radiation cloud images from China's geostationary meteorological satellite, FY2D: (a) 1246 LST 29 September; (b) 1416 LST 30 September; (c) 1416 LST 3 October; (d) 330 LST 12 October; (e) 1031 LST 12 October; and (f) 0330 LST 16 October 2010.

the northern South China Sea. An anomalous ascent is found over most of the western North Pacific. Ascending centers are also located near Hainan and Taiwan.

In the climatological mean OLR field (Fig. 4c), the value of OLR increases from the equator to the midlatitudes along with the strong convection zone near the equator and the weak convection centers in the subtropics. The OLR value of Hainan is between 240 and 250 W m^{-2}. In October 2010, there was anomalous negative OLR in most of the area (Fig. 4d). Specifically, the negative OLR centers were in the southeastern tropical Indian Ocean, the northern Bay of Bengal, and the South China Sea, indicating strong convection in these regions. Hainan is located in the negative center in the northern South China Sea. Figures 4b and 4d show that the pattern of the 500 hPa vertical *p*-velocity is in accordance with the OLR field. The anomalous convective centers correspond to the anomalous ascending centers quite well.

In order to reveal the possible mechanisms for the 10–20-day oscillation of the Hainan precipitation, the 10–20-day oscillation was extracted from the raw data for all variables.

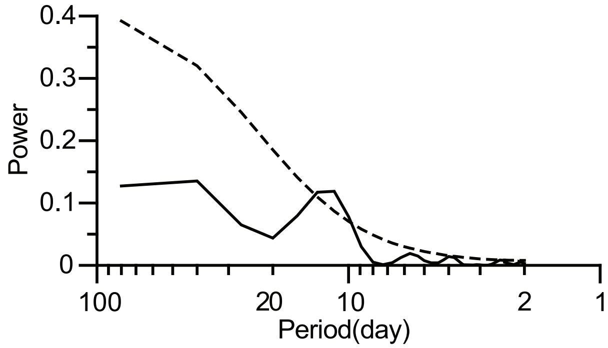

Fig. 3. Power spectrum (solid line) of regional mean daily precipitation over Hainan from August to October 2010. The dashed line denotes the power spectrum for red noise at a significance level of $\alpha = 0.05$.

First, we analyze the variance and percentage variance of OLR for October from 1979 to 2010 and for October 2010 to show to what extent the 10–20-day oscillation was enhanced around the tropical Indian Ocean and the western North Pacific. Here, we define the percentage variance of the 10–20-day oscillation as the ratio of the variance of the 10–20-day oscillation to the total variance at each grid. In Fig. 5a, both the maximum value of the variance and the percentage variance of the 10–20-day oscillation are located in the subtropics, indicating that the 10–20-day oscillation of convection plays a more important role in the subtropics than at the equator. In 2010 (Fig. 5b), the distinctive center of the variance of the 10–20-day oscillation of convection is located over the northern South China Sea, where the variance can exceed 1200 W^2 m^{-4}. Correspondingly, the percentage variance exceeds 60% in this region. Compared with Fig. 5a, Fig. 5b shows the specific 10–20-day oscillation of convection in 2010, with an enhancement in the variance and percentage variance that is almost three times greater than usual.

During the two rainstorms, the 10–20-day oscillations of convective activities and atmospheric circulation are accompanied by low-pressure systems in the tropical–subtropical region. With an apparent cyclonic circulation, notable negative OLR and sustained rainfall appear over the northern South China Sea and South China (Fig. 6a) in the first storm. Correspondingly, there is cyclonic water vapor transportation over the northern South China Sea, and the northerly and southerly water vapor transportation converge over Hainan (Fig. 6c). During the second rainstorm (Fig. 6b), there are two remarkable cyclonic circulations, one over the eastern Bay of Bengal and the western South China Sea across the Indochina Peninsula, and the other to the east of the Philippines. Accordingly, there are two strong convective centers in the aforementioned regions, with the more intensive convective center in the eastern Indochina Peninsula. Hainan is subject to intensive converged flow in the northeastern part of the cyclonic circulation over the Indochina Peninsula, which is accompanied by strong convective activity that induces the rainstorm. Meanwhile, the sustained rainfall is also obviously attributable to the cyclonic water vapor transportation, which transports sufficient water vapor from the southern South China Sea to Hainan (Fig. 6d). Hainan is near the convergence center of water vapor flux.

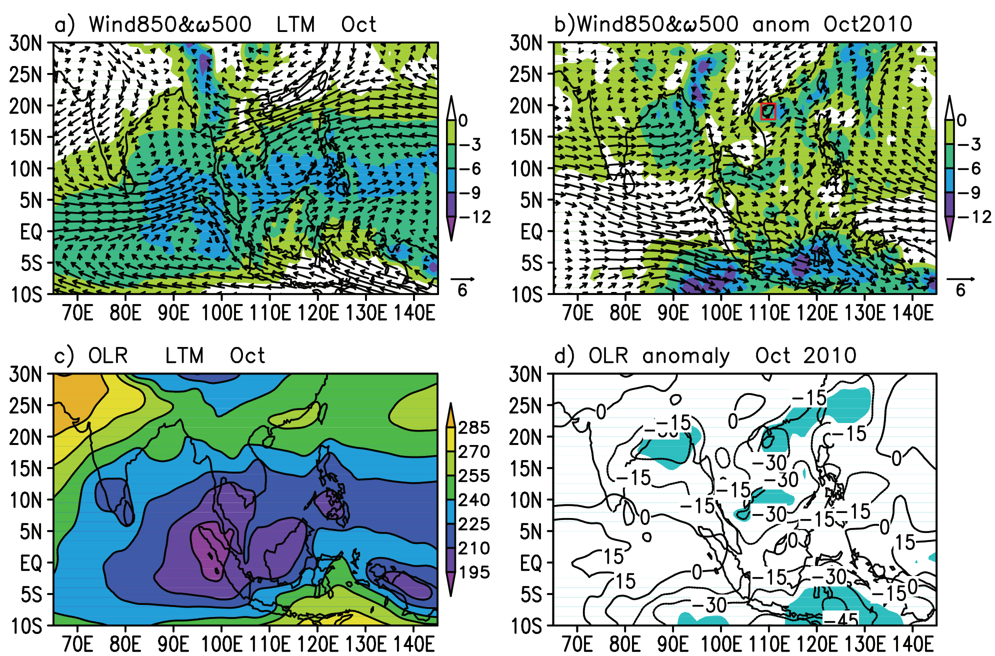

Fig. 4. Climatological mean (a) winds at 850 hPa (vectors, units: m s^{-1}) and vertical p-velocity at 500 hPa (shaded, units: 10^{-2} Pa s^{-1}) and (c) OLR (units: W m^{-2}) in October averaged from 1979 to 2010, and the anomalies of (b) winds at 850 hPa and vertical p-velocity at 500 hPa and (d) OLR in October 2010 (shaded areas show the 95% confidence level).

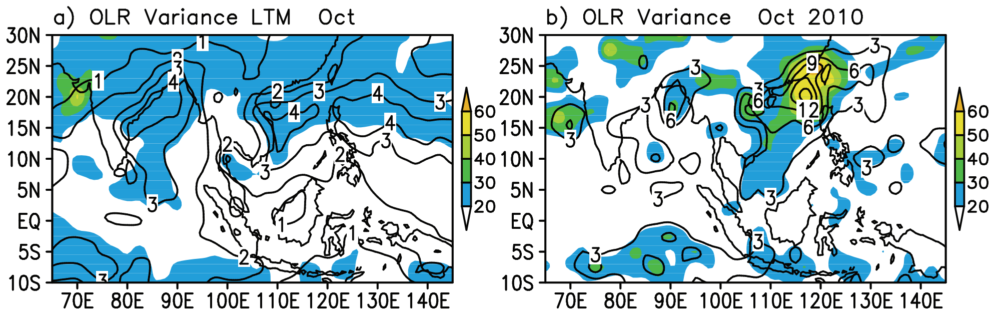

Fig. 5. (a) Mean variance (contours, units: 100 W^2 m^{-4}) and the percentage variance (shading) of the 10–20-day oscillation of OLR for the period October 1979–2010. Panel (b) is the same as (a), but for October 2010.

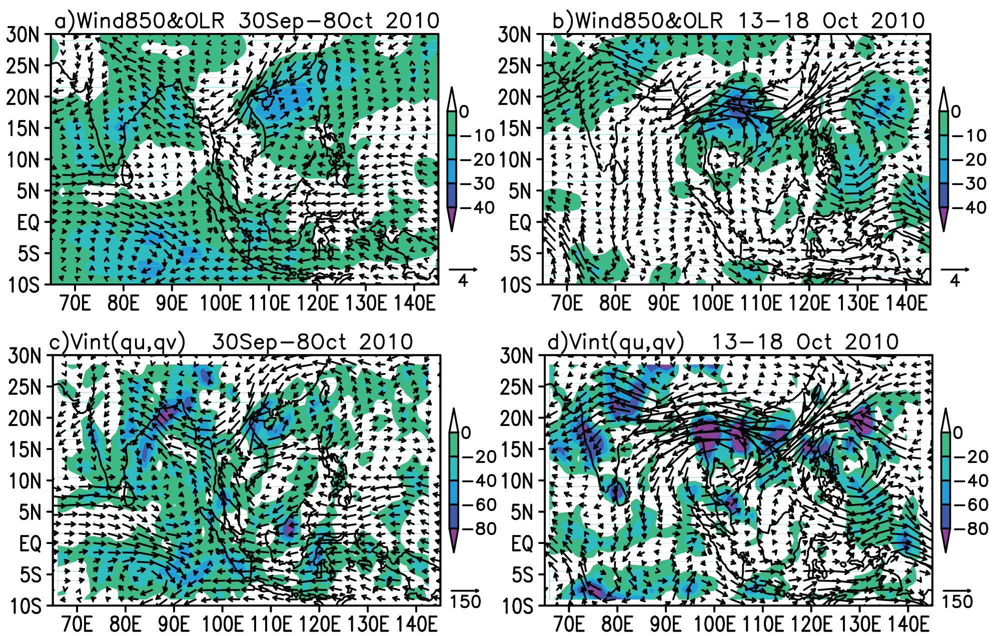

Fig. 6. 10–20-day components of winds at 850 hPa (vectors, units: m s^{-1}) and OLR (shaded, units: W m^{-2}) averaged (a) from 30 September to 8 October and (b) from 13 October to 18 October 2010. 10–20-day components of vertically integrated water vapor flux (vectors, units: kg m^{-1} s^{-1}) and its divergence (shading, units: 10^{-6} kg m^{-2} s^{-1}) averaged (c) from 30 September to 8 October and (d) from 13 to 18 October, 2010. Shaded areas denote negative values.

5. Propagation of the 10–20-day oscillations of convection and circulation

5.1. *Propagation of the 10–20-day oscillation of OLR and winds at 850 hPa*

To focus on the possible physical processes of the rainstorms over Hainan, we investigate the temporal evolution of the 10–20-day oscillation of OLR at (18°N, 110°E), which represents the approximate location of Hainan. From August to October, there were several cycles of the 10–20-day oscillation (Fig. 7). We can see that the amplitude of the oscillation was very large from mid-September to late October, and two major negative peaks occurred on 3 October and 17 October, respectively. In terms of the 30–60-day oscillation, a notable negative peak appeared on 6 October. Under the

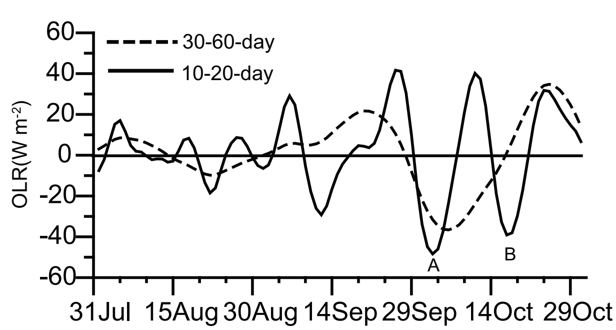

Fig. 7. Time series of the 10–20-day and 30–60-day oscillations of OLR (units: W m^{-2}) at (18°N, 110°E) from August to October 2010. "A" and "B" denote the two phases of the 10–20-day oscillation associated with the two rainstorm events in Hainan.

modulation of the 30–60-day oscillation, more precipitation occurred during the first rainstorm over Hainan than the second.

On 20 September, obvious convection activities appeared over the west-central tropical Indian Ocean (Fig. 8a). Correspondingly, there was a pair of cyclonic circulations along the equator between 80°E and 90°E. At the same time, there was another convective region in the western North Pacific between 0° and 10°N, with its western margin near 135°E. On 25 September, the convective center over the tropical Indian Ocean migrated eastward and the other convective center migrated simultaneously westward from the western Pacific, and they then combined over the maritime continent. Meanwhile, a weak cyclonic circulation existed to the north of the convective center (Fig. 8b). On 29 September, both the convective center and the cyclonic circulation were enhanced and migrated northward to the Indochina Peninsula, southern South China Sea, and the western North Pacific (Fig. 8c). On 3 October, the convective center and the cyclonic circulation migrated farther northward to the northern South China Sea and South China. Hainan was near the convective center (Fig. 8d), similar to the situation shown in Fig. 6a. Figures

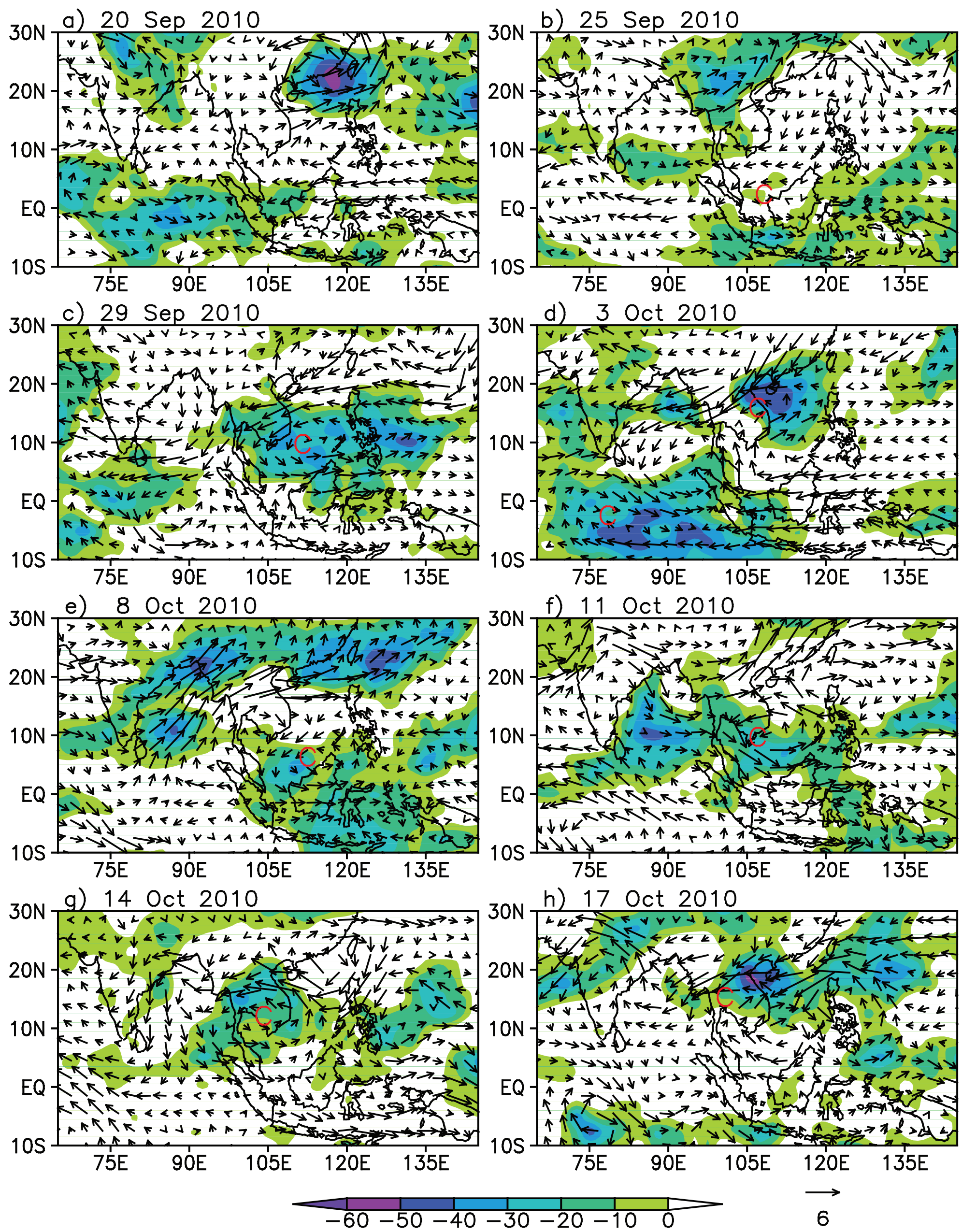

Fig. 8. 10–20-day oscillation of winds at 850 hPa (vectors, units: m s^{-1}) and OLR (shading, units: W m^{-2}) on (a) 20 September; (b) 25 September; (c) 29 September; (d) 3 October; (e) 8 October; (f) 11 October; (g) 14 October; and (h) 17 October 2010. Shaded areas denote negative values of OLR. "C" denotes cyclonic circulation.

8a–d suggest that the eastward propagation of the convective center from the west-central tropical Indian Ocean to the maritime continent and then the northward propagation from the maritime continent to Hainan could have been the major cause of the sustained rainstorm over Hainan in early October. Additionally, the westward propagation of the 10–20-day convection that originated in the western North Pacific also contributed to this rainstorm. Compared with a study of rainstorms over the Xijiang River valley of South China in the rainy season from April to June (Ji et al., 2011), the present research shows that, not only the northward and westward propagation, but also the eastward propagation from the tropical Indian Ocean, should be paid special attention in relation to autumn rainstorms over Hainan. This is consistent with a study on the onset of the summer monsoon in the South China Sea (Yuan and Chen, 2012).

From Fig. 8d, we can see that another convective center was accompanied by a cyclonic circulation in the south-central tropical Indian Ocean, which was a leading signal of the second rainstorm in Hainan. On 8 October, the convective center migrated eastward to the maritime continent region. Correspondingly, the wind fields were characterized by a cyclonic circulation over the maritime continent and an anticyclonic circulation over the Indochina Peninsula (Fig. 8e). The convective center and cyclonic circulation then turned to migrate northward to the southern Indochina Peninsula and the southern South China Sea on 11 October, and to the Indochina Peninsula on 14 October (Figs. 8f and g). On 17 October, the strong convective center migrated farther, to the northern Indochina Peninsula and northern South China Sea. Hainan was located just beside the convective center and at the southern margin of the cyclonic circulation, which spanned from 80°E to 120°E in the subtropics. The winds at 850 hPa converged over Hainan (Fig. 8h). During the second rainstorm, there was also eastward propagation of convection from the west-central tropical Indian Ocean to the maritime continent, as well as northward propagation to the South China Sea, which induced the rainstorm over Hainan in mid-October.

The above convection propagation phenomena can be demonstrated more clearly by longitude–time and latitude–time evolution diagrams. In the OLR field (Figs. 9a and b), there was an obvious eastward propagation of oscillations along 10°S–0° and then a northward propagation along 110°E–120°E from August to October 2010. An obvious convective center that was near (10°S–0°, 60°E) on 14 September propagated eastward to roughly 80°E on 19 September and continued to propagate to roughly 110°E over the maritime continent on 21 September. In addition, the convective center over the maritime continent propagated northward to Hainan from 21 September to early October, which induced the first rainstorm over Hainan in October. Moreover, another remarkable eastward propagation of OLR appeared from 60°E to 115°E from late September to early October. The convective activity then propagated northward to Hainan in mid-October, causing the second rainstorm.

Furthermore, the 10–20-day oscillation from the western North Pacific (Figs. 9c and d) showed that on 25 September, a remarkable negative OLR appeared at about (2.5°–10°N, 140°E). According to the research of Chen and Sui (2010), the origin of the quasi-biweekly oscillation over the western North Pacific is closely associated with the theoretical equatorial Rossby wave. The convective center then propagated westward and reached 110°E along 2.5°–10°N on 30 September, and subsequently propagated northward to Hainan on 5 October. The westward propagation of OLR centers in

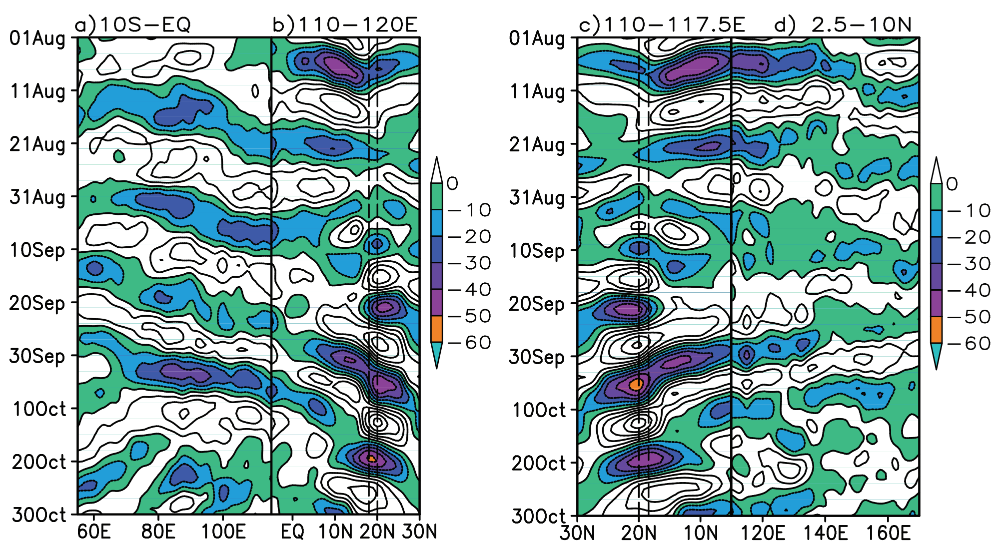

Fig. 9. (a) Longitude–time section along 10°S–0° and (b) latitude–time section along 110°–120°E of the 10–20-day oscillation of OLR (units: W m^{-2}; contour interval is 10 W m^{-2}). Shaded areas denote negatives value of OLR. (c) Latitude–time section along 110°–117.5°E and (d) longitude–time section along 2.5°–10°N of the 10–20-day oscillation of OLR (units: W m^{-2}; contour interval is 10 W m^{-2}). Shaded areas denote negative values of OLR. The dashed line indicates the latitude of Hainan.

the western Pacific, with a propagation speed of 6.4 m s^{-1}, was quite similar to the equatorial Rossby wave speed of 4.5 m s^{-1} (Kikuchi and Wang, 2009; Kiladis et al., 2009).

The above evidence suggests that, during the first rainstorm, the eastward propagation of the 10–20-day oscillation from the west-central Indian Ocean and the westward propagation from the western North Pacific worked together to reinforce the convective activity over the maritime continent. During the second rainstorm, the eastward propagation of the 10–20-day oscillation from the west-central Indian Ocean was the major signal for the convective activity over the maritime continent. The direct cause of the rainstorm events in Hainan was the northward propagation of convective activity from the maritime continent to the South China Sea.

5.2. *Possible mechanisms of the eastward propagation*

To understand the possible mechanisms of the eastward propagation of convection from the Indian Ocean to the maritime continent, we analyze the lagged regression coefficients of the OLR and 850-hPa winds anomalies with respect to the normalized 10–20-day component of OLR at (5°S, 85°E) from Day (−6) to Day (+3) (Figs. 10a, c, e and g). Because negative OLR anomalies indicate enhanced convection, the 10–20-day component of OLR at (5°S, 85°E) was multiplied by −1 before the regression process. Thus, the variations of all the variables in Fig. 10 correspond with the enhanced convection at (5°S, 85°E). At Day (−6) (Fig. 10a), a small negative center of OLR appeared near 60°E at the equator, indicating the origination of the anomalous convective activity. The convective center developed rapidly and expanded eastward to 100°E from Day (−3) to Day (0). At Day (+3) (Fig. 10g), the convective activity migrated eastward to the east of the maritime continent. The 850 hPa winds exhibited a close relationship with the OLR. The evolution of the convective activity showed a feature similar to the coupled Kelvin–Rossby mode, which was suggested by Hayashi and Sumi (1986) and Hendon (1988).

Wang and Rui (1990) further proposed that frictional moisture convergence in the boundary layer is essential for the growth of the unstable Kelvin–Rossby mode. Figures 10b, d, f, and h show the regressed moisture flux divergence anomalies at 950 hPa from Day (−6) to Day (+3). At Day (−6) (Fig. 10b), there was a convergence region from 55°E to 75°E in the tropics, which was located to the east of the convective center shown in Fig. 10a. The convergence region spanned from 60° to 110°E in the tropics with a center between 60° and 70°E at Day (−3) (Fig. 10d). It can be seen that a small divergence region appeared to the west of 60°E. At Day (0) (Fig. 10f), the convergence region migrated eastward and covered from the central equatorial Indian Ocean to the western equatorial Pacific Ocean with several intensified centers, which were also located to the east of the corresponding convective center shown in Fig. 10e, while the divergence centers were located to the west of the convective activity. At Day (+3) (Fig. 10h), the convergence center moved farther eastward and expanded even to the central Pacific; the centers were located in the maritime continent–western Pacific region, while the divergence center was located to the west of the convective region in Fig. 10g.

A careful comparison between all the OLR and divergence figures (Figs. 10a–h) reveals that the convergence centers were always located to the east of the deep convection, moistening the boundary layer and creating potentially unstable conditions, favoring the eastward propagation of the Kelvin wave. In contrast, near-surface divergence anomalies were located to the west of the convective activity, which was not conducive to the westward propagation of the Rossby wave. The convectively coupled Kelvin–Rossby wave therefore propagated eastward. This finding is similar to the work of Hsu et al. (2004) on the eastward propagation of the intraseasonal oscillation during boreal summer.

6. Discussion and conclusion

Hainan experienced two rainstorms in October 2010. The daily precipitation averaged over Hainan showed a prominent 10–20-day oscillation from August to October in 2010. According to the 10–20-day components of all the variables extracted from the raw data, an obvious cyclonic circulation over the northern South China Sea and South China, accompanied by convective activity, was responsible for the first sustained rainfall over Hainan. During the second rainstorm, there were two remarkable cyclonic circulations, one over the eastern Bay of Bengal and the western South China Sea across the Indochina Peninsula, and the other over the region east of the Philippines. Hainan was subject to intensive convergent flow associated with the cyclonic circulation over the southern Indochina Peninsula, and the strong convective activity induced the rainstorm over Hainan.

For both rainstorms, the convective centers and cyclonic circulations at 850 hPa originated over the west-central Indian Ocean. These systems propagated eastward to the maritime continent and then northward to the South China Sea and South China, causing the rainstorms over Hainan. In addition, the westward propagation of the 10–20-day convection originating in the western Pacific contributed to the first rainstorm.

Although previous studies have shown that the Madden–Julian Oscillation is a major phenomenon over the Indian Ocean (Madden and Julian, 1971, 1972, 1994; Zhang, 2005), the peak corresponding to the 30–60-day oscillation does not pass the significance test of $\alpha = 0.05$ in this case study. We emphasize the impact of the zonal propagation of the 10–20-day oscillation from the west-central Indian Ocean on the rainstorms over Hainan in October 2010 because the peaks of this oscillation pass the significance test of $\alpha = 0.05$. Meanwhile, the 30–60-day oscillation modulated the impact of the 10–20-day oscillation on the rainstorms over Hainan. The eastward propagation of the 10–20-day oscillation in the tropical Indian Ocean is similar to the convectively coupled Kelvin–Rossby wave. In addition, the westward propagation of the 10–20-day oscillation from the western Pacific is roughly similar to the equatorial Rossby wave in both its pe-

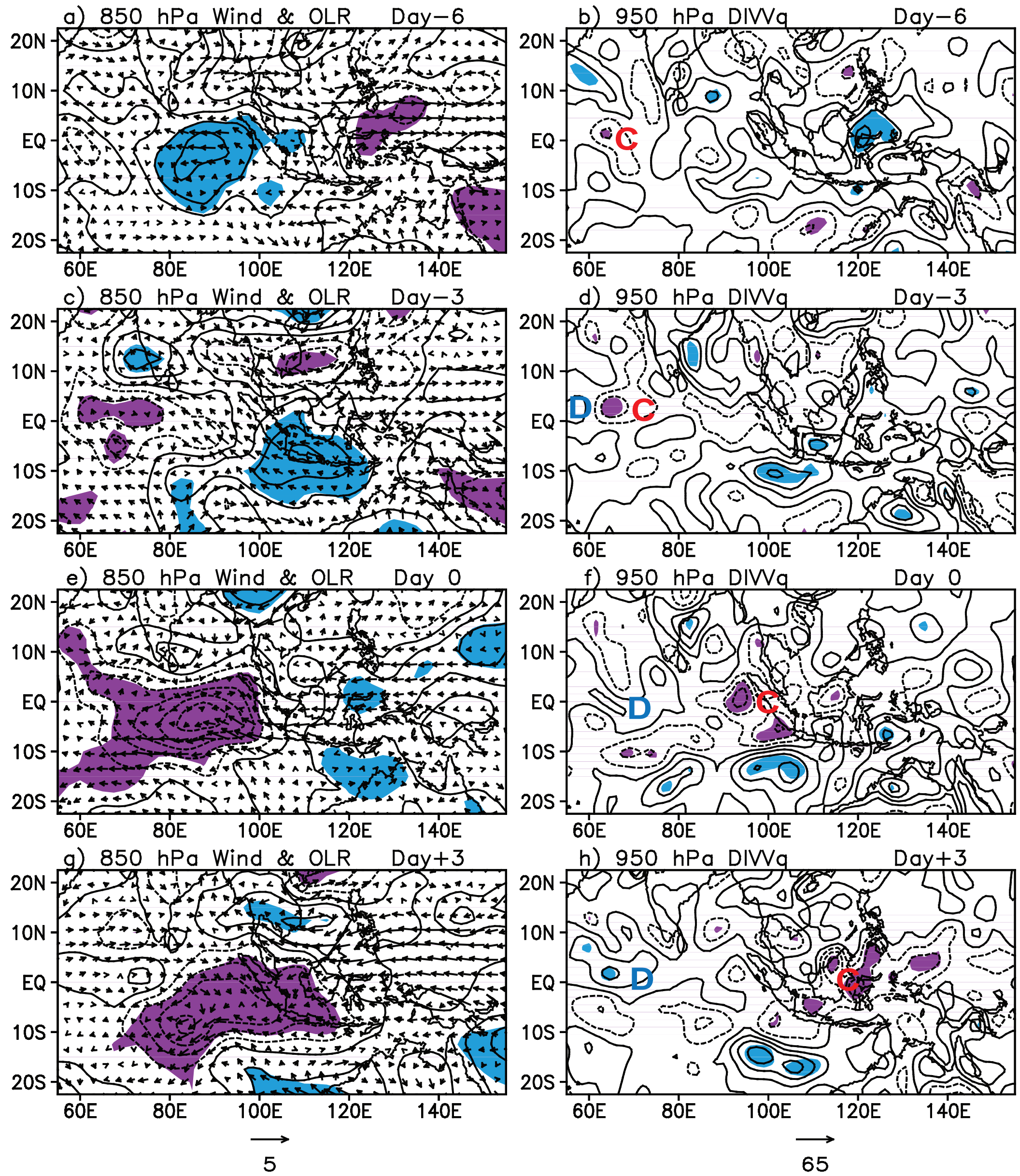

Fig. 10. Lagged regression coefficients of the OLR (contours, units: W m^{-2}) and 850 hPa wind (vectors, units: m s^{-1}) anomalies with respect to the normalized 10–20-day component of OLR at (5°S, 85°E) (multiplied by -1) at (a) Day (-6), (c) Day (-3), (e) Day (0) and (g) Day ($+3$) during August to October 2010. The contour interval is 5 W m^{-2}, with negative contours dashed. Shaded areas are significant at the $\alpha = 0.05$ significance level. The right-hand panels are the same as the left-hand panels, but for the moisture flux divergence anomalies at 950 hPa. The contour interval is 10^{-5}g kg^{-1} s^{-2}; "C" denotes convergence and "D" denotes divergence in (b), (d), (f) and (g).

riodicity and propagation speed. Thus, the coupled Kelvin–Rossby wave and equatorial Rossby wave may have worked together to induce the rainstorms over Hainan in October 2010. We also investigated the propagation of the 30–60-day oscillation (figure not shown), and the results showed that there was neither eastward propagation from the Indian Ocean nor westward propagation from the western Pacific on the 30–60-day timescale.

The second reason we emphasize the impact of the 10–20-day oscillation is that only the northward propagation of the 10–20-day oscillation from the tropics has been noticed in previous studies on heavy rainfall events in South China (Tong et al., 2007; Ji et al., 2010; Ji et al., 2011). In this study, we have discussed not only the northward propagation of the 10–20-day oscillation, but also the zonal propagation in the tropics. The combination of the zonal propagation and the northward propagation of convection reflects an integrated evolution of the 10–20-day oscillation contributing to the sustained rainstorms over Hainan. In fact, the propagation of the 10–20-day oscillation may affect the moving track of a tropical synoptic depression or tropical cyclone (Ko and Hsu, 2006).

Third, air–sea coupling over the tropical Indian Ocean significantly enhances the intensity of both the eastward and northward propagations of the boreal summer intraseasonal oscillation (Lin et al., 2011). We also examined SST anomalies in September and October 2010 (figure not shown). The spatial distribution of the SST anomaly showed a La Niña pattern. Positive SST anomalies existed almost throughout the tropical Indian Ocean and western Pacific, forcing the active convection center and favoring the corresponding propagation.

Finally, it is important to further discuss why the October 2010 case was so special. We believe its uniqueness to be a result of the combined impacts of many factors. First, tropical depressions moved from the tropical Indian Ocean and tropical western Pacific Ocean to the northern South China Sea and induced rainstorms over Hainan in October 2010. The features could be seen more clearly in the evolution of the 10–20-day oscillation of convection and cyclonic circulation. The track of the tropical depressions may have been influenced by the 10–20-day oscillation. From the perspective of tropical waves, the eastward-moving coupled Kelvin–Rossby wave and the westward-moving equatorial Rossby wave collided in this particular period. In addition, the La Niña event favored strong and warm SSTs over the tropical Indian Ocean and western Pacific, forcing the active convection center and favoring the corresponding propagation from the Indian Ocean to the maritime continent. According to other research on ISO and ENSO (Lin and Li, 2008; Hong and Li, 2009), during the La Niña event, the westward shift of the suppressed convection and easterly anomalies prevented the ISO from penetrating farther eastward, and consequently the ISO remained at the maritime continent longitudes. There may be other factors involved that have not been mentioned here. The case should be studied further to gain a better understanding of the sustained rainfall over Hainan.

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