Origins of intraseasonal rainfall variations over the southern South China Sea in boreal winter

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ABSTRACT
This study investigates the origins of intraseasonal rainfall variations over the southern South China Sea (SCS) region in boreal winter. It is found that intraseasonal rainfall variations over the southern SCS have different origins on the 10–20-day and 30–60-day time scales. On the 10–20-day time scale, large rainfall anomalies over the southern SCS are preceded by strong northerly wind anomalies associated with the East Asian winter monsoon (EAWM), by about two days. On the 30–60-day time scale, the strong EAWM-related northerly wind anomalies almost appear simultaneously with large rainfall anomalies over the southern SCS. In addition, obvious large rainfall anomalies occur over the southeastern tropical Indian Ocean about one week before the peak southern SCS rainfall anomalies. It indicates that the convection and related circulation anomalies with origins over the tropical Indian Ocean may play an important role in inducing intraseasonal rainfall variations over the southern SCS on the 30–60-day time scale, but not on the 10–20-day time scale.

KEYWORDS
intraseasonal rainfall anomalies; southern South China Sea; boreal winter; 10–20-day and 30–60-day time scales

ARTICLE HISTORY
Received 2 March 2016
Revised 29 March 2016
Accepted 5 April 2016

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1. Introduction
The intraseasonal oscillation (ISO) is one of the most significant signals over the tropical Indian Ocean, the Maritime Continent, and the tropical western Pacific regions. Madden and Julian first detected this signal in the zonal wind field (Madden and Julian 1971). It is now generally accepted that the Madden–Julian oscillation (MJO) propagates eastward from the western Indian Ocean to the central Pacific Ocean. Thus, it is expected that the intraseasonal rainfall variations around the Maritime Continent, including the southern South China Sea (SCS), may be largely linked to those from the tropical Indian Ocean, in particular during boreal winter when the MJO signal is the strongest near the equator.

The SCS climate in boreal winter is affected by the East Asian winter monsoon (EAWM). The northeasterly winds associated with the EAWM may penetrate into the equatorial region via the SCS (Chang, Erickson, and Lau 1979; Ji et al. 1997; Chen, Graf, and Huang 2000; Wu and Chen 2015). Chang, Erickson, and Lau (1979) indicated that northeasterly cold surges are sometimes observed over the southern SCS. On the one hand, anomalous northeasterlies may induce lower-level convergence and convection along the coast of Borneo (Wu 2016); while on the other hand, the associated wind–evaporation effect may lower the SST in the southern SCS (Wu and Chen 2015; Wu 2016). The induced anomalous SST gradient may in turn lead to anomalous rainfall (Wu and Chen 2015). Thus, it is likely that the intraseasonal EAWM variability may lead to large intraseasonal variations over the SCS. Thus, the intraseasonal rainfall variations over the southern SCS may have their source related to the EAWM.

The present study investigates the association of the intraseasonal rainfall variations over the southern SCS with the MJO and the EAWM. As the convective heating around the Maritime Continent may have large impacts on atmospheric circulation in remote regions, it is important to delineate the source of rainfall variations in this region.
3. The spatial and temporal characteristics of intraseasonal rainfall variations

In this section, we analyze the characteristics of intraseasonal rainfall variations. Figure 1 shows the standard deviation of rainfall anomalies on the 3–91-day, 10–20-day, and 30–60-day time scales during NDJFM from 1998/1999 to 2012/2013. A large standard deviation is observed in the southern SCS, southeastern Indian Ocean, and east coast of the Philippines, equatorial western Pacific, and southwestern tropical Pacific, on the 3–91-day time scale (Figure 1(a)). On the 10–20-day and 30–60-day time scales, the standard deviations of rainfall anomalies display a spatial distribution similar to that on the 3–91-day time scale, but with a smaller magnitude (Figure 1(b) and (c)). In comparison, the standard deviation on the 10–20-day time scale is

Previous studies show that the ISO variability displays two dominant time scales: one with a period of 10–20 days and the other with a period of 30–60 days (e.g. Fukutomi and Yasunari 1999; Kajikawa and Yasunari 2005; Kikuchi and Wang 2009). Thus, the present study attempts to investigate whether the origins of intraseasonal rainfall variations over the southern SCS are different on the 10–20-day and 30–60-day time scales during boreal winter.

In the remainder of the paper, we describe the data and methods in Section 2. Section 3 presents the spatial distribution and temporal spectrum of intraseasonal rainfall variations in boreal winter. In Section 4, we investigate the origins of intraseasonal rainfall variations over the southern SCS. A summary and discussion are presented in Section 5.

2. Data and methods

The rain rate in the present study is derived from data gathered using the TRMM Microwave Imager (TMI) (Wentz et al. 2000). The TMI data-set is available on 0.25° × 0.25° grids starting from January 1998, which can be downloaded from http://www.remss.com/missions/tmi. The original TMI data have missing values and have been converted to 1° × 1° grids. The present analysis uses a three-day running mean to reduce the grids of missing data.

The daily surface zonal and meridional winds used in the present analysis are derived from NCEP–DOE Reanalysis-2 (Kanamitsu et al. 2002). They are available on T62 Gaussian grids from January 1979 and obtained by anonymous ftp at ftp://ftp.cdc.noaa.gov/. The climatological annual cycle in the above variables is removed from the long-term daily mean for the period 1998–2014.

The present study separates the intraseasonal variations on the 10–20-day and 30–60-day time scales. Following the method of Wu (2010) and Wu, Cao, and Chen (2015), the ISO on the 10–20-day time scale is obtained by a 9-day running mean minus a 21-day running mean, and that on the 30–60-day time scale is obtained by a 29-day running mean minus a 61-day running mean. Use of the traditional band-pass filtering leads to similar results. Our analysis focuses on the variations in boreal winter, which refers to the months from November to the following March (NDJFM for brevity). The analysis period is from NDJFM 1998/1999 to NDJFM 2012/2013, when all the variables are available.

This study is concerned with intraseasonal variations in the tropical regions associated with the EAWM. We define an EAWM index (EAWMI) using area-mean meridional wind at 10 m, averaged over the region (10°–25°N, 105°–135°E), during NDJFM, where the meridional wind variability is large (Wu and Chen 2015). According to Chen, Wu, and Chen (2014), the above index represents the southern component of the EAWM variability.
larger than that on the 30–60-day time scale. According to the spatial distribution of the standard deviation of rainfall anomalies, we use area-mean rainfall averaged over the region (2.5°–12.5°N, 108°–115°E) as a measure of intraseasonal rainfall variation over the southern SCS, and that averaged over the region (10°S–5°N, 92°–105°E) (excluding the sub-region (0°–5°N, 99°–105°E), which is not part of the Indian Ocean) as a measure of intraseasonal rainfall variation over the southeastern tropical Indian Ocean.

Figure 2 further presents the power spectrum of the intraseasonal (3–91-day) rainfall anomalies over the southern SCS. The theoretical Markov spectrum and Markov upper confidence bounds are used to evaluate the significance of these spectral estimates, at the 95% confidence level. It is evident that there are peaks within the 10–20-day (14 out of 15 years) and 30–60-day (9 out of 15 years) bands. The peaks within the 10–20-day band all reach the 95% confidence level, except for 2005/2006. The peak within the 30–60-day band reaches the 95% confidence level in 1999/2000 only. The mean spectrum, which is obtained by simply averaging the spectrum in the 15 individual years, does not show spectral peaks as sharp as those in individual years, but a relatively large spectrum is visible within the 10–20-day and 30–60-day bands (Figure 2(p)). In particular, a significant peak in the 10–20-day band reaches the 95% confidence level (Figure 2(p)). This is consistent with the larger standard deviation of rainfall anomalies on the 10–20–day time scale than on the 30–60-day time scale, as shown in Figure 1. These results indicate that the 10–20-day ISO is robust over the southern SCS in boreal winter. In addition, this is consistent with the findings of previous studies that the ISO in boreal winter is more inclined to high frequency (Wu 2016). A spectral peak is observed in the 20–30-day band in 1998/1999, 2000/2001, 2005/2006, and 2009/2010. However, the 20–30-day spectral peak is not as frequent and robust as the 10–20–day and 30–60-day spectral peaks.

4. The origins of intraseasonal rainfall variations over the southern SCS

To investigate the origins of intraseasonal rainfall anomalies, we examine the spatiotemporal evolution of intraseasonal rainfall anomalies and associated surface wind anomalies. The normalized rainfall anomalies in the region (2.5°–12.5°N, 108°–115°E) are used as a reference to construct the evolving anomalies through the lead–lag regression on the 10–20–day and 30–60–day time scales, respectively. Figure 3 shows the anomalies starting from 6 days before (lag(−6)) to 6 days after (lag(+6)) the normalized rainfall anomalies on the 10–20–day time scale, and from 12 days before (lag(−12)) to 12 days after (lag(+12)) the normalized rainfall anomalies on the 30–60–day time scale. All these anomalies are based on the period NDJFM during 1998/1999 to 2012/2013. And note that only rainfall anomalies significant at the 95% confidence level are shown.

On the 10–20–day time scale, the intraseasonal rainfall anomalies over the southern SCS are mainly associated with the wind variations over East Asia, the SCS, and the western North Pacific (WNP). At lead(−6), negative rainfall anomalies appear over the southern SCS and positive rainfall anomalies are present over the subtropical WNP (Figure 3(a)), forming a south–north dipole anomaly pattern (Wu 2016). The positive rainfall anomalies in the north are associated with lower-level converging wind anomalies. At lead(−3), positive rainfall anomalies develop over the southern SCS in association with large northerly wind anomalies that penetrate southward into the southern SCS from East Asia (Figure 3(b)). These positive rainfall and northerly wind anomalies intensify during the following few days (Figure 3(c)). The rainfall anomalies over the subtropical WNP switch to be negative in association with lower-level diverging wind anomalies. As such, the south–north dipole pattern changes its polarity. At lag(+3), the positive rainfall anomalies weaken over the southern SCS and northerly wind anomalies disappear over the SCS (Figure 3(d)). Southerly wind anomalies dominate over East Asia. At lag(+6), positive rainfall anomalies are replaced by negative anomalies over the southern SCS and, meantime, southerly wind anomalies extend southward from eastern China into the SCS (Figure 3(e)).

Over the tropical Indian Ocean, positive rainfall anomalies are observed over the equatorial eastern Indian Ocean at lead(−6) (Figure 3(a)). These rainfall anomalies move northwestward in the following days to the southwest Bay of Bengal, where they weaken (Figure 3(b)–(e)). Some weak negative rainfall anomalies appear to propagate eastward from the equatorial central to eastern Indian Ocean (Figure 3(b)–(d)), and then turn to move northwestward (Figure 3(e)). These Indian Ocean rainfall anomalies are not connected to those over the southern SCS. Thus, it is inferred that the 10–20–day rainfall anomalies over the southern SCS are mainly associated with the EAWM.

On the 30–60–day time scale, the rainfall anomalies over the southern SCS are preceded by those over the Indian Ocean. At lead(−12), positive rainfall anomalies cover the tropical eastern Indian Ocean, with penetration into the southwestern SCS (Figure 3(f)). In association, westerly wind anomalies are observed over the tropical South Indian Ocean. In the following days, the positive rainfall anomalies over the southern SCS intensify (Figure 3(g) and (h)). This intensification is accompanied by the development of large northerly wind anomalies over the SCS, WNP, and East Asia, signifying the association with the
rainfall and rainfall over the southeastern tropical Indian Ocean, we show in Figure 4(a) lead–lag correlation of the EAWM and rainfall over the southeastern Indian Ocean with respect to the normalized southern SCS rainfall anomalies on the 10–20-day and 30–60-day time scales. Clearly, on the 10–20-day time scale, large northerly wind anomalies (denoted by negative EAWMI) appear about two days before the peak rainfall anomalies over the SCS, and southerly wind anomalies are observed about one week after the SCS rainfall peak (Figure 4(a)). The significant correlation suggests a close association between intraseasonal SCS rainfall variation and EAWM on the 10–20-day time scale. However, there is no clear correlation between the southern SCS and southeastern tropical Indian Ocean rainfall variations.

In order to illustrate more clearly the time lag relationship between SCS rainfall and EAWM and between SCS rainfall and rainfall over the southeastern tropical Indian Ocean, we show in Figure 4(a) lead–lag correlation of the EAWM and rainfall over the southeastern Indian Ocean with respect to the normalized southern SCS rainfall anomalies on the 10–20-day and 30–60-day time scales. Clearly, on the 10–20-day time scale, large northerly wind anomalies (denoted by negative EAWMI) appear about two days before the peak rainfall anomalies over the SCS, and southerly wind anomalies are observed about one week after the SCS rainfall peak (Figure 4(a)). The significant correlation suggests a close association between intraseasonal SCS rainfall variation and EAWM on the 10–20-day time scale. However, there is no clear correlation between the southern SCS and southeastern tropical Indian Ocean rainfall variations. This indicates that the rainfall anomalies

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**Figure 2.** Power spectrum (black solid curve) of area-mean intraseasonal (3–91-day) rainfall variations in the domain (2.5°–12.5°N, 108°–115°E). Area-mean time series are firstly treated with a 3–91-day running mean, and power spectrum analysis is then applied to these area-mean time series during November through March in each year during 1998/1999–2012/2013.

Notes: The average of the 15-year spectrum is also shown. The dotted and dashed lines represent the red noise and the 95% confidence level, respectively.
Figure 3. Anomalies of rainfall (shading; units: mm h$^{-1}$) and 10 m wind (vectors with scale at top; units: m s$^{-1}$) from 6 days before (12 days before) to 6 days after (12 days after), obtained by regression with respect to the normalized southern SCS rainfall anomalies on the (a–e) 10–20-day (f–j) 30–60-day time scale during November through March from 1998/1999 to 2012/2013. Notes: Only the rainfall anomalies significant at the 95% confidence level are shown.
the SCS rainfall variation on the 30–60-day time scale is associated with the EAWM and rainfall anomalies over the tropical Indian Ocean.

To conclude, there are different origins of the southern SCS rainfall variations on the 10–20-day and 30–60-day time scales. On the 10–20-day time scale, the winter monsoon winds over East Asia may propagate southward into the southern SCS and enhance local convergence, which can induce strong rainfall. On the 30–60-day time scale, the wind anomalies associated with the EAWM and MJO from the tropical Indian Ocean may both contribute to the intraseasonal variations of rainfall over the southern SCS.

5. Summary and discussions

During boreal winter, large standard deviations of intraseasonal rainfall anomalies are observed in the southern SCS, southeastern Indian Ocean, and east of the Philippines. The intraseasonal rainfall variations over the southern SCS display two prominent periods: one in the 10–20-day band, and the other in the 30–60-day band. The present study detects notable differences in the origins of intraseasonal rainfall anomalies over the southern SCS region during boreal winter on the 10–20-day and 30–60-day time scales.

Through the lead–lag regression analysis, it is found that the SCS rainfall anomalies are associated with the northerly winds from East Asia on the 10–20-day time scale. Large northerly wind anomalies appear about two days before the positive SCS rainfall anomalies, and southerly wind anomalies are observed almost one week after the peak SCS rainfall anomalies. There is no obvious connection between the southern SCS and the tropical Indian Ocean rainfall variations on the 10–20-day time scale. On the 30–60-day time scale, the strong EAWM anomalies and strong SCS rainfall anomalies almost appear at the same time. The strong northerly wind anomalies enhance the convergence and induce the large rainfall anomalies over the southern SCS. In addition, there is an obvious positive correlation between the rainfall anomalies over the northern SCS and the southeastern tropical Indian Ocean, with a lead time of about one week. The intraseasonal rainfall variations over the southeastern tropical Indian Ocean may be associated with the MJO signals that propagate eastward along the equator. This indicates that the MJO, with origins over the tropical Indian Ocean, may play an important role in inducing the intraseasonal variations of SCS rainfall on the 30–60-day time scale.

The present study has focused on the origins of intraseasonal rainfall variations over the southern SCS. As seen in Figure 1, large intraseasonal rainfall variability is observed over the southeastern tropical Indian Ocean and along the east coast of the Philippines. In the future, intraseasonal
rainfall anomalies over the southeastern tropical Indian Ocean and along the east coast of the Philippines will be analyzed and compared with those over the southern SCS on the 10–20-day and 30–60-day time scales, from the perspective of the origins, interrelations, and effects of the MJO and EAWM.

Acknowledgements

The TMI data were obtained from http://www.remss.com/missions/tmi. The NCEP–DOE Reanalysis-2 data were obtained from ftp://ftp.cdc.noaa.gov/.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was supported by the National Natural Science Foundation of China [grant numbers 41475081, 41275081, 41505048, 41505061, and 41461164005] and the State Key Laboratory of Severe Weather Special Fund [grant number 2015LASW-B04].

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