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An improved south Asian summer monsoon index with Monte Carlo test*

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The Indian monsoon intensity index suggested by Webster and Yang (WY index) is optimized and improved in this paper. At first, the area (40°E–110°E, 0°–20°N) for calculating the zonal wind-shear between 850hPa and 200hPa in the WY index is optimized and adjusted according to the significance test of differences of wind fields. Then the regionally averaged zonal wind is computed over the optimized area. Finally, the optimal linear combination of the zonal winds at the two levels is performed using the regression method, thus defining a new broad-scale circulation index for the interannual variability of the south Asian summer monsoon, i.e. the improved south Asian summer monsoon index. Results indicate that the improved south Asian summer monsoon index has two advantages: its correlation with the All Indian Summer Monsoon Rainfall index is higher than that of WY index, and its computational domain of circulation is also larger than that of WY index. The computational results based on the 1948–98 NCAR/NCEP wind data indicate that the correlation of the improved SASM index with the All Indian Summer Monsoon Rainfall index is higher than that of WY index by 0.27.

Keywords: Indian summer monsoon, zonal wind-shear between 850hPa and 200hPa, south Asian summer monsoon index, Monte Carlo test

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1. Introduction

The interannual variation of the Asian monsoon is one of the strongest signals of the Earth's climate variability.[1−4] The All Indian Summer Monsoon Rainfall (hereafter AISMR) index was defined by the seasonally averaged precipitation over all India subdivision from June to September,[5,6] and has long been used as a measure of the Indian summer monsoon (ISM) in the studies of ISM and ENSO or tropical biennial oscillation.[7−11] Using concise and meaningful indices to characterize monsoon variability can greatly facilitate empirical studies of the relationship between monsoon variability and lower boundary forcing. Webster and Yang[12] proposed a circulation index (the WY index) of the ISM as the zonal wind shear between 850hPa and 200hPa (U850–U200) averaged over 40°E–110°E, 0°–20°N. The WY index is based on the dynamical premise that the monsoon flow is a first baroclinic response to the diabatic heating over the south Asian region, and is strongly correlated with the indices of ENSO.[13] In a recent report, Ailikun and Yasunari[14] showed that the WY index is associated with the convective activity over the western Pacific rather than over the South Asian monsoon region. This implies that the computational domain wherefrom the WY index is calculated is too much to the east. The weak correlation between the WY index and AISMR index motivated Goswami[15] to focus on the rainfall averaged over a large region (70°–110°E, 10°–30°N), termed Extended Indian Monsoon Rainfall (EIMR), which covers not only the Indian subcontinent but also the northern Bay of Bengal and a portion of south China. They found that the shear between 850hPa and 200hPa (V850–V200) averaged over the same domain as the EIMR. The EIMR is well cor-

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related with the monsoon Hadley index (MHI), which is defined as the meridional wind, also exhibits a better correlation with AISMR than WY index. However, The above conclusion was made based on merging rain-gauge data with satellite estimates of precipitation for 1979–1996. Before 1979, we have no data of satellite estimates of precipitation, that is to say, we only have a short series of EIMR, but a very long one of AISMR, which is also easy to extend. The optimization and improvement of the WY index in this paper was performed under the circumstance that the AISMR is still used. Firstly, the area (40° E–110°E, 0°–20°N) for calculating the zonal wind–shear between 850hPa and 200hPa in the WY index is optimized and adjusted according to the significance test of differences of wind fields. The procedure is that the significance test of differences of composite wind fields at 200hPa and 850hPa for the strong/weak AISMR year was performed, yielding the significant area reflecting strong/weak AISMR, and then the regionally averaged zonal wind was computed over the significant area. Finally, the optimal linear combination of the zonal winds at the two levels was made using the regression method, thus defining a new broad-scale circulation index for the interannual variability of the south Asian summer monsoon (SASM) i.e. the improved SASM index. Results indicate that the improved SASM index has a significant correlation with the AISMR index.

2. Data

The main circulation data (U and V field) covering the period 1948–99 used in this study are the products of the National Centres for Environmental Prediction / National Centre for Atmospheric Research (NCEP/NCAR) reanalysis project[16] based on a frozen state-of-the-art global data-assimilation system which includes a T63 forecast model and a database that is as complete as possible. The AISMR used in this study are the precipitation analysis data created by Parthasarathy *et al*,[6] and the data have been extended to 1998 on the web at http://www.tropmet.res.in/. According to the AISMR, 11 maximum / 12 minimum years were selected as the strong/weak Indian summer monsoon year in the period 1948–98 (Table 1), respectively.

Table 1. Strong and weak ISM years during the period 1948 to 1998.

Strong ISM	1961	1956	1975	1988	1983	1994	1959	1970	1955	1953	1964	
Weak ISM	1972	1987	1979	1965	1982	1951	1966	1986	1974	1968	1985	1991

3. Significance test and Monte Carlo test of differences of mean wind fields for strong/weak ISM years

3.1 Significance test of differences of mean wind fields

Webster and Yang[12] proposed a circulation index (WY index) of the ISM, which is defined by

$$\text{WY index} = \text{U850} - \text{U200}. \quad (1)$$

The wind field shear is computed for the area bounded by 40°E–110°E and 0°–20°N. However, whether the above computational area is the area most significantly correlated with the AISMR needs to be statistically tested. For two different climatic states: the strong ISM year (n_A) and weak ISM year ($n_{\bar{A}}$), the difference field of their composite wind fields is the E field (the strong ISM year mean wind field minus the weak ISM year one), which consists of 10512 grid points over the globe, and contains both differences (strong ISM year minus weak ISM year) of zonal (U) and meridional (V) wind components at each grid point. Is there a distinct difference between mean wind fields of strong and weak ISM years? where does the distinct difference exist? Is it the area (40°E–110°E, 0°–20°N) defined by Webster and Yang (1992)? This paper is going to answer these questions.

As we know, the horizontal wind field is a 2D field consisting of U and V components, therefore the 2D statistical test is used in the significance test of differences of composite wind fields.[17,18] That is to say, calculate F statistic

$$F = \frac{n_A n_{\bar{A}}(n_A + n_{\bar{A}} - m - 1)}{m(n_A + n_{\bar{A}})(n_A + n_{\bar{A}} - 2)} D_m^2, \quad (2)$$

where $m = 2$. D_m^2 is the Mahalanobis distance between the mean wind fields of strong/weak ISM years, and is determined by

$$D_m^2 = (\bar{X}(A) _ \bar{X}(\bar{A}))^{\mathrm{T}} S^{-1} (\bar{X}(A) _ \bar{X}(\bar{A})), \quad (3)$$

where A ($\bar{A}$) denotes strong (weak) ISM respectively, and

$$\bar{X}(A) = \begin{pmatrix} \bar{U}(A) \\ \bar{V}(A) \end{pmatrix}, \quad \bar{X}(\bar{A}) = \begin{pmatrix} \bar{U}(\bar{A}) \\ \bar{V}(\bar{A}) \end{pmatrix}$$

are the mean vectors consisting of zonal wind U and meridional wind V at some grid point for strong and weak ISMs, respectively. Therefore, $\bar{X}(A) - \bar{X}(\bar{A})$ is the difference of the mean winds of strong and weak ISM at some grid point, and is a 2D vector. S is a covariance matrix,

$$S = (s_{ij}), \quad i, j = 1, 2 \tag{4}$$

where s_{ij} can be calculated using the yearly zonal wind and meridional wind of strong/weak ISM years, and then D_m^2 obtained from equation (3). Substituting D_m^2 and others into equation (2) yields the statistic F. When F is greater than the criterion value, F_α, of the F distribution with the confidence level being α and the degree of freedom being $(m, n-m-1)$, where $n = n_A + n_{\bar{A}}$, then the difference of strong/weak ISM years is significant, otherwise, the difference is stochastic. This test was performed at each of the 10512 grid points, thus yielding the significant area of differences of wind fields.

3.2. Statistical test of the Monte Carlo simulation of wind fields

Although the difference of wind fields has been tested using F statistic test, the wind field-tested is the global field consisting of 10512 grid points. Livezey and Chen,[19] and Wolter *et al*[20] pointed out that it is necessary to perform the statistical test of the Monte Carlo simulation for the correlation of the meteorological fields which consists of a large number of grid points. They held that only when the number of significant correlation grid points exceeds a certain threshold is the field correlation reliable. Otherwise the correlation may still be stochastic and unreliable. Based on Wolter *et al*'s method (see Appendix A in Ref.[20], we performed the statistical test of the Monte Carlo simulation for the difference of wind fields. Shi and Chen,[21] Shi *et al*,[22] Huang and Shi[23] and Yang *et al*[24] have successfully applied the method to one-dimensional scalar fields.

3.3. Significant area of the difference of mean winds for strong/weak ISM years

Figure 1 gives the global 200hPa wind field composites for the strong/weak (Fig.1(a)/Fig.1(b)) ISM years (see Table 1) calculated from the NECP/NCAR June–September mean wind data, and the F statistic (Fig.1(c)) of their difference (strong year minus weak year). It can be observed from Figs.1(a) and (b) that the features of the global wind fields for strong/weak ISM years are almost opposite. Table 2 lists the Monte Carlo simulation results of the difference of wind fields, suggesting that Fig.1(c) has passed the Monte Carlo test.

Table 2. Test results of the difference of 200hPa wind fields for strong/weak ISM years.

F test confidence level (α)	0.05	0.01	0.001
No. of grids passing F test criterion	4029	1928	623
Monte Carlo criterion (0.05)	1399	413	64
Monte Carlo criterion (0.01)	1830	627	150
Monte Carlo criterion (0.001)	2749	1068	497

Figure 1(c) indicates that the difference is significant in a large area (45°W–60°E, 20°S–35°N). However, the maximum value area of F is in the area (40°E–90°E, 5°N–35°N) of 289 grid points. This area is different from that defined by Webster and Yang[12] for calculating the WY index. It can be seen from Fig.1(c) that the east boundary of the WY area is too far to the east, the north boundary too south, and its area (261 grid points) is also smaller than that (289 grid points) in this paper. Similar computation was performed for 850hPa wind fields. The most significant area (37.5°E–90°E, 7.5°N–20°N; 273 grid points in the total) was determined from the figure (omitted) of the difference of 850hPa composite wind fields.

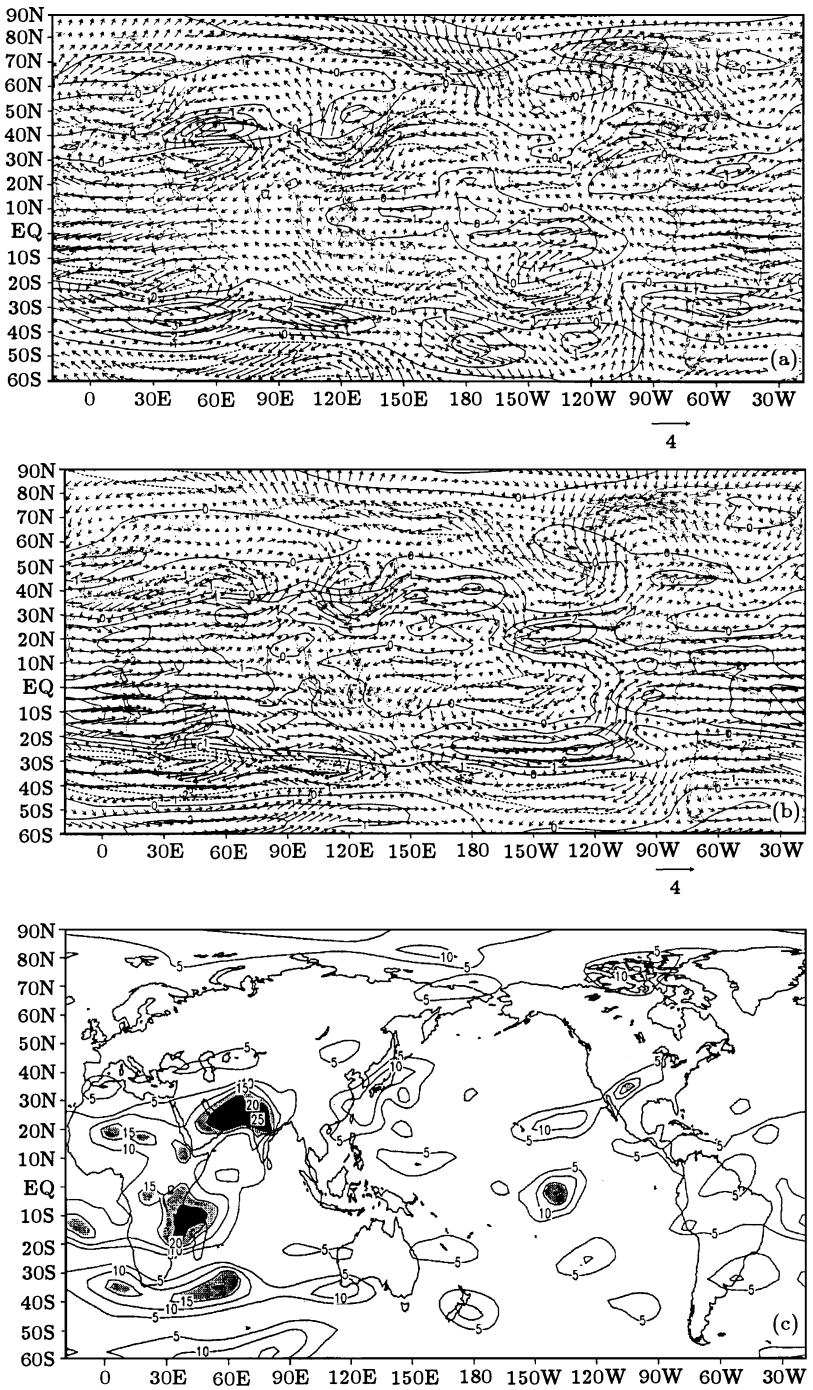


Fig.1. Global wind field composites for strong/weak ISM years (Fig.1(a)/Fig.1(b)), and the F statistic of their difference (Fig.1(c), grey and black colours denote the areas where the confidence levels reach 0.01 and 0.001.

Table 3 shows the correlation coefficients of 200hPa and 850hPa regional mean U, V winds with the AISMR based on Webster and Yang[12] and this paper, the correlation coefficients of the mean U, V winds over the area defined in this paper with the AISMR is obviously higher than that in WY.[12]

Table 3. Correlation coefficients of 200hPa and 850hPa regional mean zonal wind U and meridional wind V with the AISMR in 1948–1999 based on Webster and Yang[12] and this paper.

	Webster and Yang[12]				Shi and Gu *et al* (this paper)			
Area calculating	40°–110°E, 0°–25°N		40°–110°E, 0°–25°N		40°–90°E, 5o–35°N		37.5°–90°E, 7.50–20°N	
mean wind	261 grid points		261 grid points		289 grid points		273 grid points	
Correl. coeff	U200	200	U850	V850	U200	V200	U850	V850
	–0.49	–0.27	0.34	0.35	–0.68	–0.50	0.70	0.40

4. An improved broad-scale circulation index for the interannual variability of the ISM

Now, we optimally combine 200hPa and 850hPa zonal winds. Webster and Yang[12] simply subtracted U200 from U850; that is to say, the equivalent weighting method was used. However, the mean square deviations of 200hPa and 850hPa zonal winds are different, Eq.(1) may not be an optimal form of combination. We combine U200 and U850 using regression equation (5),

$$\text{Improved circulation index} = 2.4\text{U850} - \text{U200}. \quad (5)$$

Where U850 and U200 denote the zonal winds averaged over the season (June –September) and over the area defined in this paper at 850hPa and 200hPa, respectively. Table 4 shows the relevant results of comparison. It can be seen from Eq.(5) and Table 4 that the new circulation index can describe the interannual variability of the ISM, and its correlation coefficient with the AISMR is as high as 0.77, i.e. 0.27 higher than that of the WY index

Table 4. Shears of zonal and meridional wind between 200hPa and 850hPa and their correlations with the AISMR.

	Webster and Yang[12]		Shi and Gu *et al* (this paper)	
Mean wind Correl. Coeff.	U850–U200	V850–V200	2.4 U850–U200	1.24 V850–V200
	0.50	0.36	0.77	0.56

We have plotted the temporal evolution diagram of the new circulation index (Eq.(5)) and the AISMR (figure omitted), and they have good coincidence.

5. Summary and conclusions

Based on the significance test of the difference of wind fields, the area (40°E–110°E, 0°–20°N) for calculating the zonal wind–shear between 850hPa and 200hPa in the WY index has been optimized and adjusted in this paper. The areas (40°E–90°E, 5°–35°N)and (37.5°E–90°E, 7.5°N–20°N) are defined in this paper for calculating 200hPa and 850hPa regional mean winds in the improved SASM index. The areas defined in this paper are larger than those in Wesbster and Yang,[12] and the mean zonal and meridional winds over the areas defined here have a closer relation with the AISMR. After the optimal combination using the regression method, an improved SASM index (2.4U850–U200) is presented, and its correlation coefficient with the AISMR is 0.77, 0.27 higher than that of the WY index. Since the length (from 1948 to 1999) of the data used in this paper is quite different from that (from 1979 to 1996) in Goswami *et al.*[15] The comparison between the improved SASM index and the monsoon Hadley circulation index are not performed in this paper. However, the areas for calculating the circulation index in this paper are much larger than that for the MHI, therefore this is also an advantage of our computational scheme. Goswami's computational domain only contains 153 grid points; it is even smaller than WY's.

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