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A multi-time scale Australian monsoon index

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ABSTRACT: A broad-scale Australian monsoon index (AUSMI) describing multi-time scale variations is defined by using 850 hPa zonal wind averaged over the area (5 °S–15 °S, 110 °E–130 °E). This circulation index reflects monsoonal rainfall variability over Northern Australia and maritime continent. The index can be used to depict the seasonal cycle (for instance the onset) and measure the intraseasonal, interannual, and interdecadal variations of the Australian monsoon. The interannual variation of the Australian monsoon onset determined by the AUSMI agrees well with that derived from the rainfall and winds at Darwin in the previous studies. We found a significant anti-correlation between the monsoon onset date and the seasonal (DJF) mean AUSMI anomalies; namely an early onset is accompanied by a strong Australian summer monsoon and vice versa. These interannual variations are also strongly associated with El Niño-Southern Oscillation (ENSO). In contrast, the retreat dates are not significantly different between the strong and weak Australian summer monsoon years. The AUSMI is useful in monitoring the weather and climate variations of the Australian monsoon and validating the performance of climate models. Copyright © 2009 Royal Meteorological Society

KEY WORDS Australian monsoon; multi-scale; circulation index; monsoon onset

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1. Introduction

The Australian monsoon is one of the energetic components of the Asian–Australian monsoon system and a major heat source of atmospheric general circulation. The intraseasonal to interannual variability of Australian monsoon is connected to global tropical and subtropical climate variability. The onset of Australian summer monsoon and its interannul variation are an important subject of monsoon studies, which have been investigated in many previous studies (Troup, 1961; Nicholls *et al.*, 1982; Holland, 1986; Drosdowsky, 1996; Suppiah, 2004; Kim *et al.*, 2006). The primary data analysed in majority of these previous studies are wind and rainfall records at Darwin (12 °S, 130 °E). Few studies have discussed interannual and interdecadal variability of broad-scale Australian summer monsoon due to limited satellite and objective analysis data. It is therefore meaningful to discuss the broad scale Australian monsoon seasonal cycle and climate variability from a broad scale circulation perspective with a simple yet effective index. Such an approach has provided useful insights to understand the dynamic structure and teleconnection for Indian summer monsoon and the western North Pacific monsoon (Webster and Yang, 1992; Wang and Fan, 1999; Wang *et al.*, 2001).

To facilitate monitoring of intraseasonal to interannual variations as well as daily fluctuations of Australian summer monsoon, it is advantageous to use an objective and effective circulation index. Use of the circulation index has advantages compared to that of rainfall index. Use of broad scale wind variation can (1) avoid random noise associated with local rainfall variability (2) better represent large-scale Australian summer monsoon (3) obtain dataset readily for real-time monitoring (4) establish a historical record with reanalysis dataset, and (5) facilitate a validation of monsoon performance in GCM simulation and forecast.

Wang *et al.* (2004a) defined an Australian summer monsoon index by using 850 hPa zonal wind anomalies averaged over the region (EQ-10 °S, 120 °E–150 °E) following traditional notion used by Australian meteorologists. It can capture seasonal cycle well but not the interannual variation of the Australian summer monsoon rainfall, because of lack of significant correlation with the rainfall over the Australian monsoon region (Figure 1(b)). Webster (2006) also defined a vertical wind shear index between 850 hPa and 200 hPa zonal wind averaged over the same region as Wang *et al.* (2004a), which strongly depends on zonal wind at 200 hPa. This index has some positive correlation with Australian monsoon rainfall anomalies (Figure 1(c)); but the variability centre is different from the desired monsoonal rainfall area (Figure 1(a)). Besides, seasonal variation is not predominant in the 200 hPa zonal wind over that region.

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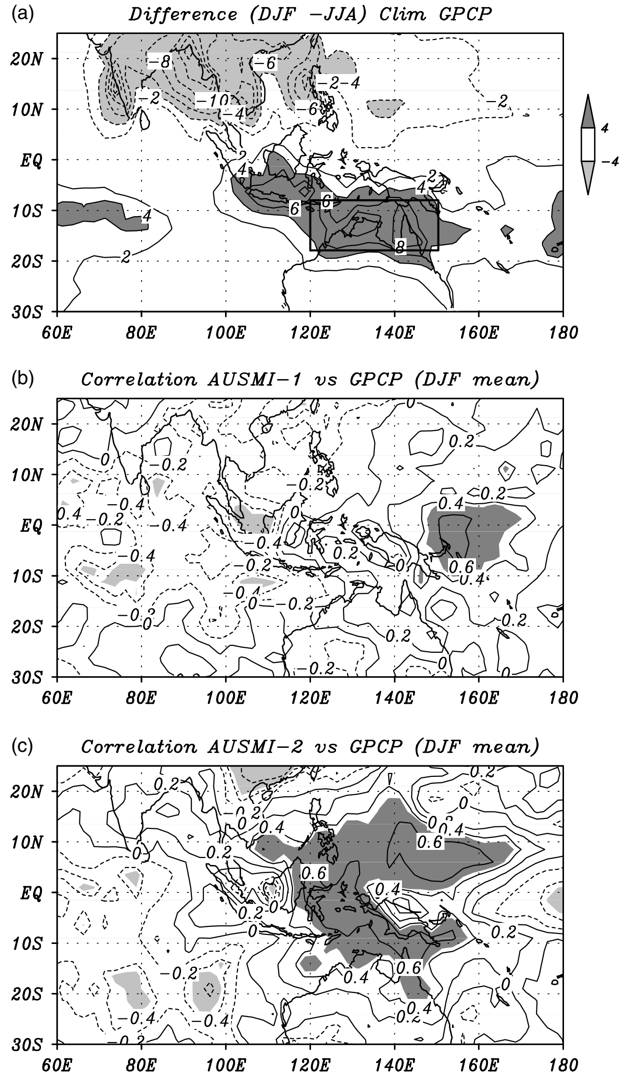

Figure 1. (a) Difference of climatological seasonal mean precipitation between austral summer (December–February: DJF) and winter (June–August: JJA). (b) Correlation coefficient between DJF mean 850 hPa zonal wind averaged in EQ-10 °S, 120 °E-150 °E, and DJF mean GPCP rainfall. (c) Correlation coefficients between the DJF mean zonal wind shear (850hPa–200hPa) averaged in EQ-10 °S, 120 °E–150 °E and DJF mean GPCP rainfall. Box shows monsoonal rainfall area. Correlations in (b) and (c) that are significant at the 99% confidence level are shaded.

Also there is a discrepancy between the decreasing trends in this index and the interdecadal variations of the rainfall over the Australian continent as Webster (2006) noted.

The purpose of this study is to examine the possibility of redefining and improving the Australian monsoon index, which can quantify the variability on multi-time scales of both the circulation and rainfall over the Australian monsoon region. Such an index will be useful for real-time monitoring of monsoon events such as its onset and for investigating intraseasonal to interdecadal variability of the Australian monsoon strength. After data description in the next section, we define an improved broad scale Australian monsoon index (AUSMI) and confirm its applicability to multi-time scale from intraseasonal to interdecadal in Section 3. The interannual variability of the onset date and seasonal mean strength of the Australian summer monsoon are investigated by using the new AUSMI in Section 4. Conclusion and discussions are given in the final section.

2. Datasets

The datasets employed in this study include the daily outgoing longwave radiation (OLR) data interpolated by NOAA-CIRES Climate Diagnostic Center (Liebmann and Smith, 1996) for the period 1979–2006, the pentad mean Global Precipitation Climatology Project (GPCP) satellite-gauge combined grid precipitation data (Huffman *et al*., 1997) for the period 1979–2006, and the daily NCEP reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/, for the period 1948–2006 (Kalnay *et al*., 1996). These datasets are acquired as a regular array with a 2.5° × 2.5° grid. We also used the monthly mean Nino3 SST index and southern oscillation index (SOI) from the Climate Prediction Center in NCEP.

3. Defining an Australian monsoon index

A monsoon circulation index should reflect seasonal cycle and interannual variability of monsoonal rainfall. The difference of climatological seasonal mean precipitation between austral summer (December–February: DJF) and winter (June–August: JJA) is shown in Figure 1(a). Large seasonal difference of rainfall is seen over the maritime continent and Northern Australia as well as over the Indian subcontinent, the Bay of Bengal, the Indochina peninsula, and the South China Sea. The Australian summer monsoon rainfall is roughly located in the region (7.5 °S–17.5 °S, 120 °E–150 °E,) as indicated by the box shown in Figure 1(a). In order to identify the region where the interannual variability of lower zonal wind is best related to the Australian monsoon rainfall anomalies, we plot the correlation coefficient of 850 hPa zonal wind field with respect to the DJF mean Australian monsoon rainfall averaged over the boxed region in Figure 2(a). The enhancement of the monsoon rainfall is associated with westerly wind anomalies over the area 5 °S–15 °S, 100 °E–130 °E, especially along 10 °S, and easterly wind anomalies over the southwest of the monsoonal rainfall regions. These zonal wind anomalies, which are parts of the cyclonic circulation anomalies, essentially reflect the Rossby wave response forced by the latent heat released in the monsoon rainfall (Gill, 1980). Figure 2(b) shows the difference of climatological seasonal mean zonal wind at 850 hPa between austral summer and winter. The large seasonal variation in 850 hPa zonal wind field is located over the maritime continent around 5 °S–15 °S and expanded in the zonal direction from the

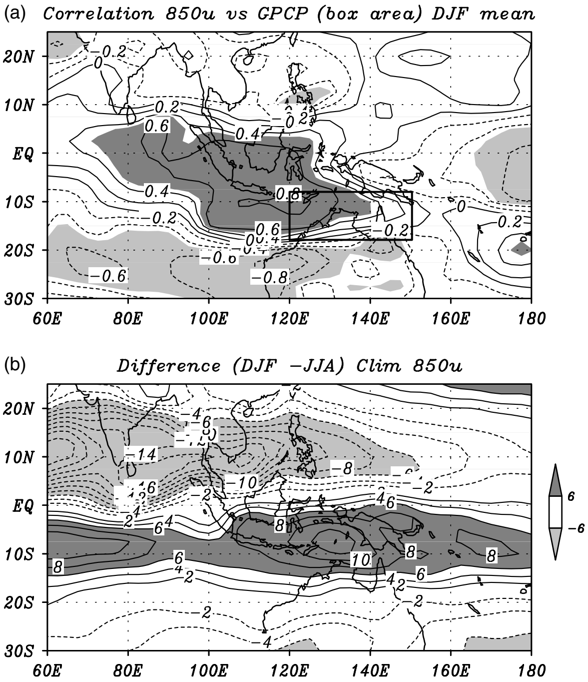

Figure 2. (a) Correlation coefficient between DJF mean anomalous 850 hPa zonal wind and the Australian monsoon rainfall averaged over the region (7.5 °S–17.5 °S, 120 °E–150 °E; shown by the box in the Figure). Correlations that are significant at the 99% confidence level are shaded. (b) Difference of climatological seasonal mean zonal wind at 850 hPa between austral summer (December–February: DJF) and winter (June–August: JJA).

equatorial Indian Ocean to the dateline. On the basis of these results, we defined the AUSMI as 850 hPa zonal wind averaged over the area (5 °S–15 °S, 10 °E–130 °E), which can reflect the broad scale Australian monsoon in terms of both the seasonal cycle and interannual variability.

To confirm the adequacy of the AUSMI in describing interannual variability, the correlation coefficients between the AUSMI and OLR (and GPCP rainfall) were calculated by using DJF seasonal mean anomaly data (Figure 3(a) and (b)). Significant correlations are widely seen in the maritime continent and Northern Australia. As such, the AUSMI can capture well the interannual variability of large-scale monsoon rainfall. The AUSMI can also faithfully represent the relationship between Australian summer monsoon and El Niño Southern Oscillation (ENSO), as well interdecadal changes in the Australian monsoon. Figure 4 shows the time series of normalized seasonal (DJF) mean AUSMI and Nino3 SST anomaly. The interannual variability of the AUSMI is negatively correlated with the Nino3 SST index with a simultaneous correlation coefficient of −0.51 and an especially negative correlation (−0.65) for the period as ENSO itself was intensified after 1965; these correlations are statistically significant at 99% confidence level. This negative correlation suggests that a weak (strong) Australian monsoon is associated with warm (cold) SST anomalies in the Eastern Pacific. This agrees with the previous results (Holland, 1986; Kullgren and Kim, 2006). Thus, the AUSMI well represents the interannual variability of the Australian monsoonal rainfall.

The AUSMI can also describe large intraseasonal variability of the Australian summer monsoon. Figure 5(a) and (b) shows the correlation coefficient between the AUSMI and OLR (and GPCP rainfall) computed by using pentad mean anomalies during austral summer (from December to February). Statistically significant correlations are found over the maritime and Australian continents in both OLR and rainfall fields. Therefore, the AUSMI represents not only interannual variability and annual cycle but also intraseasonal variability of the Australian monsoon rainfall. Moreover, the interdecadal variability of the Australian summer monsoon strength can be clearly seen from the 11-year running mean AUSMI in Figure 4 (thick line), which shows weak monsoon during 1950–1970 and 1980–1995 and strong monsoon during 1970–1980 and after 1995. There is no significant trend in the AUSMI. The phase of this interdecadal variability is consistent with the results found by Lavery *et al.* (1997) and Suppiah (2004), which showed the interdecadal variability of the rainfall over the northern part of Australia by using rain gauge data. Thus, the AUSMI can reflect the rainfall variations over the

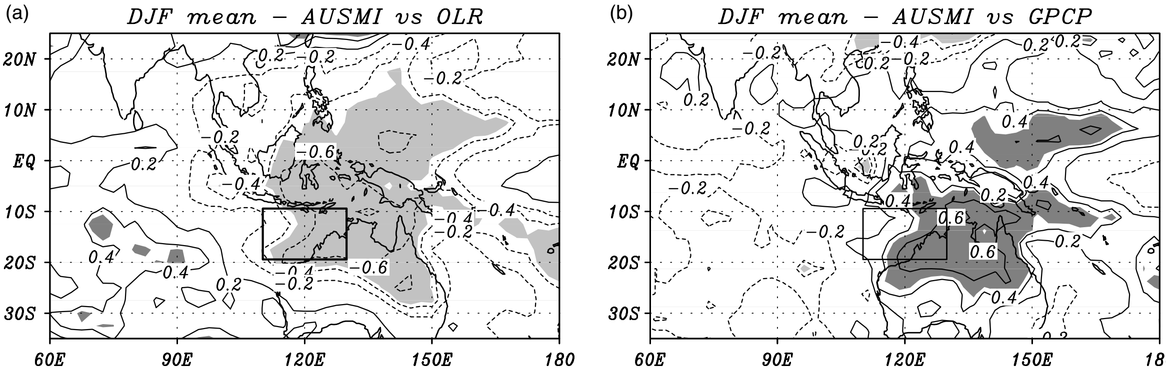

Figure 3. Correlation coefficients between the DJF mean AUSMI (850 hPa zonal wind averaged in 5 °S–15 °S, 110 °E–130 °E; the box in Figures) and the DJF mean (a) OLR and (b) GPCP rainfall anomalies at each grid. Correlations in (a) and (b) that are significant at the 99% confidence level are shaded.

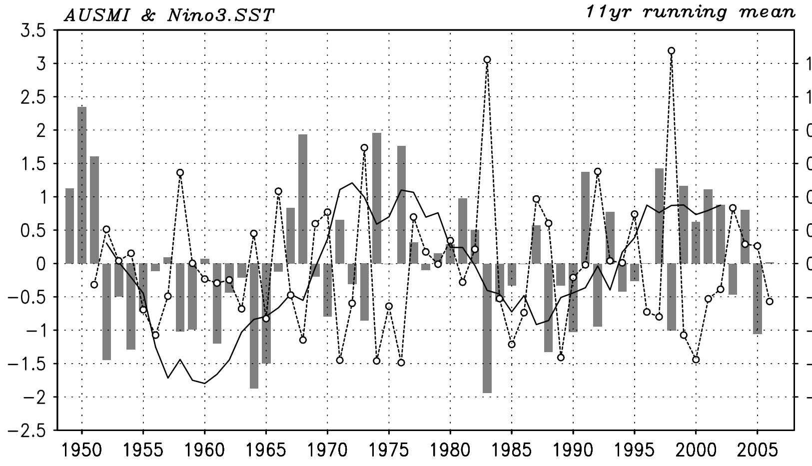

Figure 4. Time series of the normalized DJF mean AUSMI (850 hPa zonal wind averaged in 5 °S–15 °S, 110 °E–130 °E) (bar) with 11-year running mean of the AUSMI (thick line), and normalized Nino3 SST anomaly (dashed line).

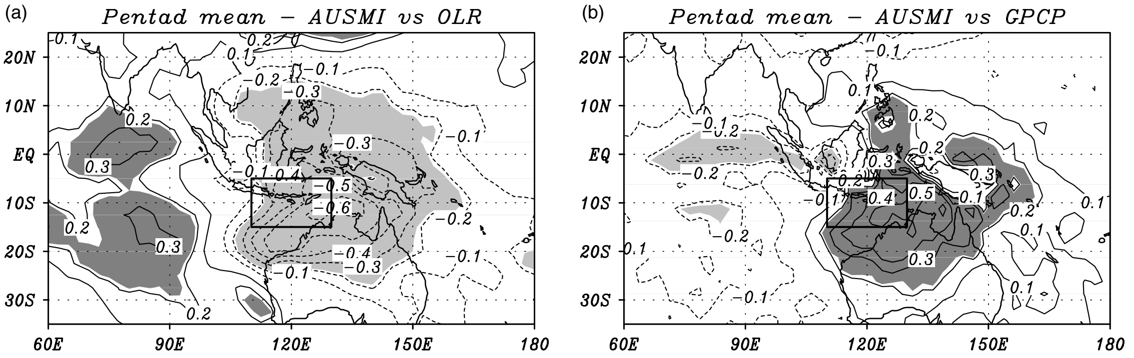

Figure 5. Correlation coefficients between the pentad mean AUSMI (850 hPa zonal wind averaged in 5 °S–15 °S, 110 °E–130 °E; the box in Figures) and the pentad mean (a) OLR and (b) GPCP rainfall anomalies during austral summer (DJF). Correlations in (a) and (b) that are significant at the 99% confidence level are shaded.

Australian monsoon region not only on seasonal, intraseasonal, and interannual time scales but also on interdecadal variability.

4. Onset of the Australian summer monsoon and its relation with the seasonal mean rainfall

The climatological daily mean AUSMI and pentad mean GPCP rainfalls over the Australian monsoon area (7.5 °S–17.5 °S, 120 °E–150 °E; shown by the box in the Figure 1(a)) averaged for the period 1979–2006 are shown in Figure 6. Seasonal evolution of the climatological mean AUSMI is characterized by a clear annual reversal between easterly (winter) and westerly (summer). The gradual transition from easterly to westerly occurs during the beginning of December; the westerly abruptly turns to easterly during the early mid March. It corresponds well to the seasonal cycle of Australian monsoon rainfall. It has been well known that the Australian summer monsoon in each year starts abruptly with a large-scale disturbance associated with a wet phase of the 40-50-day intraseasonal oscillation. According to the composite study, the peak-to-peak amplitude of zonal wind is about 10 m s^{-1} during 5–10 days around the onset date (Hendon and Liebmann, 1990). However, the climatological onset is gradual from easterly to westerly in Figure 6, suggesting that the Australian summer monsoon onset has large interannual variability and they are not phase locked to the annual cycle. In contrast, the abrupt retreat of the climatological mean Australian summer monsoon occurring clearly in the middle of March suggests that the retreat is more tightly phase-locked to the annual cycle around the middle of March (Wang and Xu, 1997).

The Australian summer monsoon onset generally concurs with the transition of lower troposphere zonal wind from easterly to westerly (Holland, 1986; McBride, 1987; Hendon and Liebmann, 1990; Drosdowsky, 1996; Kim *et al.*, 2006). Here, similar to the South China Sea monsoon onset date defined by Wang *et al.* (2004b), the onset date of the Australian summer monsoon in each year is defined as follows. The onset day should be the first day after 1 November that satisfies the following criteria: (1) on the onset day and during the 5 days after the onset day the averaged AUSMI must be greater than 0 (meaning that the westerly is steadily established) (2) in the subsequent four pentads, the AUSMI must be positive in at least three pentads and (3) the accumulative four-pentad mean

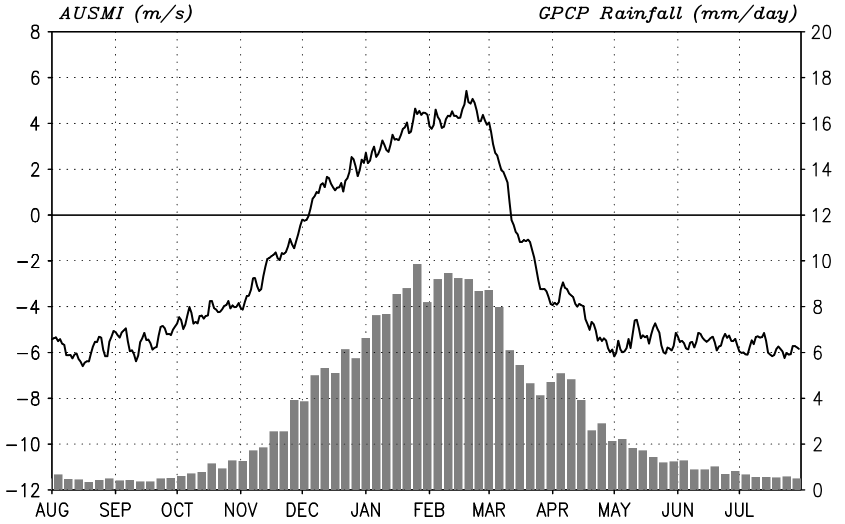

Figure 6. The climatological daily mean AUSMI (in units of m s^{-1}) and the pentad mean GPCP rainfall (in units of mm day^{-1}) over the Australian monsoon (see the box in Figure 1(a)). The climatology was derived using data from 1979 to 2006.

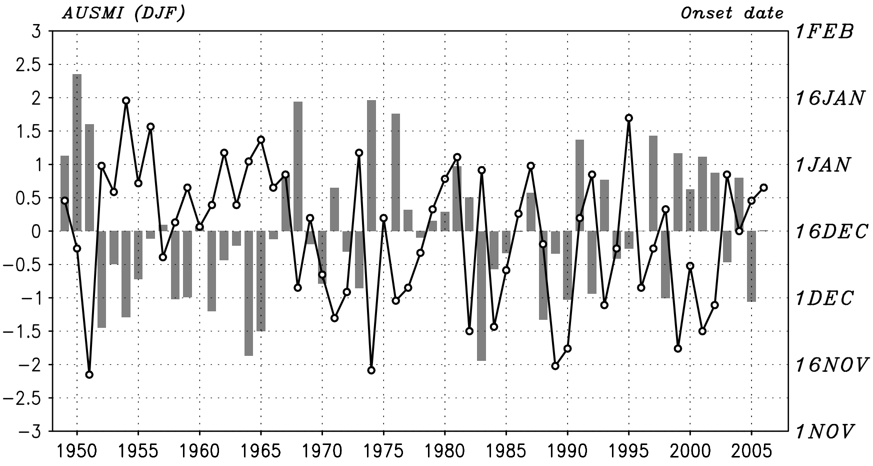

Figure 7. Time series of the Australian summer monsoon onset date (solid line) and the normalized DJF seasonal mean AUSMI (bar). See Section 4 in the text for the definition of the AUSMI and the Australian monsoon onset date. Unit of the AUSMI is m s^{-1}.

AUSMI >1 m s^{-1} (meaning a persistent seasonal transition).

The time series of the onset date and the seasonal (DJF) mean AUSMI are shown in Figure 7. The climatological mean onset date defined by the AUSMI is December 16 and the standard deviation is about 15 days. The mean onset date in this study differs from that in the previous studies obtained by using station data at Darwin (9 days earlier than that in Drosdowsky (1996), and 5 days earlier than that in Hendon and Liebmann (1990)), whereas the interannual standard deviation is close to the previous studies; 15 days for Drosdowsky (1996) and 16 days for Hendon and Liebmann (1990). However, the present definition of monsoon onset date is still reasonable in terms of its interannual variation because the onset date defined by the AUSMI has a significant correlation with the onset date defined in the previous studies: 0.54 with Drosdowsky (1996) and 0.59 with Hendon and Liebmann (1990); these correlations are statistically significant at 99% confidence level. One of the possible reasons that the onset dates in this study are earlier than previous studies could be due to the fact that the westerly anomalies associated with eastward propagating intraseasonal disturbance might take several days to travel from the AUSMI region to Darwin. The interannual variability of the onset date is well correlated with the SOI during November and December with the same correlation coefficient of 0.48. This result is consistent with previous studies with the SOI (Nicholls *et al.*, 1982; Holland, 1986; Drosdowsky, 1996). More importantly, there is a significant negative correlation between the onset date and seasonal mean strength of the broad scale Australian monsoon (−0.47); namely an early (late) onset is accompanied by a strong (weak) Australian summer monsoon in terms of seasonal mean strength. This relationship was also evident even in the period when the ENSO was inactive before 1965, although this relationship was not strong during some period like in late 1980s.

In order to clarify the relationship discussed above, we selected 10 strong and 12 weak Australian summer

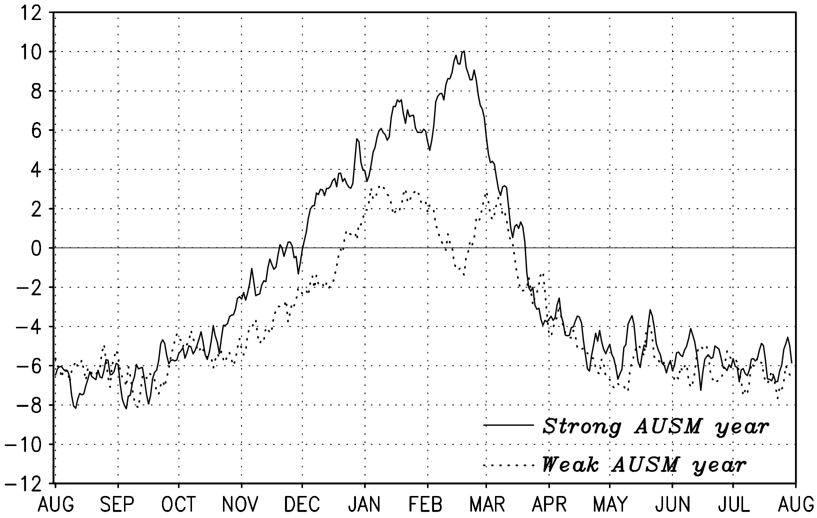

Figure 8. Time series of composite AUSMI averaged for 10 strong Australian summer monsoon years (solid line) and 12 weak Australian summer monsoon years (dotted line). See the text for the details of strong and weak monsoon years. Unit of the AUSMI is m s^{-1}.

monsoon years with the criteria that the AUSMI during DJF is above (strong) and below (weak) one standard deviation, respectively (Figure 4). The Strong monsoon years are 1949, 1950, 1951, 1968, 1974, 1976, 1991, 1997, 1999 and 2001; whereas weak monsoon years are 1952, 1954, 1958, 1959, 1961, 1964, 1965, 1983, 1988, 1990, 1998 and 2005. Figure 8 shows the time series of composite daily AUSMI in strong and weak monsoon years. The onset date in strong monsoon years (around 1 December) is earlier than that in the weak monsoon years (around 22 December). The largest difference of the AUSMI seen in February is remarkable. In terms of the retreat of the Australian monsoon, it is also interesting that there is no significant difference between strong and weak monsoon years. This indicates that the signal of the interannual variability of the Australian monsoon is clear only in the onset phase and mature phase of the Australian summer monsoon. In addition, the precursor signal starts from one month before onset date (during November).

5. Summary and discussions

On the basis of analysis of the action centres for both the seasonal and interannual variations, we proposed an improved AUSMI which is defined as 850 hPa zonal wind averaged over the area (5 °S–15 °S, 110 °E–130 °E). This circulation index represents well the monsoonal rainfall over the maritime continent and northern part of the Australia on not only seasonal and interannual time scales but also on the intraseasonal and interdecadal time scales. The interannual variability of the seasonal mean AUSMI is associated with the ENSO: weak (strong) Australian summer monsoon in El Niño (La Niña) year. The interdecadal variability of the AUSMI is consistent with the previous studies that used rain gauge data over the Australian continent (Lavery *et al.*, 1997; Suppiah, 2004). The Australian summer monsoon onset date is also defined by using daily and pentad mean AUSMI. The interannual variability of this monsoon onset date is well correlated with Nino3 SST anomalies during November and December. It is also found that an early (late) onset is accompanied by a strong (weak) Australian summer monsoon. In contrast, the monsoon retreat in both strong and weak Australian summer monsoon years occurs around the middle of March. This suggests that the Australian monsoon retreat tends to be phase-locked to the annual cycle. In other words, the Australian monsoon retreat has less interannual variability, whereas the monsoon onset has large interannual variability. This feature is different from the western North Pacific monsoon, whose stepwise onset has been discussed as a result from seasonal phase locking of the intraseasonal variability (Nakazawa, 1992; Ueda *et al.*, 1995; Wu and Wang, 2001).

The seasonality of the El Niño evolution is essential for understanding the relationship between the onset date and the seasonal mean of the Australian summer monsoon. In general, the El Niño has developed during boreal summer and autumn, the pre-Australian monsoon season (Harrison and Larkin, 1998). It has been suggested that the ENSO could impact on the Australian monsoon onset date through anomalous Walker circulation and SST anomalies around the Australian continent (Nicholls *et al.*, 1982; Holland, 1986; Drosdowsky, 1996). As the climatological mean Australian summer monsoon starts around middle of December and the standard deviation of the onset date is about 15 days, the interannual variation of the onset date can significantly affect the duration of rainy season thereby the total amount of summer monsoon rainfall. As this relationship is still significant during an inactive ENSO period, the onset date may provide a useful short-term precursor for the seasonal (DJF) mean Australian summer monsoon strength. The El Niño events usually decay during boreal spring, concurring with the Australian summer monsoon retreat. Why the Australian summer monsoon retreat has moderate interannual variability and tends phase-locked to the annual cycle remains elusive. This may be associated with timing of the El Niño decay as a phase lock system on annual cycle (Torrence and Webster, 1998) and with the consecutive stepwise western North Pacific monsoon onset.

The new AUSMI is useful in representing multi-time scale variability of the Australian monsoon on intraseasonal to interdecadal time scales. It is worthwhile to use this index for analysing and monitoring the Australian monsoon variations. The monsoon onset over the South China Sea is associated with the activity of the intraseasonal variability during early summer (Kajikawa and Yasunari, 2005). Thus, the relationship between Australian monsoon onset/retreat and the intraseasonal variability is another interesting issue for future studies of the Asian–Australian monsoon system.

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