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A broad-scale circulation index for the interannual variability of the Indian summer monsoon

By B. N. GOSWAMI[1]*, V. KRISHNAMURTHY[2] and H. ANNAMALAI[3]
[1] *Indian Institute of Science, India*
[2] *Center for Ocean–Land–Atmosphere Studies, USA*
[3] *University of Reading, UK*

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SUMMARY

A broad-scale circulation index representing the interannual variability of the Indian summer monsoon is proposed and is shown to be well correlated with the interannual variability of precipitation in the Indian monsoon region. Using monthly precipitation analysis based on merging rain-gauge data with satellite estimates of precipitation for the period 1979–96, it is shown that the variability of precipitation on seasonal to interannual time-scales is coherent over a large region covering the Indian continent as well as the north Bay of Bengal and parts of south China. A new index, termed Extended Indian Monsoon Rainfall (EIMR), is defined as the precipitation averaged over the region 70°E–110°E, 10°N–30°N. The EIMR index is expected to represent the convective heating fluctuations associated with the Indian monsoon better than the traditional all India Monsoon Rainfall (IMR) based only on the precipitation over the Indian continent. It is shown that large precipitation over the Bay of Bengal with significant interannual variability cannot be ignored in the definition of Indian summer monsoon and its variability. The June-to-September climatological mean EIMR is found to be larger than that of the IMR even though the former is averaged over a larger area. The dominant mode of interannual variability of the Indian summer monsoon is associated with a dipole between the EIMR region and the north-western Pacific region (110°E–160°E, 10°N–30°N) and a meridional dipole between the EIMR region and the equatorial Indian Ocean (70°E–110°E, 10°S–5°N).

It is argued that the interannual variability of the monsoon circulation is primarily driven by gradients of diabatic heating associated with variations of the EIMR, and that the regional monsoon Hadley circulation is a manifestation of this heating. An index of the monsoon Hadley (MH) circulation is defined as the meridional wind-shear anomaly (between 850 hPa and 200 hPa) averaged over the same domain as the EIMR. Using circulation data from two independent reanalysis products, namely the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis and the European Centre for Medium-Range Weather Forecasts reanalysis, it is shown that the MH index is significantly correlated with the EIMR. Also it is shown that both the EIMR and MH indices have a dominant quasi-biennial variability, consistent with previous studies of IMR. Teleconnections of IMR, EIMR and MH indices with summer sea surface temperature (SST) have also been investigated. There are indications that the south equatorial Indian Ocean SST has a strong positive correlation with the EIMR. Also it is noted that the correlation of the monsoon indices with the eastern Pacific SST was weak during the period under consideration primarily due to almost a reverse relationship between monsoon and El Niño and Southern Oscillation during the latest eight years.

KEYWORDS: Meridional circulation Tropical precipitation

1. INTRODUCTION

The need for a large-scale circulation index for the Indian summer monsoon and its variability has been recognized for a long time. Such an index is useful as a diagnostic tool for studying the monsoon variability of the past as well as to evaluate the performance of general-circulation models in simulating the seasonal mean monsoon. Webster and Yang (1992) articulated this need and proposed a circulation index (hereafter referred to as the WY index) of the Indian summer monsoon as the zonal wind-shear (between 850 and 200 hPa) anomaly averaged over 40°E–110°E, 0°–20°N. The definition of 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 (Gill 1980; Webster and Yang 1992). The WY index is strongly correlated with the indices of El Niño and Southern Oscillation (ENSO) (Sperber and Palmer 1996), and is a good indicator of the planetary-scale variations of the Indian summer monsoon. However, the WY index has low correlation with the all India Monsoon Rainfall (IMR) index for the summer season defined by Parthasarathy *et al.*

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* Corresponding author: Centre for Atmospheric Sciences, Indian Institute of Science, Bangalore, India 560012.

(1992, 1995), a point also noted by Webster and Yang (1992, p. 897). If any circulation index represents response to the 'monsoon diabatic heating', it should correlate well with the 'monsoon precipitation', as the convective heating is the major component of the monsoon diabatic heating. One possible reason for the lack of correlation between the WY index and monsoon rainfall may be that the IMR index, based primarily on rain-gauge data over the Indian continent, is not representative of the total monsoon convective heating. With the availability of a global precipitation analysis based on rain-gauge data as well as satellite estimates for the period 1979–96 (Xie and Arkin 1996), we present a better representation of the summer monsoon convective heating variability. For this purpose, we will define a new broad-scale precipitation index for the Indian monsoon that includes precipitation not only over the Indian continent but also over the neighbouring oceans and land. We assert that this precipitation index is a more realistic estimate of the convective heating associated with the Indian summer monsoon. We will show that the WY index does not correlate well even with such an estimate of monsoon heating. Recently, Ailikun and Yasunari (1998) have shown that the WY index is more closely associated with the convective activity over the western Pacific and not with the convective activity over the Indian monsoon region. Since precipitation is an integral part of the definition of the Indian summer monsoon, any circulation index of the Indian summer monsoon should correlate well with the precipitation variability in the region. While the WY index may still be useful in representing the planetary-scale variations associated with the Indian summer monsoon, it does not represent the regional aspects of the Indian summer monsoon. The objective of the present study is to find an alternative circulation index that represents the regional character (not necessarily of small scale) of the Indian summer monsoon and also correlates well with Indian summer monsoon precipitation.

While it is important to recognize the planetary-scale component of the Indian summer monsoon and its role in modulating the summer precipitation in the region, the role of the regional-scale circulation cannot be ignored. The importance of the regional-scale circulation is illustrated by the climatological seasonal mean precipitation shown in Fig. 1. The most striking feature of the northern hemisphere (NH) summer mean climate is the large shift of the intertropical convergence zone (ITCZ) compared with its mean winter position. While the mean precipitation zone associated with the ITCZ is zonal in winter, centred around 5°S and extending from the Indian Ocean to the western Pacific, the mean position of the maximum precipitation zone shifts to about 20°N during the northern summer. A secondary band of precipitation is, however, still seen just south of the equator between 70°E and 100°E. The major component of the summer mean ITCZ in the northern summer is in a tilted position with its centre in the Indian region (between 15°N and 20°N) while its position in the western Pacific remains around 5°N. This mean displacement of the precipitation zone over the Indian region during the NH summer represents a strong asymmetric heat source. The heating gradients associated with such a heat source drives a regional Hadley circulation with ascending motion around 20°N, and descending motion from the equator to the southern hemisphere subtropics. The precipitation maximum and hence the ascending part of the Hadley circulation during the NH summer over the rest of the globe is, however, closer to the equator and centred around 5°N. It was first noted by Schulmann (1973) that the regional monsoon Hadley cell with reverse meridional circulation in the Indian monsoon region is strong enough to make the zonally averaged Hadley cell appear very weak during the NH summer (also see Peixoto and Oort 1992). The importance of the regional Hadley circulation in the monsoon rainfall was recognized by Joseph (1978) who showed that the mean meridional wind at 150 hPa in June, July and August over India was related to the seasonal monsoon precipitation. During the NH summer, an east–west Walker circulation exists with major ascending motion in the

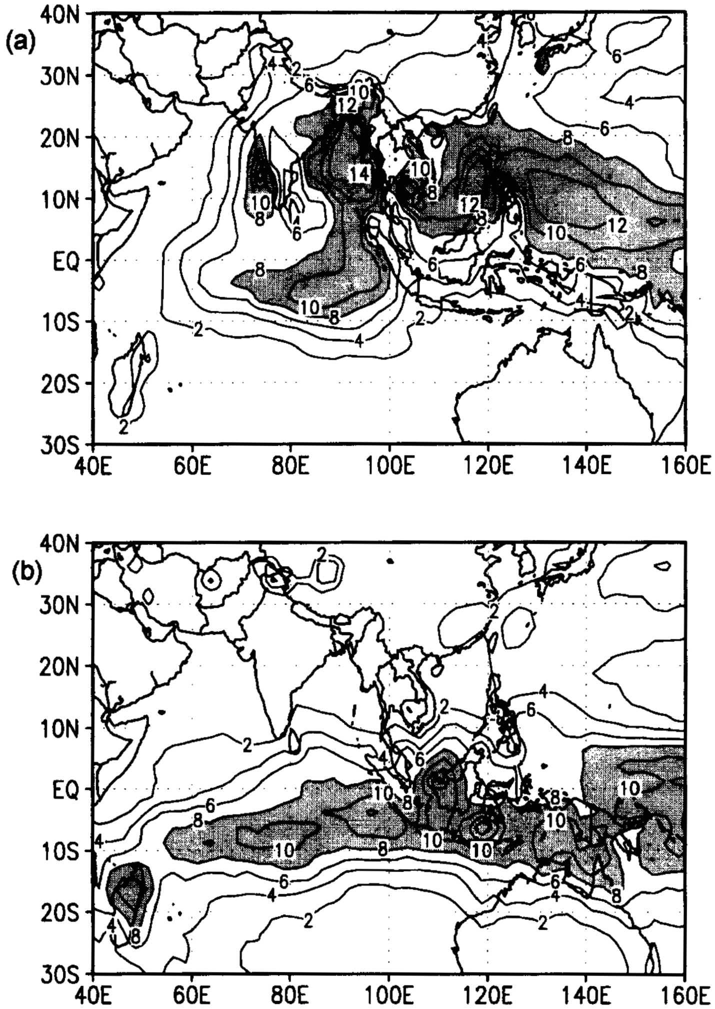

Figure 1. Climatology of precipitation (mm day^{-1}) for (a) the June to September season and (b) the December to February season using Xie–Arkin data for the period 1979–96. Values $\geqslant 8$ are shaded.

equatorial western Pacific and Indonesia and subsidence over the equatorial Indian Ocean. Thus, the Indian summer monsoon may be viewed as a superposition and interaction between a regional Hadley circulation and a planetary-scale Walker circulation (Goswami 1994). This view is similar to the lateral and transverse monsoons discussed in a review by Webster *et al.* (1998). The regional Hadley circulation is due to the direct response of the off-equatorial monsoon heat source while the Walker circulation is due to equatorial heat sources. The Walker circulation over the equatorial Indian Ocean may be influenced remotely by the movement of equatorial heat sources in the Pacific such as those associated with ENSO. The regional Hadley circulation can be affected by changes in the location and strength of the monsoon heat source.

In this study we define a broad-scale circulation index that represents the strength of the regional Hadley circulation and show that it correlates well with the monsoon precipitation. The dynamical basis for this index is more or less the same as the one proposed by Webster and Yang (1992). However, we note that the heating gradients associated with an off-equatorial heat source drives a strong Hadley circulation (Gill 1980). Assuming a first baroclinic response, meridional wind shear is an appropriate choice to represent the strength of the Hadley circulation. Therefore, we use anomalous meridional wind shear averaged over the monsoon region as an index of the monsoon circulation. The data used are described in section 2. The broad-scale precipitation index and its relation with the IMR are described in section 3. The interannual variability of the monsoon Hadley circulation index and its relation with the monsoon precipitation are discussed in section 4. The relationship between the monsoon Hadley (MH) circulation index and other global circulation features such as sea surface temperature (SST) variations associated with ENSO and the WY index is discussed in section 5. The main conclusions of the study are summarized in section 6.

2. DATA

As one of the objectives of this study is to construct a more general Indian monsoon rainfall index, we have used the new monthly precipitation analysis created by Xie and Arkin (1996), covering the period January 1979 to December 1996. This analysis is based on merging of rain-gauge observations over land and satellite-derived precipitation estimates covering global land and ocean. As this dataset provides relatively uniform precipitation estimates over both land and ocean, it is now possible to make reliable estimates of the large-scale variability of precipitation in the tropics. For the purpose of comparison, we have used the monthly IMR data based on rainfall observed at land stations uniformly distributed over India (Parthasarathy *et al.* 1995) for the period 1979–96.

The main circulation data used in this study are the products of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis project (see Kalnay *et al.* (1996) for details) that is based on a frozen state-of-the-art global data-assimilation system that includes a T63 forecast model and a database that is as complete as possible. Due to the fact that the analysis system and the model used remain unchanged throughout the period, the reanalysed data provide probably the best available circulation data for studying interannual variability. In this study monthly mean winds at standard pressure levels from the reanalysis data for the period January 1979 to December 1996 were used in most calculations, but data for the extended period January 1958 to December 1996 were used in certain calculations. We also examine the circulation based on the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA) data for the period 1979–93. The ERA was performed with a spectral version of the ECMWF operational data-assimilation system that includes a spectral T106 forecast model with 31 hybrid vertical levels (see Gibson *et al.* (1997) for details). To study the teleconnections with global SST, we have used the revised version of the Global Sea Ice and Sea Surface Temperature dataset (GISST 2.3a), created by the Hadley Centre for Climate Prediction and Research (see Parker *et al.* (1995) for a description of an earlier version of the dataset).

3. INDIAN SUMMER MONSOON RAINFALL AND ITS INTERANNUAL VARIABILITY

(*a*) *The Extended Indian Monsoon Rainfall (EIMR) index*

In this section we provide an objective definition of the Indian summer monsoon precipitation. Traditionally, the Indian monsoon has been defined by the IMR index that is based on a weighted average of rainfall observed at 306 well distributed rain-gauge stations over India (Shukla 1987; Parthasarathy *et al.* 1992, 1995). The IMR index served as an important indicator of climatic extremes such as droughts and floods in India. However, since this index does not take into account the precipitation even over the neighbouring ocean, it may not fully represent the integral convective monsoon heating. Originally, the IMR index was probably not intended for such a use. Figure 1 shows the June–September (JJAS) and December–February (DJF) climatological mean precipitation, based on the period 1979–96, from the precipitation analysis of Xie and Arkin (1996). An important characteristic of the Indian region is the presence of two maxima in the JJAS precipitation climatology (Fig. 1(a)), with a stronger continental precipitation zone (10°N–30°N) and a weaker equatorial Indian Ocean precipitation zone (10°S–5°N). In contrast to the earlier datasets, such as the climatologies constructed by Legates and Willmott (1990), the equatorial precipitation zone is stronger in the Xie–Arkin dataset. This difference may be due to the fact that the earlier climatologies were based on a small sample of observations over the ocean and probably underestimated the oceanic precipitation. Over most of the Indian continent, the amount of precipitation is between 4 and 8 mm day^{-1}, which is smaller than that (8–12 mm day^{-1}) over the northern Bay of Bengal, Bangladesh, parts of southern China and off the coast of the western Ghats. Therefore, to understand the Indian summer monsoon circulation variability, we must take into account the precipitation in the regions adjoining the Indian continent also. For this purpose, it is important to define a core monsoon precipitation region that varies coherently in space and time.

To identify the regions over which the summer monsoon precipitation variability is coherent, we conducted an empirical orthogonal function (EOF) analysis of the monthly precipitation from the Xie–Arkin dataset for the northern summer months (JJAS) of the period 1979–96. In this EOF analysis, monthly precipitation anomalies are used after removing the long-term mean, and the domain is chosen to be 40°E–160°E, 30°S–40°N. The first two EOFs and their time coefficients (principal components or PCs) are shown in Fig. 2. The first EOF explains 18.3% of the spatially averaged variance while the second EOF explains 10.5%. The first EOF represents the seasonal transition of the precipitation band while the second EOF represents the interannual variability. The second EOF shows that the interannual variability of the Indian summer monsoon is distinct from that of the western Pacific monsoon and equatorial Indian Ocean monsoon. We term the summer rainfall in the continental region (70°E–110°E, 10°N–30°N) as the 'extended Indian monsoon rainfall' (EIMR) and that over the oceanic region (70°E–110°E, 10°S–5°N) as the 'equatorial Indian Ocean monsoon rainfall'. We note that the western Pacific monsoon also has a north–south fluctuation on seasonal and interannual time-scales. As there is only one climatological maximum in this region, this dipole is due to the north–south displacement of the climatological pattern. We distinguish the two parts by calling the region 110°E–160°E, 10°N–30°N as the 'north-western Pacific monsoon region' and the region 110°E–160°E, 10°S–10°N as the 'south-western Pacific monsoon region'.

Since the first two EOFs together explain only about 29% of the total area-averaged variance, the EOFs by themselves are not sufficient to establish that the summer monsoon rainfall fluctuates coherently over the entire EIMR region on an interannual time-scale. To determine whether the interannual variation of the seasonal mean monsoon is coherent over the EIMR regions, we examine the simultaneous correlations of the EIMR with JJAS precipitation over all points presented in Fig. 3. The positive correlations over the entire EIMR region establishes that the interannual variation of the seasonal summer mean precipitation is indeed coherent over the EIMR region. Figure 3 also shows that the dominant interannual variability of the Indian summer monsoon is characterized by a north–south dipole pattern between the EIMR region and the equatorial Indian Ocean, and an east–west dipole pattern between the EIMR region and the north-western Pacific monsoon region. As the precipitation over the extended region is homogeneous and fluctuates coherently, the EIMR index is a more objective definition of the Indian summer monsoon.

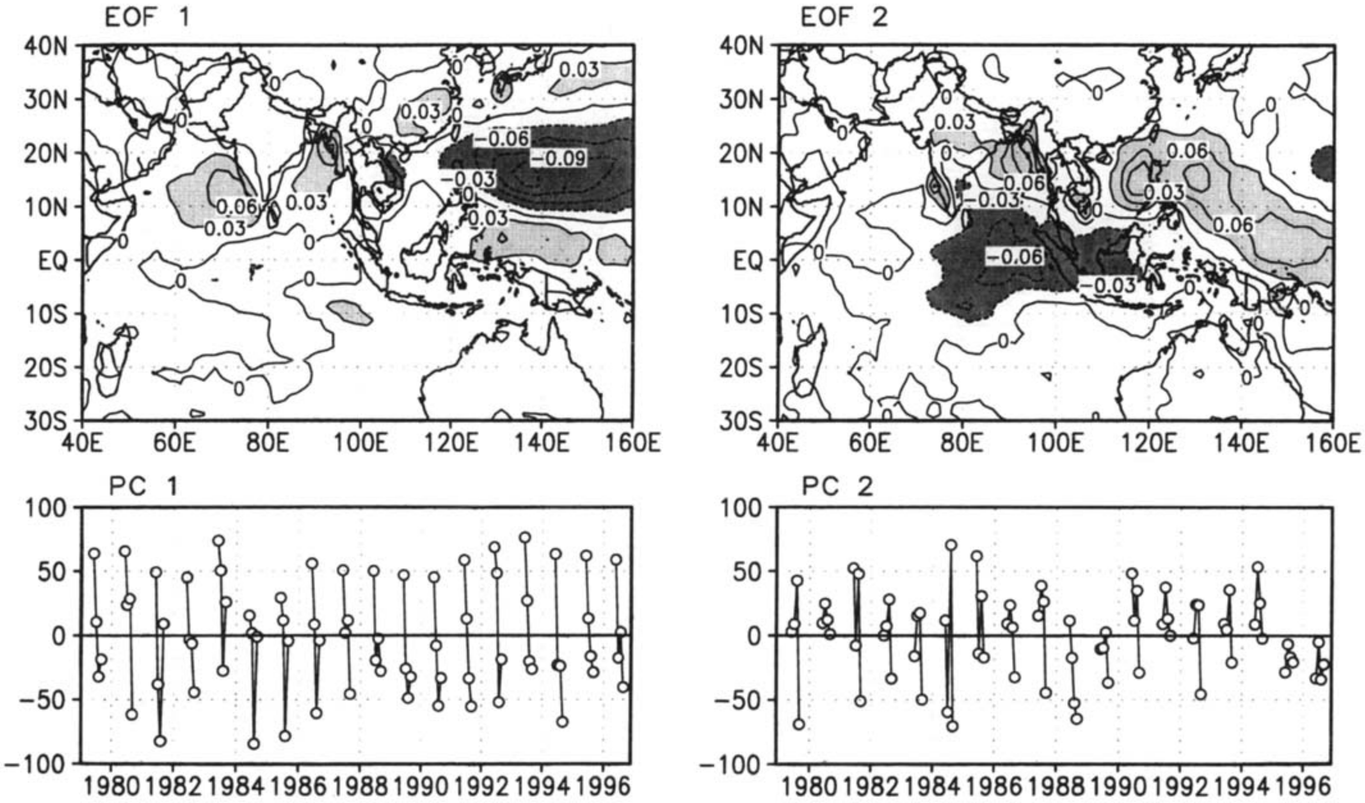

Figure 2. First two empirical orthogonal functions (EOFs) and their principal components (PCs) of monthly precipitation of Xie–Arkin data for June to September months of the period 1979–96. Areas $\geqslant 0.03$ and $\leqslant -0.03$ are in light and dark shades, respectively.

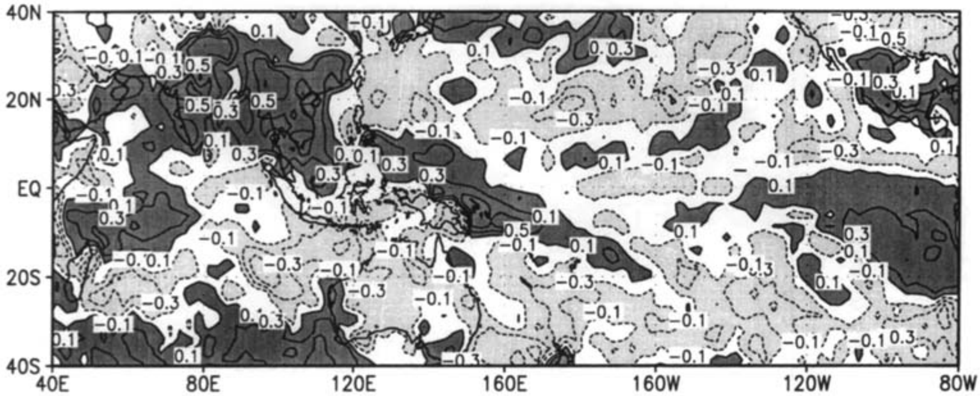

Figure 3. Simultaneous point correlations of the Extended Indian Monsoon Rainfall with June to September precipitation at all grid points. Areas $\leqslant -0.1$ and $\geqslant 0.1$ are in light and dark shades, respectively.

Figure 4(a) shows the annual cycle of the precipitation averaged over four regions, namely, (i) the EIMR region, (ii) the Indian continent, (iii) the northern Bay of Bengal, and (iv) the western Pacific. We see that the annual cycle and the mean summer precipitation in the EIMR region and the Indian continent are very similar. It is important to note that the mean summer precipitation over the northern Bay of Bengal is about 75% higher than that observed over the Indian continent. This large component of the Indian monsoon precipitation is excluded in the traditional indices of Indian monsoon rainfall (e.g. the IMR of Parthasarathy *et al.* (1995)). Other characteristics of the annual cycle of the Indian summer monsoon, such as the rapid onset between May and June, the sustained high precipitation during June-August and the slow withdrawal during September–October, are clearly evident in Fig. 4(a). The annual cycle of the western Pacific region is somewhat different from that of the Indian region. The western Pacific monsoon rainfall peaks in August and decreases slowly thereafter. As a result, the winter rainfall is larger over the western Pacific than over the Indian region. The fluctuations between the Indian monsoon and the north-western Pacific monsoon are further illustrated in Fig. 4(b), which shows the seasonal (JJAS) anomaly of precipitation averaged over three regions. We note that the oceanic component of the Indian summer monsoon (i.e. over the northern Bay of Bengal) has large interannual variability. Therefore, the interannual variability of the Indian summer monsoon cannot be adequately described without taking the oceanic component into account. The Bay of Bengal variability is negatively correlated with the north-western Pacific variability, consistent with the dipole pattern seen in Fig. 2.

(*b*) *EIMR and IMR*

To examine whether the EIMR index defined in this study is substantially different from the traditional IMR index (Mooley *et al.* 1986; Parthasarathy *et al.* 1995), the seasonal (JJAS) mean precipitation for the period 1979–96 is shown for both indices in Fig. 5. Significantly, even though the EIMR index is averaged over a much larger area, it is always equal to or higher than the IMR index. As a result, the climatological mean of the EIMR (8.19 mm day^{-1}) is larger than that of the IMR (6.84 mm day^{-1}). Although the interannual variations of the two indices are similar in most years, there are notable exceptions. For example, the IMR is much below normal during 1986 and 1987 while the EIMR is slightly below normal. Similarly, the IMR is above normal during 1989 while the EIMR is significantly below normal. The sign of the anomaly is opposite for

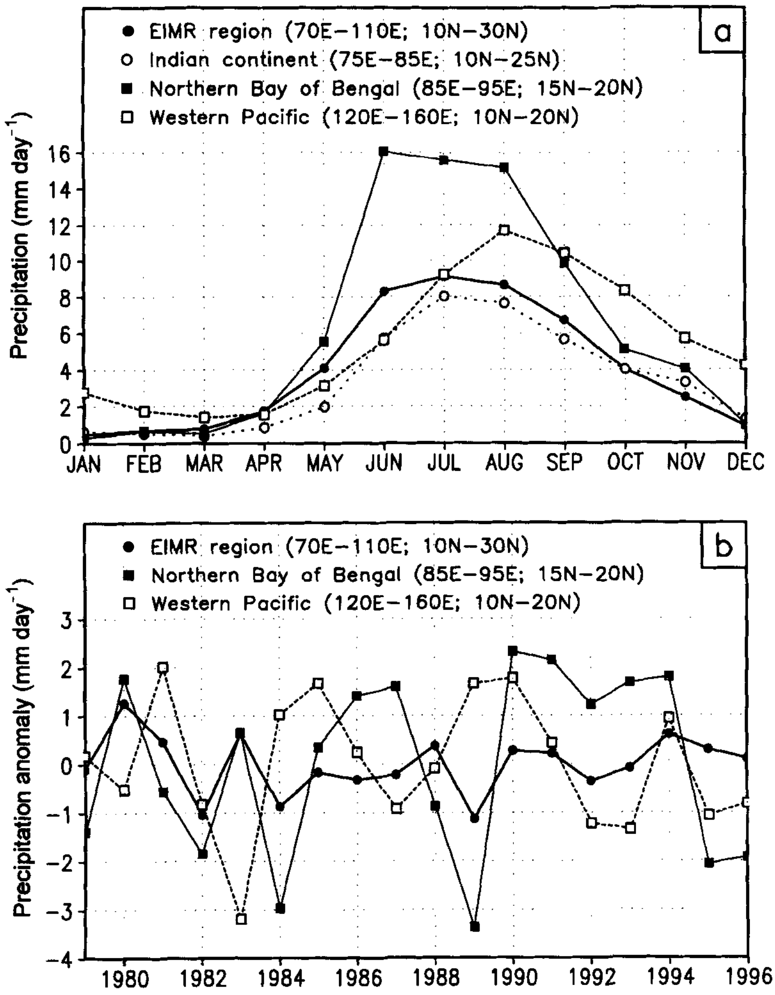

Figure 4. (a) Annual cycle of precipitation (mm day^{-1}) averaged over (i) the Extended Indian Monsoon Rainfall (EIMR) region, (ii) the Indian continent, (iii) the northern Bay of Bengal, and (iv) the western Pacific. (b) Seasonal anomaly of June–September precipitation averaged over regions (i), (iii), and (iv).

the two indices during 1991 as well, although both are close to normal. Because of these differences, the IMR is not a good representation of the convective heating associated with the Indian monsoon. These differences arise because the IMR index does not include the large precipitation over the Bay of Bengal that has significant interannual variability as seen in Fig. 4.

(*c*) *A dynamical circulation index*

From the preceding discussion, it is clear that the Indian summer monsoon represents a large-scale heat source situated off the equator at a mean position of about 20°N. The linear theory of the atmospheric response to such a heat source (Gill 1980) predicts that it will be associated with a strong Hadley circulation. Assuming that dissipation is negligible, the steady-state vorticity balance of the atmospheric response to such a heat source is governed by

$$V = yQ/gH, \tag{1}$$

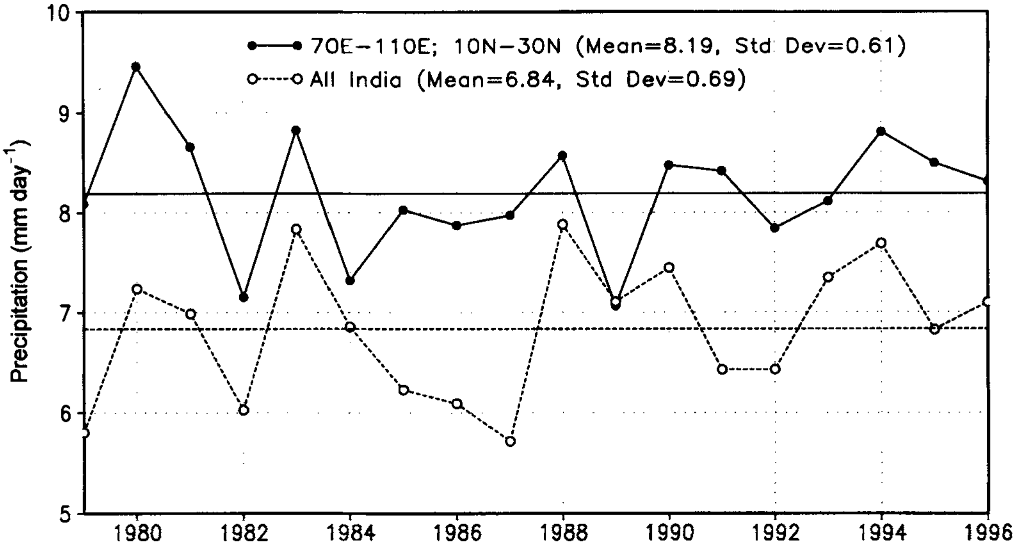

Figure 5. Seasonal (June to September) mean precipitation (mm day^{-1}) averaged over the Extended Indian Monsoon Rainfall region (solid) and all India monsoon rainfall (dashed) for the period 1979–96.

where V is the meridional velocity, y is the distance from the equator, g is the acceleration due to gravity, H is the equivalent depth of the first baroclinic mode and Q is proportional to the heating rate (see Gill (1980, p. 456) for a nondimensional form of Eq. (1)). As the convective heating has a maximum in the middle troposphere, the response is expected to be baroclinic. Thus, the shear of the meridional wind between the lower and upper troposphere is expected to be a good indicator of the Hadley circulation. Therefore, based on Eq. (1), a circulation index for the monsoon may be defined in terms of $V_{850} - V_{200}$, where V_{850} and V_{200} are the meridional velocities at 850 hPa and 200 hPa, respectively, averaged over the same region as the EIMR region, i.e. 70°E–110°E, 10°N–30°N. The time series of V_{850} and V_{200} from the NCEP/NCAR reanalysis data for the period 1979–96 are shown in Fig. 6(a). While the annual cycle is clearly visible, the out-of-phase relationship between V_{850} and V_{200} reaffirms the baroclinic nature of the circulation. We note that the meridional wind shear is positive during northern summer and negative during northern winter. The summer shear is consistent with Eq. (1) for a heat source in the northern hemisphere. The anomaly of the meridional wind shear after removing the annual cycle and averaged over the same region is shown in Fig. 6(b). It is clear that the mean amplitude as well as the anomaly are large during the NH winter. During the NH summer, the mean amplitude is about 4 m s^{-1} and the maximum interannual variability is about 0.8 m s^{-1} (20% of the mean), indicating considerable interannual variability. Based on these dynamical considerations, we define a broad-scale circulation index, termed the monsoon Hadley (MH) index, for the Indian summer monsoon variability as

$$\mathrm{MH} = V_{850}^{*} - V_{200}^{*}, \tag{2}$$

where V_{850}^{*} and V_{200}^{*} are, respectively, the meridional wind anomalies at 850 hPa and 200 hPa averaged over the season (June–September) and over the extended monsoon region (70°E–110°E, 10°N–30°N).

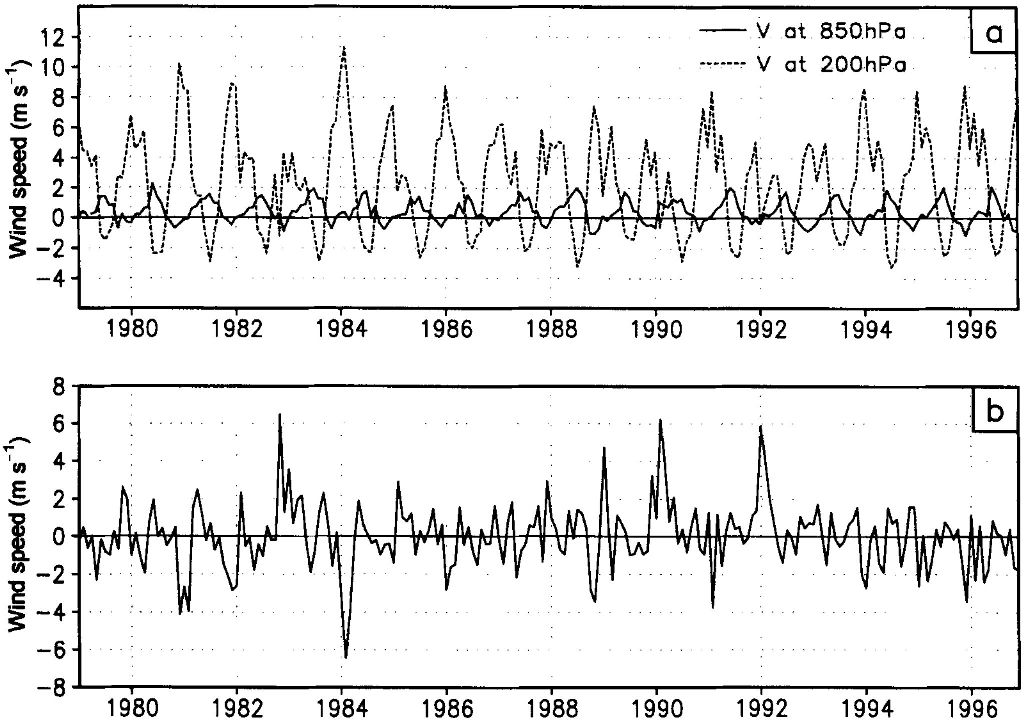

Figure 6. Time series of (a) the meridional wind (m s^{-1}) at 850 hPa (V_{850}) and 200 hPa (V_{200}) averaged over (70°E–110°E, 10°N–30°N) and (b) the monthly anomaly of meridional wind shear ($V^*_{850} - V^*_{200}$) averaged over the same region.

4. INTERANNUAL VARIABILITY OF PRECIPITATION AND CIRCULATION INDICES

We now examine the relationship between the monsoon circulation index (MH index) and the monsoon precipitation index (EIMR index). The MH index is calculated using two datasets, namely, the NCEP/NCAR reanalysis for the period 1979–96 and the ERA for the period 1979–93. We have also calculated the WY index based on the same datasets. The WY index is $U^*_{850} - U^*_{200}$, where U^*_{850} and U^*_{200} are, respectively, the zonal wind anomalies at 850 hPa and 200 hPa averaged over 40°E–110°E, 0°–20°N. The EIMR index and the MH index are both averaged over 70°E–110°E, 10°N–30°N. All the indices are averages over the summer season (June–September). Figure 7(a) shows the three indices, each normalized by its own interannual standard deviation, based on NCEP/NCAR reanalyses and Xie–Arkin precipitation data for the period 1979–96. Similarly, the three indices based on the ERA and Xie–Arkin precipitation data are shown in Fig. 7(b) for the period 1979–93. These two figures clearly show that both datasets indicate a strong relationship between the MH index and the EIMR index.

The statistics of the indices, their correlation with the precipitation index, as well as cross correlation between the indices, are presented in Tables 1 and 2. It is clear from Fig. 7 and from Table 1 that the MH index based on the NCEP/NCAR reanalysis is strongly related to the monsoon precipitation over a wider area (EIMR region). We also note that both the EIMR and MH indices are significantly correlated with the traditional monsoon rainfall index, IMR. All the monsoon indices (IMR, EIMR and MH) have negative but insignificant correlation with the eastern pacific SST (SST anomaly (SSTA) averaged over the NINO3 area (150°W–90°W, 5°S–5°N)) during this period. Similarly, Table 2 shows

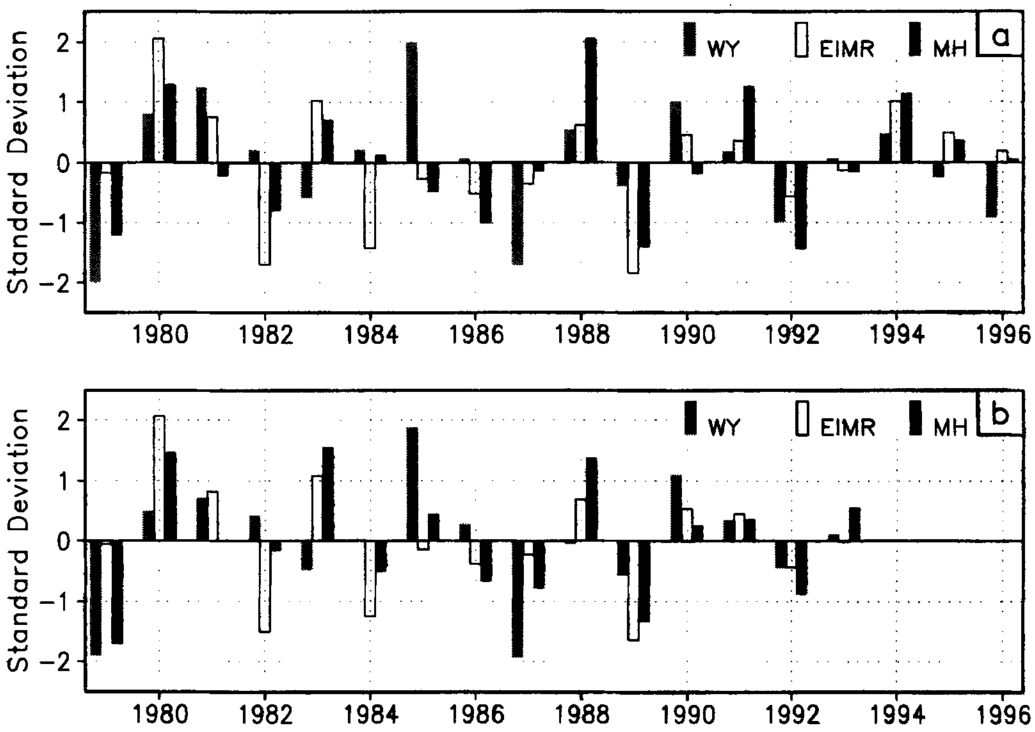

Figure 7. (a) Standardized MH and WY indices based on NCEP/NCAR reanalysis data and precipitation index (EIMR) based on Xie–Arkin data for the period 1979–96. (b) Same as in (a) but the MH and WY indices are now based on the ERA for the period 1979–93. All the indices are normalized by their own standard deviations. See text for further explanation.

TABLE 1. CROSS CORRELATION BETWEEN DIFFERENT INDICES USING THE NCEP/NCAR REANALYSIS (1979–96)

Index	IMR	EIMR	MH	WY
IMR (0.69)	1.0			
EIMR (0.61)	0.50*	1.0		
MH (0.36)	0.59**	0.69**	1.0	
WY (1.38)	0.35	0.24	0.31	1.0
NINO3 SSTA (0.58)	−0.38	−0.09	−0.27	−0.51*

The standard deviations of the IMR (mm day^{-1}), EIMR (mm day^{-1}), MH index (m s^{-1}), WY index (m s^{-1}), and NINO3 SSTA (degC) are shown in parentheses. Statistical significance at the 95% and 99% levels are shown by one and two asterisks, respectively. See text for explanation of the indices used.

TABLE 2. CROSS CORRELATION BETWEEN DIFFERENT INDICES USING THE ECMWF REANALYSIS (1979–93)

Index	IMR	EIMR	MH	WY
IMR (0.71)	1.0			
EIMR (0.65)	0.45	1.0		
MH (0.37)	0.69**	0.71**	1.0	
WY (1.68)	0.28	0.17	0.49	1.0
NINO3 SSTA (0.63)	−0.37	−0.03	−0.19	−0.44

Conventions are the same as in Table 1.

that the MH index based on the ERA is also strongly related to the monsoon precipitation. The WY index based on both datasets has insignificant correlation with the EIMR (or IMR) during this period. Thus, even though the original premise of the WY index was that it should represent the baroclinic response to the monsoon heating, it appears that other processes may also be contributing to it. The consistent relationship between the MH index based on two independent datasets and the EIMR index indicates the robustness of the MH index as a circulation index for the Indian summer monsoon variations. The above discussion validates our earlier assertion that if we can derive a reliable estimate (index) of the monsoon heat source it should relate to a measure of the intensity of the regional Hadley circulation.

Characterizing the monsoon as 'strong' and 'weak' on the basis of precipitation over the EIMR region and constructing the composites (strong and weak) of precipitation and V shear over the monsoon region, we can illustrate that the regional Hadley circulation waxes and wanes during strong and weak monsoons, respectively. Using the criterion that the years with JJAS seasonal precipitation anomalies greater than 0.5 standard deviation are considered as strong monsoons while those years with less than −0.5 standard deviation are considered as weak monsoons, the strong composites are formed from JJAS anomalies of 1980, 1981, 1983, 1988 and 1994, and weak composites are formed from JJAS anomalies of 1982, 1984, 1986, 1989 and 1992. With the exception of 1987, which does not appear as a weak monsoon averaged over the EIMR region, all the other strong and weak monsoon years defined on the basis of this index agree with those defined on the basis of the IMR alone (Parthasarathy *et al.* 1992, 1995). The difference between the strong and weak composites of precipitation anomaly, V-shear anomaly and U-shear anomaly are shown in Fig. 8. Clearly, the positive precipitation anomalies over the extended monsoon region are associated with positive V-shear anomalies. Also, the increased precipitation during a strong monsoon over the Indian monsoon region is accompanied by a decrease in precipitation over the equatorial eastern Indian Ocean. Figure 8 clearly indicates that the major mode of the interannual variations of the Indian summer monsoon precipitation consists of a bimodal meridional structure between the EIMR region and the equatorial Indian Ocean, and a bimodal structure between the EIMR region and the north-western Pacific. The composite of precipitation anomaly (Fig. 8(a)) also shows that the variability of precipitation is homogeneous in the EIMR region, as asserted in section 3(a). The composite of the V-shear anomaly (Fig. 8(b)) shows the transition from negative to positive V shear near the equator, representing a divergence at low levels or a region of subsidence. Similar transition around 30°N represents a region of ascending motion. In other words, the circulation consists of an anomalous ascent around 30°N and descent around the equator during a strong monsoon, and a reverse anomalous meridional circulation during a weak monsoon. With a similar anomalous cell in the southern hemisphere, the meridional scale of the anomalous Hadley circulation is about 30°.

To illustrate the characteristics of the mean and anomalous Hadley circulations in some detail and to establish that $V^*_{850} - V^*_{200}$ is a good measure of the anomalous Hadley circulation, we present a latitude–height section of the climatological seasonal (JJAS) mean meridional winds averaged over 70°E–110°E in Fig. 9(a). A strong regional Hadley circulation with ascending motion around 30°N and descending motion around 30°S is indicated in Fig. 9(a). Using the same strong and weak monsoon years as before, we show the difference between the strong and weak composites of JJAS anomaly of V averaged over 70°E–110°E in Fig. 9(b). The coherent and large differences between the anomalous strong and weak composites suggest that the locations of the ascent and descent during strong and weak years are the same, and the anomalous Hadley circulation changes sign from strong to weak monsoon years. Figure 9(b) also shows that the ascent over

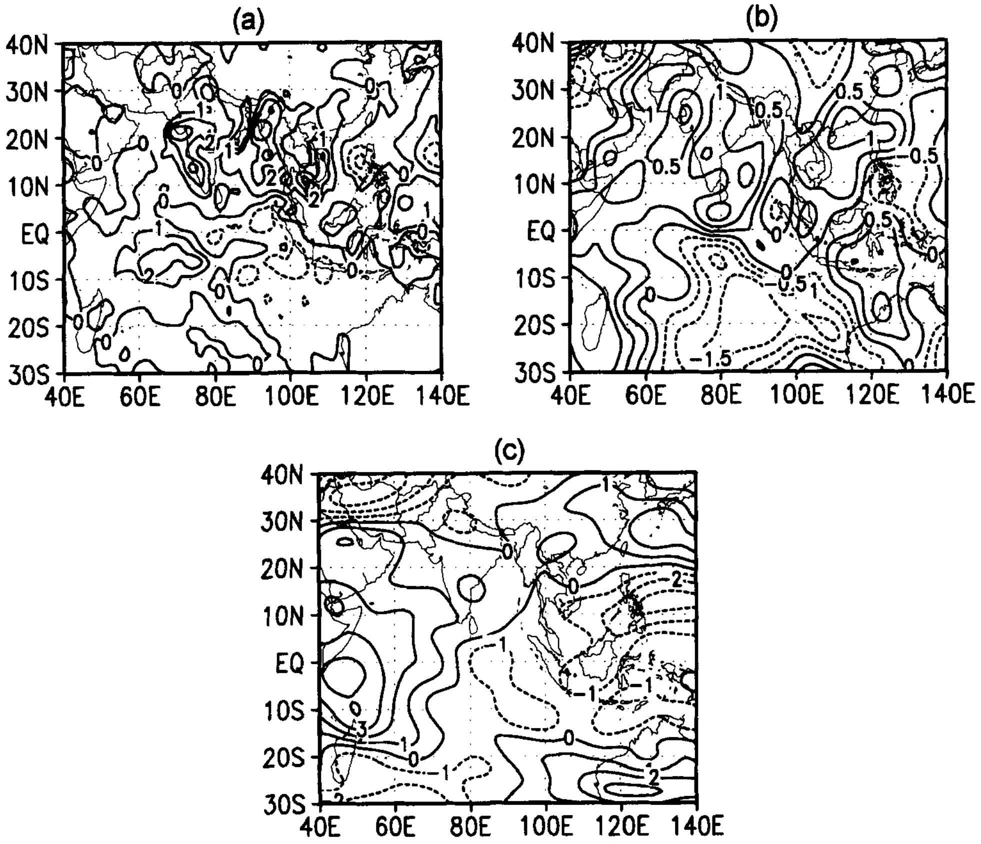

Figure 8. Difference between 'strong' and 'weak' composites of seasonal (June to September) anomalies of (a) precipitation (mm day^{-1}), (b) $V^*_{850} - V^*_{200}$ (m s^{-1}), and (c) $U^*_{850} - U^*_{200}$ (m s^{-1}), see text. The 'strong' years are 1980, 1981, 1983, 1988 and 1994 while 'weak' years are 1982, 1984, 1986, 1989 and 1992. Negative values are shown dashed.

the monsoon continent is enhanced during strong monsoon years compared with that during weak monsoon years. As the meridional wind anomalies change sign between the lower and upper atmosphere, $V^*_{850} - V^*_{200}$ is a good measure of the strength of the anomalous Hadley circulation. The above conclusions are strictly valid only if there is no flow across the eastern and western boundaries of the averaging region. Even if there is some cross boundary flow, the qualitative conclusions are expected to be valid for the regional circulation.

A comparison between Fig. 1 and Fig. 8 explains why the mean Hadley circulation has a much larger meridional scale than the anomalous Hadley circulation. For the mean, the entire region from the equatorial Indian Ocean to 30°N is a forcing region with ascending motion in the northern hemisphere and descending motion in the southern hemisphere. For the interannual variability, the forcing is limited to a much smaller meridional scale (Fig. 8), leading to a smaller meridional scale for the anomalous Hadley circulation.

Having established that the MH index represents the strength of the Indian summer monsoon circulation, we also examined the index for the earlier period (1958–78) of the NCEP/NCAR reanalysis. As an observed precipitation analysis is not available for this period, we cannot define the EIMR with confidence over this period. Therefore, we

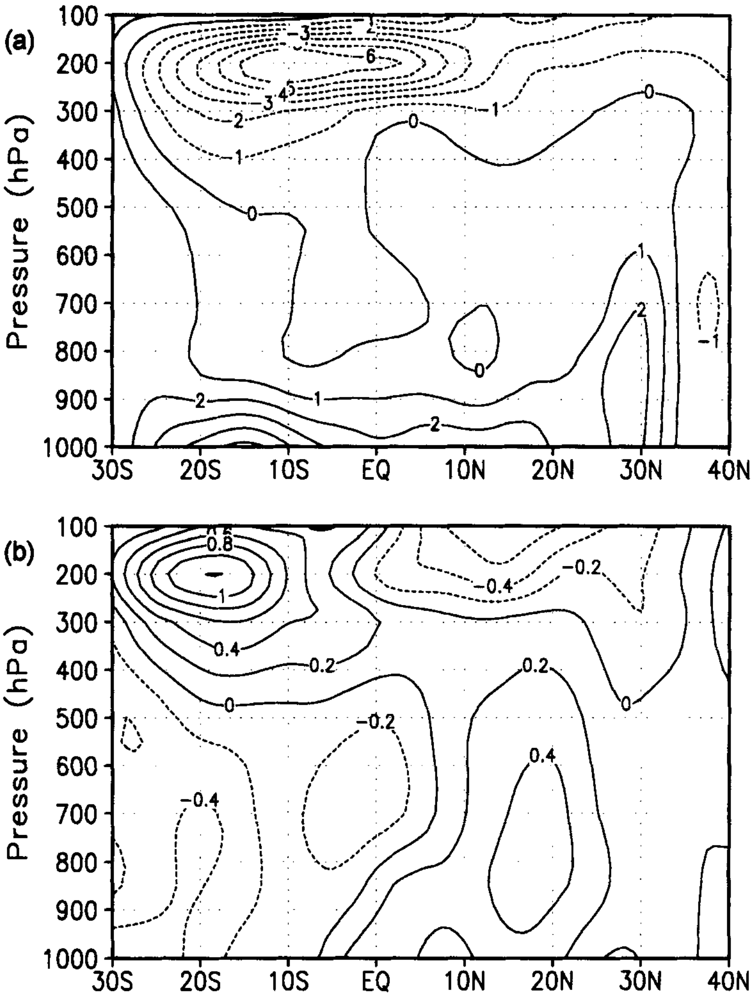

Figure 9. (a) Climatological seasonal mean (June to September (JJAS)) of the regional Hadley circulation (i.e. climatological mean meridional wind (m s^{-1}) averaged over 70°E–110°E as a function of latitude and height). (b) Difference between 'strong' and 'weak' composites of the anomalous regional summer Hadley circulation (i.e. seasonal (JJAS) meridional wind anomaly averaged over 70°E–110°E for the same 'strong' and 'weak' years as in Fig. 8). Negative values are shown dashed.

examined the relation between the MH index and the IMR. The correlation between the MH index and IMR during this period is found to be 0.68 (significant at 99% level). Thus, it appears that the MH index is a good indicator of the strength of the Indian summer monsoon during 1958–78 also.

5. RELATIONSHIP WITH THE TBO AND ENSO

In this section, we examine how the indices of monsoon rainfall (EIMR) and circulation (MH) relate to other measures of large-scale tropical variability. First, we investigate the relationship between the MH index and the WY index based on the 18-year NCEP/NCAR reanalysis data. We then investigate how the MH index relates to the tropical biennial oscillation (TBO) and ENSO. While the dynamical basis for the WY index appears sound, the WY index still does not correlate well with the monsoon precipitation,

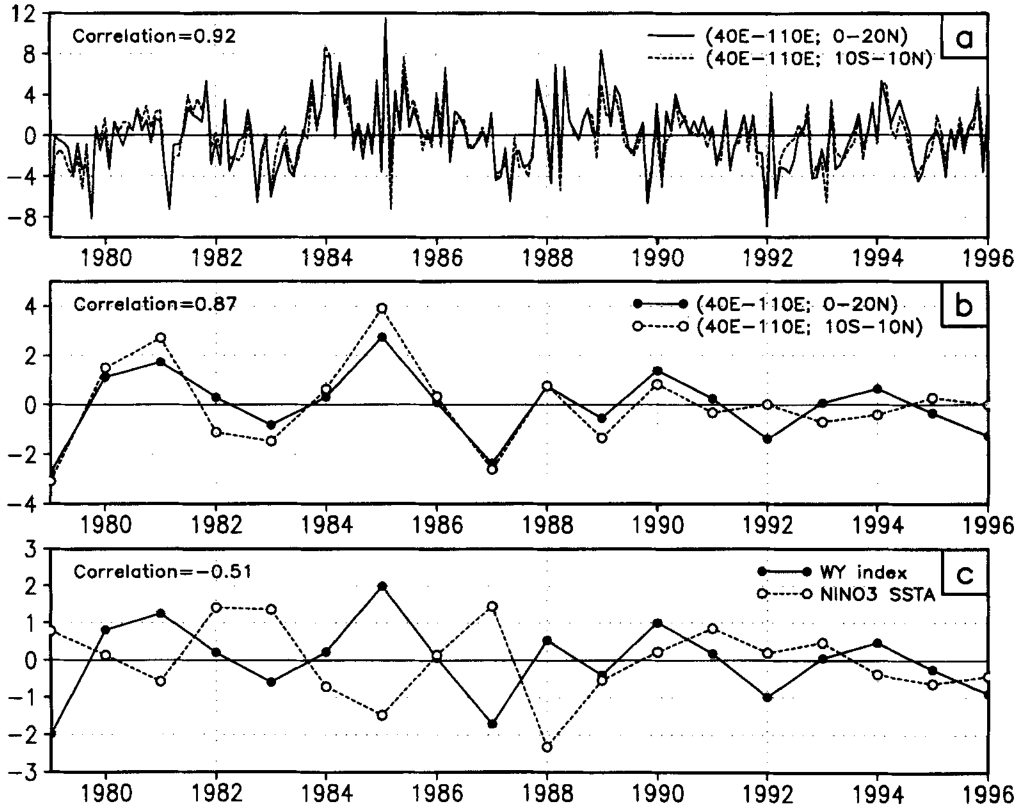

Figure 10. (a) Time series of monthly WY index ($U^*_{850} - U^*_{200}$ averaged over 40°E–110°E, 0°–20°N) and $U^*_{850} - U^*_{200}$ averaged over the equatorial region 40°E–110°E, 10°S–10°N. (b) Same as (a) but averaged over the northern summer monsoon season (June to September (JJAS)). (c) Seasonal WY index as in (b) and NINO3 SST anomalies of the JJAS season. See text for further explanation.

as shown in the previous section. To understand this apparent contradiction, we examined the monthly WY index based on the NCEP/NCAR reanalysis data from January 1979 to December 1996. In Fig. 10(a), the time series of the WY index is shown along with that of the zonal wind-shear anomalies ($U^*_{850} - U^*_{200}$) averaged over the equatorial belt and the same zonal section, namely, over 40°E–110°E, 10°S–10°N. The correlation coefficient between the two time series is 0.92. The striking similarity and strong correlation between the two time series indicate that the main contribution to the WY index comes from the equatorial zonal wind shear. The equatorial zonal wind shear is a measure of the east–west Walker circulation in this region.

Thus, the WY index relates to the interannual variability of the Walker circulation over the Indian Ocean region. Figure 10(a) also shows that the largest anomalies in this index occur mostly during the NH winter. To illustrate the relationship between the Walker circulation index and the WY index during the Indian summer monsoon season, the two indices averaged over the summer months (JJAS) are plotted in Fig. 10(b). The two curves are again remarkably similar, with a correlation coefficient of 0.87. The variations in the Walker circulation manifest in the variations of the zonal wind shear around the equator. Since the WY index is based mainly on the equatorial zonal wind shear, it is likely to reflect the Walker circulation rather than the regional Hadley circulation. This conclusion is further supported by the significant correlation (−0.51, statistically significant at the 95% level)

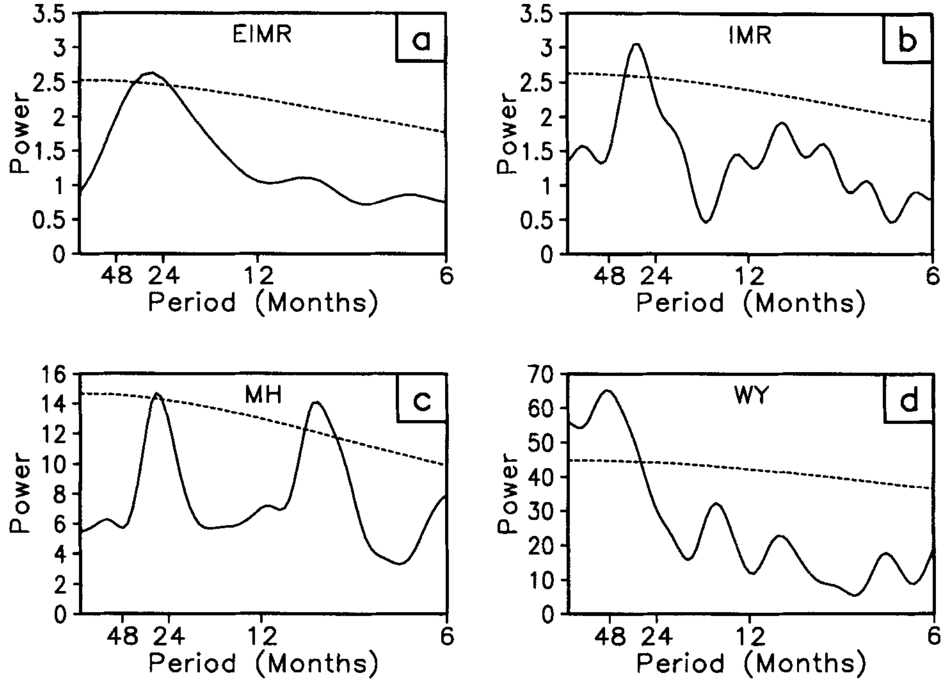

Figure 11. Power spectra (full lines) of monthly (a) EIMR index (monthly precipitation anomaly averaged over 70°E–110°E, 10°N–30°N), (b) IMR index, (c) MH index (monthly V-shear anomaly averaged over 70°E–110°E, 10°N–30°N), and (d) WY index (monthly U-shear anomaly averaged over 40°E–110°E, 0°–20°N). The corresponding red-noise spectra (dashed lines) are at the 90% confidence level. See text for further explanation.

between the WY index and an ENSO index such as the NINO3 (160°W–90°W, 5°S–5°N) SST anomaly (Fig. 10(c)). The WY index and the eastern Pacific SST have a stronger negative correlation between 1979 and 1988. Thus, the WY index generally represents the large-scale circulation changes over the Indian Ocean associated with ENSO. We also note that, during the most recent eight years, the relationship between ENSO SST and the WY index seems to have undergone a change. Between 1989 and 1996 the magnitude of the WY index has been weak (Fig. 10(b)) and its correlation with the eastern Pacific SST has been weakly positive.

Further insight regarding the lack of correlation between the WY index and EIMR (or IMR) may be gained by examining the difference between the strong and weak composites of the zonal wind-shear anomaly (defined on the basis of EIMR) shown earlier in Fig. 8(c). As seen in Fig. 8(c), associated with the interannual variations of the summer monsoon rainfall, the zonal wind-shear anomaly is largest around the equator. However, the zonal wind-shear anomalies associated with summer monsoon variations are not homogeneous over the region in which the WY index is defined (40°E–100°E, 0°–20°N). In fact, by defining a zonal wind-shear index averaged over 40°E–65°E, 15°S–15°N, we found that its correlation with the EIMR index is comparable with the correlation between the MH index and the EIMR index.

We now examine the temporal variability of the circulation and precipitation indices. The spectra of the monthly anomalies of precipitation (EIMR and IMR) and meridional wind shear averaged over the region 70°E–110°E, 10°N–30°N and of zonal wind shear averaged over the region 40°E–110°E, 0°–20°N are shown in Fig. 11. The EIMR index has a dominant oscillation with a period around 2 years and does not show any peak around 4 years (Fig. 11(a)). Thus, the monsoon precipitation index derived from Xie–Arkin precipitation data has the same low-frequency temporal variability as the IMR (Fig. 11(b); Mooley and Munot 1993; Annamalai 1995; Tomita and Yasunari 1996). It is striking to note that the V shear also has a significant low-frequency peak around the quasi-biennial period (Fig. 11(c)). The similarity between the three spectra reflects that the anomalous Hadley circulation is closely related to the anomalous convective heating in the same region. Thus, the MH index captures the dominant component of the summer monsoon variability, namely, the quasi-biennial component. In contrast to the MH index, the spectrum of the monthly WY index (Fig. 11(d)) has a strong low-frequency component with a period around 4 years, indicating that the WY index strongly reflects the ENSO response over the Indian monsoon region. The corresponding red-noise spectra at the 90% confidence level are also shown in Fig. 11. However, the quasi-biennial peaks in the spectra of EIMR, IMR and MH indices appear physical as their amplitudes are significantly larger than would be expected from a pure red-noise process.

The relationship between the indices and ENSO is further examined in terms of the teleconnection patterns revealed by zero-lag correlations between the indices and summer SST anomaly (similar to Sperber and Palmer (1996)). The correlations between the JJAS SST anomaly and the IMR, EIMR and MH indices, based on observed data for the period 1979–96, are shown in Fig. 12. The patterns are similar in all three cases. The eastern equatorial Pacific SST is negatively correlated with the Indian summer monsoon, while the western Pacific and parts of the Indian Ocean SST are positively correlated. However, only a small region of the equatorial eastern Pacific and parts of the western Pacific are significantly correlated to IMR during this period. The closely similar patterns of correlation between the EIMR index and SST and between the MH index and SST reinforce the assertion that the MH index is a good indicator of the circulation associated with the Indian summer monsoon precipitation.

The teleconnection between the Indian summer monsoon rainfall (whether it is IMR or EIMR) and the eastern equatorial Pacific SST (an index of ENSO) is rather weak during the period 1979–96, much weaker than the correlations obtained in earlier studies in which SST up to only 1988 or earlier was used (Parthasarathy and Pant 1984; Sperber and Palmer 1996). The weaker correlation is because the teleconnection between the eastern equatorial Pacific SST and the Asian monsoon has been very weak in recent years (i.e. 1989–96). We also note that, during 1979–96, the Indian monsoon and the southern equatorial Indian Ocean SST have been much more strongly related. Both the EIMR and MH indices have strong simultaneous positive correlations with the Indian Ocean SST, consistent with the argument that a warmer southern equatorial Indian Ocean should be associated with enhanced moisture flux to the monsoon region, facilitating higher convective activity and, hence a stronger monsoon.

The change in the teleconnection between the Pacific SST and the Indian monsoon in recent years is further examined in Fig. 13 by contrasting the teleconnection patterns during the two periods, 1979–88 and 1989–96. It is striking that the correlation patterns of the EIMR and MH with the Pacific SST have reversed sign in recent years, while both the correlation patterns are nearly identical during each period. Another interesting point to note is that the teleconnection with the Indian Ocean SST has remained unchanged during these two periods. Although these correlations during these periods are based on rather small samples (120 and 96 months, respectively), the coherence of the patterns lends them credibility. Regions of correlations significant at the 95% level are indicated in Fig. 13. During recent years, the positive correlations of the EIMR (or MH) with central Pacific SST and Indian Ocean SST are significant. The change in the relationship between ENSO and the Indian summer monsoon is also brought out in lagged correlations between NINO3

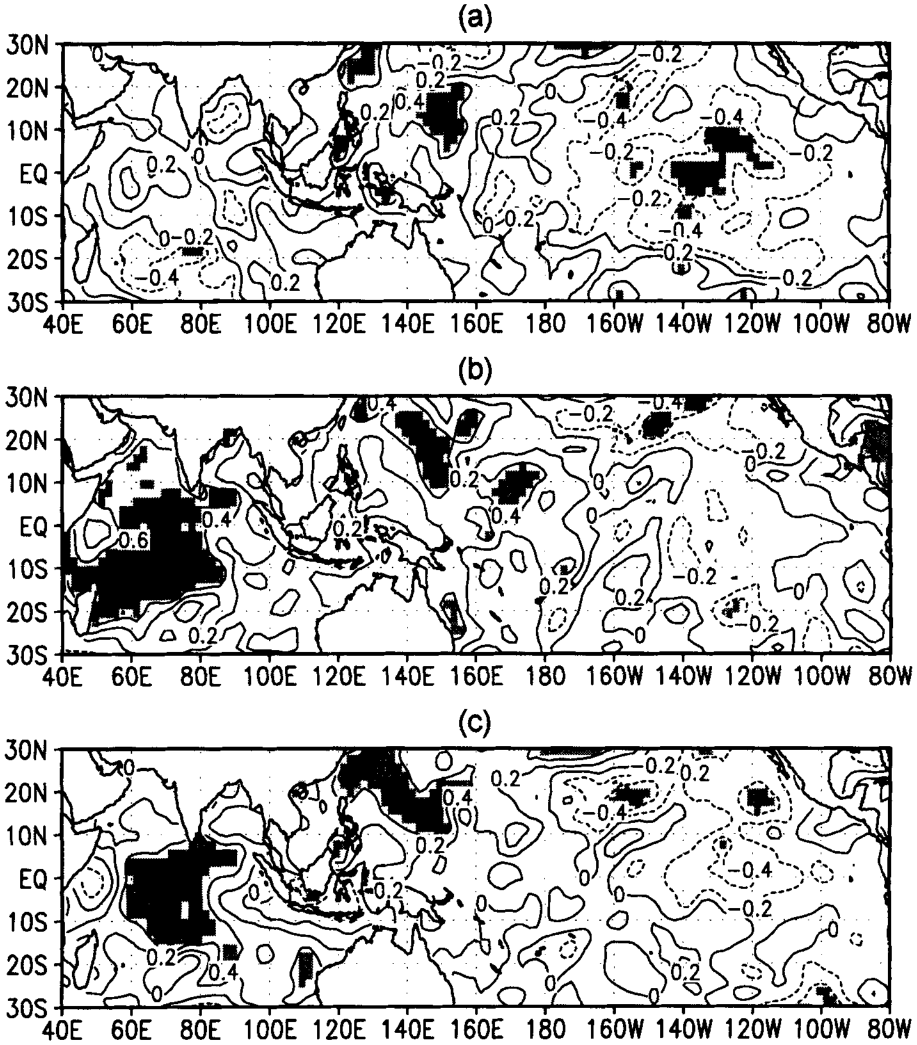

Figure 12. Simultaneous point correlations of seasonal (June to September) seasonal anomalies of sea surface temperature with (a) IMR index, (b) EIMR index and (c) MH index (see text) for the period 1979–96. Regions with correlations significant at the 95% level or higher are shaded and negative values are shown dashed.

SST and the Indian monsoon precipitation (IMR and EIMR) and circulation (MH) indices shown in Fig. 14. As compared with similar lagged correlations shown in earlier studies (e.g. Yasunari 1991), the peak correlation is a bit weaker. When the SST anomalies lag monsoon precipitation (i.e. SST occurring after the JJAS monsoon precipitation), they have no significant correlation with the EIMR and MH indices up to a 24-month lag time. SST anomalies leading the monsoon (i.e. SST occurring before the JJAS monsoon precipitation) by about 10–12 months have a moderate positive correlation with the Indian monsoon rainfall. The lag relationships between the NINO3 SST and all three monsoon indices are similar.

We have shown (Fig. 13) that the relationship between the Pacific SST and the Indian summer monsoon has reversed during 1989–96 as compared with 1979–88. We have also argued that the WY index is a good indicator of the planetary-scale response of ENSO over

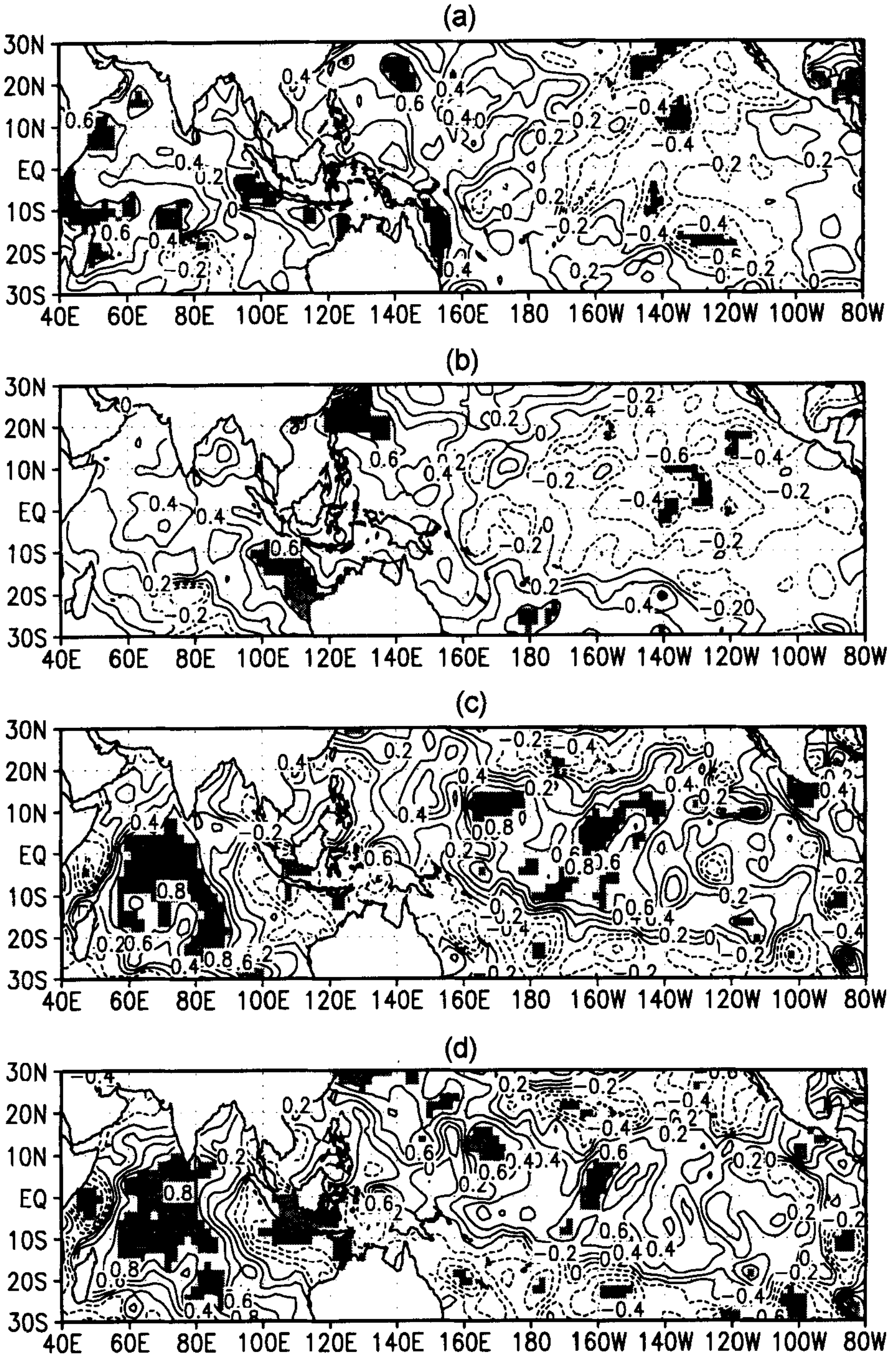

Figure 13. Simultaneous point correlations of June to September seasonal anomalies of sea surface temperature with (a) and (c) EIMR and with (b) and (d) MH indices (see text). Maps (a) and (b) are based on 1979–88 data while (c) and (d) are based on 1989–96 data. Shaded regions denote significance at the 95% level or higher and negative values are shown dashed.

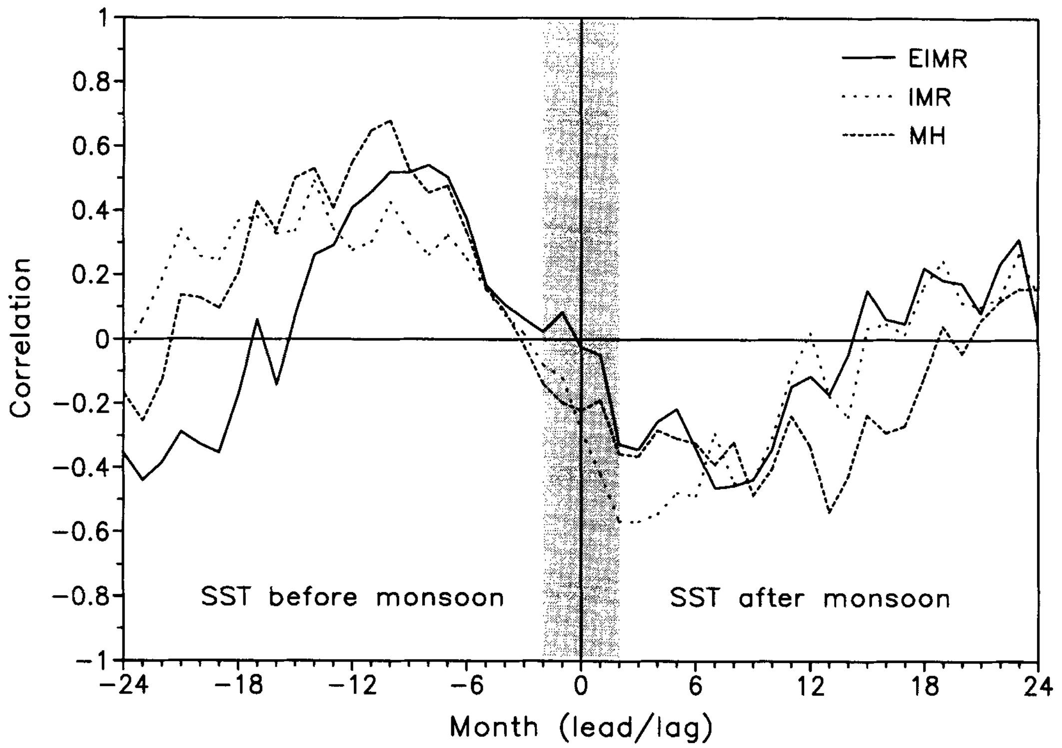

Figure 14. Lagged correlation between NINO3 sea surface temperature (SST) anomaly and the EIMR index, IMR index, and MH index (see text) for 1979–96. Shading denotes the June to September monsoon season.

the Indian Ocean region. Therefore, we expect the relationship between the WY index and ENSO (e.g. NINO3 SST) also to reverse sign between these two periods, which is exactly what is seen in Fig. 10(c). In the earlier period, the EIMR index and ENSO are negatively correlated and so are the WY index and ENSO. In the recent period, the EIMR index and ENSO are positively correlated as are the WY index and ENSO.

6. CONCLUSIONS

Using the precipitation data set based on land rain-gauge records as well as estimates from satellite observations, compiled by Xie and Arkin (1996), we have shown that the core region of the Indian monsoon rainfall not only includes the oceans around the Indian continent but extends eastward to about 110°E, covering the land masses of Myanmar, Thailand and parts of southern China. Based on this finding, we have defined a new Extended Indian Monsoon Rainfall (EIMR) index as precipitation averaged over 70°E–110°E, 10°N–30°N. The interannual variations of the IMR and EIMR are similar, with a few years of notable exceptions. The dominant mode of interannual variability of the Indian summer monsoon consists of an east–west dipole pattern in which intensification (or weakening) of precipitation over the core region is associated with weakening (or intensification) of the north-western Pacific monsoon and a north–south dipole pattern between the core region and the equatorial Indian Ocean. Due to the larger area coverage and coherent fluctuations over the core region, the EIMR should be a better index of the convective heating associated with the Indian summer monsoon.

To address the long recognized need for a large-scale circulation index that reflects the variations of the monsoon heating, Webster and Yang (1992) defined a broad-scale circulation index as the zonal wind-shear anomaly ($U^*_{850} - U^*_{200}$) averaged over 40°E–110°E, 0°–20°N. However, in this study, we have shown that the WY index has little correlation with either the IMR or EIMR. We have also identified a broad-scale circulation index that relates well with the interannual variability of the Indian summer monsoon.

We argue that the Indian monsoon's heating represents an asymmetric heat source. The atmospheric response to such an asymmetric heat source manifests itself as a strong regional Hadley circulation and a weak Walker circulation in contrast to the response to a symmetric heat source which results in a strong east–west Walker circulation in addition to a north–south Hadley circulation (Gill 1980). Therefore, a measure of the regional Hadley circulation should be a good measure of the monsoon heating as well. While the climatological mean monsoon circulation is driven largely by the convective heating, it is also affected by a strong surface heating at lower layers. Therefore, the mean monsoon circulation is not precisely a first baroclinic mode in the vertical structure. However, the anomalous monsoon circulation (i.e. interannual variability) is almost entirely driven by convective heating changes and should be baroclinic in nature. The vertical shear of anomalous meridional winds between lower and upper layers ($V^*_{850} - V^*_{200}$) may be used as a measure of the strength of the anomalous Hadley circulation. A steady-state linear vorticity balance indicates that the response of the meridional winds should be more or less colocated with the heat source. Equipped with this dynamical basis, we have defined a large-scale monsoon circulation index (MH index) as the meridional wind-shear anomaly ($V^*_{850} - V^*_{200}$) averaged over the summer season (JJAS) and over 70°E–110°E, 10°N–30°N. The MH index, calculated from reanalysis data from the NCEP/NCAR and the ECMWF, correlates strongly with the EIMR index. We have shown that the strong correlation between the MH index and the EIMR index is at least partially due to the fact that the MH index captures the dominant quasi-biennial variability of the EIMR.

The teleconnection patterns of the Indian summer monsoon precipitation and circulation indices with summer SST over the global oceans have changed in recent years. Simultaneous correlations between the IMR or EIMR and the eastern equatorial Pacific SST during 1979–96 are much weaker than those during the earlier two or three decades, primarily due to a lack of correlation during the most recent years. We have shown that the south equatorial Indian Ocean SST is strongly correlated with the newly defined indices of monsoon rainfall (EIMR) and circulation (MH) during this entire period. This result is new and possibly important. The lack of a consistent and strong relationship between IMR and Indian Ocean SST had led us to believe in the past that the Indian Ocean has no significant role to play in the variability of the Indian monsoon. This lack of relationship between IMR and Indian Ocean SST is likely to be due to the fact that the IMR does not represent the total monsoon convective heating. The significant relationship between EIMR and Indian Ocean SST establishes that the Indian Ocean indeed has an important role to play in the variability of the Indian summer monsoon. The correlations between the MH index and SST are almost identical to those between the EIMR index and SST. The changing monsoon–ENSO relationship in recent years presented in this study is a new and interesting result that needs to be studied in greater detail.

The strong relationship between the MH and EIMR indices validates our assertion that the interannual variability of the Indian summer monsoon is largely driven by fluctuations of the monsoon convective heat source. However, the lack of a perfect correlation indicates that other factors may play some role. Surface hydrological process (such as changes in soil moisture), as well as radiative forcing associated with cloudiness changes may also contribute to the driving of the monsoon Hadley circulation (Webster *et al.* 1998).

Additionally, there may be extratropical circulation influences on the regional Hadley circulation. Moreover, the linear relationship between heating and meridional velocity has been based on the assumption of no mean flow. In any case, the proposed large-scale circulation index for the monsoon is expected to be useful as a diagnostic tool. We suggest that this index be used in monsoon variability and predictability studies and model verification studies.

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