DIAGNOSING LOW FREQUENCY HYDROLOGIC VARIABILITY IN THE MONSOON-ENSO TELECONNECTION

J. Fasullo and P.J. Webster,
PAOS, University of Colorado, Boulder, CO

1. INTRODUCTION

Variations in summer rainfall across southeast Asia have long played a fundamental role in determining the region s agricultural productivity and economic prosperity (e.g. Sikka, 1999). Also, as fluctuations in these monsoon rains are accompanied by intense changes in local atmospheric heating, the monsoon interacts with other modes of tropical variability such as the El-Ni o Southern Oscillation (ENSO).

The interaction between the monsoon and ENSO is complex however. Early investigations of teleconnections with the monsoon region reveal a strong negative coupling between anomalies in seasonal monsoon rainfall and sea surface temperatures (SST) in the Ni o-3 region on an interannual timescale (e.g. Walker, 1923).The physical nature of the teleconnection is often explained as an interaction between the Hadley circulation in the monsoon region with modified trade winds due to a perturbed Walker circulation during ENSO (Rasmusson and Carpenter, 1983; Webster and Yang, 1992; Ju and Slingo, 1995; Lau and Bua, 1998; Goswami, 1998). The net result is a reduction in moisture convergence in southeast Asia during El Ni o events and enhanced convergence during La Nina events (Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983; Shukla and Paolino, 1983, Parthasarathy and Pant, 1985; Shukla, 1987; Webster and Yang, 1992; Krishnamurthy and Goswami, 2000). However early attempts to translate the monsoon-ENSO coupling into a skillful predictive relationship for monsoon precipitation were largely unsuccessful due to the lack of significant persistence of SST anomalies through boreal spring and sufficient forecasting lead time (Norman, 1953). Today, with promise of skillful ENSO forecasts extending over several seasons, the monsoon-ENSO relationship holds renewed interest.

Unfortunately, while seasonal lead forecasts of ENSO have become more skillful, the monsoon-ENSO relationship has languished. Figure 1 shows the 10-year sliding correlation between All India Rainfall (AIR) and Ni o-3 SST over the past century. Correlations during the 1980 s and 1990 s have dropped significantly from their long term mean of -0.54. Recent weakness in the monsoon-ENSO correlation is not unprecedented however as the correlation has fallen below 90% statistical significance at several other times during the past century. In fact, only during three intervals: 1880 to 1895, 1906 to 1910, and 1966 to 1976, have the indices shared more than half of their variance, or alternatively, has the correlation s significance exceeded 99%.

Thus, in order to exploit improved predictive skill in the Ni o-3 region for the purpose of monsoon forecasting low frequency variability in the monsoon-ENSO relationship must be understood and considered. A number of questions regarding the monsoon-ENSO correlation and its low frequency variability can be asked. Most basically, what are the basic physical processes that communicate the monsoon-ENSO coupling? Do the physical processes differ noticeably during periods of strong versus weak monsoon-ENSO correlation?

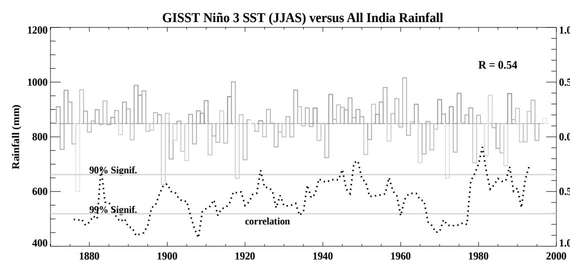

Figure 1: The sliding 10-year correlation between All India Rainfall and Ni o-3 SST estimated from Reconstructed Reynolds SST fields and a) observed All India Rainfall Index and b) rainfall fields from the NCEP/NCAR reanalysis.

As the lateral and transverse heating gradients that drive the monsoon are strongly tied to moist processes (Webster, 19994), a focus is given to diagnosing the monsoon-ENSO relationship through the atmospheric hydrologic cycle. Composite anomalies during ENSO events over the past 40 years are examined to determine the basic forcings that communicate the monsoon-ENSO teleconnection on an interannual time scale. Differences between periods of strong and weak monsoon-ENSO coupling are then investigated.

2. DATA AND METHOD

The NCEP/NCAR reanalyses are used to estimate variability of the hydrologic cycle from 1958 to the present (Kalnay et al., 1996). The reanalyses incorporate global rawinsonde data, COADS surface marine data, and surface land synoptic data throughout the current study s analysis period (1958-present). Total moisture transport is calculated from the reanalysis fields from the surface to 300 mb.

Table 1: ENSO years as defined by filtered Niño-3 SST anomalies.

Cold Events	Warm Events
1964, 1967, 1970, 1971, 1973, 1975, 1978,1988	1965, 1972, 1982, 1983, 1987, 1991, 1992, 1993, 1997, 1998

For the composite assessments, strong and weak monsoons, and warm and cold ENSO events are identified. Monsoon strength is gauged by All-India Rainfall Index anomalies of 10% or more. ENSO events are gauged from the concurrent detrended Reconstructed Reynolds SST anomalies in the Ni o-3 region (150 ^{o}E:90 ^{o}E, 5^{o}N:5^{o}S) of greater than 0.8^{o}C. Because SST anomalies during ENSO events do not always experience the same phase relationship with the seasonal cycle, the events identified differ slightly from other ENSO definitions (e.g. Kiladis and Diaz, 1989). However, the events identified are believed to be relevant to the monsoon-ENSO coupling as they reflect concurrent Ni o-3 conditions.

3. ENSO ANOMALIES AND THE MONSOON HYDROLOGIC CYCLE

Figure 2 shows the differences in SST (shading) and moisture advection (vectors) for La Ni a versus El Ni o conditions from 1958 to 1999. Important differences between ENSO phases are apparent. During Pacific cold events, easterly transports are enhanced across 140^{o}E. As integrated moisture transports are strongly biased towards the low-level flow, the anomalies across 140^{o}E are consistent with the enhancement of low-level trade winds due to the perturbed Walker circulation.

However, by 100^{o}E, anomalous zonal transports are westerly and enhanced moisture convergence over India and the Bay of Bengal is primarily the result of enhanced zonal flow from the Arabian Sea rather than from the Pacific. Moisture transport into the Arabian Sea is also greater during La Ni a as compared to El Ni o. Thus the interaction between ENSO and the monsoon is complex and is not the result of enhanced moisture convergence due to easterly transport anomalies into the Bay of Bengal. The manner in which transports change with ENSO during periods of strong and weak monsoon-ENSO coupling is now examined. In doing so, the ENSO impact from 1958 to 1999 will be considered to be the climatological ENSO impact.

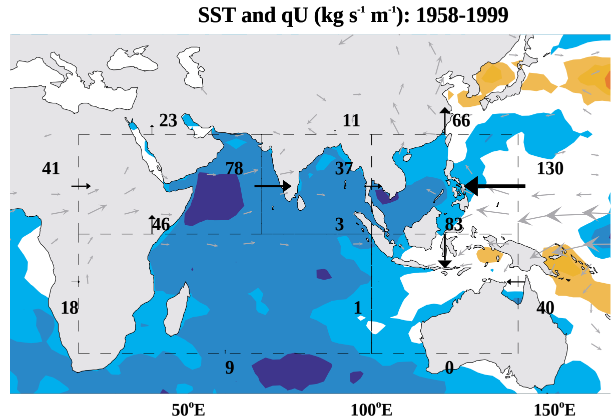

Figure 2: The composite difference in moisture transport (vectors) and SST anomalies (shading) for monsoons during La Ni a versus El Ni o events from 1958 to 1999. Light shading, such as in the Pacific subtropics, denotes positive SST differences (La Ni a warmer than El Ni o) while dark shading (Indian Ocean) denotes cold differences. Moisture transport differences represent integrated differences across various boundaries in and around the Indian Ocean (dashed)

4. DIFFERENCES BETWEEN PERIODS OF STRONG AND WEAK MONSOON-ENSO CORRELATION

Figure 3 shows the difference in moisture transport and SST between cold and warm ENSO events from a) 1958 to 1976, when the monsoon-ENSO correlation was strong, and b) 1977 to 1999, when the correlation was weak. During periods of strong monsoon-ENSO coupling, differences in SST between La Ni a and El Ni o events are large under the Somali Jet and western Indian Ocean. SST differences in the Bay of Bengal and much of the eastern Indian Ocean are small however. Anomalous easterly transport of water vapor across 140^{o}E between 30^{o}S and 25^{o}N is 49% larger than climatology. Differences in transports across 100^{o}E are small. Enhanced moisture convergence near India and the Bay of Bengal results primarily from enhanced westerly transport from the Arabian Sea which is almost 50% stronger than the climatological ENSO difference (Fig. 2). Northwards anomalous transports through the Somali Jet are 80% stronger than the climatological difference.

During periods of weak monsoon-ENSO correlation, differences in SST are strongest in the southeastern Indian Ocean and eastern Pacific while modest cool anomalies are evident in the northern Indian Ocean. The SST difference distribution reflects a dramatic shift for the eastern Indian Ocean from the SST difference field during the period of strong correlation when little difference existed in the eastern Indian Ocean. Anomalies in easterly transports from the Pacific across 140^{o}E and southerly transports through the Somali Jet are weakened from climatology (Fig. 2) by about 14% and 50%, respectively.

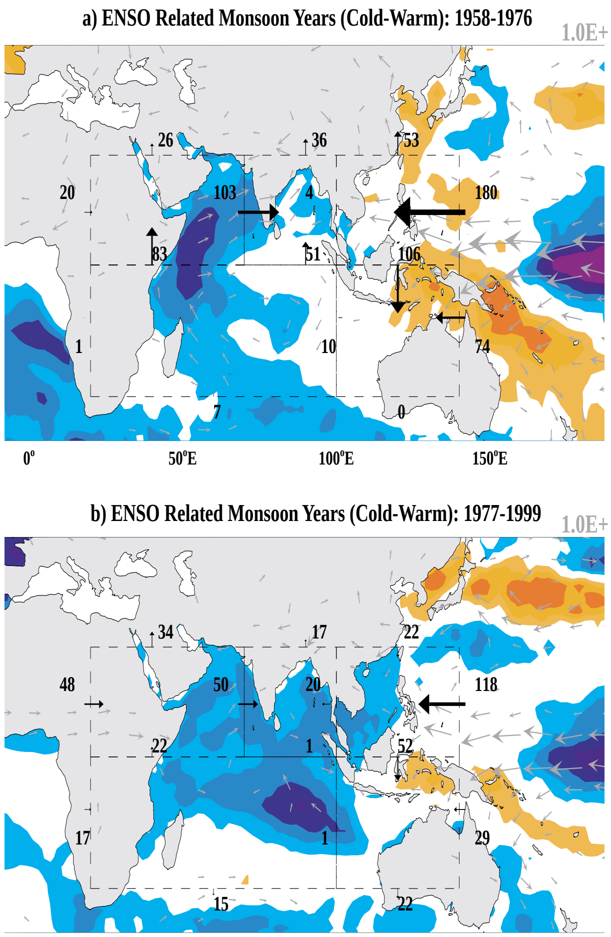

Figure 3: The difference in SST (contours) and moisture transports (vectors) for Pacific warm and cold events from a) 1958-1976 and b) 1977 to 1999. Light shading, such as north of Australia in a), denotes positive SST differences (La Ni a warmer than El Ni o) while dark shading (Somali current in a) denotes cold differences.

In comparing differences in the hydrologic cycle during ENSO events at times when the monsoon-ENSO coupling is both strong and weak, a number of observations can be made. The period of weak monsoon-ENSO coupling is generally associated with a reduced difference in the basic components of the hydrologic cycle between La Ni a and El Ni o years. The reduced difference is apparent throughout the Indian Ocean and is particularly evident in the Somali Jet and in the westerly transports across India s west coast. The reduction in moisture transport difference is not only evident in the Indian Ocean but also in the Pacific, where transports across 150^{o}E are significantly less from 1977 to 1999 than during 1958 to 1976. Moreover, transport differences in the western and central Pacific Ocean are substantially less during the period of weakened correlation.

6.0 DISCUSSION AND CONCLUSIONS

Some key conclusions can be made about the nature of the monsoon-ENSO interaction. First, modification of moisture convergence in India and the Bay of Bengal is not due to anomalous easterly transport of moisture across 100^{o}E but from enhanced westerly transports from the Arabian Sea. ENSO s influence on rainfall over India is therefore only realized through its interaction with the larger monsoon system and its amplification of the processes that transport moisture towards India in the seasonal mean, which act predominantly from the west. Also, it can be concluded that not only has the monsoon-ENSO correlation weakened in recent decades, but the differences in the hydrologic cycle between La Ni a and El Ni o years have lessened. Finally, the role of ocean processes in modulating the monsoon-ENSO correlation is raised based on the strikingly different nature of SST difference at times when the ENSO-monsoon relationship is strong versus times in which it is weak.

Establishing causality between the monsoon and ENSO is a key challenge in further interpreting the results of this analysis. Are weakened differences in moisture transports over recent decades the result of a lack of extreme monsoon events or the cause of it? Changes in the hydrologic cycle could result either from the steadiness of the monsoon system, particularly during the 1990 s, or from changes in its teleconnection with ENSO. Assessment of SST fields during periods of strong and weak correlation also shows that modes of variability that dictate longitudinal asymmetries in the SST distribution (e.g. Webster et al., 1998) are associated with the change in monsoon-ENSO coupling. Are these modes of variability actively involved in modulating the monsoon-ENSO relationship or passive signatures of its changes?

Many questions remain. This study develops a rationale for examining the interactions between rainfall over India and the Bay of Bengal with other convective centers of the monsoon system and processes within the Indian Ocean in explaining low frequency variability in the monsoon-ENSO correlation. Modeling efforts that focus on the interaction between these essential components of the monsoon system hold the promise of distilling the multiple and complex interactions between the monsoon and ENSO systems.

REFERENCES

Barnett, T. P. 1983: Interaction of the monsoon and Pacific trade wind systems at interannual time scale. Part I: The equatorial zone. Mon. Wea. Rev., 111, 756-773.

Barnett, T. P., 1984: Interaction of the monsoon and Pacific trade wind system at interannual time scales. Part III. A partial anatomy of the Southern Oscillation. Mon. Wea. Rev., 112, 2388-2400.

Elliot, W. P. and J. K. Angell, 1988: Evidence for change in Southern Oscillation relationships during the last 100 years. J. Climate, 1, 729-737.

Findlater, J., 1969: Interhemispheric transport of air in the lower troposphere over the western Indian Ocean. Quart. Jour. Roy. Met. Soc., 95, 400-403.

Gershunov, A. and T. P. Barnett, 1998: Interdecadal modulation of ENSO teleconnectins. Bull. Amer. Meteor. Soc., 79, 2715-2725.

Goswami, B. N., 1998: Interannual variations of Indian summer monsoon in a GCM: External conditions versus internal feedbacks. J. Climate, 11, 501-522.

Ju, J., and J. Slingo, 1995: The Asian summer monsoon and ENSO. Quart. J. Roy. Meteor. Soc., 121, 1133-1168.

Kalnay, E., and Coauthors, 1996: The NCEP-NCAR 40-Year Reanalysis Project. Bull. Amer. Meteor. Soc., 77, 437-471.

Kiladis, G. N., and H. F. Diaz, 1989: Global climatic anomalies associated with extremes in the Southern Oscillation. J. Climate, 2, 1069-1090.

Krishnamurthy, V., and B. N. Goswami, 2000; Indian Monsoon-ENSO Relationship on Interdecadal Timescale, J. Climate, 13, 579-595.

Lau, K-M., and W. Bua, 1998: Mechanism of monsoon-Southern Oscillation coupling: insights from GCM experiments. Climate Dynamics, 14, 759-779.

Lau, K-M., K-M Kim, and S. Yang, 2000; Dynamical and boundary forcing characteristics of regional components of the Asian summer monsoon. J. Climate, 13, 2461-2482.

Mantua, J.N., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Amer. Meteor. Soc., 78, 1069-1080.

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

Normand, C., 1953: Monsoon seasonal forecasting. Quart. J. Roy. Meteor. Soc., 79, 463-473.

Pant, G. B., and B. Parthasarathy, 1981; Some aspects of an association between the Southern Oscillation and Indian summer monsoon. Arch. Met. Gaffes. Biokl., 1329, 245-252.

Parthasarathy, B., and G. B. Pant, 1985: Seasonal relationship between Indian summer monsoon rainfall and Southern Oscillation, *J. Climatol.*, **5**, 369-378.

Rasmusson, E. M., and T. H. Carpenter, 1983: The relationship between eastern equatorial Pacific sea surface temperature and rainfall over India and Sri Lanka. *Mon. Wea. Rev.*, **111**, 517-528.

Shukla, J., and D. A. Paolino, 1983: The Southern Oscillation and long-range forecasting of the summer monsoon rainfall over India. *Mon. Wea. Rev.*, **111**, 1830-1837.

Shukla, J., 1987: Interannual variability of monsoons. Monsoons, J. S. Fein and P. L. Stephens, Eds., Wiley and Sons, 399-464.

Sikka, 1980; Some aspects of the large scale fluctuations of summer monsoon rainfall over India in relation to fluctuations in the planetary and regional scale circulation parameters. Proc. Ind. Acad. Sci. (Earth & Planet. Sci.), 89, 179-195.

Sikka, D.R., 1999: Monsoon drought in India. Joint COLA/CARE Technical Report No. 2, July, 1999, 270 pp.

Torrence, C. and P.J. Webster, 1999: Interdecadal changes in the ENSO-monsoon system. J. Climate, 12, 2679-2690.

Trenberth, K.E. and J.W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific. Clim. Dyn., 9, 303-319.

Walker, G. T., 1923: Correlations in seasonal variations of weather, VIII. *Mem. India Meteor. Dept.*, **24**, 75-131.

Webster, P. J., and S. Yang, 1992: Monsoon and ENSO: Selectively interactive systems. Quart. J. Roy. Meteor. Soc., 118, 877-926.

Webster, P. J. V. O. Magana, T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoon: Processes predictability, and the prospects for prediction. *J. Geophys. Res.*, **103C**, 14 451-14 510.