A joint monsoon index for East Asian–Australian monsoons during boreal summer

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Abstract

Using National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis and other data, a joint monsoon index \( I_{\text{EAAM}} \) is defined for capturing variation features of East Asian summer monsoon and Australian winter monsoon as an entity. The East Asian–Australian monsoons (EAAM) are found to be stronger after 1993 whereas weaker before this year. When EAAM is anomalously strong, cold sea surface temperature anomalies appear around north coast of Australia, facilitating easterly wind near equator to strengthen in lower troposphere and both the Australia High and the northwestern subtropical anticyclone to intensify. The divergent flows emanating from the Southern Pacific Convergence Zone (SPCZ) region and tropical north Pacific, respectively, force Australian High and northwestern Pacific subtropical anticyclone to reinforce. The anomalous convergence around Kalimantan Island links East Asian monsoon to Australian monsoon via the divergent flows. During strong EAAM years, rainfall is surplus over south coast of China and southern Japan whereas deficient over northwestern tropical Pacific and southwestern tropical Indian Ocean.

Keywords: joint monsoon index; East Asian–Australian monsoon; Maritime Continent; boreal summer

1. Introduction

The Asian–Australian monsoon (AAM) is an important phenomenon occurring over region (40°–160°E, 30°S–30°N) (e.g. Lau and Wu, 1999; Wang et al., 2003), which is closely related to El Niño-Southern Oscillation (ENSO) (Webster et al., 1998; Li et al., 2015) and has profound impacts on global weather and climate (e.g. Lau and Weng, 2001). During boreal summer, in East Asian and Australian regions, there prevail the East Asian summer monsoon (EASM) and Australian winter monsoon (AWM). When the monsoons vary anomalously, strong anomalous precipitation in East Asia and Australia regions will occur, resulting in severe floods and droughts and henceforth causing tremendous economic losses (e.g. Meehl and Arblaster, 1998; Hsu et al., 2011). Therefore, to understand the mechanisms and impacts of variations, both EASM and AWM are extremely important for climate prediction and disaster mitigation.

It is well known that the EASM in the lower troposphere mainly comprises of the cross-equatorial flows, the inter-tropical convergence zone (ITCZ) around 10°N, the western Pacific subtropical high (WPSH), and the Meiyu/Baiu frontal system over regions from the Yangtze River basin eastward to south Japan whereas AWM mainly comprises of the Australian anticyclone and the cross-equatorial flows (Figure 1(a)) (Tao and Chen, 1987). The EASM and AWM interact with each other via variations of both the cross-equatorial airflow and zonal wind along equator in the Maritime Continent (MC) region (Ramage, 1968; Manton and McBride, 1992; Matsumoto, 1992; Taschetto et al., 2009; Zhang et al., 2016). This interaction may lead to some concurrent variations of EASM and AWM. Hence, we here consider EASM and AWM as an entity and use the EAAM as the shortened name for EASM and AWM.

The variations of EAAM are very complicated on different timescales. The EAAM is not only dominated by the local land–atmosphere–ocean interactions but also strongly influenced by many other factors (Yoshino, 1965; Ding, 1992; Shi and Zhu, 1995; Ashok et al., 2001; Wang et al., 2001; Fan, 2006). For example, the EAAM is strongly affected by the south Asian summer monsoon with warm and moist airflow from the Bay of Bengal (Figure 1(a)). The Rossby waves from middle latitudes can also affect the EASM. In the tropics, some signals including intra-seasonal oscillation (ISO) (Li, 2014), ENSO (Webster and Yang, 1992; Zhang et al., 2010a, 2010b), and Indian Ocean dipole (IOD) (Saji et al., 1999; Guan and Yamagata, 2003) also play very important roles in variations of EAAM.

To simply describe the complicated variations of EASM and AWM, scientists have defined many monsoon indexes (Li and Zeng, 2002; Zhu et al., 2005; Wang et al., 2008; McPhaden et al., 2009; Kajikawa et al., 2010). Each different index is designed for different research purpose, being capable of capturing partial features of the EASM or AWM variability.
Figure 1. JJA mean climatology of circulations (a) and the first leading SVD mode (b, c) for anomalous winds at 850 hPa over period 1979–2013. Blue streamlines are for JJA mean climatology of 850 hPa winds whereas green arrows for divergent component of the winds (m s⁻¹). Shown in (b) and (c) are the heterogeneous correlations of the SVD1 for meridional wind anomalies over East Asia (right field) and zonal wind anomalies over Australia (left field), respectively.

With these indices, the characteristics of EASM or AWM have been widely and respectively investigated. However, as the EASM and AWM interact with each other, the component of EASM variations in association with AWM is still unknown. There could be a mode that describes the concurrent variation features of EASM and AWM, exhibiting the EASM and AWM as an entity. Hence, in this article, we explore the possible concurrent variations features of EASM and AWM. A joint monsoon index is therefore defined, which can be used to capture the co-variation features of EASM and AWM simply. The results of this study will be meaningful for our better understanding the variations of EAAM and their mechanisms. The joint monsoon index is useful in seeking for clues to regional climate prediction and monitoring.

2. Data and methodology

The data used in this study include: (1) the Hadley Centre Global 1° × 1° Sea Surface Temperature dataset (HadISST) (Rayner et al., 2003); (2) the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) with a resolution of 2.5° × 2.5° (Schneider et al., 2011); (3) the NCEP/NCAR reanalysis product, which includes monthly mean wind and temperature fields at 17 pressure levels, vertical velocity and humidity fields at 12 pressure levels, surface pressure, and so on. The resolution of these reanalysis products is 2.5° × 2.5° (Kanamitsu et al., 1997).

The study period is from January 1979 to December 2013. The summer season is defined as June–July–August (JJA). The singular value decomposition (SVD) is applied to identify the spatial pattern of East Asian monsoon circulation that is most closely connected with the AWM.

3. Definition of the joint monsoon index of EAAM

The most pronounced feature of Australian summer monsoons characterized by equatorial westerly winds at 850 hPa along with the equatorial easterly winds at 200 hPa. During austral winter, directions of prevailing winds noticeably change near equator north of Australia, particularly in the lower troposphere. The average of zonal winds at 850 hPa above north Australia is often used as an index to describe the Australian monsoon (Webster, 1983; McBride, 1987). On the other hand, in the lower troposphere, the alternation of wind direction between summer and winter is also obvious in East Asia (Wang and Fan, 2013). Thereby, the meridional winds at 850 hPa can be used as the index to describe the East Asian monsoon. These suggests that, if we want to define a joint monsoon index for EAAM, variations of the meridional winds in East Asia and zonal winds near north coast of Australia must be considered. Thus, as the
first step, we perform the SVD by taking the zonal wind anomalies over \((110^\circ\text{E} -160^\circ\text{W}, 40^\circ\text{S} - 10^\circ\text{S})\) Australia as the left field and the meridional wind anomalies over \((110^\circ\text{E} -140^\circ\text{W}, 20^\circ\text{N} - 45^\circ\text{N})\) East Asia as the right field.

The first leading SVD mode (SVD1) accounts for 45.24% of the total covariance and the correlation between the time series of coefficients of right and left fields is found to be 0.72, suggesting a close relationship between the EASM and the AWM. The spatial pattern of the leading mode SVD1 exhibits large negative values in the northeastern part of Australia (Figure 1(c)) and large positive values in the southeastern part of China (Figure 1(b)), indicating that when the winter monsoon in northern Australia strengthens, the EASM concurrently intensifies.

Based on the spatial pattern of SVD1, key areas of high correlation between the EASM and AWM are identified over Box A \((130^\circ\text{E} -157.5^\circ\text{E}, 25^\circ\text{S} - 10^\circ\text{S})\) (Figure 1(c)) and Box B \((115^\circ\text{E} -122.5^\circ\text{E}, 20^\circ\text{N} - 27.5^\circ\text{N})\) (Figure 1(b)). It is found that the zonal wind anomalies averaged over Box A are highly correlated with the zonal wind anomalies averaged over region \((120^\circ\text{E} -150^\circ\text{E}, 5^\circ -20^\circ\text{S})\) (Kajikawa et al., 2010) with a correlation coefficient of 0.93, indicating that the zonal wind in Box A varies in phase with AWM.

Similarly, the meridional wind anomalies averaged over Box B can also largely indicate the variations of EASM over southern part of East Asia. Let \([v'_{850}]^*\) Box B and \([u'_{850}]^*\) Box A denote the normalized time series of meridional wind anomalies \((v'_{850})\) averaged over Box B and the normalized time series of zonal wind anomalies \((u'_{850})\) averaged over Box A, respectively. It is seen from Figure 2 that the \([v'_{850}]^*\) Box B varies almost oppositely against \([u'_{850}]^*\) Box A; \([v'_{850}]^*\) Box B significantly correlates \([u'_{850}]^*\) Box A with a correlation coefficient of \(-0.48\). Particularly, time series of \(v'_{850}\) at point \((115^\circ\text{E}, 20^\circ\text{N})\) is strongly correlated with time series of \(u'_{850}\) at point \((147.5^\circ\text{E}, 17.5^\circ\text{S})\) with a correlation value of \(-0.61\). Therefore, the joint index of EAAM, \(I_{\text{EAAM}}\), can be defined as the difference between \([v'_{850}]^*\) Box B and \([u'_{850}]^*\) Box A, which is expressed as:

\[
I_{\text{EAAM}} = \frac{1}{2} \left( [v'_{850}]^*_{\text{Box B}} - [u'_{850}]^*_{\text{Box A}} \right) \tag{1}
\]

According to Equation (1), a larger positive \(I_{\text{EAAM}}\) indicates a stronger EAAM while a larger negative \(I_{\text{EAAM}}\) indicates a weaker EAAM. This index basically describes the relationship that stronger (weaker) AWM corresponds to stronger (weaker) EASM. The correlation coefficient between the time series of \(I_{\text{EAAM}}\) (Figure 2) and that of the sum of time series of coefficients of the left and right fields for SVD1 is up to 0.87, suggesting that the \(I_{\text{EAAM}}\) is reasonably defined.

The EAAM varies on both inter-annual and inter-decadal timescales (Figure 2). Weaker EAAM tends to occur more frequently before 1993 whereas stronger EAAM does after this year. Of course, few occasionally occurred stronger EAAM events are observed before 1993 whereas some significant weaker events after 1993.

Based on variations of EAAM as indicated by index \(I_{\text{EAAM}}\), circulation anomalies can be revealed using the composite analysis. The years for composites are then selected as the years when \(I_{\text{EAAM}} \geq 0.75\) for strong EAAM events and years when \(I_{\text{EAAM}} \leq -0.75\) for weak EAAM events. Then it is found there ten strong EAAM years in total, including 1980, 1993, 1994, 1995, 1997, 2005, 2006, 2007, 2008 and 2013. There are nine weak EAAM years in total, including 1981, 1984, 1986, 1989, 1990, 1992, 2004, 2009 and 2012.

4. EAAM circulation anomalies

The EAAM is affected by SSTA, and also exerts feedback to SSTA in turn. The anomalous thermal forcing induced by SSTA can trigger anomalous circulation through the Gill-type response (Gill, 1980; Rodwell and Hoskins, 1996), leading to abnormal baroclinic circulation in the tropics.

4.1. Relationship with SSTA

In strong EAAM years, colder SST anomalies are observed in regions near coast of northern Australia (Figure 3(a)), which is partly associated with the upwelling of cold subsurface water induced by strong equatorial easterly anomalies since the easterly anomalies near the ocean surface are in the tropics.
explained by both downwelling of the upper ocean as a response to the anomalous anticyclonic circulation and absorptions of more solar radiation that reaches the ocean surface in the anticyclonic region.

4.2. Circulation anomalies in the troposphere

When the joint monsoon index is anomalously high, the anomalous thermal forcing induced by the cold SSTA (Figure 3(a)) in the coast of northeastern Australia and the SPCZ regions partly favorable of triggering an anomalous anticyclonic circulation at 850 hPa over Australia due to the anomalous divergences (Figure 3(b)). As a result, the Australian High is intensified and its northern flank extends equator-ward, which is favorable for the maintenance of easterly anomalies in the southern part of the MC. The formation of the anomalous anticyclonic circulation over the northwestern Pacific is associated with the anomalous divergent flows in its southeastern flank (Figure 3(b)). Circulation in the upper troposphere at 200 hPa (Figure 3(c)) exhibits the reversed pattern as compared to the anomalous circulation at 850 hPa (Figure 3(b)), indicating a baroclinic vertical structure of circulation anomalies in tropical regions.

The zonal wind anomaly around Indonesia in the key region (10°S–10°N, 95°–145°E) of the MC (Xu and Guan, 2017a, 2017b) plays a crucial role in the close relation between EASM and the AWM. When the easterly near equator at 850 hPa is intensified (Figure 3(b)), the negative anomalous vorticity in the Northern Hemisphere but positive in the Southern Hemispheres enhanced, inducing the intensification of the anomalous anticyclonic circulations over both the tropical northwestern Pacific and Australian continent. This zonal wind anomaly near equator is possibly related to the eastward propagation Kelvin wave, which is excited over equatorial Indian Ocean (Saji et al., 1999; Xie et al., 2009). On the other hand, the simultaneous anomalous divergent flows over tropical northwestern Pacific and SPCZ are also very important in exciting and maintaining the anomalous anticyclonic circulations over South China Sea-Northwestern Pacific and the Australian continent. The anomalous convergence around Kalimantan Island (Figure 3(b)) is favorable for divergent flows emanating from both the SPCZ region and the northwestern Pacific towards Indonesia islands, connecting Australian High and northwestern subtropical anticyclonic circulation.

4.3. Regional precipitation anomalies

Precipitation is strongly influenced by anomalous activities of EAAM. When EAAM is anomalously stronger, water vapor fluxes anomalously converge over regions including south coast of China and southern part of Japan and inducing surplus rainfall in these regions (Figure 4). In contrast, water vapor fluxes diverge anomalously over large area of tropical northwestern Pacific as well as the northern Philippines, inducing deficient rainfall there. Over southeastern tropical Indian Ocean, less rainfall is received whereas no significant rainfall anomalies occur over Australian continent. Some parts of Indonesia and New Zealand are also affected, receiving more or less rainfall there.

5. Summary and discussion

For describing the concurrent variations of EASM and AWM as an entity, a joint monsoon index $I_{EAAM}$ for the EAAM defined as the difference of meridional wind anomalies averaged over Box B at 850 hPa from the zonal wind anomalies averaged over Box A. It is
found that the EAAM varies on both inter-annual and inter-decadal timescales. Before 1993, the EAAM is weaker whereas it is stronger after 1993.

In strong EAAM years, there exists a large area of cold SSTA in the northern coast of Australia, which may be explained by the upwelling of cold subsurface ocean water induced by the equatorial easterly anomalies and the possible stronger evaporation near sea surface. The intensification of Australia anticyclone at 850 hPa is related to this cold SSTA. The strengthening of Australian High is also related to the vorticity forcing due to the anomalous divergent flows emanating from the SPCZ region into Australia continent. Concurrently, the western Pacific subtropical anticyclone is also anomalously intensified and stretches westward to South China Sea, which is induced by the anomalous divergent flows emanating from the tropical north Pacific region east of 160°E westward to northwestern Pacific.

In years when EAAM is significantly strong, the water vapor transport is strengthened along the northwestern flank of the anomalous western subtropical anticyclone, leading to anomalous convergence in south coast of China and southern part of Japan, causing surplus rainfall in these regions. Over the northwestern Pacific and northern Philippines, rainfall is much less than normal. Rainfall is also deficient over southeastern tropical Indian Ocean. However, no significant deficit of rainfall is observed in Australia during strong EAAM years.

It is known that the central and eastern Pacific SSTAs during ENSO or ENSO Modoki events play important roles in inducing the atmospheric circulation anomalies over both East Asia and Australia (Wang et al., 2001; Ashok et al., 2007; Feng et al., 2011). The Indian Ocean SSTAs also exert striking impacts on EASM (Guan and Yamagata, 2003; Xie et al., 2009). In this study, it is found that during strong EAAM years, the warmer SSTA are observed in the South China Sea and northwest Pacific underneathe the anomalous anticyclonic circulation, suggesting an oceanic response to the anomalous atmospheric forcing. At the same time, there may occur warm SSTA in central equatorial Indian Ocean during boreal summer, which is able to excite the Kelvin waves that propagate eastward to equatorial Pacific, possibly inducing the intensification of the easterly winds. This anomalous easterly winds will facilitate the intensifications of both the Australian High and the western Pacific subtropical anticyclone. Whether such mechanisms work or not remains further investigations.

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Supporting information

The following supporting information is available:

Figure S1. The SVD1 pattern which is similar to Figures 1(b) and (c) but for the smaller domain of Asia.

Figure S2. Mean composite differences of SSTA (in °C) and anomalous circulation at 1000 hPa (arrows, in m s−1) between strong and weak EAAM years (strong minus weak). Stippled areas are for SSTA values significant at/above the 95% confidence level whereas the blue arrows are for anomalous winds significant at/above the 90% confidence level.

Figure S3. Mean composite differences of SSTA (in °C) and anomalous circulation at 1000 hPa (arrows, in m s−1) between strong and weak EAAM years (strong minus weak). Stippled areas are for SSTA values significant at/above the 95% confidence level whereas the blue arrows are for anomalous winds significant at/above the 90% confidence level.

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