Relation between Indian Monsoon Variability and SST

V. KRISHNAMURTHY
Center for Ocean–Land–Atmosphere Studies, Institute of Global Environment and Society, Calverton, Maryland, and Department of Atmospheric, Oceanic, and Earth Sciences, George Mason University, Fairfax, Virginia

BEN P. KIRTMAN
Center for Ocean–Land–Atmosphere Studies, Institute of Global Environment and Society, Calverton, Maryland, and Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida

(Manuscript received 10 March 2008, in final form 6 March 2009)

ABSTRACT

The relation between the intraseasonal modes of the South Asian monsoon and the sea surface temperature (SST) in the tropical oceans on a daily time scale has been investigated. Long lead–lag relations of the daily SST anomalies with the dominant monsoon modes obtained from a multichannel singular spectrum analysis (MSSA) of the daily outgoing longwave radiation (OLR) over the South Asian monsoon region are presented. The dominant MSSA monsoon modes, consisting of two oscillatory modes (at 45- and 28-day time scales) and two seasonally persistent modes, are found to have varying degrees of lead–lag relation with the SSTs in the Indian and Pacific Oceans. While the 45-day oscillatory mode has weak correlations with the SSTs in the Pacific and Indian Ocean, it also reveals a possible 45-day oscillation in the SST in the northwestern Pacific and northern Indian Ocean. The 28-day oscillatory mode has negligible correlation with the tropical SST. One of the persistent monsoon modes has a very strong relation with the El Niño–Southern Oscillation (ENSO)–related SST in the Pacific with correlation above 0.8 for a long lead–lag time range. The other persistent monsoon mode has moderate lead–lag correlation with the Indian Ocean dipole (IOD) SST as well as with the ENSO-like SST in the Pacific. The strong relation of the persistent modes, which mainly determine the seasonal mean monsoon, when the SST leads, provides hope for long-term prediction of the seasonal mean monsoon. The strong relation between the monsoon and the SST, when the monsoon leads, points toward the strong influence of the monsoon on the variability of ENSO and IOD.

1. Introduction

The tropical climate is suggested to have potential for long-term prediction because a significant part of its long-term variability seems to be determined by slowly varying components of the climate system such as the sea surface temperature (SST) rather than by synoptic-scale instabilities (Charney and Shukla 1981). Predictors involving SST parameters are used in the statistical forecasts of seasonal mean monsoon rainfall over India issued every year by the India Meteorological Department (IMD; Rajeevan 2001). However, the ability of SST in the Indian and Pacific Oceans to predict the seasonal mean monsoon has not been firmly established. While the Indian monsoon is known to be associated with El Niño–Southern Oscillation (ENSO), its relation with the Indian Ocean is not so clear (see review by Krishnamurthy and Kinter 2003). Many drought (flood) seasons of the Indian monsoon are accompanied by developing El Niño (La Niña) events in the Pacific Ocean (Sikka 1980; Rasmusson and Carpenter 1983), although there are notable exceptions, such as the normal monsoon of 1997 followed by the strong El Niño event of 1997–98. The seasonal mean Indian rainfall has been shown, in observational and model studies, to have maximum correlation with the SST of the east Pacific Ocean when the monsoon leads the SST by four to six months (e.g., Kirtman and Shukla 2000). The relation between intraseasonal variability involving active and break phases of the monsoon and the SST is poorly understood.

When the SST is contemporaneous with or leads the summer monsoon season, a strong relation between the SST and monsoon rainfall has not been detected, as
expected by the Charney–Shukla hypothesis. A possible reason is that, on a daily or subseasonal time scale, the intraseasonal variability of the monsoon may be masking the atmospheric response to slowly varying components such as ENSO. In a recent study, Krishnamurthy and Shukla (2008) obtained the dominant space–time structure of the monsoon variability by applying multichannel singular spectrum analysis (MSSA) to daily outgoing longwave radiation (OLR) over the Indian monsoon region. They found that the dominant monsoon modes consist of two nonlinear oscillations at 45- and 28-day time scales and two seasonally persistent large-scale patterns. One of the persistent patterns seemed to be related to ENSO, and the other to the Indian Ocean dipole (IOD). Similar space–time monsoon modes were also found in the daily rainfall over India (Krishnamurthy and Shukla 2007). While the oscillatory patterns describe the intraseasonal variability of active and break phases of the monsoon, the persistent patterns account for most of the interannual variability of the seasonal mean monsoon.

The Charney–Shukla hypothesis was modified in an earlier study by Krishnamurthy and Shukla (2000), who suggested a conceptual model in which the interannual variability of the seasonal mean monsoon is composed of large-scale persistent seasonal mean component and a statistical average of intraseasonal variations. The recent results of Krishnamurthy and Shukla (2007, 2008) have provided strong support for this conceptual model. During a particular year, the persistent ENSO and IOD modes can interfere either constructively or destructively; therefore, the seasonal mean is determined by the relative strengths of the persistent modes. While the average of the intraseasonal oscillatory modes contributes very little to the seasonal mean, it may be a factor during certain years when the monsoon is normal. The relation between the dominant modes of monsoon variability and SST must be investigated to determine if the modified Charney–Shukla hypothesis is further supported. If the slowly varying SST is found to have predictive influence on the seasonally persistent atmospheric modes of the monsoon, the prospect of long-term prediction of seasonal mean monsoon appears more promising.

Several studies have investigated the relation between atmospheric variables and SST in the monsoon region using data that are bandpass filtered on the intraseasonal time scale. Krishnamurty et al. (1988) suggested that 30–50-day oscillations of SST and wind contribute to a strong atmosphere–ocean coupling in the Indian and west Pacific Oceans. Coherent relations between SST and convection and other atmospheric variables on intraseasonal time scales were shown to exist in studies that examined the dynamics of Madden–Julian oscillation (Hendon and Glick 1997; Shinoda et al. 1998; Woolnough et al. 2000). For the boreal summer intraseasonal oscillation, air–sea interaction in the Indian Ocean was suggested to be important for northward and eastward propagation of convection (Kemball-Cook and Wang 2001). There is also a study showing that the intraseasonal variability of convection in the summer monsoon region is not correlated with SST variability (Lawrence and Webster 2001). The droughts in India are shown to be associated more with the warmest SST anomalies in the central equatorial Pacific than those in the eastern Pacific (Krishna Kumar et al. 2006). Several studies have presented evidence for subseasonal oscillation in SST and its possible relation with the atmosphere in satellite and buoy data (Sengupta et al. 2001; Sengupta and Ravichandran 2001; Vecchi and Harrison 2002; Wang et al. 2006). Strong coupling between Indian Ocean SST and intraseasonal oscillations is demonstrated in model studies (Fu et al. 2003; Fu and Wang 2004). However, these studies have not addressed the relation between SST and monsoon variability with the goal of finding slowly varying coupled ocean–atmosphere components.

The objective of this study is to understand the influence of SST on monsoon variability in a comprehensive manner within the context of modified Charney–Shukla hypothesis. This goal is achieved by determining the relation between SST and the dominant atmospheric monsoon modes found in the MSSA analysis of OLR by Krishnamurthy and Shukla (2008). The lead–lag relation between the daily reconstructed components (RCs) of the two persisting OLR modes with the daily SST anomalies will be determined in order to understand the monsoon’s relation with ENSO and IOD. It will be of great interest to find if there is a strong relation when the SST leads these persisting monsoon modes because of the implication on the prediction of seasonal monsoon. The results of these relations will also help toward understanding the “weather” within climate of such slowly varying coupled phenomena as ENSO. The relation between the daily SST anomalies and the RCs of the 45- and 28-day OLR modes will also be investigated to find the influence of SST on intraseasonal oscillations involving active and break phases of the monsoon. An understanding of the relative strengths of relation of SST with the different monsoon modes will be helpful to know the extent to which the seasonal mean monsoon is influenced by SST and to document the monsoon’s role in the variability of ENSO and IOD. In section 2, the data and method of analysis are described. The monsoon modes and their contemporaneous relations with SST are explained in section 3. The lead–lag relation of SST with the intraseasonal modes is discussed in section 4.
the relation with the persisting modes is discussed in section 5. Section 6 provides a summary and conclusions.

2. Data and method of analysis

The monsoon variability is analyzed in this study by utilizing observed rainfall over India and observed OLR, which represents deep convection. Daily mean OLR data on a 2.5° longitude × 2.5° latitude grid for the period 1975–2006 were obtained from the National Oceanic and Atmospheric Administration (NOAA; Liebmann and Smith 1996). The OLR data are not available for 1978 because of satellite problems. The dataset of daily mean rainfall on a 1° × 1° grid over land points in India for the period 1951–2004, developed by the IMD (Rajeevan et al. 2005), has also been used. The relation to SST has been studied by using two different high-resolution daily SST datasets. The first one is the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) Version 4 SST dataset available on a 0.25° × 0.25° grid for the period 1998–2006 on daily time scale (available online at http://www.ssmi.com). The second one is the newly developed optimally interpolated SST (OISST) dataset by NOAA using in situ data and satellite data from the Advanced Very High Resolution Radiometer (AVHRR). The new OISST dataset is available on a 0.25° × 0.25° grid at a temporal resolution of one day for the period 1982–2006 and is an improvement over the older weekly OISST dataset (Reynolds et al. 2007). The reason for using the two SST datasets is that both of them have certain merits and drawbacks. While the TMI dataset is better during cloudy periods compared to AVHRR data, it is available only for a short period of time. Also, the daily TMI set has large swaths of missing data, making it necessary to use 3-day running means. The AVHRR-based OISST data are better during clear skies and are available for a longer period without any missing data on a daily time scale. The daily climatology was computed as the mean for each calendar day and was subtracted from the total field to obtain the daily anomalies.

The space–time structure of the monsoon variability is obtained by performing MSSA of the daily OLR anomalies over the monsoon region. By following the mathematical formulation described by Ghil et al. (2002), the MSSA is applied to obtain oscillatory and persisting modes. The resulting MSSA modes of OLR analyzed in this study are the same as those obtained by Krishnamurthy and Shukla (2008). When the MSSA is applied to data specified at L grid points and N discrete times using 0 to $M - 1$ lags, $L \times M$ eigenvalues and $L \times M$ eigenvectors are obtained. The variance explained by each eigenmode is given by its eigenvalue. The eigenvectors are the space–time empirical orthogonal functions (ST-EOF), each containing a sequence of $M$ maps on $L$ grid points. The corresponding space–time principal components (ST-PC) are each of time length $N - M + 1$. The original time series data can then be recovered as the sum of reconstructed components (RC) formed from the corresponding ST-EOF and ST-PC. Each RC, representing a particular eigenmode, is a time series of maps on the same grid and with same time length as the original time series.

All the correlation values are presented at 5% significance level in this study. Since they involve daily time series with varying persistence, there is a need for an appropriate estimation of the degrees of freedom. For each time series, the $e$-folding time of its autocorrelation function is calculated. The degrees of freedom are estimated by dividing the total time (or total number of points) by the $e$-folding time of the autocorrelation. A 5% significance test is then applied to the normal distribution of the correlation under null hypothesis.

3. Monsoon modes and SST

a. Relation of SST with total anomalies of rainfall and OLR

During the summer monsoon season spanning June–September (JJAS), the intraseasonal variability consists of active periods of above-normal rainfall and break periods of below-normal or no rainfall over India. A general relation between the daily rainfall over India and SST can be obtained by constructing active and break composites of daily SST anomalies. A widely used measure of the monsoon is a suitable monsoon variable area averaged over the land points of India. This area average will be referred to as the all-India monsoon (AIM) index. The AIM index of rainfall was shown to have high correlation with the PC of the most dominant mode of the daily rainfall variability (Krishnamurthy and Shukla 2000). The active (break) phase is defined as the period when the AIM index of daily rainfall anomaly is above (below) a positive (negative) threshold for at least five consecutive days. The threshold is selected to be one-half of the standard deviation of the AIM rainfall index. This criterion is the same as that used by Krishnamurthy and Shukla (2000, 2007, 2008).

The active and break composites are constructed by averaging the daily SST anomalies over all active and break days during JJAS. The composites using TMI SST for the period 1998–2004 are averages over 133 active days and 292 break days, while those using OISST for the period 1985–2004 are averages over 538 active days and 733 break days. As shown in Fig. 1, the TMI...
composites are slightly stronger than the OISST composites. The composites (Fig. 1) reveal that the region where the active (break) phase is associated with the largest cold (warm) SST anomalies is in the equatorial Pacific Ocean. These anomalies cover the Niño-3.4 region (5°S–5°N, 170°–120°W), indicating that warmer (colder) temperatures in the Pacific are associated with below-normal (above normal) rainfall over India on a daily time scale. The active (break) composite shows warm (cold) SST anomalies in the northern west Pacific.

Fig. 1. (a) Active and (b) break phase composites of daily SST anomalies (K) for the period JJAS 1985–2004 with OISST. (c) Active and (d) break phase composites of 3-day running mean SST anomalies (K) for the period JJAS 1998–2004 with TMI.
In the Arabian Sea, the SST anomalies have a north–south dipole structure with warm (cold) anomalies near the Gujarat coast during active (break) phases. The southern part of this pattern extends to the Bay of Bengal although with weaker anomalies. The anomaly pattern over the southern Indian Ocean is not well defined.

A more quantitative measure of the strength of the relation, including the normal rainfall periods, is obtained by finding the daily correlation between rainfall or OLR and SST. The rest of the paper will use OLR because it is available over the oceanic monsoon region and on daily frequency. The simultaneous point correlation between the daily AIM index of OLR (i.e., OLR anomalies averaged over land points of India) and SST anomalies for JJAS is shown in Fig. 2. The OISST correlation pattern for 1985–2006 (Fig. 2a) is very similar to the TMI correlation pattern for 1998–2006 (Fig. 2b). The familiar horseshoe pattern of the ENSO variability is reflected in the correlations in the Pacific Ocean. Positive OLR anomalies (or below-normal rainfall) over India are associated with warm SST anomalies in the central and eastern Pacific and with cold SST anomalies in the western and central Pacific. The maximum positive correlation occurs in the equatorial Pacific covering the Niño-3.4 region, while the maximum negative correlations are found in northwestern Pacific. In the Indian Ocean, the eastern region has weak negative correlations while positive correlations are present in the western region except for the northern Arabian Sea (Fig. 2a). The correlation pattern over much of the Indian Ocean somewhat reflects the IOD SST anomaly pattern in Fig. 2a with OISST but not so clearly in Fig. 2b with TMI. The correlation with SST anomalies using AIM rainfall index also reveals (figure not shown) a pattern similar to that in Fig. 2 but with opposite sign. However, the area of significant rainfall correlation is slightly less than that found with the OLR correlation because of the noisy nature of rainfall.

Although the correlation patterns in Fig. 2 have a well-defined and statistically significant structure that includes signatures of ENSO and IOD, the maximum value of the correlation is only about 0.3. This weak correlation is the result of using the total OLR anomalies whose variability ranges from synoptic scale to interannual time scale. By decomposing the anomalies into components belonging to different time scales, a better...
understanding of the correlation with the SST anomalies can be obtained.

b. Relation of SST with MSSA modes of OLR

The space–time structure of convection over the monsoon region is obtained by performing multichannel singular spectrum analysis of daily OLR anomalies in the region 35°S–35°N, 40°–160°E for JJAS 1975–2006, as shown by Krishnamurthy and Shukla (2008). The dominant MSSA eigenmodes consist of two nonlinear oscillatory patterns at time scales of about 45 days (eigenmodes 1 and 2) and 28 days (eigenmodes 5 and 6) and two large-scale standing patterns (eigenmodes 3 and 4). The reconstructed components of the eigenmodes correspond to the decomposition of the total anomalies into these various modes. Following Krishnamurthy and Shukla (2008), the RCs of the 45- and 28-day oscillatory modes are denoted by \( R(1, 2) \) and \( R(5, 6) \), respectively. Similarly, \( R(3) \) and \( R(4) \) denote the two seasonally persistent standing patterns that were identified to be related to ENSO and IOD, respectively. The first six modes together account for about 16% of the total daily variance, which is remarkable considering that high-frequency variability dominates the daily variance. It is also important to note that the JJAS seasonal mean of the first six modes account for about 60% of the interannual variance, most of it from the persisting modes \( R(3) \) and \( R(4) \). The analysis of Krishnamurthy and Shukla (2008) does not include a detailed examination of the relation between SST anomalies and the MSSA modes of OLR, which is the focus of this study.

The daily variation of the MSSA modes can be examined by plotting the AIM indexes (area averages over India) of the corresponding RCs, as shown in Fig. 3 for 1987 and 1997 as examples. In 1987, when the seasonal mean rainfall (OLR) was below normal (above normal) (i.e., weak monsoon), the ENSO mode \( R(3) \) and the IOD mode \( R(4) \) both vary with positive values comparable to the seasonal mean value throughout the season (Fig. 3a). Such constructive interference of ENSO and IOD modes in contributing to the seasonal mean OLR occurs also during certain strong monsoon (above-normal rainfall) years. Although the oscillatory modes \( [R(1, 2) \text{ and } R(5, 6)] \) have considerable variance, they contribute very little to the seasonal mean. In 1997, the seasonal mean is very close to zero, making it a normal monsoon year even though a very strong El Niño event occurred that year (Fig. 3b). The strong influence of El Niño is, however, present, as seen by the variation of \( R(3) \) with large positive values throughout the season. But the IOD mode varies with negative values for a large part of the season, counteracting the influence of the ENSO mode. Clearly, the relative strength of the ENSO and IOD modes is important in determining the seasonal mean monsoon. The relative strengths of ENSO and IOD have been previously shown to be important in determining extreme monsoon events in India (Gadgil et al. 2004).

The relation between individual monsoon modes and SST anomalies is determined by computing the point correlation of the AIM index of each RC with the SST anomalies. The simultaneous daily correlations with OISST for JJAS 1985–2006 and with TMI for 1998–2006 are shown in Figs. 4 and 5 (note the different scales of the panels), respectively. The two oscillatory modes show weak correlations with the SST anomalies (Figs. 4a,b and 5a,b). Although the maximum correlation of the 45-day mode \( [R(1, 2)] \) is slightly above 0.2, there is a discernable pattern with negative correlation from the Arabian Sea to the west Pacific and positive correlation near the central equatorial Indian Ocean. This correlation pattern is structurally similar to the composite OLR pattern of the peak active phase shown by Krishnamurthy and Shukla (2008, their Fig. 4). The west Pacific warm pool region has the maximum negative correlation, while the central equatorial Pacific has weaker positive correlation. The correlation of the total OLR anomalies with the west
FIG. 4. Simultaneous point correlation of daily AIM index of (a) $R(1, 2)$, (b) $R(5, 6)$, (c) $R(3)$, and (d) $R(4)$ of OLR with daily SST anomalies of OISST during JJAS 1985–2006. Correlations below 5% significance level are left blank. The scale for the contours is shown by the color bar below each panel. Note that the panels have different scales.
Fig. 5. Same as in Fig. 4, but for SST anomalies of TMI during JJAS 1998–2006.
Pacific SST anomalies seen earlier in Fig. 2 seems to be captured by the 45-day mode (Figs. 4a and 5a). Interestingly, the maximum negative correlation also appears in a small region in the east Pacific adjoining the North American monsoon (NAM) region. Whether this relation with NAM is because of the possibility that the 45-day mode propagates over the entire Indo-Pacific region remains to be investigated. The 28-day oscillatory mode [$R(5,6)$] shows weak relation with the SST anomalies over the Arabian Sea and western Pacific (Figs. 4b and 5b).

The seasonally persisting standing patterns $R(3)$ (ENSO mode) and $R(4)$ (IOD mode), however, have a strong relation with the SST anomalies (Figs. 4c,d and 5c,d). The OLR mode $R(3)$ shows very high positive correlation in the central and eastern Pacific and negative correlation in the western Pacific with a horseshoe pattern (Figs. 4c and 5c). In parts of the Niño-3.4 region, the correlation exceeds 0.8. A large part of the Indian Ocean has moderate values of positive correlation. It is clear that there is a very strong relation between droughts (floods) over India as determined by the $R(3)$ component and El Niño (La Niña) condition in the Pacific Ocean. Comparing Figs. 2 and 4, it is evident that much of the correlation over the Pacific Ocean is due to the $R(3)$ component of the total OLR anomalies. The high daily correlation of $R(3)$ with the Pacific SST anomalies strongly suggests that the daily variability of $R(3)$ represents the atmospheric “weather” associated with ENSO interannual variability.

The IOD mode of the OLR anomalies represented by $R(4)$ has positive correlation (with a maximum value of 0.4–0.6) around the Maritime Continent, Arabian Sea, and Bay of Bengal (Figs. 4d and 5d). There is a small region of negative correlation in the central equatorial Indian Ocean implying a signature (although not strong) of the IOD. Negative correlations with values reaching up to $-0.4$ are present in a somewhat horseshoe pattern in the Pacific Ocean near the date line. The eastern Pacific consists of weak positive correlations. An interesting region of positive correlation is seen in the tropical Atlantic Ocean. A comparison between Figs. 4c and 4d (also between Figs. 5c and 5d) shows that there are regions where the ENSO and IOD OLR modes have correlations with the same sign (Arabian Sea and parts of west Pacific and east Pacific), while there are also regions of correlation of opposite signs (eastern Indian Ocean and central Pacific and Atlantic).

4. Lagged relation between 45-day OLR mode and SST anomalies

From the discussion in section 3, it is clear that three monsoon modes (45-day oscillation and persisting ENSO and IOD modes) within the total OLR anomalies indicate ocean-atmosphere interaction of varying degrees. To gain insight into the temporal characteristics of the influence of SST and monsoon on one another, lagged correlations of daily OLR RCs with SST anomalies are now examined.

The lagged point correlations of the AIM index of daily total OLR anomaly with SST anomalies are shown in Figs. 6 and 7, respectively, for OISST and TMI. The correlations are plotted at lag intervals of 30 days with lag 0 corresponding to JJAS 1985–2006 (Fig. 6) and 1998–2006 (Fig. 7). The positive (negative) lags indicate that the SST anomalies lag (lead) the AIM index of the JJAS OLR anomaly. The most noticeable feature in Figs. 6 and 7 is the presence of ENSO signature in the Pacific Ocean for all lags, although the maximum correlation is only near 0.3. The positive correlation in the central Pacific is present even when the SST leads the OLR by 120 days (lag $-120$) and then steadily expands to the east Pacific by the time the SST lags the OLR by 120 days (lag $+120$). The largest value of positive correlation occurs during lags $-30$ to $+30$ days. Similarly, a horseshoe pattern of negative correlation is present in the western and central Pacific for all lags with larger values in the northwestern Pacific appearing only during lags 0 to $+60$ days. The western Indian Ocean has positive correlations during lags 0 to $+60$ days, while a weak signature of IOD is also seen (Fig. 7). These lagged correlations suggest that there is a possibility of both the monsoon atmosphere and Indian and Pacific Oceans influencing each other through ocean–atmosphere interactions.

The lagged relation with the 45-day oscillatory OLR mode [$R(1, 2)$] is examined in this section. The daily point correlations of the AIM index of $R(1, 2)$ with the daily OISST SST anomalies from lag $-120$ to lag $+120$ days at intervals of 30 days are shown in Fig. 8. The only noticeable lead–lag relation occurs in the western Pacific and northern Indian Oceans between lag $-120$ and lag $+30$. An examination of these lagged correlation maps at 5-day lead–lag interval (figures not shown) has revealed the following. Over most of the Indian and Pacific Oceans, evidence of any oscillatory behavior in the correlations corresponding to the 45-day mode is not apparent. However, in the west Pacific north of the equator and in the northern Indian Ocean, the correlation shows noticeable oscillatory behavior of 45-day period between lags $-90$ and $+60$ days with maximum negative correlation occurring near lag 0. The TMI SST also shows similar lead–lag relation with the 45-day mode (figure not shown).

However, the possibility of an oscillatory behavior in the west Pacific SST that is related to the 45-day OLR
FIG. 6. Lagged point correlation of JJAS daily AIM index of total OLR anomaly with daily SST anomalies of OISST during 1985–2006. The lag indicated in the top left corner of each panel is in days with negative (positive) sign denoting that SST leads (lags) the OLR. Correlations below 5% significance level are left blank.
Fig. 7. Same as in Fig. 6, but for SST anomalies of TMI for 1998–2006.
FIG. 8. Lagged point correlation of JJAS daily AIM index of $R(1, 2)$ with daily SST anomalies of OISST during 1985–2006. The lag indicated in the top left corner of each panel is in days with negative (positive) sign denoting that SST leads (lags) the OLR. Correlations below 5% significance level are left blank.
mode can be investigated by constructing composites of daily SST anomalies based on the phases of the OLR oscillation. Following the method used by Krishnamurthy and Shukla (2008, see their Fig. 4 for example), the phase composites are constructed as averaged SST anomalies (OISST) for eight equal intervals in a cycle $(0, 2\pi)$ of the phase of $R(1, 2)$ during 1985–2006 and are shown in Fig. 9. During an average cycle of the 45-day oscillation, the evolution of the SST anomalies consists of warm anomalies appearing in the western Indian Ocean (phase 2), expanding to a large-scale structure that extends from the Arabian Sea to the west Pacific (phases 3 and 4), and moving to northwestern Pacific and diminishing (phases 5 to 7). This sequence involves northeasterward propagation of the SST anomalies and exhibits correspondence with the movement of the OLR anomalies shown by Krishnamurthy and Shukla (2008, their Fig. 4). A similar sequence with cold SST anomalies takes place going from phase 5 to phase 3. Thus, there is some evidence of a 45-day oscillation of the SST anomalies occurring over the northern part of the Indian Ocean and west Pacific Ocean, corresponding to the active and break cycle of the monsoon. The rest of the Pacific Ocean does not reveal any oscillatory behavior except for a small region in the North American monsoon region. The TMI SST composites also show (figure not shown) propagation similar that in Fig. 9.

5. Lagged relation between persistent OLR modes and SST anomalies

Earlier in section 3, it was seen that the two persistent OLR modes related to ENSO [$R(3)$] and IOD [$R(4)$] showed strong contemporaneous correlations with the daily SST anomalies. To find if such strong correlations exist before and after the monsoon season, the lagged correlations of SST anomalies with $R(3)$ and $R(4)$ are now examined.
a. Lagged relation with the OLR ENSO mode

The point correlations of the daily AIM index of \( R(3) \) with the daily SST anomalies for lags \(-120 \) to \(+120 \) days in intervals of 30 days are plotted in Fig. 10 for OISST and in Fig. 11 for TMI. Even when the SST leads by 120 days (lag \(-120 \)), the signature of ENSO is quite evident with significant positive correlation in the central Pacific Ocean accompanied by the negative correlation in the west Pacific and extending into the eastern Indian Ocean. The positive correlation in the western Indian Ocean is somewhat weaker. This correlation pattern in the Indo-Pacific region continues up to lag \(+120 \) days with the values of the correlation growing to become stronger (Figs. 10 and 11). The region of positive correlation expands from the central Pacific to cover most of the east Pacific by lag 0. Even at lag \(-60 \) days, the Niño-3.4 region has correlation between 0.6 and 0.8. From lag \(-30 \) to lag \(+60 \) days, a part of the Niño-3.4 region has correlation exceeding 0.8. A significant part of the equatorial central and eastern Pacific Ocean has correlation greater than 0.6 even when the lag is \(+120 \) days.

The negative correlation in the western Pacific Ocean and eastern Indian Ocean becomes slightly stronger as the lag changes from \(-120 \) to \(+60 \) days. The region of negative correlation around the Maritime Continent reaches a value of about \(-0.6 \) during lags \( 0 \) to \(+60 \) days. Much of the Indian Ocean to the west of about 90°E is covered with positive correlation from lags \(-30 \) to \(+120 \) days, although with lower values. The overall pattern of correlation indicates warm SST anomalies in the central and eastern Pacific and in the Indian Ocean separated by cold SST anomalies in the western Pacific and part of the eastern Indian Ocean when the OLR (rainfall) anomalies over India are positive (negative). This pattern of SST anomalies is similar to the pattern of covariability in the Indian and Pacific Oceans suggested by Krishnamurthy and Kirtman (2003). The strong correlation in the Pacific Ocean from lags \(-120 \) to \(+120 \) days suggests that there is mutual influence between the Indian monsoon and ENSO.

b. Lagged relation with the OLR IOD mode

The point correlations of the daily AIM index of the OLR IOD mode \( R(4) \) with the daily SST anomalies are plotted in Figs. 12 and 13 (for OISST and TMI, respectively) for lags \(-120 \) to \(+120 \) days in intervals of 30 days. The maximum correlation of \( R(4) \) for all lags is about 0.4 (Figs. 12 and 13), half the value of the maximum correlation of the ENSO mode \( R(3) \) (Figs. 10 and 11). The correlation pattern of \( R(4) \) in the Indian and Pacific Oceans for lags between \(-120 \) and \(-90 \) days (Figs. 12 and 13) resembles the correlation pattern of \( R(3) \) for positive lags (Figs. 10 and 11). The only difference is that the patterns in Figs. 12 and 13 are shifted eastward and the positive correlation region in the east Pacific extends eastward and covers the tropical Atlantic Ocean also. From lag \(-60 \) to lag 0, the horseshoe pattern of negative correlations in the western and central Pacific splits into two centers, with maximum correlation between \(-0.3 \) and \(-0.4 \) on either side of the equator. During these lags, the positive correlation in the east Pacific Ocean and the Atlantic Ocean has weakened. The correlation in the Atlantic seems like an extension of the signal in the east Pacific. At the same time, the positive correlation around the Maritime Continent has increased to reach a maximum value around 0.4 and weaker positive correlation covers the Arabian Sea and the Bay of Bengal.

From lag \(+30 \) to lag \(+120 \) days, a dipole pattern has developed in the Indian Ocean, with the largest negative correlation (about \(-0.4 \)) occurring to the southwest of the Maritime Continent. During these lags, a weak horseshoe pattern of positive correlation develops in the western Pacific Ocean (extension of the pattern over the eastern Indian Ocean), while the negative correlation appears concentrated in the equatorial central and eastern Pacific Ocean. The positive correlation region in the Atlantic Ocean gradually diminishes in magnitude and extent. Overall, the TMI correlation pattern for the shorter period 1998–2006 (Fig. 13) reveals stronger values than during the longer period 1985–2006 of OISST (Fig. 12).

The correlation patterns of \( R(3) \) and \( R(4) \) in Figs. 10–13 raise the possibility that the persistent modes may be associated with two different components or phases of SST anomalies covarying over the Indian and Pacific Oceans and related to ENSO. Such covariability of Indian and Pacific Oceans SSTs, with possible relation to the Indian monsoon, was discussed by Krishnamurthy and Kirtman (2003). Further investigation is needed to determine if there are two modes of ENSO, one of which brings out the IOD mode predominantly.

c. Lagged correlations of SST indexes with OLR indexes

So far, the spatial patterns of the correlations of the AIM index of OLR RCs with the daily SST anomalies at 30-day intervals were discussed. Now, the daily variability of the correlation of each OLR RC will be examined and compared with the others. For this purpose, lagged daily correlations of the AIM indexes of the RCs with SST indexes representing the Pacific Ocean and the Indian Oceans are calculated. For the Pacific Ocean, Niño-3.4 index defined as the SST anomaly averaged over 5°S–5°N, 170°–120°W has been used. The Indian
Fig. 10. Same as Fig. 8, but for $R(3)$. 
Fig. 11. Same as in Fig. 10, but for SST anomalies of TMI during 1998–2006.
FIG. 12. Same as Fig. 8, but for $R(4)$. 
FIG. 13. Same as in Fig. 12, but for SST anomalies of TMI during 1998–2006.
Ocean is represented separately by the western and eastern parts of the dipole mode index (DMI). These indexes are DMI-east and DMI-west, which are SST anomalies averaged over 10°S–0°, 90°–110°E and 10°S–10°N, 50°–70°E, respectively (Krishnamurthy and Kirtman 2003). The reason for examining the relation with the two parts of the DMI separately is to show that the western Indian Ocean varies in concert with the central and eastern Pacific Ocean and that the strengths of the correlations with the eastern and western Indian Ocean are different.

The lagged correlations of daily Niño-3.4 index with the daily AIM indexes of the OLR anomaly, R(1, 2), R(3), and R(4) for the period 1985–2006 with OISST are plotted in Fig. 14a. In the lags shown between −240 and +240 days at one-day intervals, the negative (positive) lag denotes that the SST index is leading (lagging) the OLR index. Similar correlations of DMI-west and DMI-east indexes are shown in Figs. 14b and 14c, respectively.

The correlations using TMI data also show similar behavior (figures not shown).

The correlation of Niño-3.4 with the total OLR anomaly is positive for all lags shown, and is in the range of 0.2–0.3 between lag −85 and lag +180 days (Fig. 14a). The correlation of Niño-3.4 with the 45-day mode R(1, 2) is negligible. However, the persisting OLR ENSO mode R(3) has very high correlation with Niño-3.4 for a wide range of lags (Fig. 14a). For R(3), there is a steady increase from 0.2 at lag −115 days to reaching a maximum of 0.88 at lag +35 days. In fact, correlation values of 0.4 and 0.6 are reached when Niño-3.4 leads R(3) by 90 and 60 days, respectively. Correlations above 0.8 persist between lags −20 and +160 days, and correlations in the range of 0.6 to 0.8 occur from lag +160 to lag +230 days. Therefore, there is a very strong relation between the central and eastern Pacific SST anomalies and the persistent OLR monsoon mode R(3) before, during, and after the monsoon season. The correlation between Niño-3.4 and the persistent OLR IOD mode R(4) is weak to moderate and ranges from −0.2 to 0.4 (Fig. 14a). While this correlation is positive for most of the negative lags (i.e., when Niño-3.4 leads), it is negative for all positive lags (i.e., when Niño-3.4 lags). Thus, when Niño-3.4 lags, the correlations with R(3) and R(4) have opposite signs (Fig. 14a).

The correlations of DMI-west index, representing the western Indian Ocean, with the total OLR anomaly, 45-day oscillatory mode R(1, 2), and IOD mode R(4), are quite small for all lags between −240 and +240 days (Fig. 14b). However, the correlation with the OLR ENSO mode R(3) is moderate when the OLR leads SST (positive lags), with values above 0.4 for lags greater than +60 days and even reaching 0.5 during lags +130 to +240 days. Thus, the strongest correlation with the western Indian Ocean SST occurs with the ENSO mode R(3) rather than with the IOD mode R(4). Comparing Figs. 14a and 14b, it is evident that the lead–lag relations of the OLR indexes with Niño-3.4 and with DMI-west are quite similar except for the difference in the magnitude, implying that the monsoon has similar covarying relations with the western Indian Ocean and the central and eastern Pacific Ocean.

The correlations of DMI-east index, representative of the eastern Indian Ocean, with the total OLR anomaly, 45-day oscillatory mode R(1, 2), and IOD mode R(4) are negligible (Fig. 14c). Moderate negative correlations (−0.4 to −0.6) occur with the OLR ENSO mode R(3) for lags +15 to +95 days, and moderate positive correlations (0.3–0.5) occur between lag +170 and lag +240 days (Fig. 14c). The correlation with the OLR IOD mode R(4) is also moderate with positive correlations in the range of 0.2 to 0.4 between lag −115 and lag +95 days (Fig. 14c).
From Fig. 14, it is clear that, although the total OLR anomaly does not reveal strong relation with the SST anomalies, the persisting components $R(3)$ and $R(4)$ show strong lead–lag relation with the SST anomalies. When the SST leads, the central and eastern Pacific SSTs show strong relation with the monsoon through $R(3)$ while the eastern Indian Ocean SST shows moderate relation through $R(4)$, indicating the potential for using SSTs in these regions to predict the seasonal mean monsoon. The western Indian Ocean SST does not reveal such predictive capability. The possible influence of the monsoon on the ocean is also revealed in the strong correlations when the SSTs lag the OLR (Fig. 14). The consistent manner in which the persistent monsoon modes are related to three regions of the Indian and Pacific oceans, as shown in Fig. 10, reflects the covariability of the Indo-Pacific SSTs suggested by Krishnamurthy and Kirtman (2003). Some indication of the relative association of the SSTs in the Indian and Pacific oceans, as shown in Fig. 10, reflects the covariability of the Indo-Pacific SSTs suggested by Krishnamurthy and Kirtman (2003). Some indication of the relative association of the SSTs in the Indian and Pacific Oceans with the Indian monsoon rainfall was discussed by Ihara et al. (2007).

6. Summary and conclusions

A detailed study of the relation between the South Asian monsoon atmosphere and the tropical oceans on a daily time scale has been presented in this paper. Using two different high-resolution SST datasets, long lead–lag relations between daily OLR anomalies over the Indian monsoon region and daily SST anomalies in the tropical oceans have been determined by considering individually the dominant modes obtained from an MSSA of the OLR anomalies. The main results of this study have established that two seasonally persistent monsoon atmospheric modes are strongly related to the SSTs in the Indian and Pacific Oceans, whereas the two oscillatory monsoon modes have weak or negligible relation with the SSTs. These results have provided strong support to Charney–Shukla hypothesis that the slowly varying SSTs have a strong influence in determining the long-term variability of the monsoon.

The active (break) phase of the monsoon over India is shown to be associated with cold (warm) condition in the central and eastern equatorial Pacific Ocean and with warm (cold) SST anomalies in the northern west Pacific Ocean. A north–south dipole in the Arabian Sea and Bay of Bengal is also related to the active and break phases. When all the days of the monsoon season are taken into consideration (not just the active and break days), the SST pattern associated with the daily all-India monsoon index consists of the ENSO pattern in the Pacific Ocean and the dipole pattern in the Indian Ocean. Although the significant correlation of the total OLR anomalies with the SST anomalies reaches only about 0.3, the ENSO pattern in the Pacific is noticeable even when the SST lags or leads the monsoon by as much as four months. With individual MSSA modes, these relations become clearer and stronger.

The 28-day oscillatory mode of the monsoon has negligible correlation with the SST anomalies in the tropical oceans. The 45-day oscillatory mode of the monsoon atmosphere has weak correlation with the SST in the northern Indian Ocean and northwestern Pacific. There is some evidence of a 45-day oscillation in the SST anomalies in a band spanning the Arabian Sea to the northwestern Pacific. This SST oscillation propagates northeastward and occurs before and during the monsoon season.

The most important results of this study are revealed in the strong relation between persistent monsoon modes and the SST anomalies. The OLR ENSO mode shows very high correlation with the SST anomalies in the Pacific Ocean, with ENSO signature and moderate correlation with the Indian Ocean SST anomalies. The positive (negative) OLR anomalies [or deficient (excess) rainfall] over India corresponding to this monsoon mode are associated with an SST pattern that has warm (cold) anomalies in the central and eastern Pacific Ocean and in most of the Indian Ocean separated by cold (warm) anomalies in the eastern Indian Ocean and western Pacific Ocean. This pattern persists from when the SST leads the monsoon by about 120 days to when the SST lags the monsoon by about 240 days. The correlation with Niño-3.4 SST anomalies exceeds 0.8 for a long lead–lag time range.

The relation of the OLR IOD monsoon mode with the SST is about half as strong as that of the OLR ENSO mode but still significant. Although the SST pattern associated with this monsoon mode shows a clear signature of the dipole in the Indian Ocean, it is also accompanied by ENSO-like pattern in the Pacific Ocean that extends all the way to the tropical Atlantic. The way in which the correlation pattern changes as a function of time seems to indicate that this ENSO-like pattern has biennial variability. The dipole pattern in the Indian Ocean exists only during and after the monsoon season, indicating the possible influence of the monsoon on the development of the SST dipole. The IOD monsoon mode shows the strongest relation with the eastern part of the Indian Ocean SST for a long lead–lag time range. Interestingly, this mode also has weak to moderate correlation with the Niño-3.4 SST anomalies.

The strong lead–lag relation between the OLR modes and the SST anomalies suggests that the atmospheric variability associated with the monsoon and the oceans influence one another. The two persistent modes of the
atmospheric variability associated with the monsoon mainly determine the seasonal mean monsoon and its interannual variability. Therefore, the strong correlation of the SST anomalies of the premonsoon period with the persistent atmospheric modes indicates a strong potential for long-term prediction of seasonal monsoon as Charney–Shukla hypothesis suggested. The slowly varying SST anomalies in the regions of Pacific and Indian Oceans where the correlations are stronger can be considered to be potential predictors of the monsoon rainfall over India. Further research is needed to come up with a suitable prediction scheme to test this possibility. The strong correlations when the monsoon leads the SST suggest that the monsoon has a role in influencing the development or enhancement of the SST dipole events in the Indian Ocean and ENSO events in the Pacific Ocean. Such ocean–atmosphere interactions also make it necessary to reinterpret Charney–Shukla hypothesis by treating them as a combined slowly varying ocean–atmosphere component of the tropical climate, instead of as a boundary-forced response.

The persistent monsoon ENSO mode andIOD mode interfere constructively during some years while they counteract each other during certain other years to determine the seasonal mean monsoon. These results suggest a new hypothesis that the SST patterns associated with these persistent monsoon modes may also behave in a similar manner to determine the total SST anomaly field in the tropical ocean that is related to the monsoon during a particular year. The SST anomaly fields associated with the two persistent monsoon modes revealed covarying SST anomaly patterns in the Pacific and Indian Oceans that included ENSO variability. The combination of the two SST anomaly fields may change interannually in such a way that there is drought over India during certain El Niño years while there may be exceptions during certain other years such as 1997. The key to understanding the influence of SST is to further investigate the new hypothesis about the covariability of the two SST anomaly fields associated with the monsoon modes. It will be of great interest to determine if these two components of the SST anomalies are merely two phases of the combined Indo-Pacific SST variability that includes ENSO andIOD. The persistent monsoon mode provides the daily variability of the atmospheric component of ENSO, or what can be referred to as the “weather” of ENSO climate, over the monsoon region. Further study is needed to understand the variability of this atmospheric weather ENSO component over the entire tropical region including the Pacific and Indian Oceans.

Acknowledgments. This research was supported by grants from the National Science Foundation (0334910), the National Oceanic and Atmospheric Administration (NA040AR4310034), and the National Aeronautics and Space Administration (NNG04GG46G). The authors are thankful to Deepthi Achuthavarier and David Straus for helpful comments.

REFERENCES