A proper monsoon index for seasonal and interannual variations of the East Asian monsoon

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[1] This study assesses how well the East Asian monsoon index (EAMI), developed on the basis of zonal and meridional land–sea thermal contrasts over the Asia-Pacific region, can represent the seasonal and interannual variations of the East Asian summer and winter monsoons (EASM and EAWM). It suggests that the EAMI can be used to estimate the timing of the onset and the relative intensity of the EASM, characterized by dominant meridional circulation and rainfall patterns over the Asia-Pacific region, as well as represent the EAWM, which is dominated by a nearly zonal dipole structure composed of Siberian high and Aleutian low prevailing in the middle and high latitudes. The EAMI is therefore of benefit in understanding the seasonal evolution of the East Asian monsoon circulation and interannual variation of the individual monsoons both in summer and in winter. **Citation:** Zhu, C., W.-S. Lee, H. Kang, and C.-K. Park (2005), A proper monsoon index for seasonal and interannual variations of the East Asian monsoon, *Geophys. Res. Lett.*, *32*, L02811, doi:10.1029/2004GL021295.

1. Introduction

[2] The East Asian monsoon (EAM) is a complex system that affects global climate. It is characterized not only by unique seasonal changes, but also by the remarkable interannual variability of the East Asian winter and summer monsoons (EAWM and EASM) [*Tao and Chen*, 1987]. The land-sea thermal contrast is considered a fundamental mechanism driving the monsoon circulation [*Webster*, 1987; *Li and Yanai*, 1996; *Wu and Wang*, 2001].

[3] During the past decade, the choice of an East Asian monsoon index (EAMI) has been widely discussed [*Webster and Yang*, 1992; *Wang and Fan*, 1999; *Li and Mu*, 2000; *Wang et al.*, 2001; *Li and Zeng*, 2002; *Jhun and Lee*, 2004; *Huang*, 2004]. However, less work has been carried out in order to address the EAMI comprehensively in the framework of covering both seasonal change and interannual variability, which is of benefit to studies of the EAM.

[4] *Zhu et al.* [2000] developed an EAMI on the basis of zonal and meridional land–sea thermal contrasts over the Asia-Pacific region and documented the relationship between the EASM and ENSO, though the efficiency of the EAMI was not discussed. In this study we assess the ability of the EAMI to represent the seasonal and interannual variations of the EASM and EAWM, and document the limitations of existing monsoon indices.

2. Data

[5] The climatological rainfall is based on the CMAP (Climate Merged Analysis of Precipitation) data from 1979 to 2003 [*Xie and Arkin*, 1997]. Pentad outgoing longwave radiation (OLR) data derived from NOAA satellite observations are used as a proxy to represent the convection in the South China Sea (SCS) from 1979 to 2000. The monthly and daily means of sea level pressure (SLP), wind vectors and geopotential height (GPH) were constructed from the NCEP-DOE AMIP-II Reanalysis (R-2) from 1979 to 2003 [*Kanamitsu et al.*, 2002]. All data sets used in this study are on $2.5° \times 2.5°$ grids.

3. EAMI and Seasonal Cycle

[6] Figure 1 shows the climatological distribution of the SLP, wind vectors at 850 hPa, and CMAP rainfall in boreal winter and summer, respectively. During winter, the EAWM is dominated by the Siberian high and the Aleutian low over the Eurasian continents and the northern Pacific at middle and high latitudes, where the westerly winds bring cold and dry air across the EAM region from the continent, and the northeasterly winds prevail in the south of the SCS. During summer, however, a warm low and the western North Pacific subtropical high (WNPSH) start to dominate the East Asian region. Related to these changes, the EASM rain band begins to prevail with low-level southwesterlies, while another rain band dominates over the SCS and east of the Philippine Sea.

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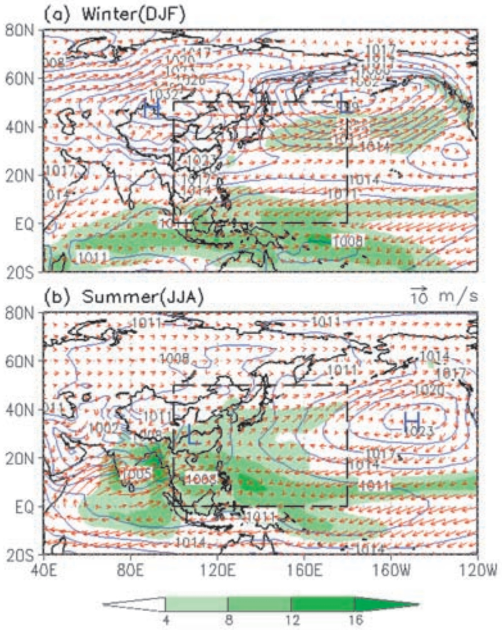

Figure 1. Climatological mean of sea-level pressure (unit: Pa), 850 hPa wind vectors (unit: m s^{-1}), and CMAP rainfall (unit: mm/day) for (a) DJF and (b) JJA. "H" and "L" denote the center of high and low pressure, respectively. The dashed box indicates the East Asian monsoon region (100°E–180°E, 0°–50°N).

Therefore, the seasonal land-sea thermal contrasts over the Asia-Pacific region are associated with changes in the SLP pattern, low-level wind direction, and related rain belts.

[7] On the basis of the seasonal zonal reversal of the SLP pattern over the Asia-Pacific region, *Guo* [1983] defined an EASM index (hereinafter referred to as GI) from the SLP difference less than −5 hPa between 160°E and 100°E, averaged between 10°N and 50°N. *Huang* [2004] defined an East Asia Pacific (EAP) teleconnection index and analyzed the GI; it was found that the GI has low correlation with EASM rainfall. Furthermore, the GI-indicated EASM onset, namely the SCS summer monsoon onset, starts as early as in April, and one month earlier than normal [*Qian and Lee*, 2000; *Wu and Wang*, 2001].

[8] The monsoon is dominated by the lowest baroclinic mode, which can be represented by the vertical shears defined by the differences of the 850 and 200 hPa zonal winds [*Wang and Fan*, 1999]. In addition to the zonal land-sea distribution, the East Asia-Pacific region has a north-south thermal contrast, which can be simply indicated by the zonal wind vertical shear between 850 and 200 hPa, averaged over the region of 100°E–130°E, 0°–10°N, where the variation of the vertical shear can be explained by the seasonal change of the 850–200 hPa vertically integrated meridional temperature gradient [*Zhu et al.*, 2000; *Wu and Wang*, 2001]. On the basis of this, *Zhu et al.* [2000] introduced a new EAMI to represent the large-scale zonal and meridional land-sea thermal contrast over East Asia and the Pacific, defined as

$$\begin{aligned} \mathrm{EAMI} = {} & (\mathrm{U}_{850\,\mathrm{hPa}} - \mathrm{U}_{200\,\mathrm{hPa}})^*_{(100-130^\circ\mathrm{E},0-10^\circ\mathrm{N})} \\ & + (\mathrm{SLP}_{160^\circ\mathrm{E}} - \mathrm{SLP}_{110^\circ\mathrm{E}})^*_{(10-50^\circ\mathrm{N})} \end{aligned} \quad (1)$$

where, the asterisk indicates the standard deviation, and the positive and negative EAMI denotes the phase of the EASM and EAWM, respectively.

[9] In this study, we selected the western North Pacific summer monsoon index (WNPSMI) to compare the ability of the EAMI to depict the EAM. The WNPSMI is defined as WNPSMI = U_{850} (5°–15°N, 100°–130°E)–U_{850} (20°–30°N, 110°–140°E), where the areas in parentheses denote the regions over which U_{850} is averaged [*Wang et al.*, 2001].

[10] Figure 2 shows the seasonal cycle of daily mean OLR, zonal wind at 850 hPa index averaged over the SCS (110°E–120°E, 0°–20°N), the EAMI and the WNPSMI. The EAMI-indicated SCS summer monsoon onset occurs in the middle of May when the EAMI changes from a negative to a positive phase. The onset period nearly coincides with that of the observed SCS summer monsoon, when the OLR index drops to 230 W/m^2 and the zonal wind direction at 850 hPa changes from easterly to westerly over the SCS [*Qian and Lee*, 2000]. The EAMI shows a peak in late June and a maximum in early August after maintaining high values for July. Such changes are consistent with the seasonal evolutions of the WNPSH and EASM rainfall over the East Asia-Pacific region [*Qian and Lee*, 2000; *Wu and Wang*, 2001]. The EASM ends in late October when the EAMI changes from the positive to negative phase and the OLR index increases to 230 W/m^2. In contrast, the WNPSMI-indicated EASM starts with a positive index in the mid of June, and the EAWM begins with a negative index in the mid of November, about one month later than observations.

4. Interannual Variations

[11] We defined the averaged EAMI for JJA (June to August) as the EASMI. The EAWMI is defined as the averaged EAMI for DJF (last December to February) multiplied by −1. Figure 3 shows the interannual variations of the EAWMI, EASMI, and the WNPSMI. Because of the different magnitude of the EAMI between winter and summer, we defined six strong EAWM years (1983, 1991, 1992, 1995, 1996, and 2003) and five weak EAWM

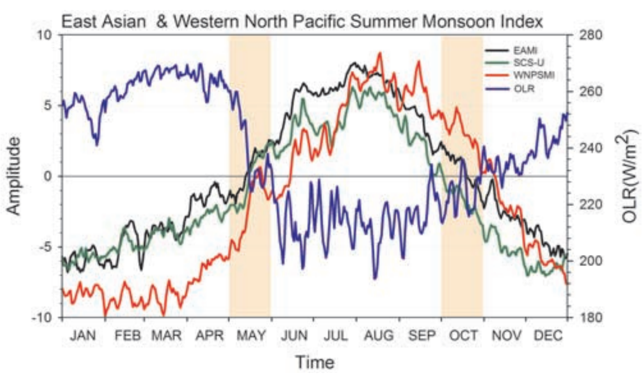

Figure 2. Climatological mean of daily East Asian monsoon index (EAMI, unit: ×2.5), Western North Pacific Summer Monsoon Index (WNPSMI, unit: m s^{-1}), 850 hPa zonal wind (SCS-U) and OLR (unit: W m^{-2}) averaged over the South China Sea region (110°E–120°E, 0°–20°N).

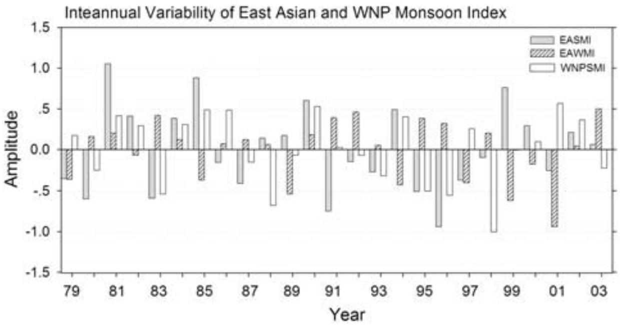

Figure 3. Interannual variability of the EASMI, EAWMI (left axis), and the WNPSMI (right axis) during 1979–2003. The correlation coefficient between the EAWMI and EASMI, EAWMI and WNPSMI, and EASMI and WNPSMI is −0.32, −0.47, and 0.50, respectively.

years (1979, 1985, 1989, 1999, and 2001) with respect to ±0.5 thresholds of EAWMI, respectively. Similarly, we selected four strong EASM years (1981, 1985, 1990, and 1999) and five weak EASM years (1980, 983, 1991, 1995, and 1996) with respect to ±1.0 thresholds of EASMI.

[12] During the strong EAWMI years, the Asia-Pacific region is dominated by an approximately zonal dipole, exhibited by the enhanced Siberian high and Aleutian low, centered on the Baikal and the mid-high latitudes of the northeast Pacific, respectively (Figure 4a). Corresponding to the increased SLP in the east of the Philippine Sea, the enhanced northerly winds over the northern East Asia, and westerly and easterly wind anomalies over the equatorial western Pacific region and the SCS to the Bay of Bengal are observed (Figures 4b and 4c). The circulations in weak EAWMI years are opposite to those in the strong EAWMI years. Such strong/weak EAWM circulation patterns agree with previous studies [*Li and Mu*, 2000; *Jhun and Lee*, 2004]. During the strong EASMI years, however, the circulation anomalies over the Asia-Pacific region are dominated by a monsoon low over the SCS to the east of the Philippine Sea, enhanced subtropical high from the Yangtze River to the southern Japanese islands, and an enhanced high latitudes trough from the Okhotsk Sea to the north Pacific with respect to the enhanced precipitation over the SCS and the suppressed rainfall (Meiyu-Changma-Baiu) from the Yangtze River to the southern Japanese islands (Figures 4d–4f). Such strong/weak circulation and rainfall anomalous patterns exhibit a typical enhanced/suppressed EASM, namely, the Pacific–Japan (P-J) pattern [e.g., *Nitta*, 1987; *Nitta and Hu*, 1996; *Wang et al.*, 2001].

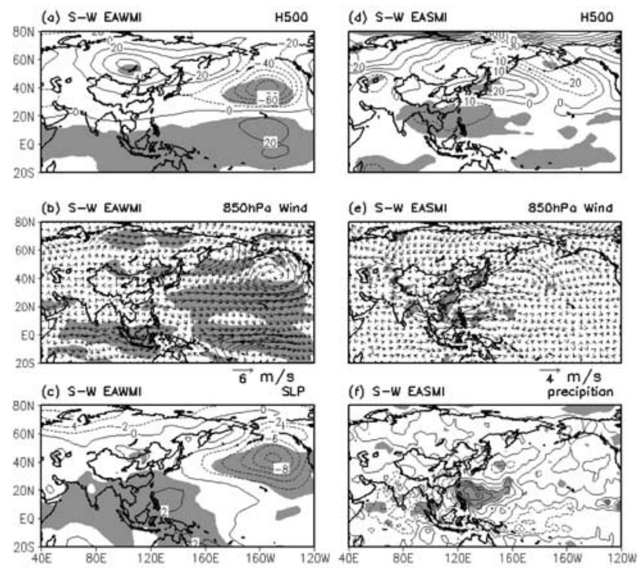

Figure 4. (a–c) Composite difference of 500 hPa GPH, 850 hPa winds, and SLP between strong and weak winter monsoon years with respect to the EAWMI, and (d–f) 500 hPa GPH, 850 hPa winds, and precipitation (the contour interval is 1 mm day^{-1}) between strong and weak summer monsoon years with respect to the EASMI. The shading denotes regions of difference at 95% t-student testing confidence level.

[13] Figure 5 shows the correlations between the monsoon indices and 500 hPa GPH and CMAP rainfall for summer. The correlation between the WNPSMI and 500 hPa GPH exhibits a remarkable P–J like pattern over the Asia-Pacific region, where the negative, positive, and negative centers are located respectively over the Indo-China peninsula to the east of Philippine Sea, central Japanese islands, and northwestern region of the Okhotsk Sea (Figure 5a). A tripole correlation pattern between the WNPSMI and the CMAP rainfall is also found in these areas. In the positive WNPSMI case, the summer rainfall is enhanced over the SCS and the eastern Philippine Sea to the south and over the Okhotsk Sea to the north, and at the same time the Meiyu-Changma-Baiu rainfall pattern is suppressed from the mid-lower reaches of the Yangtze River to the southern Japanese islands. A similar correlation pattern is also found with the EASMI, except for a much wider negative correlation region over the tropical Indian Ocean to the western Pacific Ocean in the GPH.

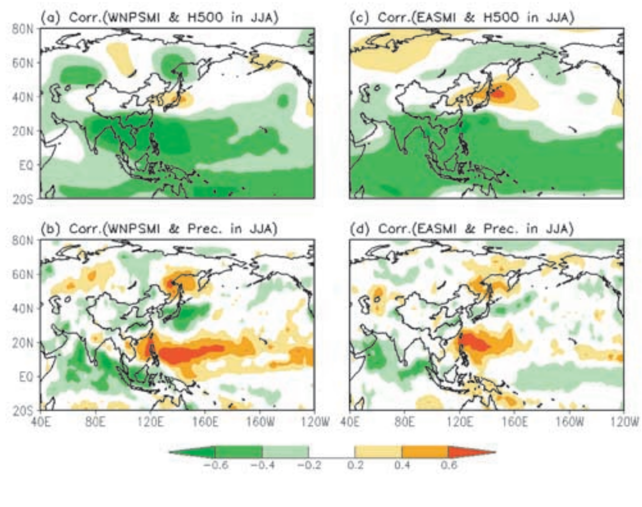

Figure 5. Correlations between (a) 500 hPa GPH and WNPSMI, (b) CMAP rainfall and WNPSMI, (c) 500 hPa GPH and EASMI, and (d) CMAP rainfall and EASMI in JJA during 1979–2003.

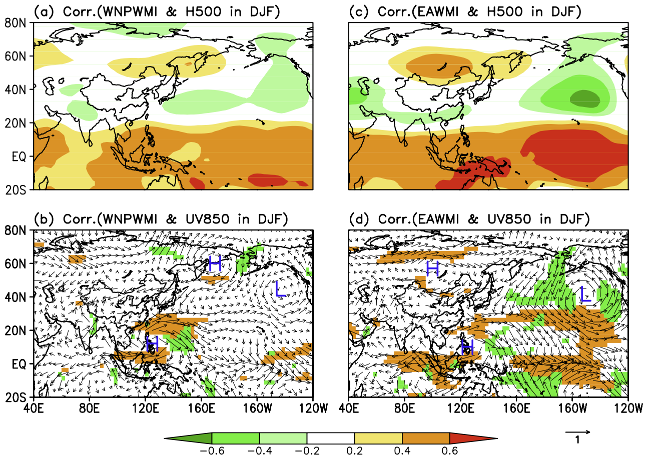

Figure 6. Correlations between (a) 500 hPa GPH and WNPWMI, (b) 850 hPa winds and WNPWMI, (c) 500 hPa GPH and EAWMI, and (d) 850 hPa winds and EAWMI in DJF during 1979–2003. "H" and "L" indicate the center of the anticyclone and cyclone-like correlation vectors, respectively. The correlations exceeding 95% confidence level in the zonal and meridional winds are shaded by yellow and green, respectively.

[14] Strictly speaking the WNPSMI was designed for the WNPSM, but in order to show the capability of such a monsoon index we extended it to winter in a similar fashion to the EAWMI, and defined the winter monsoon index (WNPWMI). We chose the wind vectors at 850 hPa instead of rainfall as the near surface variable to denote the EAWM, and calculated the correlations between the monsoon indices and the 500 hPa GPH and 850 hPa wind vectors to examine the validity of WNPWMI and EAWMI during winter (Figure 6).

[15] The dominant modes of the EAWM at 500 hPa are clearly observed in the correlation pattern between the EAWMI and the 500 hPa GPH. The anticyclone-like correlation vectors are observed over the Philippine Sea in both correlation patterns of WNPWMI and EAWMI at 850 hPa winds. The Siberian high and the Aleutian low circulation anomalies are clearly seen in the correlation pattern with the EAWMI in contrast to that of the WNPWMI. In addition, the EAWMI exhibits a remarkable positive correlation with equatorial westerly winds over the western Pacific, in agreement with *Li and Mu* [2000].

[16] The EAMI has the capability of characterizing the seasonal and interannual variations of the EAM. However, its maximum (or minimum) magnitude is not always consistent with an extreme climate event (Figure 3). For instance, during the summer of 1998, an area from the Yangtze River to the southern Japanese islands witnessed severe floods, but the EASMI exhibits relatively small negative amplitude compared to the WNPSMI due to the influence of the anomalous 30–60 day intraseasonal oscillation [*Zhu et al.*, 2003]. The correlation between EASMI and WNPSMI is 0.50 and it exceeds the significance test at the 0.01 confidence level. It is very interesting to note that the lag correlation between the EAWMI and the following WNPSMI is −0.47 in contrast to −0.32 with the EASMI, which implies that a strong (weak) EAWM year is usually followed by a weak (strong) EASM year. Such a relationship suggests the possibility of predicting the EASM a season in advance.

5. Summary

[17] The EAMI has an advantage over the existing EAM indices in comprehensively representing the SCS summer monsoon onset, the EASM, and the EAWM. Therefore, it provides the benefit of measuring the seasonal evolution of the East Asian monsoon circulation and interannual variation of the summer and winter monsoons using a single index.

[18] The WNPSMI and the EAP index are limited in that they do not correctly reproduce the seasonal cycle or the interannual variability of EAWM. Both indices are defined on the basis of the thermal state and convective activities over the tropical western Pacific region, where the heating is regarded as one of the key mechanisms responsible for the P-J pattern during the EASM [*Nitta*, 1987; *Nitta and Hu*, 1996; *Wang et al.*, 2001]. However, recent studies suggests that the P–J pattern can also be explained by the summertime diabatic heating over the Tibetan plateau [*Hsu and Liu*, 2003]. Thus, the mechanism driving the EASM circulation and rainfall may need further investigation.

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