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NOTES AND CORRESPONDENCE

Influence of the Sea Surface Temperature in the Indian Ocean on the In-Phase Transition between the South Asian and North Australian Summer Monsoons

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ABSTRACT

In this study we investigate the physical processes underlying maintenance of an in-phase transition between the South Asian summer monsoon (SASM) and the succeeding North Australian summer monsoon (NASM). In particular, our attentions were focused on identification of the roles of sea surface temperature anomaly (SSTA) in the Indian Ocean in contrast to that of the El Niño-Southern Oscillation (ENSO). To realize this goal, we partition the in-phase years into two groups, those being ENSO and non-ENSO groupings, and then we conduct a composite study. For the non-ENSO-year composite, the associated SST changes resemble a dipole structure characterized by a SST warming in the western Indian Ocean and a cooling in the southeastern Indian Ocean in the boreal summer and fall. The warm SSTA, along with a stimulated ascent, expands eastward in the boreal fall and arrives in the eastern Indian Ocean around northern Australia, concurrent with a cold SSTA to its north with a descent. Therefore, a strong ascent in northern Australia associated with the regional Hadley circulation occurring in the Philippine Sea-northern Australia region is responsible for a wet NASM. Our study also identifies the enlarged influence of the SSTA in the Indian Ocean being likely associated with change in the background SST state that occurred around 1976 - 77 over the Indian Ocean.

Key words: South Asian monsoon, Australian monsoon, ENSO, Indian Ocean, IODZM

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1. INTRODUCTION

The South Asian and North Australian summer monsoons are the most energetic monsoon systems in the world. Their opposite phase in the annual cycle and neighboring geographic locations make them closely linked to one another. When the mean annual cycle proceeds from the northern summer to the southern summer, tropical convective maximums move from southern Asia to northern Australia. Meanwhile, year-to-year variations in the South Asian summer monsoon rainfall also have a close correlation with northern Australia rainfall in the succeeding southern summer in a "monsoon year" [1] (Yasunari 1991) or in a tropical troposphere biennial oscillation cycle (Meehl 1987, 1993, 1997; Chang and Li 2000), but the preceding Australian summer monsoon rainfall has no significant correlation with the ensuing South Asian summer monsoon rainfall (Hung et al. 2004), indicating an asymmetric transition between the two monsoon systems.

Although there is an in-phase relationship between

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[1] *Yasunari (1991) introduced a concept of "monsoon year" to describe the climatic variability of the Asian-Australian monsoon system starting from May of a calendar year to April of the following year.*

the SASM and the succeeding NASM, the cause is not yet clear. Hung et al (2004) suggested that the ENSO is a major controlling influence in this relationship due to the typical life cycle of the ENSO being locked in-phase with the annual cycle within a "monsoon year". Using a series of coupled atmosphere-ocean general circulation model (CGCM) experiments, Yu et al. (2003) found sea surface temperature anomalies associated with an in-phase transition between the Indian summer monsoon and Australian summer monsoon are characterized by an ENSO-type pattern in the Pacific Ocean and basinwide warming/cooling in the Indian Ocean. Both of these works emphasize the role of the ENSO. However, as shown in our observation analysis (Table 1), the possible impact of the ENSO only explains some of the in-phase cases observed in the last 50 years. This implies that other factors may also be exerting influence on this in-phase transition. Another interesting aspect is whether or not this relationship varies in different decades since both the SASM and NASM, as well as the India and Pacific Oceans experience remarkable interdecadal variability (Nitta and Yamada 1989; Trenberth and Hurrell 1994; Wang 1995; among others).

Previous studies have revealed the contribution of the ENSO to the leading modes of SST variations in the Indian Ocean and interannual variability in the Asian-Australian monsoon system (A-AMS) (see Webster et al. 1998 for a review). The role of the Indian Ocean in the interannual variability of the A-AMS, on the other hand, has received less attention. It is implied by some recent studies that the Indian Ocean may play an active role in modulating interannual variations of the A-AMS. Li et al. (2001) and Li and Zhang (2002) found that on a quasi-biennial (2 - 3 year) time scale Indian monsoon rainfall has significant positive correlation with the Indian Ocean SST and moisture flux transport in the preceding winter and spring. Ashok et al. (2001, 2002) documented an increased correlation between Indian monsoon rainfall and the Indian Ocean dipole-zonal mode (IODZM) index since the early 1980s. Clark et al. (2000) found that summer Indian rainfall has a strong correlation with the SST in the Arabian Sea in the preceding winter and the correlation between the summer Indian rainfall and central Indian Ocean SST increases after 1977. Terray and Dominiak (2005) pointed out that, after the 1976 - 77 regime shift southern Indian Ocean SST anomalies in the boreal winter could play an active role in the Pacific climate system through remotely modulating wind anomalies over the western equatorial Pacific and the regional Hadley cell in the southwest Pacific.

Motivated by the above discussions, the objective of this work is to identify the role of the SSTA in the Indian Ocean in sustaining the SASM-NASM in-phase relationship, with a consideration given for the interdecadal changes in the SASM-NASM relationship and the background SST. For this purpose, wet-minus-dry composites are conducted by partitioning in-phase years into ENSO and non-ENSO groupings.

The remainder of the paper is organized as follow. In section 2, there is a description of data usage. The Interannual and interdecadal variations of the SASM-NASM relationship are discussed in section 3. The composite results are presented in section 4. How the Indian Ocean SSTA connects the SASM and NASM is discussed in section 5. Finally, section 6 presents a summary.

Table 1. The wet/dry SASM-NASM in-phase years with respect to ENSO and non-ENSO groupings and the values of normalized AIRI in JJAS and NARI in succeeding DJFM. Definition of ENSO is seen in section 2.

ENSO			Non ENSO		
Wet SASM-NASM in-phase years (La Niña)			**Wet SASM-NASM in-phase years**		
Year	**AIRI**	**NARI**	**Year**	**AIRI**	**NARI**
1956/57	1.3	1.9	1978/79	0.7	1.6
1971/72	1.6	1.0	1983/84	1.3	0.5
1973/74	0.5	1.0	1990/91	0.7	2.0
1975/76	0.8	3.3	1994/95	1.1	0.6
Dry SASM-NASM in-phase years (El Niño)			**Dry SASM-NASM in-phase years**		
Year	**AIRI**	**NARI**	**Year**	**AIRI**	**NARI**
1951/52	-1.3	-1.7	1985/86	-1.0	-1.0
1965/66	-1.6	-0.9	1992/93	-0.7	-0.8
1968/69	-1.1	-1.0			
1982/83	-1.3	-1.3			
1986/87	-1.2	-0.8			
1987/88	-1.7	-1.0			
1991/92	-0.7	-1.7			

2. DATA

The data used in this study include monthly National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al. 1996) and monthly Reynolds sea surface temperature data (Reynolds and Smith 1994) for 1950 - 1997. For a rainfall index, we rely on the all-Indian rainfall index (AIRI) to describe the SASM. It is an area-weighted average of 306 rain gauges distributed across India (Mooley and Parthasarathy 1984). We also use a gridded monthly precipitation dataset produced by Dr. Mike Hulme, University of East Anglia (http://www.cru.uea.ac.uk/~mikeh), and monthly outgoing long-wave radiation (OLR) derived from the twice-daily NOAA satellite series from 1979 through 1997. The latter is re-interpolated with gaps filled by the Climate Diagnostics Center (CDC), NOAA.

As the SASM and NASM cross different calendar years, in this study we consider data based on the "monsoon year" proposed by Yansunari (1991). Here a monsoon year starts from May of a calendar year to April of the following year. Therefore, SASM is in the preceding boreal summer and the

NASM is in the succeeding austral summer. Consistently, in this study an El Niño (La Niña) year is defined based on the SSTA in the NINO3 region (90°W - 150°W, 5°S - 5°N) during November - February of a monsoon year.

3. INTERANNUAL AND INTERDECADAL VARIATIONS OF THE SASM-NASM RELATIONSHIP AND THEIR RELATION TO THE ENSO AND IODZM

The relationship between the SASM and NASM has been described by Yu et al. (2003) and Hung et al. (2004). However, the shorter temporal coverage (after 1979) of the Climate Prediction Centre's merged analysis of precipitation (CMAP) that they used excludes interdecadal variations. At first, we calculate point-to-field correlation coefficients (CCs) between the AIRI during June-September and the rainfall in Australia during the succeeding and preceding December-March, respectively (Figures omitted). A strong positive correlation between SASM rainfall in the boreal summer with the succeeding austral summer is found in Northeastern Australia with a maximum larger than 0.5, exceeding a 99% significance level. But CCs between the Australian summer monsoon rainfall and the SASM rainfall in the succeeding boreal summer are very weak with a negative signal in most of Australia except for southeastern regions. Based on point-to-field correlation analysis, we design a Northern Australian rainfall index (NARI) based on average December - March rainfall in Northern Australia (i.e., north of 20°S), which corresponds to the maximum CC region. The CC between the AIRI during June - September and the NARI during the succeeding December - March for 1950 - 96 is 0.48, exceeding the 99% confidence level test. However, when the NASM precedes the SASM, the CC sharply decreases to -0.22. This indicates that the SASM is closely in-phase with the succeeding NASM, but weakly out-of-phase with the preceding NASM. This agrees with the results derived by Yu et al. (2003) and Hung et al. (2004).

Figure 1a shows normalized AIRI and NARI displayed in a "monsoon year" and their relation to ENSO events. Here an El Niño (La Niña) year is defined when magnitude of the SSTA in the NINO3 region (90°W - 150°W, 5°S - 5°N) is larger than 0.7 (less than -0.7) of a standard deviation during November - February. An exception is made for 1968/69, which is considered an El Niño year according to the definition by Trenberth (1997). In Fig. 1a, the NASM undergoes a stronger interdecadal variation than the SASM characterized by an excessive rainfall period during the 1970s and deficient ones during the 1960s and 1980s, respectively. Figure 1b shows eleven-year smoothing CCs between the AIRI and succeeding NARI, the AIRI and Niño3 SST during June - September, and NARI and Niño3 SST during December - March. A remarkable drop in the correlation between the SASM and NASM is found during the 1960s when the NASM rainfall is positively correlated to the Niño3 SST irregularly. During the 1970s the NASM undergoes an extreme wet period; this leads to a slight drop in correlation between the SASM and NASM; whereas, the NASM rainfall is distinctly negatively correlated with the Niño3 SST. The most interesting feature identified in Fig. 1b is that even though both are weakly correlated to the Niño3 SST, the SASM and NASM rainfall anomalies are still highly correlated from the late 1970s through the early 1980s. This implies that other processes may also play a determinative role in the maintenance of in-phase transition.

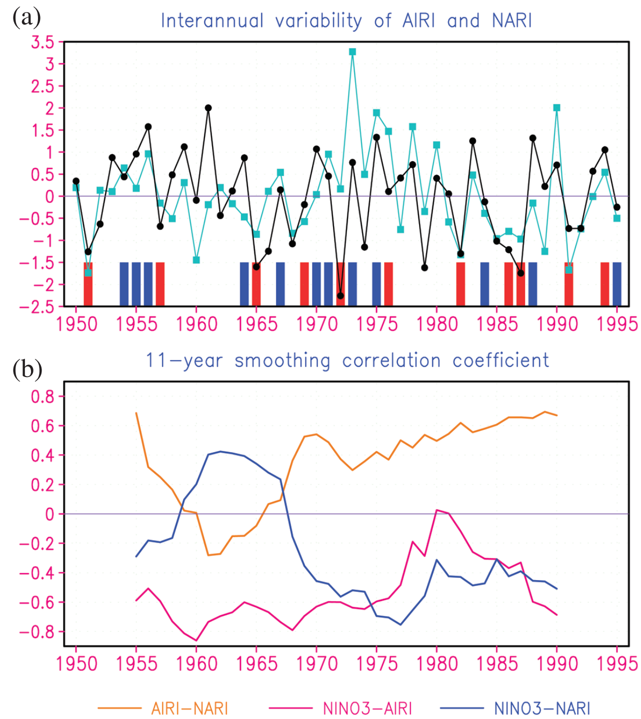

Fig. 1. (a) The normalized AIRI during June - September (black) and NARI during the succeeding December - March (green). The years belonging to the El Niño and La Niña are denoted by red and blue bars, respectively. Definition of the ENSO is seen in section 2. (b) Eleven-year smoothing correlation coefficient between AIRI during June - September and NARI during the succeeding December - March (yellow), AIRI and Niño3 SST during June - September (red), and NARI and Niño3 SST during December - March (blue).

Because of limited sample numbers, we choose a threshold of 0.5 (-0.5) standard deviation as a wet (dry) monsoon year. Table 1 lists the wet (dry) SASM-NASM in-phase years with respect to ENSO and non-ENSO partitions. It should be noticed that although 1994 - 95 is an El Niña year, it is an exceptional case compared to other El Niña years in which both the SASM and NASM are dry, implying that other processes could compete over the ENSO impact in monsoon variations. It seems that although a 0.5 standard deviation is chosen to describe a wet (dry) monsoon year, most of the rainfall magnitudes listed in Table 1 are close to or larger than 1.0. Table 1 shows that more than one third of the seventeen in-phase years are unrelated to the ENSO. This confirms again that the ENSO is not a unique factor leading to an in-phase transition between the SASM and NASM.

Table 1 also shows significant decadal variations for the in-phase years: all non-ENSO years occur after 1977 and all wet in-phase years of the El Niňa appear before 1977, when a climate regime shift appears in the Indian Ocean (Terray and Dominiak 2005). This is also accompanied by a sharp decrease in simultaneous CCs between the Niňo3 SST and AIRI from -0.69 during 1951 - 1976 to -0.41 during 1977 - 1995, and between Niňo3 SST and NARI from -0.54 to -0.29. However, the CC between AIRI and NARI increases from 0.39 to 0.59.

Based on work by Saji et al. (1999), we calculate values of the IODZM index presented by the difference in SST anomalies between the tropical western Indian Ocean (50°E - 70°E, 10°S - 10°N) and tropical southeastern Indian Ocean (90°E - 110°E, 10°S-equator) averaged from June to November. We found that for the wet non-ENSO in-phase years of 1978, 1983, 1990, and 1994, the values of the normalized IODZM index are 0.42, 0.60, -0.46, 3.05, respectively, and for the two dry non-ENSO in-phase years of 1985 and 1992, the values of the IODZM index are -0.48 and -0.85, respectively. This indicates that, except for 1990, a wet/dry in-phase year tends to appear in a positive/negative IODZM year. But the CCs of the IODZM index-AIRI and IODZM index-NARI are only 0.16 and 0.13, respectively. This is partly because when an ENSO year concurs with a high IODZM index year, the affect from the ENSO usually surpasses the impact from IODZM. For example, 1982 and 1987 are two positive IODZM years with index values of 1.00 and 0.46, respectively, but they are strong dry in-phase El Niňa years.

4. SSTA AND ATMOSPHERIC CIRCULATION PATTERNS ASSOCIATED WITH THE SASM-NASM IN-PHASE RELATIONSHIP

In this section, in order to separate possible processes from the ENSO and others, we conducted a composite study whereby we partitioned SASM-NASM in-phase years into ENSO and non-ENSO groupings. Figure 2 exhibits the wet-

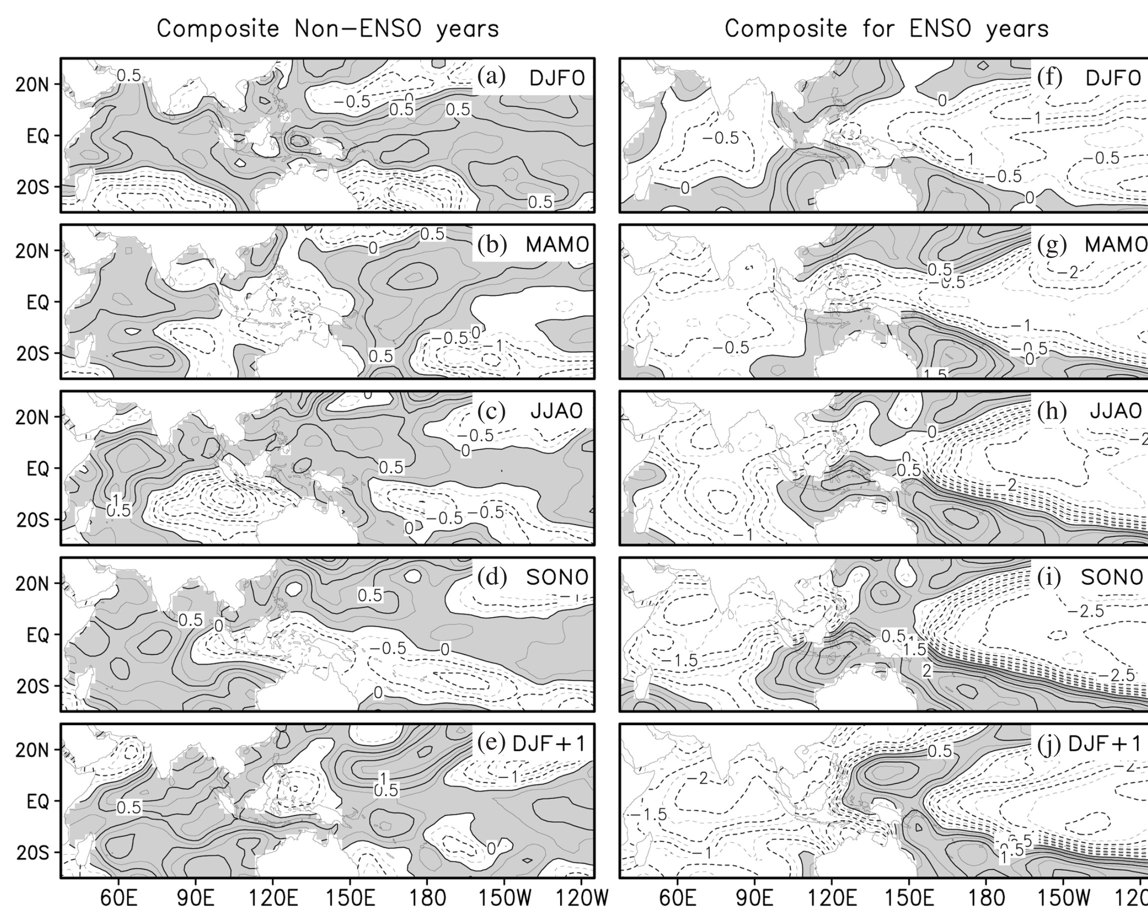

Fig. 2. The strong-minus-weak composite of the SST from winter prior to the SASM to the NASM season for the non-ENSO (left panels) and ENSO cases (right panels) which are listed in Table 1. The SST is normalized by standard deviation at each grid. The interval of the contour is 0.25. The results are subjected to a weighted 9-point smoothing in Grid Analysis and Display System (GrADS).

minus-dry composite SSTA starting from the northern winter to southern summer. It is seen that the composite SSTA pattern for the ENSO-related years differs significantly from the non-ENSO ones. For the ENSO-related years, a pronounced SST cooling is found in the central-eastern equatorial Pacific and Indian Oceans from the boreal spring through the austral summer (Figs. 2g - j) and warming occurs in the southeastern Indian Ocean around Australia (Figs. 2f - i). However, the wet-minus-dry composite for the non-ENSO years presents very weak SSTA signals in the Pacific Ocean but a significant warming in the northwestern Indian Ocean in the preceding winter and spring (Figs. 2a, b). In summer, the distribution of the SSTA resembles an Indian Ocean dipole mode (Saji et al. 1999; Webster et al. 1999) with a cooling in the southeastern part and a warming in the western part (Fig. 2c). In the following fall and winter, as the cold SSTA in the southeastern Indian Ocean starts to decrease, the warm SSTA extends eastward, covering the Maritime continent (Figs. 2d, e), while a cold SSTA appears in the Philippine Sea.

We also composed a 10-m wind vector and the velocity potential difference (VPD) between 200 and 850 hPa as shown in Fig. 3. Here, a minimum (maximum) center of VPD represents anomalous ascending (descending) motion. In the ENSO-related year composite, strongly anomalous ascending motion occurs in the maritime continent and descending motion in the eastern Pacific in the boreal summer and fall (Figs. 3d, e) and additional descending motion develops in the boreal winter (Fig. 3f). This is also accompanied by anomalous easterlies in the equatorial Pacific and westerlies in the eastern equatorial Indian Ocean (Figs. 3d - f). Therefore, it is likely that the overturning of the Walker circulation between the western and east-central Pacific Ocean associated the SSTA in these regions is responsible for a wet summer monsoon in both India and northern Australia, agreeing with those previous studies (Meehl 1987; Yu et al. 2003; and Hung et al. 2004).

However, the circulation characteristics for the non-ENSO year composite are quite different. A strong ascending branch (minimum VPD) occurs in the tropical eastern Indian Ocean near Sumatra in the boreal summer and fall (Figs. 3a, b). In the boreal winter, a strong descending branch appears in Indonesia (Fig. 3c), which is controlled by a weak negative VPD zone. For surface wind fields, a strong southwesterly is dominant in the central equatorial Indian Ocean in the boreal summer and fall (Figs. 3a, b), which is likely a response to the anomalous warming in the western Indian Ocean (Figs. 2c, d).

In order to see a detailed evolution of the SSTA and VPD along the tropical Indian Ocean, in Fig. 4, we plot a

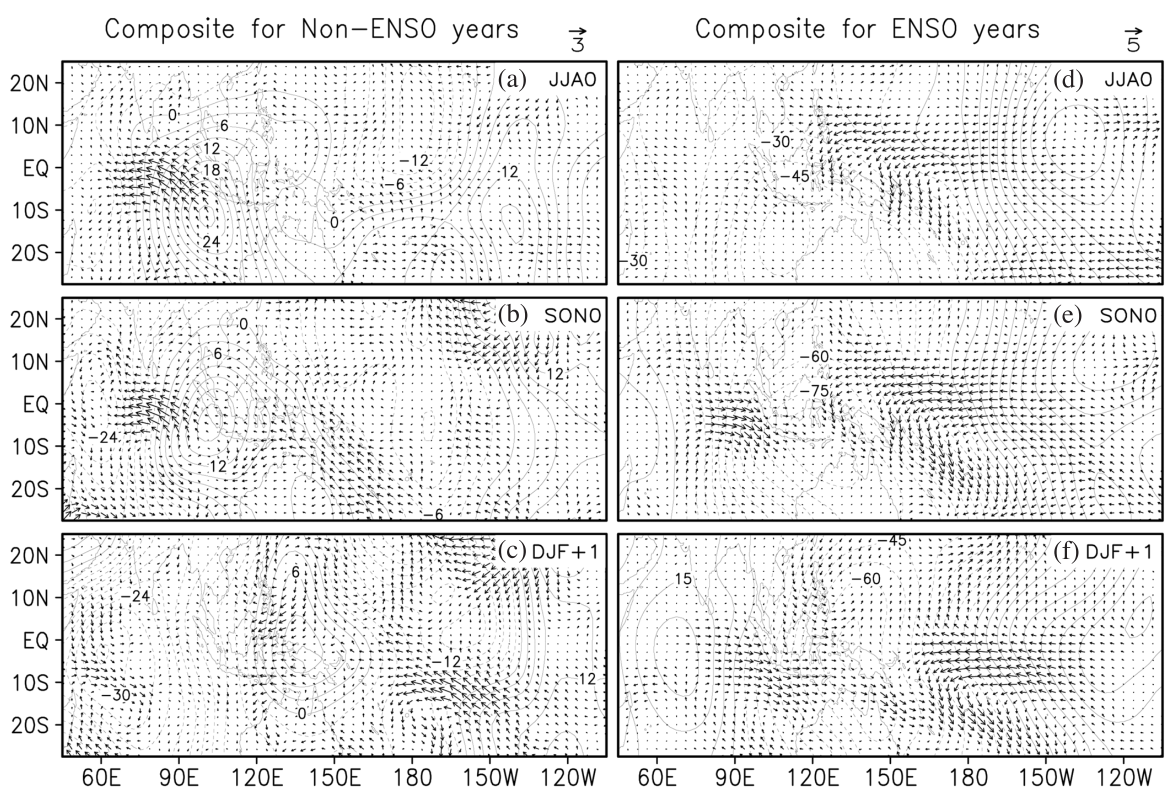

Fig. 3. Same as Fig. 2, but for the 10-m wind vector in unit of m s^{-1} and the difference of the velocity potential between 200 and 850 hPa from the northern summer to the southern summer. The intervals of the contour are 3×10^5 (left panels) and 7.5×10^5 (right panels) in unit of $m^2 s^{-1}$.

time-longitude cross-section of the monthly SSTA (contours) and VPD (shading) for the non-ENSO composite along 20°S - 5°S from June to the succeeding March. It is seen that in the boreal summer (June to August) the eastern Indian Ocean is controlled by a cold SST anomaly and a strong descending motion presented by a VPD maximum center. From September, a warm SSTA invades the central Indian Ocean, accompanied by a strong ascending motion (minimum VPD). Meanwhile, an eastward movement of the descending motion and cold SSTA is concurrent to the east of 100°E. From December, a new ascending motion branch and warm SST anomalies are established in the eastern Indian Ocean north of Australia. The coupling between the warm SSTA and ascending motion exhibited in Fig. 4 indicates that in the Indian Ocean SST anomalies may play an active role in connecting a wet SASM and NASM in these years.

Figure 4 presents a remarkable change in vertical motion in northern Australia from a descent in the boreal fall to a descent in the boreal winter while an ascent occurs in northern Australia (Fig. 3c), corresponding to a pronounced SST contrast in the eastern Indian Ocean around northern Australia and the Philippine Sea (Fig. 2e). This implies that SST anomalies in these two regions are responsible for stimulating a strong regional Hadley circulation. This is confirmed by Fig. 5, an OLR composite for non-ENSO years for the austral summer mean (December to March). As a proxy for tropical convection activity, a significant OLR minimum center is found in northern Australia. This enhanced convection activity is concurrent with a corresponding maximum in the Philippine Sea. The latter represents suppressed convection activity in the region. Therefore, it is like that the establishment of a regional Hadley circulation is responsible for a wet Australian summer.

5. DISCUSSION

The above analysis reveals that both the ENSO and the Indian Ocean SSTA can contribute to the SASM-NASM in-phase transition independently although associated SST and circulation anomalous signals forced by the Indian Ocean and western Pacific are not as strong as those forced by the central-eastern Pacific Ocean. The SASM can be affected by the ENSO through both remote and local forcing associated with the overturning of the Walker circulation (Ju and Slingo 1995; Lau and Yang 1996; Meehl 1997; Kawamura 1998; Yang and Lau 1998; Huang et al. 2003). In which case, the ascending (descending) branch in the maritime continent has a direct impact on the NASM.

The underlying processes through which the SSTA in the Indian Ocean maintains the SASM-NASM relationship without the ENSO are more complicated. Figures 2a and b suggest that SST warming in the preceding winter and spring in the northern Indian Ocean particularly in the Arabian Sea may account for a wet SASM through enhancing local moisture flux transport (Li et al. 2001; Li and Zhang 2002). This is supported by the composite of the moisture transport vectors at 1000 hPa (figures not shown), which shows that there is a strong convergence of moisture flux from the equatorial Indian Ocean to South Asia in the boreal spring. Another possible process for a wet SASM, implied

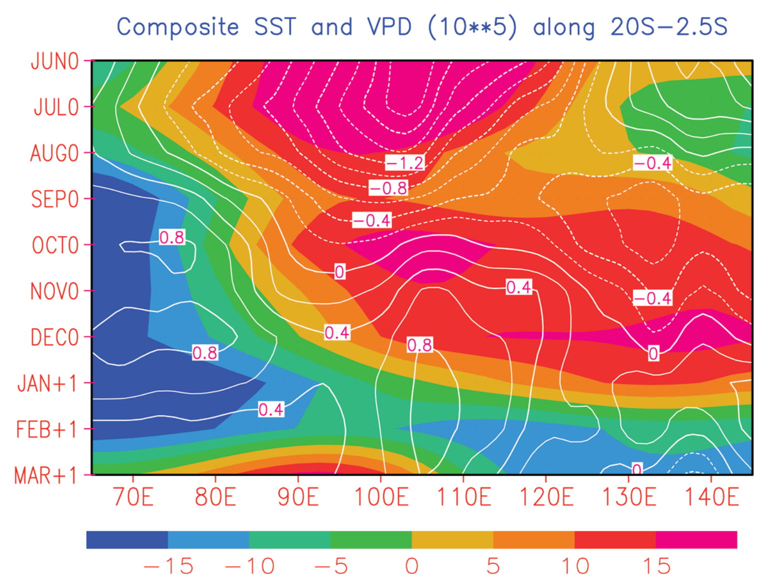

Fig. 4. The meridional average of the wet-minus-dry composite SST (contour) and velocity potential difference (shading) between 200 and 850 hPa for the non-ENSO in-phase years along 20°S - 5°S. The SST is normalized and the unit of velocity potential difference is 10^5 m^2 s^{-1}.

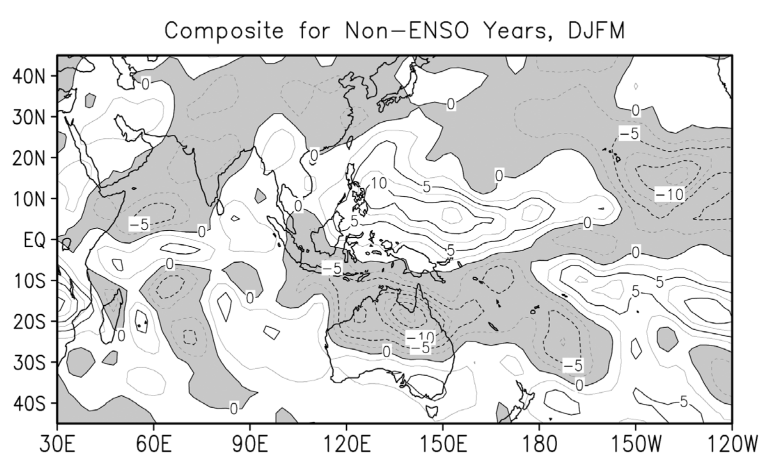

Fig. 5. Same as Fig. 2, but wet-minus-dry composite for the OLR (W m^{-2}) during austral summer (December to March) for non-ENSO in-phase years. Shading denotes the negative values. The results are subjected to a weighted 9-point smoothing in GrADS.

by Figs. 2c and 3a, may be linked to the IODZM, which may simultaneously stimulate anomalous strong southeasterlies in the southern Bay of Bengal in the boreal summer (Ashok et al. 2001).

As shown in Figs. 2c - e and Fig. 4, the eastward shift of the SST anomalous pattern in the Indian Ocean from the boreal summer through the austral summer, which resembles the IODZM, seems to play a key linkage between a wet SASM and a succeeding wet NASM. When the warm SSTA in the western and central Indian Ocean migrates slowly eastward, it is concurrent with an eastward extension of ascending motion from the western Indian Ocean to the eastern Indian Ocean while a decent occurs to its north. As a result, an ascending motion branch develops in northern Australia associated with the establishment a strong regional Hadley circulation in the Philippine Sea-northern Australia regions and, thus, leads to a wet NASM.

The cause of the eastward migration of the warming SSTA might result from complicated physical processes which involve dynamic and thermodynamic air-sea coupling in the Indian Ocean. Due to limited oceanographic data, it is difficult to model the effect of the ocean dynamic. Instead, we conducted a surface heat budget analysis using surface latent and sensible heat flux and short and long-wave radiation data produced by NCEP/NCAR reanalysis.

It is proposed that the anomalous heating associated with the warm SSTA in the western Indian Ocean induces anomalous easterlies to the east of the heating during the boreal summer (Ashok et al. 2001). Because seasonal mean flow, at this time, is from westerlies near the equator, the induced anomalous easterlies will reduce seasonal mean flow, resulting in reduced evaporation, and thus increasing the SSTA to the east of the warm SSTA maximum. This favors an eastward propagation of the warm SSTA. This proposed mechanism is supported by Fig. 6, which shows the meridional average of the composite SSTA, SST tendency, and surface latent heat flux along 20°S - 5°N for the non-ENSO group composite. It is seen that during the boreal summer maximum surface latent heat flux locates to the east of the maximum SSTA (Figs. 6a, c), and moves eastward in late fall (Fig. 6d). Concurrently, a strong SSTA tendency appears in the eastern Indian Ocean in October - November (Fig. 6b), which coincides with enhanced surface latent heat flux (Fig. 6d). This indicates that the warm SSTA is led by latent heat flux. Figures 6e and f present that while evaporation-wind feedback plays a dominant role, short-wave radiation also contributes to the eastward expansion of the SSTA; however, the magnitude is not as large as that of the latent heat flux.

It is notable that such a strong impact from the Indian Ocean occurs after the mid-1970s, when there is a significant interdecadal SST warming in the Indian Ocean. Table 1 shows that all six non-ENSO in-phase years occur after the mid-1970s, and all wet in-phase La Niňa years occur before 1976. A recent study by Terray and Dominiak (2005) indicates that after the 1976 - 77 regime shift, coupled air-sea processes in the tropical eastern Indian Ocean during the boreal winter can produce persistent remote forcing on the Pacific climate system, e.g., promoting wind anomalies over the western equatorial Pacific and modulating the regional Hadley cell in the southwest Pacific. In our study, we calculated the SST difference between 1977 - 1997 and 1951 - 76, and the results show a significantly uniform SST warming in the northern Indian Ocean in summer (June to September) and in the eastern Indian Ocean and the maritime continent to northwestern Australia in winter (December to March). The latter overlaps the warming regions of Fig. 2e. The increased background SST is expected to enhance the ascending motion branch of the regional Hadley circulation in the eastern Indian Ocean-western Pacific Ocean, and, thus, favors wetter SASM-NASM in-phase years when the ENSO is absent. This SST warming can also weaken the cooling trend in the eastern Indian Ocean in La Niňa years.

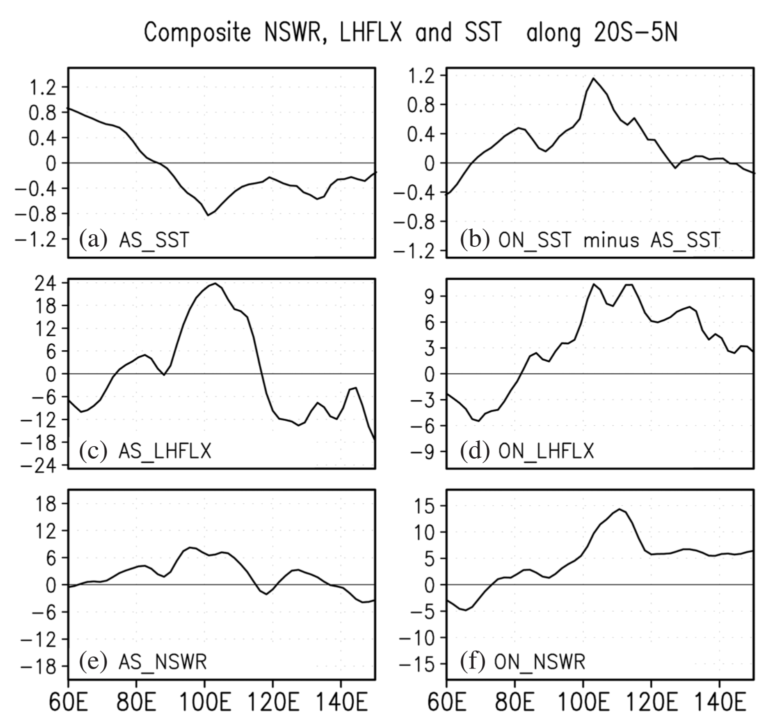

Fig. 6. The meridional average of the SST, surface latent heat flux and short-wave radiation flux for the wet-minus-dry non-ENSO composite along 20°S - 5°N: (a) SST during August - September; (b) SST difference between October - November and August - September; (c) surface latent heat flux during August - September; (d) surface latent heat flux during October - November; (e) surface short-wave radiation flux during August - September; and (d) surface short-wave radiation flux during October - November. The units for SST and flux are °C and w^2 m^{-2}, respectively.

This may partly account for why the wet-SASM-NASM in-phase transition in La Niňa years was broken after 1977.

6. SUMMARY

In this study we conduct a diagnostic analysis on the in-phase transition of the interannual variations the SASM and the succeeding NASM, and possible underlying processes using long-term rainfall, SST, and other atmospheric datasets. A wet-minus-dry composite is conducted by partitioning all SASM-NASM in-phase years into two groups with respect to ENSO and non-ENSO years. The results show that, compared to the ENSO-related years, which display a uniform SST cooling in the Indian Ocean as a response to the cold SSTA in the central-eastern Pacific Ocean, the non-ENSO years exhibit an IODZM-like pattern in the Indian Ocean (Saji et al. 1999; Webster et al. 1999; Li et al. 2003) in the boreal summer, characterized by a warm SSTA in the western Indian Ocean and a cold SSTA near Sumatra. The warm SSTA in the Indian Ocean enhances local moisture flux and southerly flow, and thus leads a wet SASM. In the subsequent boreal fall the warm SSTA migrates eastward and arrives in the north of the eastern Indian Ocean in the austral summer. Accompanying this is an eastward extension of an ascent from the western Indian Ocean to Australia, while a strong descent appears to its north concurrent with a cold SSTA in the Philippine Sea. Therefore, a strong ascent in northern Australia associated with the establishment a regional Hadley circulation in the Philippine Sea-northern Australia regions leads to a wet NASM.

In this study, the eastward propagation of the warm SSTA and anomalous ascending motion from the boreal summer through the austral summer are proposed as the important linkages between the SASM and the NASM when the ENSO is absent. Our initial surface flux analysis shows that wind-evaporation feedback appears to be a major process contributing to the eastward extension of the warm SSTA and convection. A decreased seasonal mean flow tends to enhance surface latent heat flux ahead of the warm SST region. Enhanced shortwave radiation heating to the east of the convection is another possible process. Further data analysis and modeling studies are necessary to validate the above proposed mechanism.

Our study also implies that the Indian Ocean SSTA impact is enhanced during the decades after the mid-1970s when there is a significant interdecadal SST warming in the Indian Ocean. Increased background SST in the eastern Indian Ocean around northwestern Australia may enhance ascending motion and therefore favors wetter SASM-NASM in-phase years after 1977.

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