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The Tropospheric Biennial Oscillation and Indian Monsoon Rainfall

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Abstract. An analysis of observed data shows that the tropospheric biennial oscillation (TBO, with roughly a 2-3 year period) encompasses most ENSO years (with their well-known biennial tendency) as well as additional years that contribute to biennial transitions in the Indian monsoon. Three conditions (related to anomalous surface temperatures) postulated to contribute to TBO transitions are examined for the northern spring season before the Indian monsoon:1) anomalous tropical Pacific SSTs, 2) atmospheric circulation-related anomalous south Asian land temperatures and resulting meridional temperature gradients, and 3) anomalous SSTs in the Indian Ocean. We quantify these three interannual transition conditions on a year by year basis, thus taking into account intermittent influences and secular variations in the strength of any particular linkage in any given year. The more transition conditions that are included in the analysis, the greater the TBO amplitude in terms of spectral power in the TBO periods of 2-3 years.

1. Introduction

In the context of the south Asian or Indian monsoon, the TBO is defined as the tendency for a relatively strong Indian monsoon to be followed by a relatively weak one, and vice versa, with the transitions occurring in northern spring involving coupled land-atmosphere-ocean processes over a large area of the Indo-Pacific region [*Meehl*, 1987, 1993, 1994, 1997].

Conditions set up the previous year contribute to the transitions. Of course the system is not perfectly biennial, and in some years internal dynamics or other processes can influence monsoon rainfall. Thus the TBO is not so much an oscillation, but a tendency for the system to flip-flop back and forth from year to year. The more of these interannual flip-flops or transitions, the more biennial the system. Quantifying the role of the conditions associated with these transitions in the TBO and their relationship to ENSO, and subsequently verifying their accurate representation in models, should lead to improved seasonal monsoon forecast skill.

Though there are a number of different types of ENSO events with protracted episodes that would weaken biennial signals [*Allan and D'Arrigo*, 1999; *Reason et al.*, 2000], enough ENSO events have inherent biennial tendencies so that a well-known biennial signature, with opposite sign precipitation and temperature anomalies the previous and following years, shows up in composite El Niño and La Niña events over a wide domain covering the tropical Indian and Pacific regions (e.g. *Kiladis and Diaz*, 1989). Therefore, the TBO clearly must encompass this biennial tendency of ENSO. However, it has been shown that other years display similar patterns to ENSO in this large region [*Meehl*, 1987; *Lau and Wu*, 2001]. In fact, the strength of TBO and ENSO signals is closer in magnitude over the Indian Ocean than the equatorial Pacific (Reason et al., 2000). Therefore the TBO must include most ENSO (El Niño and La Niña) years and some other years as well. Yet it has been difficult to quantify the various processes and conditions associated with this biennial tendency of monsoon-ENSO interaction and the additional non-ENSO years that contribute to the TBO [*Webster et al.*, 1998]. It has been argued that, of the wide array of conditions that could contribute to monsoon transitions in the TBO, most ultimately relate to anomalous surface temperature over south Asia and the tropical Indian and Pacific Oceans [*Meehl*, 1997]. It is the purpose of this paper to quantify the contributions from such anomalous surface conditions involved with a transition from relatively weak (strong) to relatively strong (weak) monsoons in consecutive years that contribute to the TBO.

We will examine the following hypothesis: The contributions from various anomalous surface temperature conditions prior to the monsoon to subsequent monsoon rainfall can act singly or in combination. The more conditions contributing to a relatively strong or weak monsoon (compared to the previous year) that are included, the greater the amplitude of the TBO in monsoon rainfall (i.e. the larger the spectral power of monsoon rainfall in the TBO periods of about 2--3 years).

2. Results

We first perform a singular value decomposition (SVD) analysis to define the maximum covariability of spatial associations between the transition conditions in the March-April-May (MAM) season with rainfall over the Indian region (5N-40N, 60E-100E) for the monsoon season of June-July-August-September (JJAS). A multivariate regression analysis technique could also serve to extract forcing and response, but the SVD analysis provides expansion coefficient time series that can be used to calculate the strength of year-to-year associations of the various transition conditions. For MAM, we use 1) 500 hPa height anomalies over Asia which, when positive, are associated with anomalously warm Asian land temperatures with an enhanced meridional temperature gradient that could strengthen subsequent monsoon rainfall [*Li and Yanai*, 1996; *Meehl*, 1997]; 2) Indian Ocean SSTs which, if anomalously warm, could provide a moisture source for greater monsoon rainfall through enhanced evaporation [*Rao and Goswami*, 1988] and could be related directly to the TBO [*Chang and Li*, 1999]; and 3) eastern equatorial Pacific SSTs which, if anomalously cool, could enhance monsoon rainfall through changes in the large-scale atmospheric east-

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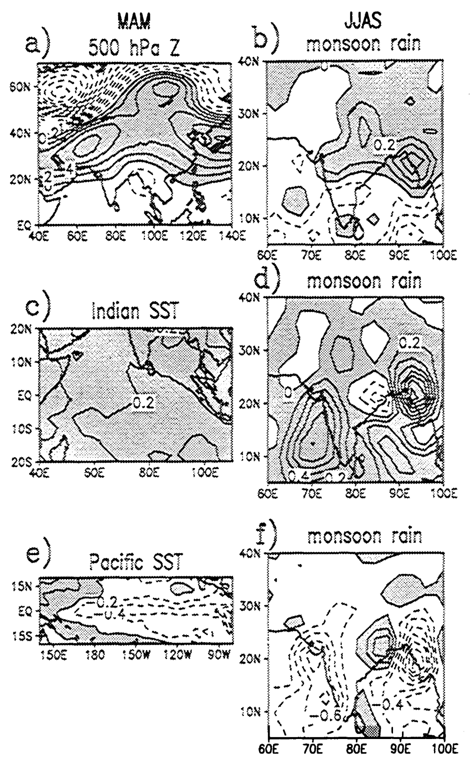

Figure 1. The first SVD components relating (a) 500 hPa height over the area 30N-70N, 50E-110E during MAM with (b) JJAS precipitation over the Indian region 5N-40N, 60E-100E. Contour intervals are 2 m per unit standard deviation of the expansion coefficients of the first precipitation vector, and 0.2 mm day^{-1} per unit standard deviation of the expansion coefficients of the first 500 hPa height vector, Correlation of the two expansion coefficient time series is +0.76, and percent of the total squared covariance explained is 39%. First SVD component relating (c) MAM surface temperature for the area in the tropical Indian Ocean 15S-20N, 40E-90E (contour interval of 0.2C per unit standard deviation of the expansion coefficients of the first precipitation vector), with (d) JJAS precipitation over the Indian region 5N-40N, 60E-100E (contour interval is 0.2 mm day^{-1} per unit standard deviation of the expansion coefficients of the first surface temperature vector). Correlation of the expansion coefficient time series is 0.75, percent of the total squared covariance explained is 58%. First SVD pattern relating (e) MAM surface temperature for the area in the eastern equatorial Pacific 20S-20N, 150E-80W (contour interval as in c), and (f) JJAS precipitation over the Indian region 5N-40N, 60E-100E (contour interval as in d). Correlation of the expansion coefficient time series is +0.70, percent of the total squared covariance explained is 39%. Note the surface temperature regressions in parts a, c, and e extend beyond the areas used in the SVD calculation. Shaded areas are positive.

west circulation [*Rasmusson and Carpenter*, 1983]. We use 21 years of observed data for the period 1979-1999 when the gridded CMAP precipitation [*Xie and Arkin*, 1996] are available, and 500 hPa heights and surface temperatures from the NCEP/NCAR reanalysis data [*Kalnay et al.*, 1996] for those same years. All data are on a T42 grid.

For positive 500 hPa height anomalies over south Asia in MAM (on the order of 5m per unit standard deviation of the expansion coefficient of the first precipitation vector, Fig. 1a), there are positive JJAS monsoon precipitation anomalies over much of central and eastern India, Bangladesh and Burma (on the order of about 0.3-0.4 mm day^{-1} per unit standard deviation of the expansion coefficient of the first 500 hPa vector, Fig. 1b). Regressing the 500 hPa SVD expansion coefficient time series from Fig. 1a (not shown) onto the surface temperature shows positive MAM land temperature regression values of greater than 0.5C (these areas are significant at greater than the 5% level) over much of southwest and central Asia (Fig. 2) with an enhanced meridional temperature gradient over Asia extending through the depth of the troposphere (not shown) as noted by other studies [*Li and Yanai*, 1996]. Comparable Asian land temperature anomalies can be linked to corresponding snow cover anomalies (e.g. *Bamzai and Shukla*, 1999), but such snow cover variations are likely a symptom of the fundamental changes in the large-scale atmospheric circulation over Asia and an indicator of the more fundamentally important surface temperature anomalies (Fig. 1a; *Meehl*, 1997).

For positive SSTs in the Indian Ocean in MAM (Fig. 1c), there are positive JJAS precipitation anomalies over southwestern and southern India, Burma, and the Arabian Sea and Bay of Bengal (Fig. 1d). Conversely, negative SST anomalies in the equatorial eastern Pacific in MAM (Fig. 1e) are associated with positive JJAS monsoon precipitation anomalies over Sri Lanka and areas of the eastern India (Fig. 1f). When we varied the boundaries of the regions used in the SVD calculation, the patterns were not significantly affected.

Since we use the first SVD components for three separate conditions, there clearly is no requirement that they be orthogonal. In fact, comparing Fig. 1d and 1f, there are indications that the patterns of precipitation for these two transition conditions are related, with one being nearly opposite to the other. In fact, there is an implied transition of Pacific SSTs from MAM to JJAS [*Meehl*, 1997] such that positive Pacific SSTs in JJAS are associated with the deficient monsoon precipitation in Fig. 1b. Thus positive MAM SSTs in the Indian Ocean also can occur with positive SSTs in the Pacific and the two ocean basins are linked in some years in their relation to the patterns of JJAS Indian monsoon rainfall. Other studies (e.g. *Kawamura*, 1998; *Yasunari and Seki*, 1992; *Clarke et al.*, 1998) have shown various connections between Indian monsoon rainfall, anomalous atmospheric circulation over Asia in the seasons prior to the monsoon, and

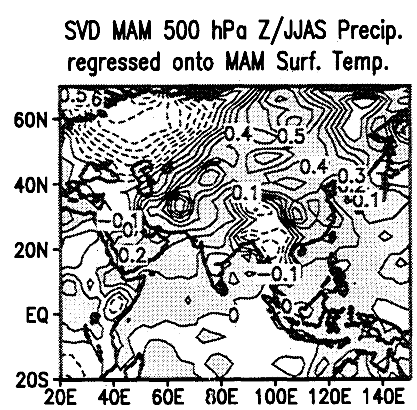

Figure 2. Regression of expansion coefficient time series for the MAM 500 hPa SVD pattern in Fig. 1a with MAM surface temperatures. Contour interval is 0.1°C, and shaded areas are positive.

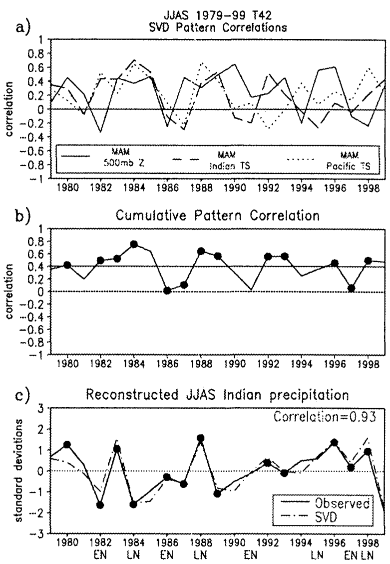

Figure 3. (a) Anomaly pattern correlations for the regional (500 hPa height, and tropical Indian SST) and large scale (Pacific surface temperatures) MAM conditions with observed JJAS Indian monsoon rainfall patterns for 5N-40N, 60E-100E, for areas defined in Fig. 1; (b) Cumulative anomaly pattern correlations for Indian monsoon rainfall combining the three conditions in (a), value of 0.4 is nominal 1% significance level as defined in the text, solid dots denote TBO monsoon transition years as noted in (c); (c) Time series of an area-averaged index of monsoon strength over the Indian monsoon region (5N-40N, 60E-100E) calculated from the full CMAP precipitation data (solid line) and for the cumulative SVD-derived precipitation (dashed line), both are normalized by their respective standard deviations, the correlation value is +0.93, El Niño (EN) and La Niña (LN) onset years are denoted on x axis and defined in the text, and solid dots denote TBO transition years as defined in the text.

tropical Indian and Pacific SST anomalies. The advantage of the present SVD technique is that we can quantify the individual associations year by year for the relationships of the first SVD modes which explain a majority of the covariance.

Thus, to determine in which years the transition conditions are connected and in which years they act independently, we calculate spatial anomaly pattern correlations between the observed JJAS rainfall patterns and the SVD projections individually and cumulatively [*Lau and Wu*, 1999]. The cumulative contribution up to the kth SVD for i transition conditions (using the first SVD component from each of the three transition conditions, so i=3 here) to the actual observed rainfall anomaly for the jth year is given by:

$$A_{i,j} = < O_j, \sum_{k=1}^{i} S(k) * C(k)_j >$$

where < > is the spatial anomaly pattern correlation over the Indian monsoon region, S is a normalized precipitation SVD pattern for JJAS associated with a MAM transition condition (Fig. 1), C is the precipitation SVD expansion coefficient for that year, and O is the observed JJAS Indian monsoon rainfall anomaly. Each anomaly pattern correlation is first calculated separately (Fig. 3a), and then the cumulative value is computed (Fig. 3b). A large positive correlation indicates a strong association with the observed monsoon rainfall pattern for that year.

The linkage between tropical Pacific and Indian SSTs and the pattern of Indian monsoon rainfall is large in some El Niño years (e.g. 1982) and La Niña years (e.g. 1988) when both have pattern correlation values greater than nearly +0.4 in Fig. 3a. In other years they act more independently (e.g. 1992 and 1994). This demonstrates that in some years the Indian Ocean can provide a regional input to monsoon rainfall separate from large scale influences emanating the Pacific. Interestingly, the Indian and Pacific conditions follow each other fairly closely before about 1990, but less so after that. This likely relates to the sustained warm conditions in the Pacific in the early 1990s and the consequent effects seen in the Indian Ocean [*Allan and D'Arrigo*, 1999]. Removing ENSO years from the present SVD analysis shows similar patterns as those in Fig. 1 for the 500 hPa height and Pacific SST conditions, but somewhat different associations for Indian SSTs with positive anomalies more concentrated in the Arabian Sea (not shown). This corroborates the result that in non-ENSO onset years, similar monsoon relationships can occur in most of the Indian-Pacific system.

In several years the regional 500 hPa atmospheric circulation/Asian land/meridional temperature gradient condition is more dominant (e.g. 1980, 1990, 1993, 1995 and 1996) with values above +0.4 in Fig. 3a. Connections between tropical Pacific SSTs, 500 hPa height and Indian SST are strong in 1984, 1985 and 1989 when all have values near to or greater than +0.4, thus confirming some of studies cited earlier. In other years (1991, 1995, 1998) the three conditions are unrelated with widely different values. In 1984 when all three transition conditions have high values (Fig. 3a), the cumulative value is about +0.8 (Fig. 3b) indicating over 60% of the spatial variance of the pattern of monsoon precipitation is accounted for in that year. However in 1986 when all of the three conditions are near zero for their individual associations, the cumulative pattern correlation is also near zero indicating other processes or internal dynamics are more important in that year. The point is that in any given year, we can quantify the magnitude of the associations of the various transition conditions (either none, some, or all) in MAM with the subsequent JJAS monsoon rainfall.

A nominal significance level of 0.4 in Fig. 3b is determined by a Monte Carlo technique whereby the seasonal pattern correlations from the SVD components are scrambled to randomly generate 865 sample pattern correlations with no overlap with the actual cumulative pattern correlations in Fig. 3b. A student t-test is performed to determine that the mean value of 0.4 is significantly different from the mean of the random samples at greater than the 1% level. For the 21 years considered here from 1979-1999, 12 (57%) exceed this nominal significance level.

To relate the precipitation anomaly patterns to an area-averaged monsoon index and consequently the magnitude of the TBO, regressions of the SVD expansion coefficient time series and the SVD rainfall patterns over the Indian region are used to produce a cumulative area-averaged Indian rainfall index (Fig. 3c). The correlation between the SVD-derived cumulative index of monsoon "strength" (normalized by its standard deviation) and the full area-averaged normalized index from the original CMAP precipitation data is +0.93 (significant at greater than the 1% level) thus showing the

SVD-derived index can capture 86% of the variance of the full index.

TBO monsoon years can be defined as a monsoon index value greater than the previous and following year, or less than the previous and following year [*Meehl*, 1987]. These are denoted in Fig. 3c for 13 years (out of 21 total). We define onset years for El Niño (1982, 1986, 1991, 1997) and La Niña (1984, 1988, 1995, 1998) as the initiation of a five month running mean area averaged SST anomaly in the eastern tropical Pacific Nino3 area (5N-5S, 150W-90W) of at least +/-0.5C for two consecutive seasons after the MAM transition season over the following one year period. Of the TBO years, 1982, 1986, 1997 are El Niño onset years, and 1984, 1988, and 1998 are La Niña onset years for a total of 6 years out of 8 possible ENSO onset years. That leaves 1980, 1983, 1987, 1989, 1992, 1993, and 1996 as 7 non-ENSO onset years (a few of these are involved with protracted ENSO events as noted by *Allan and D'Arrigo*, 1999). Some of these also are contributing to the interannual flip-flops that characterize the TBO. In Fig. 3b, 10 of these 13 TBO years have greater than the nominal significance value of 0.4, indicating that the transition conditions in Fig. 1 are strongly associated with 77% of the years with TBO transitions. Thus the magnitude of the associations of the different transition conditions can be quantified each year in terms of monsoon precipitation patterns (Fig. 3a), and information on monsoon strength is obtained from the reconstructed area-averaged monsoon precipitation index (Fig. 3c).

Another way of quantifying the TBO is to first compute spectra of area-averaged time series of SVD-reconstructed monsoon rainfall as in Fig. 3c for each condition in Fig. 3a individually and then cumulatively and then average the power in the TBO band of 2.1 to 2.8 years. The TBO spectral density or power ((mm^2 day^{-2} year) x 10^{-1}) for the individual 500 hPa SVD in Fig. 3a is 0.1. Adding the contribution of the Pacific SST conditions increases the TBO amplitude to 2.2. Including the effects from the Indian Ocean SST conditions, such that all three transition conditions are accounted for, increases TBO amplitude to 8.3, which is 8% greater than the spectral density in the periods of 3--7 years derived in the same way. This increase in TBO amplitude with the inclusion of Indian Ocean SSTs is related to area-averaged precipitation and is not as clear for the pattern correlations in Fig. 3a. In that figure, neither of the three conditions exhibits a dominant overall effect on the pattern of monsoon rainfall. For the monsoon index computed from the original data (solid line in Fig. 3c), spectral density in the TBO periods is 52% greater than in the 3-7 year periods. Thus there is more power in the TBO periods for both the reconstructed and original monsoon indices. These results confirm the hypothesis above such that the more transition conditions included in the analysis and the more these processes work, the more likely it is for a transition to occur in a given year, and thus the higher the amplitude of the TBO in area-averaged monsoon rainfall.

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