Interannual variability of the 10–25- and 30–60-day variation over the South China Sea during boreal summer

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[1] The interannual variability (IAV) of the intraseasonal variation (ISV) over the South China Sea (SCS) was investigated, focusing on the relationship between the 10–25- and 30–60-day variation. Both ISV activities over the SCS had larger IAV than those of the Bay of Bengal and Arabian Sea. The 10–25- (30–60-) day variation was relatively active when the 30–60- (10–25-) day variation was suppressed in June, July and September. The IAV of the ISV during early summer (June–July) was related to the IAV of the SCS monsoon onset. A late (early) onset was accompanied by active 10–25- (30–60-) day variation. The IAV of the ISV could be divided into early and late summer (September), because there was little persistence between these two periods. Moreover, large-scale circulation anomalies associated with the IAV had different spatial structures in these two periods. **Citation:** Kajikawa, Y., and T. Yasunari (2005), Interannual variability of the 10–25- and 30–60-day variation over the South China Sea during boreal summer, *Geophys. Res. Lett.*, *32*, L04710, doi:10.1029/2004GL021836.

1. Introduction

[2] The South China Sea monsoon (SCSM) is an important component of the western North Pacific monsoon (WNPM) [*Murakami and Matsumoto*, 1994] and strongly influences the interannual variability (IAV) in the WNPM and surrounding regions. For instance, convection anomalies over the WNPM can affect the eastern Asian summer weather condition via the Pacific-Japan teleconnection pattern [*Nitta*, 1987], while enhanced convection anomalies over the South China Sea (SCS) can play an important role in the onset processes of the Indian Ocean dipole mode [*Kajikawa et al.*, 2003]. Moreover, the SCSM also has large intraseasonal variability (ISV) with two dominant time scales, one with a period of 30–60 days and the other with a period of 10–25 days [*Lau et al.*, 1998; *Annamalai and Slingo*, 2001]. The 30–60-day variation shows northward propagation [*Lau and Chan*, 1988; *Hsu and Weng*, 2001], while the 10–25-day variation is characterized by westward phase propagation [*Chen and Chen*, 1993; *Chen and Weng*, 1999].

[3] The prominent periodicity of the ISV differs each year, for instance, the 30–60-day variation was dominant in 1998 [*Chan et al.*, 2002; *Zhu et al.*, 2003]. Some problems with the IAV of the ISV remain. First, is the IAV of the ISV over the SCS actually significant compared with other Asian monsoon regions? Is there a relationship between the 10–25- and 30–60-day variation activity in IAV? It is also not clear whether there is a relationship between ISV activity and seasonal or monthly mean anomalies of the IAV [*Goswami and Mohan*, 2001; *Krishnamurthy and Shukla*, 2000]. The persistency and transitivity of the IAV throughout the boreal summer is also an important issue.

[4] This study investigated the IAV of the ISV over the SCS with a special focus on the relationship between the 10–25- and 30–60-day variation, to answer these questions. Here, we used the daily interpolated outgoing longwave radiation (OLR) from the NOAA satellite [*Liebmann and Smith*, 1996] and wind data from the NCEP/NCAR reanalysis project [*Kalnay et al.*, 1996]. Anomalies were generated by removing the climatology computed for 1979–2002. The band-pass filter used in this study was a Lanczos filter [*Duchon*, 1979].

2. Relationship Between the 10–25- and 30–60-Day Variation

[5] To clarify the IAV of the 10–25- and 30–60 day variation, the distribution of the mean ISV activity and the interannual standard deviation of the ISV activity during boreal summer are presented for each period in Figure 1. In advance, we defined the standard deviation of the each band-pass filtered daily OLR data averaged over the SCS (110°–120°E, 10°–20°N) as the ISV activity index. Climatologically, the 10–25-day variation is active over the Bay of Bengal (BOB), SCS and Philippine Sea (PS), while the 30–60-day variation is active over the Arabian Sea (AS), SCS and PS (Figures 1a and 1b). The IAV of the ISV activity is remarkably strong over the SCS, PS and part of the

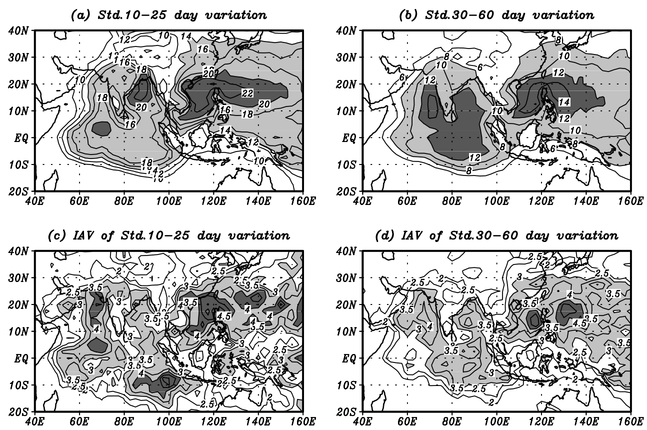

Figure 1. The mean standard deviation of the (a) 10–25-day and (b) 30–60-day filtered OLR (W/m^2). The standard deviation of the interannual variation of the (c) 10–25-day and (d) 30–60-day variation activity.

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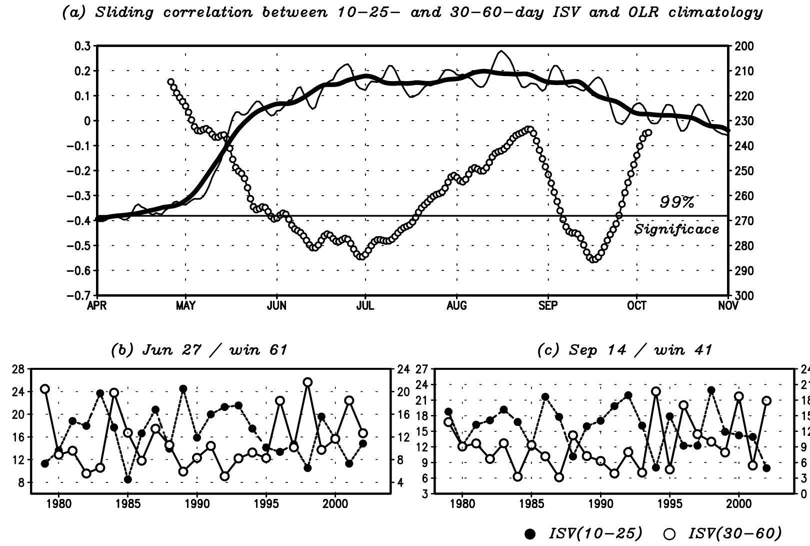

Figure 2. (a) Time series of 5- (thin line) and 31- (thick line) day running mean OLR over the SCS and the sliding correlation between 10–25-day and 30–60-day variation calculated using the 51-day time window (circle). The time series of each ISV activity calculated for (b) 61 days around June 27th, the maximum negative correlation day during early summer and for 41 days around September 14th, maximum negative correlation day during late summer.

southeastern Indian Ocean. In particular, prominent IAV of both ISV activities occurs only over the SCS (Figures 1c and 1d). Therefore, it is obvious that the SCS is an important area for IAV of both the 10–25–day and 30–60-day variation activity.

[6] Figure 2a shows the mean time series of the OLR and sliding correlations between the 10–25- and 30–60-day variation activity calculated using a 51-day window, to investigate the temporal change in the correlation between these two ISVs. Climatologically, the convection over the SCS abruptly becomes active in mid-May and the active convection continues until late September with ISV. Nevertheless, there are significant negative correlations during early (June–July) and late (September) summer. This indicates that when one ISV is relatively active, the other is suppressed during those two periods. In other words, these two forms of ISV are rarely active or suppressed simultaneously. The sliding correlations calculated with other windows (41-, 61-, and 71-day) gave the same result. Figures 2b and 2c show the time series of each ISV activity during early and late summer, centered on the day with maximum negative correlation. The 10–25-day variation was relatively active in 1983, 1987, 1989, 1992, and 1993, while the 30–60-day variation was active in 1979, 1984, 1996, 1998, and 2001 during early summer. This is consistent with case studies conducted in 1979 [*Chen and Chen*, 1995] and 1998 [*Chan et al.*, 2002; *Zhu et al.*, 2003].

[7] Figure 3 shows the time series of the auto-correlation of the 10–25- and 30–60-day variation activities from the maximum negative correlation day during early and late summer in Figure 2. The seasonal persistence of the IAV of the ISV from early to mid summer was weak, showing little correlation of the ISV activity between early and mid summer (August). The persistence from mid to late summer was also weak from little auto-correlations. This suggests that the IAV of the ISV over the SCS could be divided into two periods across August. In following section, the IAV during early summer is mainly focused and investigated its relation to the SCSM onset and mean anomaly field.

3. Relationship Between ISV Activity and SCSM Onset, Mean Anomaly Field

[8] The SCSM onset implies the beginning of the monsoon over East Asia and the western Pacific [*Wang et al.*, 2004]. To examine the relationship between ISV activity and the onset date, the time series of ISV activity during early summer and the SCSM onset day for the maximum correlation day and time window are plotted in Figures 4a and 4b. The SCSM onset day was defined as the first day when the OLR over the SCS fell below 220 (W/m^2) for more than five consecutive days. The 10–25-day variation activity shows a good positive correlation with the onset date, except for 1985 and 1999 (r = 0.51). This indicates that a late (early) onset was accompanied by active (suppressed) 10–25-day variation. In contrast, the 30–60-day variation activity was negatively correlated with the onset day (r = −0.44). Thus, the IAV of the ISV activity during early summer (June–July) was strongly correlated with the

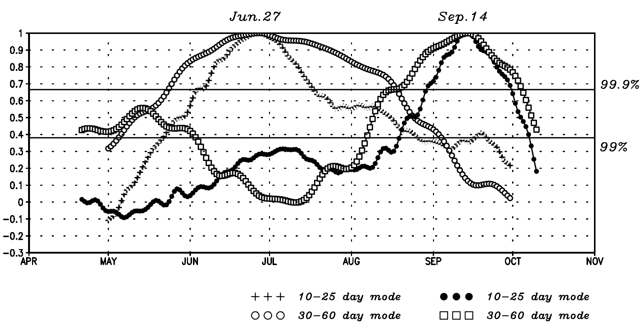

Figure 3. The time series of the auto-correlation of 10–25- and 30–60-day variation activities from the center day of early summer peak (Jun. 27) and late summer peak (Sep. 14).

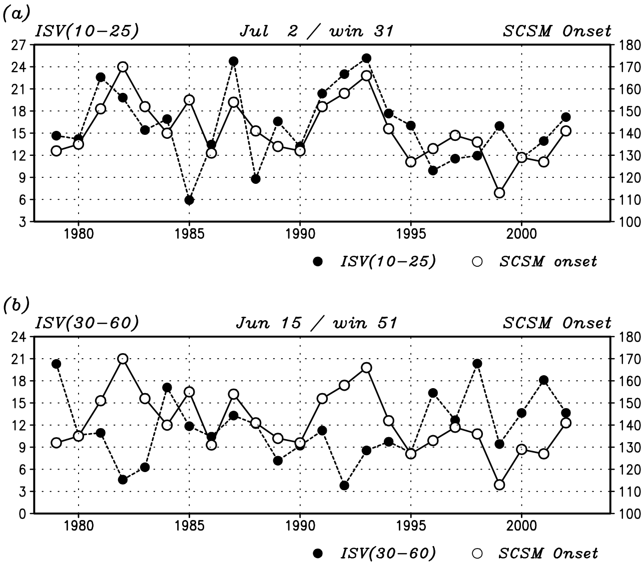

Figure 4. Time series of the ISV activity and SCSM onset date. (a) The 10–25-day variation activity was calculated for 31 days around July 2nd. (b) The 30–60-day variation activity was calculated for 51 days around June 15th.

IAV of the SCSM onset with the opposite sign for 10–25- and 30–60-day variation.

[9] Figures 5a and 5b show composite fields for early summer during 5 active yeas (refer to Section 2) for velocity potential and divergent wind anomalies at 200-hPa, and OLR and 850-hPa wind anomalies for the 10–25-day variation, respectively. The active 10–25-day variation is accompanied by enhanced convection over the equatorial eastern and middle Pacific and suppressed convection along the band 10°–20°N over the Asian monsoon region and maritime continent. Easterly and northerly wind anomalies at 850-hPa also prevail over the Asian monsoon region. This indicates that the active 10–25-day variation during early summer is related to weakening of the large-scale monsoon circulation and east-west circulation over the Pacific. Meanwhile, the composite fields for the active 30–60-day variation years show different features from those for the 10–25-day variation (Figures 5c and 5d). The active 30–60-day variation is accompanied by suppressed convection over the equatorial western-middle Pacific and enhanced convection over the equatorial eastern-middle Indian Ocean. Northeasterly divergent wind anomalies at 200-hPa are also remarkable only over the maritime continent. Consequently, weakening of the local Hadley circulation between the maritime continent and western Pacific is caused by east-west asymmetric convection anomalies between the Indian and Pacific oceans. This suggests that both the 10–25- and 30–60-day variation activities during early summer are associated with the large-scale anomalies within the Indian and Pacific oceans.

4. Summary and Discussion

[10] Both of the 10–25- and 30–60-day variation over the SCS had large interannual variation compared with those over the BOB and AS. The IAV of the 10–25- (30–60-) day variation was relatively active while 30–60- (10–25-) day variation was suppressed during early (June–July) and late (September) summer. The IAV of the ISV during early summer was associated with the onset date of the SCSM. The 10–25- (30–60-) day variation prevailed with a later (earlier) onset than usual. These ISV activities were

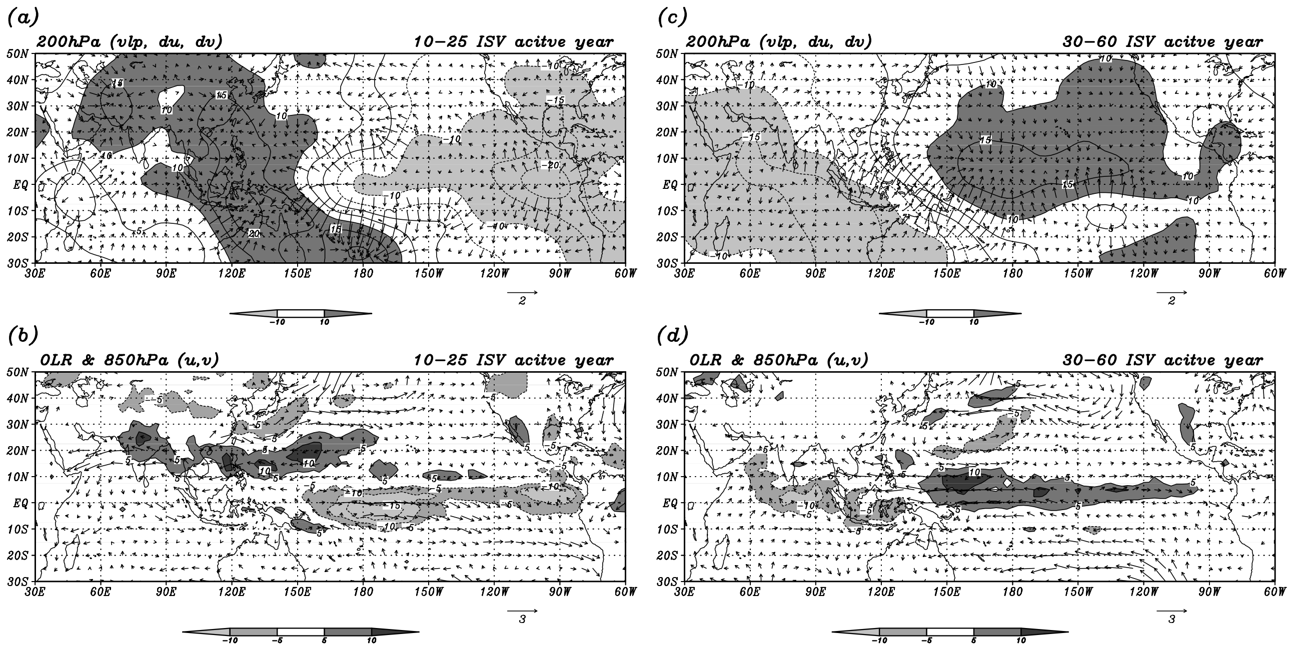

Figure 5. Composite diagram of (a) the 200-hPa velocity potential and divergent wind (the counter interval is $5 \times 10^5\ s^{-1}$ and the units are 2 m/s) and (b) the OLR and 850-hPa wind (the counter interval is 5 W/m^2 and the units are 3 m/s) for the years with active 10–25-day variation (1983, 1987, 1989, 1992, 1993) during northern early summer (June and July). (c) and (d) are the same as (a) and (b), but for the years with the 30–60-day variation (1979, 1984, 1996, 1998, 2001).

associated with a large-scale anomaly field during early summer. The active 10–25-day variation was related to enhanced convection over the equatorial middle Pacific. The 10–25-day variation with westward propagation originated over the equatorial west-mid Pacific [*Annamalai and Slingo*, 2001]. This implies that the active 10–25-day variation is initiated by relatively enhanced convection of the early summer mean field over the middle Pacific. In contrast, the active 30–60-day variation is related to enhanced convection over the equatorial eastern Indian Ocean. This agrees with the observation that the warmer SST and enhanced convection over the eastern Indian Ocean produce the pronounced activity of the 20–60-day mode (H. Annamalai and B. Wang, Interannual variation of the boreal summer intra-seasonal variability: Role of the low-frequency circulations, submitted to *Journal of Climate*, 2004).

[11] The IAV of the ISV over the SCS could be divided into the early and late summer across August as suggested in section 2. The anomalous filed for the IAV of the ISV during early and late summer showed different temporal and spatial pattern, respectively. The composite anomaly fields for active ISV years during late summer showed conspicuous east-west asymmetric convection anomalies over the Indian Ocean and few significant signals over the Pacific (figure not shown). This implies that the IAV during late summer is decoupled from anomalies over the Pacific. The mechanism that separates the IAV in August remains unclear. However, *LinHo and Wang* [2002] showed that the Asian monsoon has two fast cycles, which are divided by an abrupt change event: the first from mid-May to early July, and the second from late July to early September. *Ueda et al.* [1995] also described an abrupt northward shift of convection over the WNP in late July. Therefore, we speculate that a seasonal cycle within a drastic change could play an important role in decreasing the anomalies of ISV activity during early summer.

[12] This paper investigated the IAV of the ISV over the SCS, and found the relationships between 10–25- and 30–60-day variation, and the SCSM onset date and mean large-scale anomalies. The processes causing the alternation in the two ISVs and their relation to the SCSM onset are an interesting issue that will be examined in the future. The seasonality of these relationships is also an important subject. To solve this, it will be necessary to investigate not only the activity but also phase of each ISV.

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