A unified monsoon index

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[1] There are several monsoon regions in the world. Some monsoon indices have been proposed to describe their variability, but a unified monsoon index suitable for all known monsoon regions has not yet been found. Here we present a unified dynamical index of monsoon, the dynamical normalized seasonality (DNS), and carry out an analysis of observation data over the past 40 years. The analysis shows that the DNS index can characterize the seasonal cycle and interannual variability of monsoons over different areas very well. The South Asia summer monsoon (SASM) sector (5°–22.5°N, 35°–97.5°E) is composed of two independent components, SASM1 (2.5°–20°N, 35°–70°E) and SASM2 (2.5°–20°N, 70°–110°E), with quite different relations with the monsoon rainfall over the South Asia. The African summer monsoon (ASM) is dominated by variability on the decadal time-scale, and its decadal abrupt decrease in 1967 may be an important cause of the persistent drought over the Sahel region. It is also found that there is a remarkable global correlation pattern between the South China Sea summer monsoon index (SCSSMI) and global precipitation during boreal summer. *INDEX TERMS:* 3300 Meteorology and Atmospheric Dynamics; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology

1. Introduction

[2] The monsoon is a macro-scale phenomenon in character and its intriguing features of the climate fascinate meteorologists, oceanographers and geographers. Moreover, there is extremely socioeconomical importance for being able to forecast the monsoon [*Ramage*, 1971; *Webster et al.*, 1998; *Lau et al.*, 2000a, 2000b; *Webster and Yang*, 1992; *World Climate Research Programme* (*WCRP*), 1998]. Therefore, in recent years there has been a steady growth of interest on the problems of the monsoons. In order to objectively delimit the monsoon and quantify its variability, an objective and representative index (or indices) needs to be proposed. To this end, some indices, e.g. the All Indian Rainfall Index (AIRI) [*Shukla and Paolino*, 1983; *Shukla and Mooley*, 1987], Webster and Yang Index (WYI) [*Webster and Yang*, 1992], Monsoon Hadley Circulation Index (MHI) [*Goswami et al.*, 1999], convection index (CI) [*Wang and Fan*, 1999], etc., have been developed to characterize monsoon variation. However, not only the choice of proper monsoon indices has notable controversy [*Webster and Yang*, 1992; *Lau et al.*, 2000b; *Ailikun and Yasunari*, 1998; *Goswami*, 2000; *Wang*, 2000], but also most of them are only available for the South Asia summer monsoon (SASM). Therefore, these efforts have not led to a consensus. The aim of this study is to provide a unified monsoon index that has a unified solid dynamics basis and that is appropriate for different monsoon regions. Here we use the NECP reanalysis [*Kalnay et al.*, 1996] (1958–99), the AIRI [*Parthasarathy et al.*, 1994] (1958–98), the Xie-Arkin rainfall analysis [*Xie and Arkin*, 1997] (1979.1–98.1), the historical monthly precipitation dataset for global land areas [*Hulme et al.*, 1998] (1900–98) and the China's 160-station monthly rainfall (1958–99) to present our findings.

2. Results

[3] The monsoons possess very strong seasonal variation [*Ramage*, 1971; *Webster et al.*, 1998; *Lau et al.*, 2000a, 2000b; *Webster and Yang*, 1992], it is therefore a reasonable idea that strong and weak monsoons may be measured by use of the seasonal variation magnitude of wind field. Such a quantity is a dynamical normalized seasonality (DNS) given by

$$\delta = \frac{\|\overline{\mathbf{V}}_1 - \mathbf{V}_i\|}{\|\overline{\mathbf{V}}\|} - 2 \qquad (1)$$

where $\overline{\mathbf{V}}_1$, $\mathbf{V}_i$ are the January climatological and monthly wind vectors at a point, respectively, $\overline{\mathbf{V}}$ is the mean of January and July climatological wind vectors at the same point. The norm $\|A\|$ is defined as $\|A\| = (\iint_S |A|^2 dS)^{1/2}$ where S denotes the domain of integration (In calculations at a point (i, j), $\|A_{i,j}\| \approx \sqrt{a}((|A^2_{i-1,j}|+|A^2_{i,j}|+|A^2_{i+1,j}|)\cos\varphi_j + |A^2_{i,j-1}|\cos\varphi_{j-1} + |A^2_{i,j+1}|\cos\varphi_{j+1})^{1/2}$ where a is the mean radius of the earth and φ_j the latitude at the point (i, j)). The DNS index is an extension of the static normalized seasonality (SNS) index, which is defined by $\|\overline{\mathbf{V}}_1 - \overline{\mathbf{V}}_7\|/\|\overline{\mathbf{V}}\|$, presented by *Zeng et al.* [1994]. 2 is subtracted in the right hand of the formula (1) because the critical value of significance of the quantity $\|\overline{\mathbf{V}}_1 - \overline{\mathbf{V}}_7\|/\|\overline{\mathbf{V}}\|$ is 2 [*Li and Zeng*, 2000]. In this manner, in the Northern (Southern) Hemisphere, $\delta < 0$ represents winter (summer) monsoon, and $\delta > 0$ summer (winter) monsoon. Using the July climatological wind vector $\overline{\mathbf{V}}_7$ instead of $\mathbf{V}_i$ in the formula (1), the DNS index becomes the SNS index, and according to the DNS index of single point we can outline the global distribution of the monsoons [*Li and Zeng*, 2000]. As shown in *Li and Zeng* [2000], all the classical monsoons such as the Asia-Australia monsoon [*Webster et al.*, 1998; *Lau et al.*, 2000a] and the west Africa monsoon [*Ramage*, 1971; *Webster et al.*, 1998], and the American monsoon systems such as the North American monsoon [*Higgins and Shi*, 2000] and the South American monsoon [*Zhou and Lau*, 1998] are indicated in the significant regions of SNS.

[4] The annual cycle of the monsoon is a very important aspect of monsoon climate [*Webster et al.*, 1998; *Lau et al.*, 2000a; *Webster and Yang*, 1992; *Yanai and Liu*, 2000]. Figure 1 shows the seasonal variation of the areal average δ, referred to as the broad scale monsoon index, for eight key monsoon sectors of the South Asian, East Asian, South China Sea, African, North American, Australian, South American and Southern Equatorial West Indian Ocean. It could be found that the summer monsoon seasons of these regions are June–September, June–August, May–October, May–September, June–September, December–March, October–March and November–March, respectively. The periods are in fair agreement with the rainy seasons of these areas, respectively

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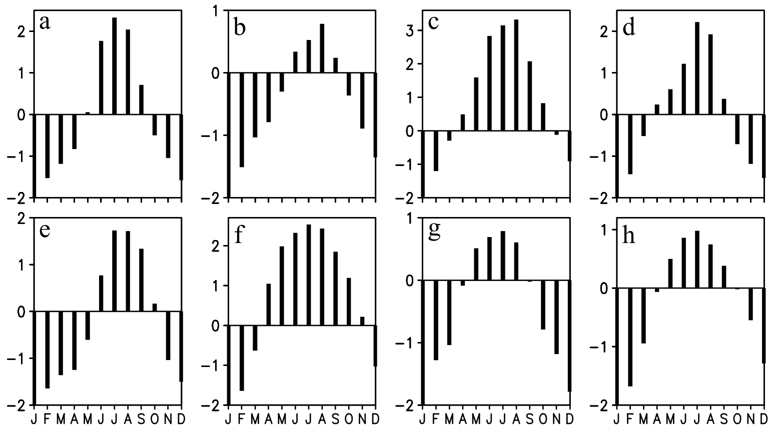

Figure 1. Seasonal variation of the DNS index calculated in the eight key monsoon sectors of (a), South Asian (5°–22.5°N, 35°–97.5°E) at 850hPa, (b), East Asian (10°–40°N, 110°–140°E) at 850hPa, (c), South China Sea (0°–25°N, 100°–125°E) at 925hPa, (d), African (5°–17.5°N, 20°W–40°E) at 850hPa, (e), North American (17.5°–35°N, 100°–120°W) at 700hPa, (f), Australian (5°–20°S, 100°–160°E) at 925hPa, (g), South American (10°–17.5°S, 50°–62.5°W) at 925hPa and (h), Southern Equatorial West Indian Ocean (0°–20°S, 37.5°–50°E) at 925hPa for the period 1979–99.

[*Ramage*, 1971; *Webster et al.*, 1998; *Tao and Chen*, 1987; *Lau et al.*, 2000b; *Higgins and Shi*, 2000; *Zhou and Lau*, 1998]. Hence, the DNS index can very well characterize the seasonal cycle of broad–scale monsoon circulation over different monsoon areas. For the sake of convenience, SASMI, ASMI, EASMI and SCSSMI represent the mean seasonal DNS index for the South Asian summer monsoon, African summer monsoon, East Asian summer monsoon and South China Sea summer monsoon, respectively.

[5] The South Asia summer monsoon (SASM) is a most typical monsoon. There are some good indicators of the monsoon strength for the SASM, i.e., the Webster and Yang Index (WYI) [*Webster and Yang*, 1992], MHI [*Goswami et al.*, 1999], AIRI [*Shukla and Paolino*, 1983; *Parthasarathy et al.*, 1994] and CI [*Wang and Fan*, 1999]. Table 1 lists the correlation coefficients between various SASM indices. The SASMI is well correlated with WYI, MHI and AIRI. The SASMI also exhibits a better correlation with AIRI than WYI and MHI do. Moreover, there is a similar pattern in the maps of correlation coefficients of AIRI and SASMI with respect to precipitation over the South Asian monsoon regime (Figures 2a and 2b). These indicate that the SASMI may be more effective in characterizing the interannual variation of Indian summer monsoon.

[6] The SASMI contains two independent components, SASMI1 and SASMI2 that are the DNS index for the summer monsoons of South Asian sub-sectors (2.5°–20°N, 35°–70°E) and (2.5°–20°N, 70°–110°E) respectively, with quite different relations with the monsoon rainfall over the South Asia. As shown in Table 1, there are the weak correlation between the SASMI1 and SASMI2, the strong correlations between SASMI1 and WYI, MHI, and AIRI, and the very poor correlations (~0.08) between SASMI2 and MHI or AIRI, in agreement with the studies of *Wang and Fan* [1999]. The region of significantly positive correlations between the SASMI1 and precipitation is confined to the most of north and central Indian-the Bay of Bengal (Figure 2c). The significantly negative correlations between the SASMI2 and precipitation are located in a broad area extending from the Arabian Sea across the tropical Indian Ocean to Indonesia and Malaysia (Figure 2d). It follows, therefore, that the summer rainfall anomalies over the South Asia associated with SASMI exhibit a north-south dipole pattern (Figure 2b).

[7] A remarkable feature of the African summer monsoon (ASM) different from other monsoons is that the ASM is dominated by variability on the decadal time-scale (Figure 3a). Moreover, the ASM occurred a decadal abrupt decrease in 1967 which may has the crucial role in reducing rainfall over the Sahel. The ASMI shows a very high correlation of 0.76 with the Sahel summer rainfall (Figures 3a and 3b). Moreover, a broad region of significantly positive correlations between the ASMI and summer rainfall over the African monsoon regime is just found

Table 1. Correlation Coefficients Between Various SASM Indices

	SASMI	WYI	MHI	AIRI	SASMI1	SASMI2
SASMI	1.00	**0.72**	**0.58**	**0.68**	**0.88**	**0.63**
WYI		1.00	**0.49**	**0.49**	**0.65**	**0.46**
MHI			1.00	**0.63**	**0.61**	0.08
AIRI				1.00	**0.73**	0.08
SASMI1					1.00	0.26
SASMI2						1.00

Calculations are based on seasonal means on June–September 1958–98. Coefficients that are significant at the 99.9% confidence level are bolded. SASMI, SASMI1 and SASMI2, see text. WYI [*Webster and Yang*, 1992], the zonal wind shear between 850hPa and 200hPa averaged over the area (0°–20°N, 40°–110°E). MHI [*Goswami et al.*, 1999], the meridional wind shear between 850hPa and 200hPa average over the region (10°–30°N, 70°–110°E). AIRI [*Shukla and Paolino*, 1983; *Parthasarathy et al.*, 1994], the seasonally average precipitation over the Indian subcontinent from June to September.

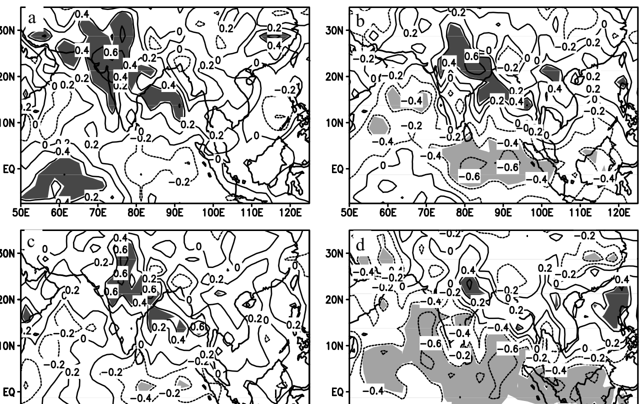

Figure 2. Correlations between the seasonal (June–September) rainfall and (a), AIRI, (b), SASMI, (c), SASMI1, and (d), SASAMI2 for the period 1979–97. Critical positive (negative) values of the correlation at the 95% confidence level are shaded dark (light).

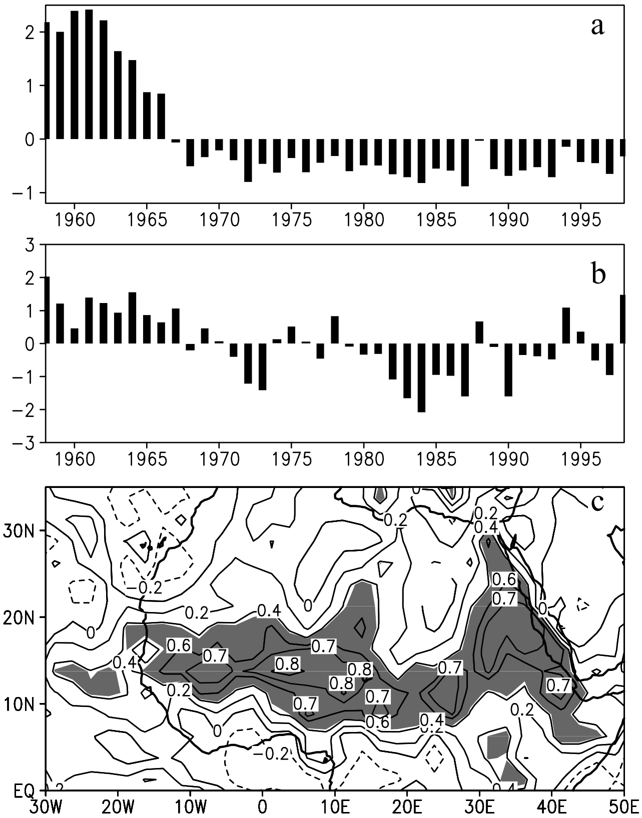

Figure 3. Normalized time series of ASMI (a) and summer rainfall (June–September) over the West African Sahel (12.5°–17.5°N, 20°W–30°E) from Hulme [*Hulme et al.*, 1998] (b) for the period 1958–98. (c), Correlations between the seasonal (June–September) rainfall from the Xie-Arkin rainfall analysis [*Xie and Arkin*, 1997] and DNS index for the ASM (1979–97). Critical positive (negative) values of the correlation at the 95% confidence level are shaded dark (light).

in the Sahel (Figure 3c). The analysis for moisture flux indicates that during the persistent weak African monsoon period (1967–98) the 925hPa flux of moisture from the Atlantic into the Sahel region is decreased by about 20–50% of the climatological values (1958–98) (not shown) and by about 40–80% of the average values for the strong African monsoon period (1958–66). As a result the supply of moisture for precipitation over there is insufficient. The facts imply that the persistent weak ASM can lead to a persistent reduction in moisture flux from the Atlantic into the Sahel. Additionally, the ASMI is significantly positively correlated with the summer rains in the Pakistan, northwest Indian, south Afghanistan and southeast Iran (not shown).

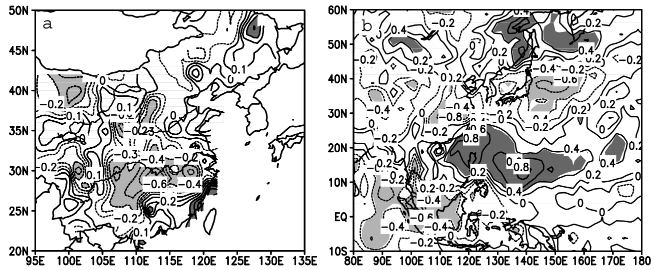

Figure 4. Correlations between the seasonal (June–August) East Asia index and (a), precipitation over China (1958–99), and (b), precipitation over the East Asia from the Xie-Arkin rainfall analysis [*Xie and Arkin*, 1997] (1979–97).

[8] The East Asian summer monsoon (EASM) belongs to the subtropical monsoon distinct from the tropical monsoon [*Tao and Chen*, 1987]. Figure 4a indicates that there is an apparent connection between the EASMI and the summer rainfall in the middle and lower reaches of the Yangtze River in China. Drought years over the valley are associated with the strong EASM, and flood years with the weak EASM (Figures 4a and 4b). Moreover, the correlations between the EASMI and summer precipitation in the East Asia clearly display a Pacific-Japan pattern (Figure 4b) found previously by Nitta et al [*Nitta*, 1987]. The EASMI has the largest positive correlation with convective activity over the vicinity of the Philippines and the warm pool region of the western Pacific.

[9] The South China Sea monsoon is an important subsystem of Asian-Australian monsoon [*Lau et al.*, 2000a, 2000b; *WCRP*, 1998] and has received a lot of attention recently [*Lau et al.*, 2000a]. As shown in Figure 5, during boreal summer, the SCSSMI exhibits strongly positive correlations with rainfall over the warm pool of the western Pacific, North Pacific between 10°N and 25°N, South American monsoon regime and southeast South Pacific, and is well negatively correlated with precipitation over a broad domain extending from the Arabian Sea across the tropical Indian Ocean to Indonesia and Malaysia, a region extending from the Central American across the Caribbean Island countries to the North Atlantic Ocean between 10°N and 20°N and the Indian Ocean regions adjacent to the south and west Australia. The global teleconnection pattern is remarkably strong. From Figure 6, the correlations between the seasonal (June–September) sea level pressure anomalies and SCSSMI appear a remarkable global-scale teleconnection pattern. In the strong (weak) SCSSMI stages large shifts in atmosphere mass occur so that the sea level pressure decreases

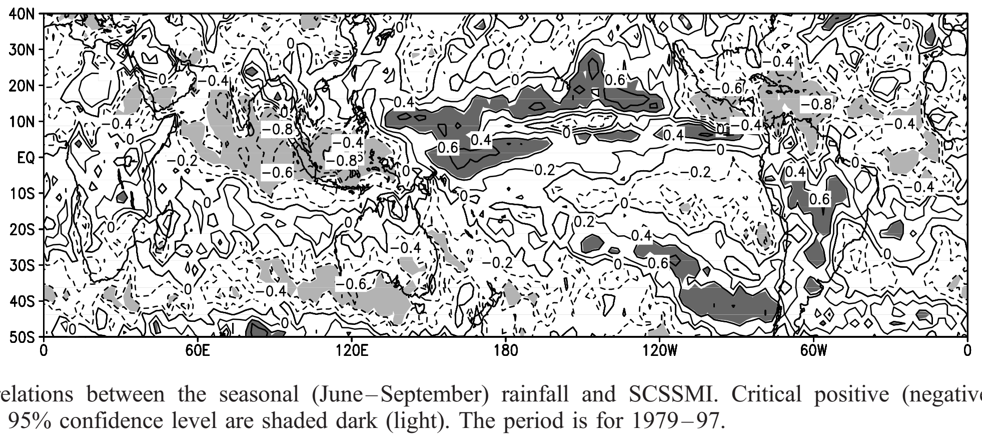

Figure 5. Correlations between the seasonal (June–September) rainfall and SCSSMI. Critical positive (negative) values of the correlation at the 95% confidence level are shaded dark (light). The period is for 1979–97.

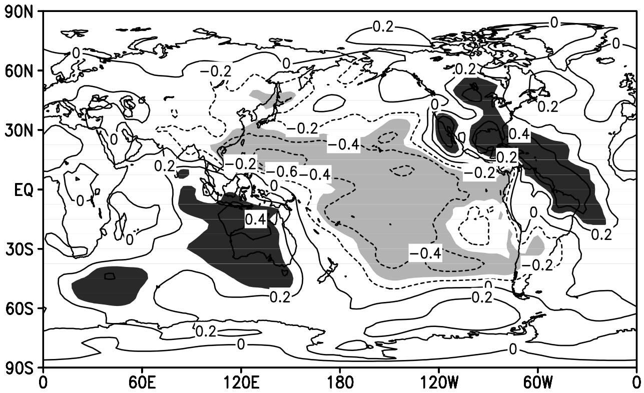

Figure 6. Horizontal distribution of the correlation coefficient between the seasonal (June–September) sea level pressure anomalies and SCSSMI for the period 1958–97. Critical positive (negative) values of the correlation at the 95% confidence level are shaded dark (light). The map shows that global shifts of atmospheric mass take place during strong South China Sea summer monsoon anomalies period.

(increases) over almost the entire Pacific Ocean and increases (decreases) over almost the entire Indian Ocean and the North America-Atlantic Ocean.

3. Summary

[10] There is strong evidence that the DNS index, a unified monsoon index we present, may be successful in describing the seasonal and interannual variability of the monsoons. By using the index some results are indicated, e.g. a north-south dipole pattern of correlations between SASMI and the summer rainfall anomalies over the South Asia, very strong positive correlation between ASMI and the Sahel summer rainfall, and the links between SCSSMI and the global precipitation, etc. However, the further mechanisms for these phenomena need to be more fully explored in the future. In a word, the DNS index, a dynamical monsoon index that has a unified solid dynamic basis, would be useful in understanding climate variability of the monsoon system and in exploring the relationship of monsoon variability with other major climate variations such as the El Niño-Southern Oscillation (ENSO).

[11] **Acknowledgments.** We would like to thank Dr. E. Kalnay for providing the NCEP/NCAR reanalysis data, Dr. M. Hulme for providing the historical monthly precipitation dataset from 1900 to 1998 (i.e., gu23wld0098.dat dataset, Version 1.0, 1999), and anonymous reviewers for their helpful comments and suggestions. This work was supported by the Projects G1998040900, KZCX2-203 and 40023001.

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