Local intraseasonal air–sea relationship over the North Indian Ocean and western North Pacific during the spring-to-summer transition

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ABSTRACT
This study investigates the local air–sea relationship associated with the two dominant intraseasonal oscillation (ISO) components during the spring-to-summer transition and compares their properties using multiple air–sea variables in the period 1998–2013. The amplitude of percentage variance in SST in periods of 10–20 and 30–60 days are comparable, but the locations of the maxima differ. A strong percentage variance in the 10–20-day SST is evident in the equatorial western Pacific, whereas for the 30–60-day SST the strongest ratio occurs in the North Indian Ocean (NIO), South China Sea (SCS), and North Pacific. Over the NIO, SCS, and Philippine Sea, there are significant correlations between SST and precipitation for both 10–20-day and 30–60-day ISOs. In contrast, the correlations between SST and surface heat fluxes cover a broader region and have larger coefficients. Thus, the atmospheric variables and surface heat fluxes show larger variations within the higher frequency band. However, the amplitude of the correlation coefficients between SST and surface heat fluxes, and SST and rainfall, is greater in the lower frequency band. The corresponding time lags for the different variables reveal that a strong local air–sea interaction is indicated over the NIO, SCS, and western North Pacific, from April to June in both timescales; however, the strength of the air–sea relationship depends on the region and variable.

1. Introduction
The tropical intraseasonal oscillation (ISO) that occurs during boreal summer has more complicated features and propagation patterns than the boreal winter ISO (also known as the Madden–Julian Oscillation). The summer ISO shows a north-northeastwards propagation over the north Indian Ocean (NIO) (Yasunari 1979, 1980; Annamalai and Sperber 2005; Wang, Webster, and Teng 2005), but propagates north-northwestwards over the western North Pacific (WNP) (Murakami 1984; Kajikawa and Yasunari 2005; Mao, Sun, and Wu 2010). The wet and dry spells of the tropical ISO during boreal summer strongly affect the onset, as well as the active and break phases, of the monsoon, causing extreme hydrometeorological events (Annamalai and Slingo 2001; Hoyos and Webster 2007; Ding and Wang 2009; Li and Luo 2014).

In addition, ISOs have been found in SST, mixed layer depth, and sea surface height in the NIO, South China Sea (SCS), and WNP warm pool (Sengupta and Senan 2001; Zhu, Nakazawa, and Li 2003; Li, Wang, and Guan 2008; Duncan and Han 2009; Wu 2010; Zhuang et al. 2010; Keerthi et al. 2016). This indicates the occurrence of air–sea interactions at the intraseasonal scale in these ocean regions, as described previously (Kemball-Cook and Wang 2001; Fu et al. 2007; Wang et al. 2009; Roxy and Tanimoto 2012). Overall, the effects of wind evaporation and cloud radiation play an important role in these SST changes, which are closely related to the propagation of ISOs in rainfall, wind, and surface heat fluxes.
Two different periodicities of boreal summer tropical ISO have been identified: 30–60 and 10–20 days (Wang, Webster, and Teng 2005; Kikuchi and Wang 2009, 2010; Wang et al. 2009). Ye and Wu (2015) compared the local air–sea relationship of these two different modes of ISO over the SCS and WNP from May to September. However, as noted by Wu and Wang (2000), the mean circulation in the above regions changes significantly in May because of the onset of the summer monsoon; therefore, it is necessary to investigate the differences in the local air–sea relationship associated with the two modes of ISO during the spring-to-summer transition period from April to June (AMJ). This provided the motivation for the present study.

Following this introduction, Section 2 introduces the data and methods used. A detailed comparison of the local air–sea relationship associated with the 10–20 and 30–60-day oscillations is provided in Section 3, and Section 4 presents a summary of the findings.

2. Data and methods

TropFlux provides air–sea heat and momentum flux data for the tropical region of 30°S–30°N that are comparable with the OAFlux product (Praveen Kumar et al. 2012). This data-set can be obtained at http://www.incois.gov.in/tropflux/overview.html. Daily surface shortwave radiation (SWR) and latent heat flux (LHF) data on a 1° × 1° grid, and covering the period 1998–2013, are used in this study.

The TRMM microwave imager (TMI) uses a satellite microwave radiometer to measure multiple variables over the ocean (Wentz, Ashcroft, and Gentemann 2001). In the present study, we use a 3-day running mean of SST, rainfall, cloud liquid water (CLD), and 37 GHz surface wind speed (W37) measurements with a horizontal resolution of 0.25° × 0.25° that cover the period 1998–2013. The TMI data are available at http://www.remss.com/missions/tmi.

For consistency, the TMI data-set is converted to a 1° × 1° resolution by area averaging to reduce the influence of missing values on the diagnosis.

The climatological daily mean is removed from the raw data to eliminate the climatological seasonal cycle. Then, a Lanczos filter (Duchon 1979) is used to extract the 10–20-day and 30–60-day ISO components from the SST, rainfall, SWR, LHF, CLD, and W37. The point-wise lag–lead correlation is calculated to detect any relationships between SST and precipitation or surface heat fluxes at the intra-seasonal scale. The Student’s t-test is used to examine the significance of these relationships. The effective degrees of freedom $N^*$ is employed in this study, which can be estimated by the formula

$$N^* = N \frac{1 - r_1}{1 + r_1},$$

where $N$ is the sample size and $r_1$ is the first-order autocorrelation coefficient. The sign convention used for the surface heat flux is positive for downward SWR and upward LHF.

3. Results

Before conducting the comparison described below, power spectrum analysis is applied to the area-mean SST over the region (14°–18°N, 115°–120°E) to confirm the dominant periodicities of the ISO during AMJ each year. The results show two main periods, with peaks in the 10–20-day (15 of 16 years) and 30–60-day (8 of 16 years) bands, which pass the 95% confidence level (Figure S1). Typically, both periodicities are evident in most years; however, in two years the dominant period is a cycle of 20–30 days.

The comparisons of the percentage variance explained by the two modes of ISO (10–20 and 30–60 days) are shown in Figures 1 and 2. Figure 1 shows the percentage variance of 10–20-day oscillation accounting for 3–90-day oscillation of SST, precipitation, SWR, LHF, CLD, and W37 during AMJ for the period 1998–2013. The ratio pattern of SST (Figure 1(a)) has its maxima in the equatorial western Pacific, whereas a relatively small ratio is seen in the NIO, SCS, and North Pacific. Closely related to the occurrence of rainfall, CLD shows a similar variance ratio pattern to precipitation (Figure 1(e) vs. (b)); two bands of maximum percentage variance appear in the tropical Indian Ocean and western Pacific parallel to the equator in both hemispheres. A large loading of the percentage variance of surface wind speed (Figure 1(f)) is located in the SCS, WNP, and in the Southern Hemisphere. As for the surface fluxes, the LHF variance ratio explained by the 10–20-day oscillation is larger than that for the SWR variance ratio (Figure 1(c) vs. (d)). The regions in which the percentage variance is greater than 25% for SWR (Figure 1(c)) include the western Arabian Sea, northern Bay of Bengal, SCS, Philippine Sea, tropical southeastern Indian Ocean, and southwestern Pacific.

Figure 2 is similar to Figure 1, but for the 30–60-day oscillation. The percentage variance of the 30–60-day SST variations is comparable with that of the 10–20-day variations, but the maxima regions differ (Figures 1(a) vs. 2(a)) and show strong variance in the NIO, SCS, and North Pacific. In contrast, the percentage variance of the other five variables over the 30–60-day timescale is smaller than that of SST (Figure 2(b)–(f)). The 30–60-day variance ratio of rain and CLD is focused on the Bay of Bengal, SCS, Maritime Continent, and the north of Australia (Figure 2(b) and (e)). The maximum center of percentage variance in surface wind speed is located over the NIO (Figure 2(f)), whereas the variance percentages of the surface heat fluxes reach their peaks in
the equatorial Indian Ocean and the north of Australia (Figure 2(c) and (d)).

The comparison between Figures 1 and 2 shows that the percentage variances of precipitation, cloud liquid water, surface wind speed, and surface heat fluxes over the 10–20-day timescale are larger than those over the 30–60-day timescale, whereas the magnitude of the SST variance for the two ISO modes is comparable. Put simply, the atmospheric variables and surface heat fluxes have larger variations in the high-frequency band. During the spring-to-summer transition, the SST over the equatorial western Pacific has a larger component in the high-frequency band, while the SST over the NIO, SCS, and the North Pacific has a larger component in the low-frequency band. Previous studies have pointed out that 30–60-day oscillation in atmospheric variables is dominant in the NIO, while 10–20-day oscillation is dominant over the WNP. Thus, the different locations of SST maximum percentage variance between the two ISO modes are greatly influenced by the atmospheric intraseasonal variability with different periodicities over different oceans through the air–sea feedback.

To further investigate the intraseasonal relationships between SST and precipitation, surface wind, and the heat fluxes, the method of point-wise lag–lead correlation is used to calculate the maximum and minimum values of the correlation coefficient and the corresponding number of lag or lead days. This approach allows us to examine the strength of the air–sea relationship more directly. The maximum and minimum lag–lead correlation coefficients of SST with rain rate, SWR, and LHF, and the corresponding number of lag–lead days are shown in Figure 3 for the 10–20-day ISO, and in Figure 4 for the 30–60-day ISO. The lag–lead ranges from −6 to +6 days for the 10–20-day
interaction over the 10–20-day timescale in the above regions during the spring-to-summer transition.

For the 10–20-day oscillation, the high correlation between SST and precipitation covers the eastern Arabian Sea, Bay of Bengal, SCS, and Philippine Sea, with maximum (minimum) values greater (less) than 0.4 (−0.4) (Figure 3(a) and (d)). In contrast, the correlation between SST and surface heat fluxes (SWR and LHF) is located over a broader region that covers almost the entire Indian Ocean and WNP. This correlation is generally stronger than the correlation between SST and rain rate (Figure 3(b), (c), (e), and (f)). The centers of maximum and minimum coefficients are consistent among the three relationships, being located over the eastern SCS. This highlights a strong local air–sea interaction over the 10–20-day timescale in the above regions during the spring-to-summer transition.

ISO, and from −15 to +15 days for the 30–60-day ISO. To standardize the sign used with the number of lead–lag days, the order of the maximum and minimum correlations for SWR is reversed in Figures 3 and 4.

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The horizontal patterns of corresponding days by which SST leads or lags rain and the surface heat fluxes are given in Figure 3(g)–(l). Over the NIO, SCS, and the Philippine Sea, SST leads (lags) rain by approximately four (three) days (Figure 3(g) and (j)). The lag of SST with respect to the surface heat fluxes is comparable with that of SST to rain, but covers a broader region (Figure 3(h), (i), (k), and (l)). The time lag between changes in SST and the response of the different variables indicates that over the NIO, SCS, and WNP, warmer (cooler) SSTs cause more (less) rain, weaker (stronger) downward SWR, and stronger (weaker) upward LHF, leading by approximately three days (Figure 3(g)–(i)), and then cooler (warmer) SSTs develop after three to four days (Figure 3(j)–(l)).
The time by which SST leads SWR tends to be longer over the eastern SCS and WNP, whereas the SWR lead over SST is longer over the Arabian Sea, Bay of Bengal, western SCS, and Maritime Continent (Figure 4(h) and (k)). Moreover, the time lag of SST leading LHF is longer for the NIO and the north of Australia, and LHF leads SST by a greater amount in the southern Indian Ocean.

Our analysis of the local air–sea relationship shows that significant correlations between SST and precipitation in both modes of ISO are located in the NIO, SCS, and Philippine Sea. The strong air–sea interactions there may be connected to the relatively shallow mixed layer depth, which favors a quick change in SST given the same heat input. The correlations between SST and surface heat fluxes cover a broader region with larger coefficients than that between SST and rain. In comparison, the correlations between SST and rain, and SST and surface heat fluxes for the 30–60-day oscillation, the maximum and minimum correlation covers the equatorial Indian Ocean, eastern SCS, and Philippine Sea (Figure 4(a) and (d)). The value of the maximum or minimum is larger than that for 10–20-day oscillation, reaching 0.6 or −0.6. Generally, the correlation coefficients between SST and surface heat fluxes are larger than those between SST and precipitation (Figure 4(b), (c), (e), and (f)). Moreover, compared with the distribution of the correlation between SST and SWR, the region of correlation between SST and LHR extends to the Southern Hemisphere with a center over the north of Australia (Figure 4(c) and (f)). A similar air–sea coupling process to the 10–20-day oscillation is evident in the variations of the 30–60-day oscillation, which can be seen from the pattern of the time lags (Figure 4(g)–(l)). In the equatorial Indian Ocean, eastern SCS, and Philippine Sea, SST leads (lags) precipitation by more than 13 (11) days (Figure 4(g) and (j)). The time by which SST leads SWR tends to be longer over the eastern SCS and WNP, whereas the SWR lead over SST is longer over the Arabian Sea, Bay of Bengal, western SCS, and Maritime Continent (Figure 4(h) and (k)). Moreover, the time lag of SST leading LHF is longer for the NIO and the north of Australia, and LHF leads SST by a greater amount in the southern Indian Ocean.

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4. Summary

This study investigates the local air–sea relationships of two dominant ISO components during the spring-to-summer transition, using the air–sea variables of SST, rain rate, cloud liquid water, surface winds, and heat fluxes during the period 1998–2013. The results show that the strength of the local air–sea relationship depends on both the region and variable used in the analysis. The spatial distribution of the percentage variance in SST demonstrates that the amplitudes in the 10–20- and 30–60-day timescales are comparable, but the locations of the maxima are different. Strong percentage variance of the 10–20-day SST with respect to 3–90-day SST are smaller than those for the 30–60-day period. This signifies the differences among regions and variables of strong local air–sea interactions between the two modes of ISO. The time lag between SST, rainfall, and heat fluxes in both ISO modes indicates similar evolutionary features of local air–sea coupling over the NIO, SCS and WNP. In the above ocean regions, warmer SST may destabilize the lower troposphere and enhance low-level moisture convergence, which favors the development of convection and precipitation. It leads to stronger upward LHF and weaker downward SWR in the same ocean region. In turn, the enhanced convection effectively induce decreased SST through surface heat flux exchanges and a variety of rain-induced oceanic processes.

Figure 4. Spatial distribution of (a, e, c) maximum and (d, b, f) minimum coefficients of SST lag–lead correlated with (a, d) precipitation, (b, e) SWR, and (c, f) LHF, and the corresponding number of days by which SST leads/lags (g, j) precipitation, (h, k) SWR, and (i, l) LHF, for the 30–60-day oscillation during AMJ 1998–2013. Only regions with correlations significant at the 95% confidence level are shown.
evident in the equatorial western Pacific, whereas that of the 30–60-day SST occurs in the NIO, SCS, and North Pacific. Moreover, the percentage variances of the other five variables are larger than the SST at the 10–20-day scale, but smaller than that at the 30–60-day scale. As such, the atmospheric variables and surface heat fluxes show larger variations within the higher frequency band.

We also examine the intraseasonal relationships between SST and precipitation, surface wind, and heat fluxes, using point-wise lag–lead correlation. Significant correlations are found between SST and precipitation in both modes of ISO located over the NIO, SCS, and Philippine Sea. In comparison, the correlations of SST with regard to the surface heat fluxes cover a broader region and with larger coefficients. The amplitude of the correlation coefficients between SST and rainfall, and SST and surface heat fluxes at the 10–20-day scale are smaller than those at the 30–60-day scale. This indicates strong local air–sea interaction in the above regions during AMJ, but the strength of this air–sea relationship depends on the specific region and variable. The corresponding time lags associated with different variables reveal that warmer (cooler) SSTs lead to more (less) precipitation, weaker (stronger) downward SWR, and stronger (weaker) upward LHF, which are followed by cooler (warmer) SSTs in the NIO, SCS, and WNP over both timescales.

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