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Tropical Pacific upper ocean heat content variations and Indian summer monsoon rainfall

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[1] Indian southwest monsoon rainfall (ISMR) has strong links with El Niño/Southern Oscillation (ENSO). However, sea surface temperature (SST) anomalies during the premonsoon season do not have any predictive value for ensuing monsoon rainfalls. Recent studies have suggested that warm water volume (WWV) in the tropical Pacific Ocean in boreal winter is a good precursor of ENSO warm and cold events (El Niño and La Niña). In this study, we have analyzed inter-annual variations in the WWV in the tropical Pacific Ocean and Indian summer monsoon rainfall (ISMR) using upper ocean thermal field analyses spanning 54 years (1950–2003). Significant negative correlations have been observed between WWV anomalies in the boreal winter and spring seasons and ISMR, with deficient (excess) monsoon years corresponding to positive (negative) WWV anomalies. This relationship provides a much longer lead time than ENSO SST indicators for prediction of ensuing monsoon rainfall. Twenty-one year moving correlations show that the correlation between WWV anomalies in boreal winter and spring and subsequent ISMR anomalies has strengthened since the mid-1980s. *INDEX TERMS:* 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 4522 Oceanography: Physical: El Nino; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 4504 Oceanography: Physical: Air/sea interactions (0312). **Citation:** Rajeevan, M., and M. J. McPhaden (2004), Tropical Pacific upper ocean heat content variations and Indian summer monsoon rainfall, *Geophys. Res. Lett.*, *31*, L18203, doi:10.1029/2004GL020631.

1. Introduction

[2] Indian southwest monsoon rainfall (ISMR) contributes about 70–90% of annual rainfall over India. The inter-annual variation of ISMR significantly affects agricultural production and the farm sector in India, which ultimately influences the Indian economy. Thus, the severe drought of 2002 resulted in significant economic hardship in India. However, timely and well distributed rainfall during the 2003 monsoon season revived the farm sector boosting India's gross domestic product by about 8% compared to 2002.

[3] Accurate long-range prediction of ISMR offers substantial benefits to the Indian economy. In 2003, the India Meteorological Department (IMD) introduced several new statistical models for long-range forecasts of ISMR. The details of the new models are given by *Rajeevan et al.* [2004]. IMD now prepares forecasts for ISMR in 2 stages. The first forecast is issued in mid-April using an 8 parameter non-linear regression model, which is initialized with data up to March. Then in the first week of July, the ISMR forecast is updated with a 10 parameter regression model, initialized with data up to June.

[4] ENSO information is an important input into the long-range forecast models. In the 1980s *Sikka* [1980], and *Rasmusson and Carpenter* [1983] found that during El Niño (La Niña) years, there is higher probability of below (above) normal ISMR. However, statistically significant inverse relationships between ISMR and ENSO are observed during and after the monsoon season. During the premonsoon period, the correlations between NINO-3 and ISMR are weak and cannot be used in the forecast models (Figure 1). In the 8 parameter forecast model, NINO−3 SST anomalies averaged over July–September of the previous year are used as one of the predictors. However, these correlations are relatively weak and simply represent the cyclic nature of the correlation pattern between ISMR and ENSO. Therefore, there is a need for a parameter during the winter and spring prior to the southwest monsoon, which indicates the likely evolution of an El Niño/La Niña during the subsequent monsoon season.

[5] Several studies indicated that variability in heat content or its equivalent of volume of warm water (WWV) in the tropical Pacific is important in governing the evolution of the ENSO cycle [*Wyrtki*, 1975; *Cane et al.*, 1986; *Jin*, 1997]. Warm water builds up in the equatorial Pacific prior to El Niño and then is transported to higher latitudes during El Niño. It has been suggested that this buildup of the WWV in the equatorial Pacific is a necessary precondition for the development of an El Niño [*Wyrtki*, 1975; *Cane et al.*, 1986]. In addition, *Meinen and McPhaden* [2000] examined the observed changes in surface winds, sea surface temperature (SST) and the WWV in the equatorial Pacific Ocean and found that the magnitude of ENSO SST anomalies is directly related to the magnitude of zonal mean WWV anomalies over the equatorial Pacific. Therefore, zonally averaged WWV changes along the equator are a useful predictor of ENSO time scale SST variations. *McPhaden* [2003] further demonstrated that, unlike SST, there is no spring persistence barrier [*Webster and Yang*, 1992] when considering upper ocean heat content, which is important for making skillful ENSO forecasts early in the calendar year.

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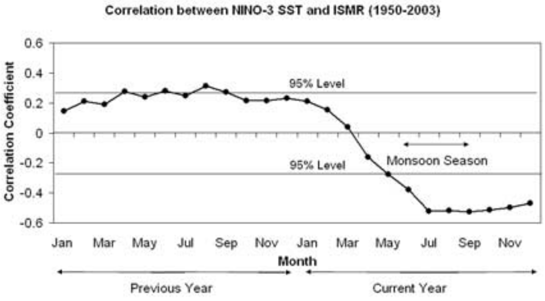

Figure 1. Correlation coefficients between NINO-3 SST anomalies and Indian Summer Monsoon Rainfall (ISMR) starting from January of the previous year to December of the monsoon year based on data for the period 1950–2003. The Indian summer monsoon season period is also shown.

[6] It is the purpose of this study to examine inter-annual variations of WWV in the tropical Pacific and their predictive relationship with ISMR.

2. Data Sets

[7] For this study, we have used Warm Water Volume (WWV) data as described in *Meinen and McPhaden* [2000] and *McPhaden* [2003]. Their analysis was based on the *Smith* [1995] upper ocean temperature field analysis derived primarily from ship of opportunity XBT measurements and TAO/TRITON moored time series measurements [*McPhaden et al.*, 1998]. Monthly averages of warm water volume (WWV) were computed between 5°N and 5°S integrated across the Pacific basin including all ocean areas between 80°W and 120°E. The lower boundary for this integration is the depth of the 20°C isotherm, which is located in the middle of the upper thermocline. The time series of WWV begins in 1980, when sufficient XBT data first became available for reliable basin scale analyses. The analysis with 24 years of WWV anomalies (January 1980–March 2004) is relatively short for a study of inter-annual variability and is not optimal for developing long-range monsoon forecast models. Therefore, we augment this analysis with WWV computed from *Carton et al.* [2000a, 2000b].

[8] *Carton et al.* [2000a] have constructed a simple ocean data assimilation (SODA) analysis of the global upper ocean for 1950–2000 using a Geophysical Fluid Dynamics Laboratory (GFDL) ocean general circulation model. Assimilated data includes temperature and salinity profiles from the World Ocean Atlas-94 (MBT, XBT, CTD and station data) as well as additional hydrography, sea surface temperature and satellite altimeter sea level. WWV anomalies from SODA from January 1950 to December 2000 are computed relative to the mean seasonal cycle averaged over the base period of 1971–2000.

[9] Overall there is a good correspondence between WWV anomalies based on the *Smith* [1995] and *Carton et al.* [2000a] analyses. The correlation coefficient between the two time series is 0.88 and the root mean square difference between the two time series is 0.9×10^{14} m^3 which is significantly smaller than the 1.6×10^{14} m^3 standard deviation of time series. The data available for the SODA analysis in the tropical Pacific prior to 1980 is much sparser than after 1980. Therefore, we expect the quality of SODA analysis to be higher after 1980.

[10] NINO-3 SST anomalies were derived from the SST data of *Reynolds and Smith* [1995]. ISMR time series has been derived as the area weighted rainfall of 36 meteorological sub divisions of India [*Rajeevan et al.*, 2004]. ISMR time series of the period 1950–2003 has been used for this analysis. ISMR is considered to be normal if rainfall departure is within ±10%.

3. Results

[11] Correlation coefficients between monthly WWV anomalies and ISMR using 51 years of data (1950–2000) indicate a statistically significant (95% level) negative correlation between the ISMR and the WWV anomalies from February to June (Figure 2). The correlations from March to May are significant even at the 99% level. Positive WWV anomalies in the tropical Pacific in boreal winter and spring are associated with below normal ISMR, and vice versa. This is in the same sense as the inverse association between the NINO-3 SST anomalies and ISMR. The correlation between WWV and IMSR weakens during the monsoon season itself which is consistent with the weak simultaneous correlation between ENSO SST and WWV anomalies in the Pacific at this time of year [*McPhaden*, 2003].

[12] Based on Figure 2, we averaged WWV anomalies for February–March (FM) to examine their potential use as a predictor in the long-range forecasts issued in mid-April. Since there is good correspondence between the WWV time series based on the *Carton et al.* [2000a] and *Smith* [1995] temperature analyses, we appended the Smith analysis for 2001–2003 to the SODA analysis for 1950–2000. Comparison of this time series with ISMR anomalies (Figure 3) show that there is a tendency for years of rainfall deficit (excess) to correspond with periods of elevated (depressed) WWV. While there are many exceptions to this relationship, the correlation between WWV (FM) and ISMR for the period 1950–2003 is −0.36 which is significant at 99% level assuming each year is independent.

[13] The scatterplot between WWV (FM) anomalies and ISMR anomalies for the period 1950–2003 (Figure 4) shows that most El Niño years fall in bottom right sector with positive WWV (FM) and negative ISMR anomalies. Similarly, most of La Niña Years fall in the top left sector

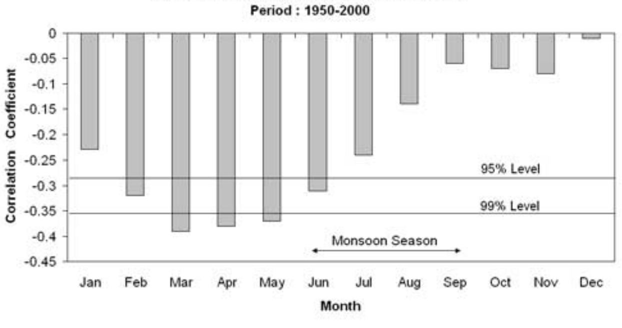

Figure 2. Monthly correlation coefficients between WWV anomaly and ISMR based on data for the period 1950–2000. The 95% and 99% confidence levels are also shown.

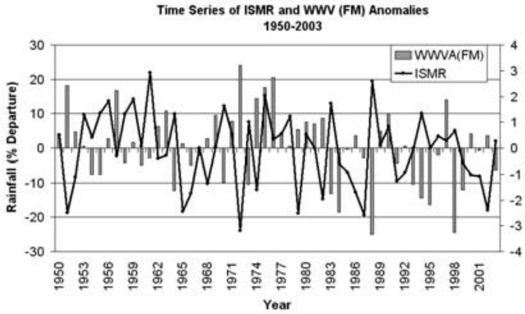

Figure 3. Time series of WWV anomaly averaged for February and March (vertical bars) and ISMR percentage departures (continuous line) for 1950–2003.

with negative WWV (FM) and positive ISMR anomalies. One major exception occurs in 1997 with large positive WWV (FM) but southwest monsoon rainfall 2% above normal. The slope of the linear regression line between WWV (FM) and ISMR is -2.7% per 10^{14} m^3 indicating that a positive (negative) change in WWV (FM) by 1×10^{14} m^3 will decrease (increase) ISMR by about 2.7%.

[14] It has been well documented that relationship between the ISMR predictors and ISMR show significant secular variations [*Parthasarathy et al.*, 1991; *Hastenrath and Greischar*, 1993; *Rajeevan*, 2001]. In particular, the relationship between ISMR and ENSO SST indices has weakened since the mid-1970s [*Krishna Kumar et al.*, 1999]. This weakening is evident in 21-year running correlations between June-July-August (JJA) NINO-3 SST and ISMR (Figure 5), which drop below 95% significance beginning in the late 1980s. Correlations between WWV (FM) and ISMR also undergo decadal changes, for the most part hovering at or just below the 95% significance level. However, the IMSR and WWV (FM) 21-year running correlations show a sharp increase beginning in the mid-1980s, opposite to the trend exhibited in the NINO-3/ISMR correlations. This increase in the correlation between ISMR and WWV (FM) reflects a decadal modulation in the relationship between WWV (FM) and NINO-3 SST for which in certain periods WWV (FM) anomalies are a better predictor of NINO-3 SST (JAS) anomalies than in others (Figure 5). Such a decadal modulation in the relationship of ENSO SST and WWV anomalies has been noted in Pacific ocean-atmosphere coupled model simulations [*Cai et al.*, 2004], though the precise reasons for this modulation are not well understood. Also, significantly increased availability of upper ocean temperature data as a result of the Tropical Ocean-Global Atmosphere (TOGA) program [*McPhaden et al.*, 1998] has made it possible to more accurately define WWV anomalies in the Pacific since the mid-1980s. Thus, while underlying decadal time scale shifts in the climate system have reduced the sensitivity of ISMR to ENSO variations in the latter part of the 20th century, possibly in association with basin wide warming trends in the tropical Indo-Pacific [*Knutson et al.*, 1999], WWV anomalies have increasingly become a better predictor of boreal summer NINO-3 SST (JAS) anomalies since the mid-1980s. A full understanding of the relationship between these ENSO predictors and ISMR requires improved knowledge of the teleconnections between the Pacific and Indian Ocean regions. However, our results suggest that should the ISMR revert to being more sensitive to ENSO as it was prior to the mid-1970s, WWV may be an even better predictor of ISMR rainfall than it is now.

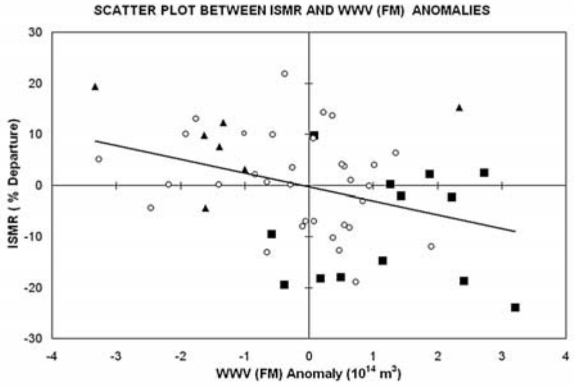

Figure 4. Scatterplot between WWV (FM) anomalies and ISMR percentage departures for the period 1950–2003. The El Niño years are shown as filled squares; La Niña Years are shown as filled triangles. Other years are shown as open circles. The regression line slope is -2.7% per 10^{14} m^3.

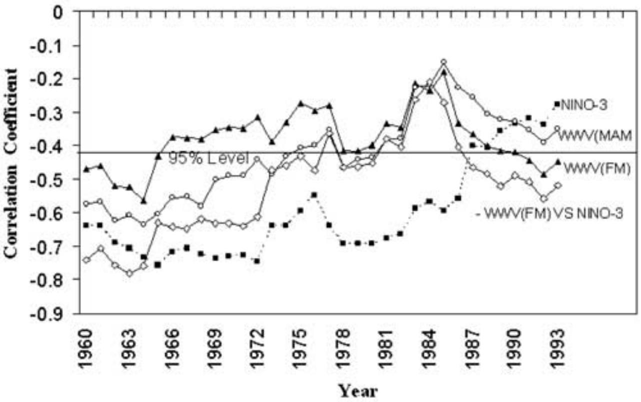

Figure 5. The 21-year moving correlations between WWV (FM) anomalies and ISMR (filled triangles), NINO-3 SST (JAS) and ISMR (filled squares), WWV (MAM) and ISMR (open circles) and WWV (FM) and NINO-3 (JAS) (sign reversed) (open diamonds). The middle year of the 21-year period is shown on the x-axis. The data corresponding to 1993 is the correlation coefficient during the period 1983–2003.

[15] We have further explored the relationships of WWV anomalies averaged over March to May, designated as WWV (MAM), to determine their utility in the 10 parameter model forecasts issued in June. The correlation coefficient between WWV (MAM) and ISMR for the entire record is -0.38 which is statistically significant at 99% level and slightly greater in magnitude than for the correlation between ISMR and WWV (FM) (-0.36). The 21-year moving correlations of WWV (MAM) with ISMR (Figure 5) show a similar pattern to that of correlations of WWV (FM) and ISMR.

4. Summary and Discussion

[16] We have analyzed inter-annual variations in Indian summer monsoon rainfall (ISMR) and WWV in the tropical

Pacific Ocean using upper ocean thermal field analyses spanning 54 years (1950–2003). Our results indicate that there is a significant negative correlation between WWV anomalies in the boreal winter and spring seasons and subsequent ISMR. This relationship is not perfect and any given year may experience monsoon rains that deviate from those expected based on WWV anomalies. However, in a statistical sense, WWV provides a much better predictor at long lead times than ENSO SST for ensuing summer monsoon rainfall. The correlation between WWV anomalies in boreal winter and spring and subsequent ISMR anomalies is also decadally modulated, having significantly strengthened since the mid-1980s.

[17] It is noteworthy that in 2002, a prolonged 30-day break in summer rains had lead to an extremely dry monsoon season whereas IMD models in use at the time had predicted normal rains in 2002. We lack a full explanation for why the prolonged break developed [*Gadgil et al.*, 2002; *Sikka*, 2003]. While the moderate amplitude of the positive WWV anomaly would not have foretold the extremity of the drought in 2002, inclusion of this anomaly as a predictor in the forecast model would have predicted a slight rainfall deficit, which is in the correct sense of what actually transpired. In view of our results, Pacific WWV anomalies will be included in the new models developed at IMD for future ISMR forecasts.

[18] **Acknowledgments.** The first author (MR) is thankful to DGM, IMD for his support and encouragement. MJM acknowledges NOAA's Office of Oceanic and Atmospheric Research and Office of Global Programs for supporting this research. The authors thank Margie McCarty and Xuebin Zhang of PMEL and the Joint Institute for the study of the Atmosphere and Ocean for preparation of the WWV time series. PMEL publication No. 2725.

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