On the Relationship between Indian Ocean Sea Surface Temperature and Asian Summer Monsoon

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Abstract. Indian Ocean SST has been thought to play a weaker role in Indian summer monsoon rainfall than does the equatorial eastern Pacific SST. In this study we show that on the tropical biennial oscillation (TBO, 2-3 year) time scale the Indian monsoon rainfall has significant positive correlations with the Indian Ocean SST and moisture flux transport in the preceding winter and spring. The effect of this SST influence is quite different from the remote forcing of the Indian monsoon rainfall by the eastern Pacific SST, which is more dominant on the El Nino-Southern Oscillation (ENSO, 3-7 year) time scale. We conclude that while the eastern Pacific SST and the Eurasian land temperature both may affect the monsoon on the ENSO time scale, they are not important on the TBO time scale. Our results support the tropical and local feedback theories of TBO that this most important component of the monsoon variation is largely influenced by the Indian Ocean SST and interactions within the tropical atmosphere-ocean system (Chang and Li, Nichols).

1. Introduction

The relationship between the interannual variations of sea surface temperature (SST) and the Asian monsoon rainfall has been a subject of many studies. A prevailing view is that the summer monsoon rainfall has the strongest relationship with the equatorial eastern Pacific SST (e.g., Webster et al. 1998). For example, Lau and Yang (1996) showed that the simultaneous correlation between Indian summer rainfall and equatorial eastern Pacific SST is -0.5, while that with the equatorial Indian Ocean SST is only 0.2. These results seem to suggest that the South Asian monsoon is more heavily influenced by events in the eastern Pacific such as El Nino/Southern Oscillation (ENSO) than by the Indian Ocean SST. During 1997-98 the global climate was affected by one of the strongest El Nino episodes. The major regional rainfall anomalies over a large portion of the topical and extra-tropical Pacific regions were generally consistent with those observed during past warm episodes (e.g., Bell and Halpert 1998). However, contrary to the long recognized negative correlation between the Indian summer monsoon rainfall and ENSO, India received slightly above normal summer rainfall in 1997. There have been hypotheses that this result is due to variations of Walker and Hadley circulations forced by the equatorial Pacific SST anomalies (SSTA) (Slingo and Annamalai 2000) or due to Eurasian surface warming (Kumar et al. 1999). In this note we will show evidence that, at the temporal scale of the tropical biennial oscillation (TBO) (Nicholls 1978, 1979; Meehl 1987) - the most significant period in the interannual variation of the monsoon rainfall, the strongest correlation is with the Indian Ocean SST in the preceding boreal winter and spring seasons. Thus, the India summer rainfall seems to be affected strongly by equatorial Indian Ocean SST one to two seasons prior to the monsoon, such that the Indian Ocean SST may be used as a predictor for the monsoon rainfall.

We will also analyze low-level wind and tropospheric thickness fields to show important differences between the TBO and ENSO scales. The result infers significantly different natures in the thermal forcing of the Indian monsoon between these two time scales. The difference appears in both the moisture fluxes from the tropical Indian Ocean and the surface heating over Tibetan Plateau and Eurasia.

2. Data

The data used are the June-September all-Indian rainfall and the NCAR/NCEP reanalysis data set including SST, wind, moisture, and geopotential height for 1950-1997. A band-pass filter (Murakami 1979) is used to separate the data into approximately 2-3 year (TBO) and the 3-7 year (ENSO) period windows, with half-power points of the response functions located at 18 and 36 months and 42 and 86 months, respectively (not shown). These two bands have been shown to have the two most significant spectral peaks in the first EOF mode of global precipitation (Lau and Sheu 1988, Meehl 1997). A spectral analysis of the all-India rainfall during

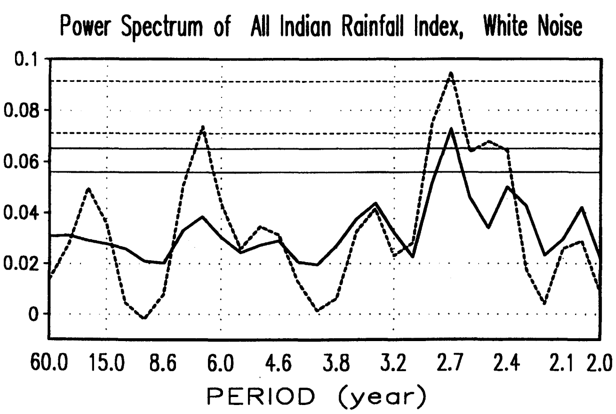

Figure 1. Power spectrum of all-Indian rainfall index over the 127-year (1871-1997, thick solid line) period and the 48-year NCEP data period (1950-1997, thick dashed line). The respective 90% and 95% confidence limits are also plotted for each period (thin lines).

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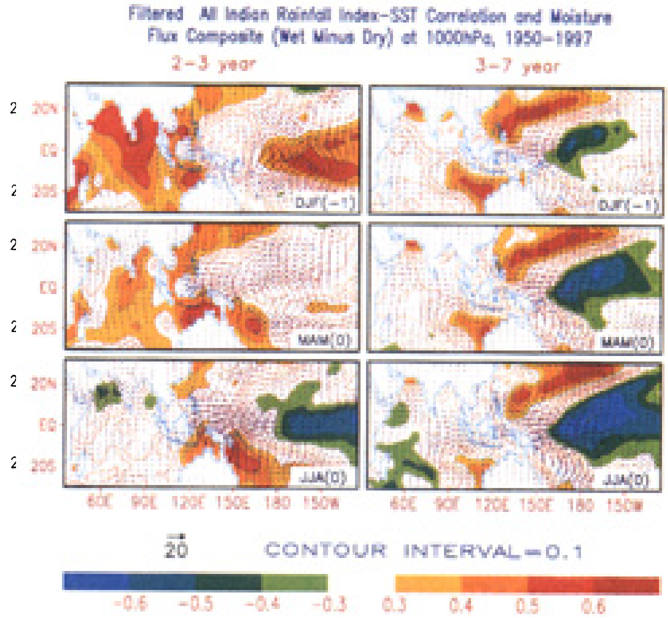

Figure 2. Lagged correlation maps between the India monsoon rainfall and SST anomalies in DJF(-1), MAM(0) and JJA(0) for the TBO (2-3 year) and ENSO (3-7 year) scales (where "0" denotes the reference monsoon year, contour interval: 0.1). The regions where the positive (negative) correlation (magnitude) exceeds 0.3 are shaded. Taking into account the reduction of the degree of freedom for each band-pass window, the statistical significance exceeds the 95% level when the correlation is 0.4 or above. Also plotted are the wet-minus-dry composites of the moisture transport (units: $ms^{-1}gkg^{-1}$) at 1000 hPa for DJF (-1), MAM (0) and JJA (0) on the TBO (2-3 year) and ENSO (3-7 year) time scales. The composites are conducted based on ten wettest and driest cases obtained from the time-filtered rainfall data.

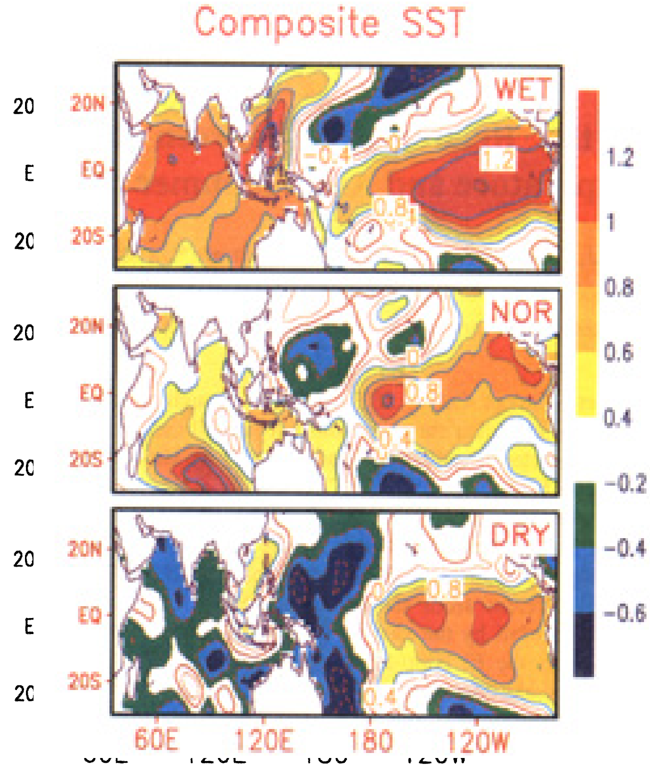

Figure 3. Composite of normalized (with respect to standard deviation of each grid point) winter SSTA associated with peak El Nino events according to three categories of Indian summer rainfall: wet (rainfall > + 0.7 standard deviation), normal, and dry (rainfall < - 0.7 standard deviation). The contour interval is 0.2. The wet years are 1970, 1973, 1983, and 1988. The normal years are 1958, 1977, and 1995. The dry years are 1952, 1966, 1987, and 1992.

summer shows that the 2-3 year peak is the only significant peak (at the 90% level) for both the entire 1871-1997 (127 years) data and the 48-year period of the NCAR/NCEP reanalysis (Fig. 1). This is consistent with the TBO signals that are frequently observed in the Asian-Australian monsoon region. A composite analysis of the pre-filtered data is also carried out to crosscheck the correlation results obtained from the band-pass filtering.

3. Results

Figure 2 shows the 2-3 year and the 3-7 year correlations between the all-Indian summer rainfall for 1950-1997 and the SST of three successive seasons, from the preceding winter to the current summer. For the 3-7 year window (right) the highest SST correlation is in the tropical Pacific, with cool eastern Pacific SSTA correlated with strong monsoon. The maximum negative correlation magnitude increases from ~0.5 in the preceding winter to >0.6 in summer. The correlation with Indian Ocean SSTA (IO) is weak for all seasons, which is consistent with those reported by previous studies using unfiltered data. However, for the 2-3 year window (left) the IO SSTA in the preceding winter and spring are highly correlated (~ 0.5) with the monsoon rainfall. The leading correlation in spring suggests that the IO SSTA may have a significant effect on the strength of the subsequent Indian monsoon.

Since SSTA may influence monsoon rainfall through their effects on evaporation and the resultant moisture transport

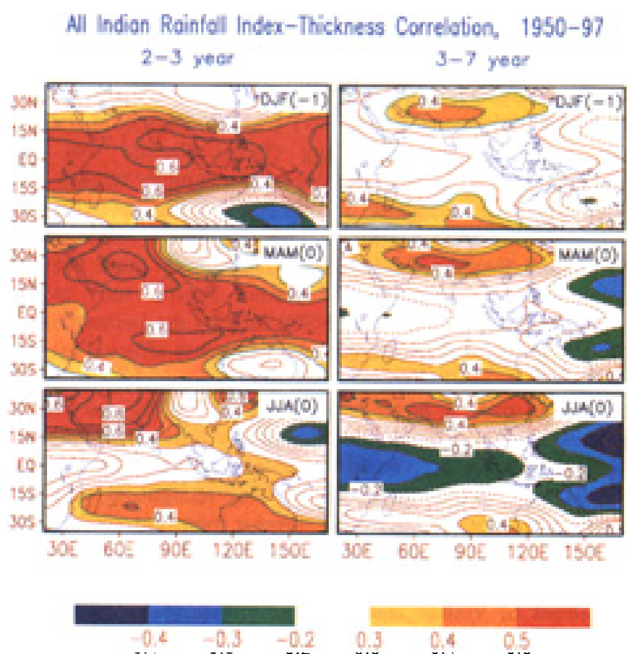

Figure 4. Lagged correlation maps between the India monsoon rainfall and the 200-500 hPa thickness anomalies in DJF(-1), MAM(0) and JJA(0) for the TBO (2-3 year) and ENSO (3-7 year) scales (where "0" denotes the reference monsoon year, contour interval: 0.1). The regions where the positive (negative) correlation exceeds 0.3 (-0.2) are shaded. The statistical significance exceeds the 95% level when the correlation is 0.4 or above.

(Meehl 1997, Chang and Li 2000), we composite the 1000 hPa zonal and meridional moisture fluxes computed from the NCEP reanalysis based on the difference between the 10 wettest seasons and 10 driest seasons. The differences of wet-minus-dry moisture flux composites are plotted in Fig. 2 in vector form. At the 2-3 year window, the 1000 hPa moisture flux composite has a substantial northward component and indicates an anomalous moisture transport from the equatorial Indian Ocean, Arabian Sea, and Bay of Bengal to the India subcontinent during the spring prior to a wet summer monsoon. This transport results in an anomalous moisture convergence over India. On the other hand, the moisture flux composite for the 3-7 year window in the winter and spring prior to a wet monsoon is quite different. The transport is mostly from west to east. It either converges in the eastern Arabian Sea before reaching the India subcontinent, or directs from the equatorial Indian Ocean toward the maritime continent. Thus, on the TBO time scale, there is correlation between monsoon intensity and the persistent transport of low-level moisture into the monsoon region in northern winter and spring before a wet summer monsoon. But on the ENSO time scale, there is little correlation between prior-season moisture transport and the monsoon.

The results presented above are not an artificial outcome of the band pass filters. This may be verified by a SST composite analysis without the use of the filtered data. Here the fall-winter NINO3 SSTA are partitioned into 3 categories: warm, cold, and normal, where the warm and cold categories are meant to represent El Nino and La Nina events and are defined by SSTA magnitude larger than 0.7 standard deviation for at least 2 months during September-February. The all-India summer rainfall anomaly is also partitioned into 3 categories: wet, dry, and normal, with the wet and dry categories defined by anomaly magnitude larger than 0.7 standard deviation. Fig. 3 shows the northern winter SSTA for El Nino events during the 48-year NCEP reanalysis data period, composited according to the three categories of the subsequent Indian summer rainfall. Although the eastern Pacific (EP) SSTA are positive for all three rainfall categories, a large difference exists in the IO SSTA between the wet and dry cases. The IO SSTA composite is mostly warm before the wet monsoon, and mostly cold before the dry monsoon. This situation in which the preceding IO SST is a better predictor than the EP SST for the Indian summer rainfall also appears in the northern spring composites (not shown). This relationship between the preceding IO SSTA and the subsequent Indian monsoon rainfall verifies the results of the filtered data for the 2-3 year window in Fig. 2.

An important conclusion derived from this analysis is that the IO SSTA is highly correlated, at a leading time of 3-6 months, with the Indian monsoon rainfall on the TBO time scale, but not on the ENSO scale (Fig. 2). Whereas the simultaneous correlation between the monsoon rain and IO SSTA is very low, the 6-month lag correlation is high. These results support the TBO hypothesis that a positive SSTA in IO leads to the increase of surface moisture (due to the enhanced surface evaporation) and thus a strong monsoon owing to the increased moisture fluxes into the monsoon region (Chang and Li 2000). A strong monsoon induces stronger surface winds that cool the ocean through evaporation, resulting in cold IO SSTA that will reduce moisture accumulation in the following seasons and lead to a weak monsoon next year. The low simultaneous correlation between the IO SSTA and the monsoon rainfall is a natural result, as summer is the season of sign change in the TBO.

The above results suggest that the physical processes for SSTA to affect the rainfall anomaly on the TBO and ENSO time scales differ significantly. On the TBO scale the effect is primarily due to the increase (or decrease) of the local surface moisture flux that accumulates in the monsoon region associated with the warm (or cold) SSTA in IO. On the other hand, the variation of the monsoon rain on the ENSO scale is related to a remote effect exerted by the EP SSTA.

Three possible processes contributing to the rainfall anomaly on the ENSO time scale may be identified in the difference between composites of wet Indian monsoon and those of dry Indian monsoon. The first is the direct impact of the EP SSTA through the large-scale east-west overturning (e.g. Meehl 1987). This is observed in the wet-minus-dry difference of the velocity potential composites of the NCEP data set (not shown). The second is through the compensating SSTA change in the Western Pacific (WP) that has a direct impact on the local convective activity. In association with a cold SSTA in EP, a positive SSTA appears in WP that increases convective activity along the monsoon trough, which is a region for the development of synoptic wave disturbances. This development may be seen in the right panels (3-7 year window) of Fig. 2, which show a warm SSTA region just east of the Philippines, particularly during summer. The moisture flux pattern indicates a cyclonic circulation center immediately downstream over the Philippines and the South China Sea. Many of the disturbances develop in this region and move toward Southeast Asia, and some reach the Indian subcontinent (Lau and Lau 1990). In contrary, in the left panels of Fig. 3 (the 2-3 year window) the western Pacific moisture flux field shows an anomalous anticyclonic circulation that penetrates into the northern South China Sea. Thus, the tendency for more synoptic disturbance activity in the northwestern Pacific near Philippines during the wet Indian monsoon season appears on the ENSO scale, but not on the TBO scale.

The third possible process on the ENSO scale is the remote SSTA impact on the midlatitude circulation. The wet-minus-dry 200-500 hPa thickness composite shows that six months prior to a wet monsoon onset a north-south thermal contrast has already been established across South Asia and the Indian Ocean, with the warm core centered over the Tibetan Plateau (Fig. 4, right panel). The location of this warm core is consistent with the hypotheses that Tibetan heating and/or Eurasia snow cover before the onset of the summer monsoon play an important role in the strength of the monsoon (e.g., Mooley and Shukla 1987, Yanai et al. 1992). This differs markedly from the TBO mode, in which the Indian subcontinent and the Indian Ocean are both covered by the same tropical warm anomaly belt during winter and spring before a wet season. A north-south thermal contrast between India and equatorial Indian Ocean develops simultaneously with the onset of the wet monsoon (Fig. 4, left panel). It follows that the land-ocean thermal contrast precedes a strong or weak monsoon on the ENSO time scale, but it does not on the TBO scale.

4. Conclusion and discussion

In this study, the possible processes that affect the Indian monsoon rainfall anomaly on the TBO (2-3 year) and ENSO

(3-7 year) time scales are studied using time-filtering on the NCEP reanalysis data between 1950-1997. We found that the mechanisms that affect the monsoon rainfall anomaly on the two time scales differ significantly. The monsoon rainfall on the TBO scale is affected by local moisture convergence that is associated with the change of the tropical Indian Ocean SST and is accumulated during the preceding spring and winter seasons. The rainfall on the ENSO time scale, on the other hand, results from three possible processes due to remote SST forcing from the equatorial eastern Pacific: anomalous large-scale east-west overturning, the enhancement/suppression of convective activity along the monsoon trough in association with the local SSTA in the western Pacific, and the land-ocean thermal contrast due to the influence of the midlatitude circulation.

While it is important to point out the role of the IO SST on the TBO, this observational analysis does not rule out TBO influences on the monsoon from the EP. It is well known that ENSO has a biennial component in the EP. It is likely that this biennial component of ENSO results from both internal ocean-atmosphere interactions in the Pacific (Chang et al. 2000) and the external forcing of the monsoon (Li et al. 2001; Kim and Lau 2001). This observational study suggests that the interannual variations of the monsoon depend on the combined effects of the TBO and ENSO. The Indian Ocean may act independently from the eastern Pacific in some years to contribute directly to the TBO regionally. The lag relationship identified in the biennial time scale is more useful for predictive purposes than the simultaneous correlation between the monsoon and the eastern Pacific SST. Further studies are needed to understand the effects of the anomalous IO SST and moisture flux in the preceding seasons on the monsoon and the dynamics of the tropical-midlatitude teleconnection.

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References

Bell, G. D., and M. S. Halpert, 1998: Climate assessment for 1997. *Bull. Am. Meteorol. Soc.*, **79**, s1-s50.

Chang, C.-P., and T. Li, 2000: A theory for the tropical tropospheric biennial oscillation. *J. Atmos. Sci.*, in press.

________, Y.S. Zhang, and T. Li, 2000: Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs: Part I: Role of subtropic ridges. *J. Climate*, 13, 4310-4325.

Kim, K.-M., and K.-M. Lau, 2001: Dynamics of monsoon-induced biennial variability in ENSO. *Geophy. Res. Let.*, in press.

Krishnamurti, T. N., 1971: Tropical east-west circulation during the northern summer. *J. Atmos. Sci.*, **28**, 1342-1347.

Kumar K. K., Rajagopalan, B. and M. A. Cane, 1999: On the weakening relationship between the Indian monsoon and ENSO. *Science*, **284**, 2156-2159.

Lau, K.-H., and N.-C. Lau, 1990: Observed structure and propagation characteristics of summertime synoptic-scale disturbances. *Mon. Wea. Rev.*, 118, 1888-1913.

Lau, K. M. and P. J. Sheu, 1988: Annual cycle, quasi-biennial oscillation, and Southern Oscillation in global precipitation. *J. Geophys. Res.*, **93**, 10975-10988.

________, and S. Yang, 1996: The Asian monsoon and predictability of the tropical ocean-atmosphere system. *Q. J. Roy. Meteorol. Soc.*, **122**, 945-957.

Li, T., C.-W. Tham, and C.-P. Chang, 2001: A coupled air-sea-monsoon oscillator for the tropospheric biennial oscillation. *J. Climate*, 752-764.

Meehl, G. A., 1987: The annual cycle and interannual variability in the tropical Pacific and Indian Ocean region. *Mon. Wea. Rev.*, 115, 27-50.

________, 1997: The South Asian monsoon and the tropospheric biennial oscillation. *J. Climate*, **10**, 1921-1943.

Mooley, D.A., and Shukla, 1987: Variability and forecasting of the summer monsoon rainfall over India. Monsoon Meteorology, C.-P. Chang and T.N. Krishnamurti, eds, Oxford University Press, 26-59.

Murakami, M., 1979: Large-scale aspects of deep convective activity over the GATE data. *Mon. Wea. Rev.*, **107**, 994-1013.

Nicholls, N., 1978: Air-sea interaction and the quasi-biennial oscillation. *Mon. Wea. Rev.*, **106**, 1505-1508.

______, 1979: A simple air-sea interaction model. *Quart. J. Roy. Meteorol. Soc.*, **105**, 93-105.

Slingo, J. M., and H. Annamalai 2000: 1997: The El Nino of the century and the response of the Indian summer monsoon. *Mon. Wea. Rev.*, **128**, in press.

Webster, P. J., V. O. Magana, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.*, **103-C7**, 14451-14510.

Yanai, M., Li, C. and Z. Song, 1992: Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon. *J. Meteorol. Soc. Japan.*, **70**, 319-351.

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