

The Relationship between Tibetan Snow Depth, ENSO, River Discharge and the Monsoons of Bangladesh

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Abstract

We examine the interannual variability of the monsoon rains of Bangladesh, an area greatly affected by land surface hydrologic processes including Himalayan snow pack size, snowmelt river flooding, and Bay of Bengal storm surge. For the 20th century, we find Bangladesh monsoon rainfall (BMR) to be uncorrelated with the All-Indian Monsoon Index. We use satellite estimates of April snow depth for the Himalayan region and concurrent seasonal El Niño-Southern Oscillation (ENSO) conditions in the equatorial Pacific to develop an empirical model that explains a high percentage of BMR interannual variability. Inclusion of late spring river discharge levels further improves empirical model representation of BMR for June-September. These results, though for a limited record length, suggest that BMR interannual variability is constrained by concurrent ENSO conditions, spring Himalayan snow pack size and

land surface flooding. The 20th century analysis indicates that BMR should be considered independently of Indian monsoon rainfall.

1. Introduction

The impact of Eurasian snow cover and land surface hydrologic processes on the monsoons of South Asia has been studied for over a century. Blanford (1884) first suggested that the strength of the South Asian monsoons is affected by the size of the Himalayan snow pack. Differences in the extent of this snow pack alter the heating of the land surface and overlying atmosphere. Given the relative constancy of Indian Ocean sea surface temperatures (SSTs), such changes in land surface heating can strengthen or weaken the land-sea temperature gradient controlling monsoon winds and the landfall of rain.

The most intense south Asian monsoon rains occur over Bangladesh and the adjacent eastern portions of India. This area records some of the highest annual rainfall totals in the world. Bangladesh lies to the immediate south of the Himalayas on the delta confluence of the Ganges, Brahmaputra and Meghna Rivers above the Bay of Bengal. During much of the northern hemisphere summer, large portions of the country are under water. Monsoon rains, the confluence of Himalayan meltwaters, and surging, windswept waters from the Bay all contribute to these flood conditions.

Much study heretofore has focused upon monsoon rains in India, southeast Asia, or China at the exclusion of Bangladesh. In fact, the Indian monsoon is often used as proxy for the entire South Asian monsoon. In this study, however, we focus exclusively on the monsoons over and immediately around Bangladesh. This country's unique position as a locus of so much

intense hydrologic activity warrants analysis independent of other components of the South Asian monsoon system. Furthermore, previous studies have shown that rainfall recorded at individual station sites in Bangladesh are not significantly correlated with Indian monsoon rainfall (Kripalani et al. 1996). In this study we will examine the effect of three variables on the monsoons of Bangladesh: Himalayan snowpack size, El Niño-Southern Oscillation (ENSO) conditions, and river discharge levels.

An inverse relationship between snowfall on regions of the Eurasian continent and the Indian summer monsoon has been both observed (Hahn and Shukla, 1976; Dickson, 1984; Ropelewski and Halpert, 1989; Bamzai and Shukla, 1999) and modeled (Meehl, 1994a; Bamzai and Marx, 2000). An increased snowpack increases land surface albedo; incident solar radiation that would otherwise have heated the land surface instead melts and sublimates the snowpack. The melting snow also increases land surface wetness, so that subsequent evaporation further cools the land surface. These effects conspire to reduce the land-sea summer thermal gradient between the Eurasian continent and the Indian Ocean.

Studies have explored the effects of both Eurasian snow cover and snow volume (depth) on the Indian monsoons. Observational investigations have demonstrated inverse relationships between Eurasian snow cover and subsequent summer rainfall over India (Hahn and Shukla 1976; Sankar-Rao et al. 1996). Kripalani et al. (1996) used Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR) satellite estimates of snow depth and found an inverse relationship between snow depth over areas of the former Soviet Union and Indian Monsoon Rainfall (IMR). Similarly, Bamzai and Shukla (1999) found some evidence of a relationship between snow depth over central Eurasia and June-September IMR. Others have noted a dipole effect, with less western/European Russia snow depth and more central Siberia snow depth

associated with greater Indian rainfall in the following season (Kripalani and Kulkarni, 1999; Ye and Bao 2001).

The covariability of the Indian monsoons and ENSO has been explored in numerous studies (Walker, 1918; Rasmusson and Carpenter, 1983; Webster and Yang, 1992; Mehta and Lau, 1997; Webster et al., 1999). During an El Niño event, subsidence over South Asia generally increases (Krishna Kumar et al., 1999b). This anomalous subsidence suppresses convection over South Asia and is thought to produce the weaker monsoons that often develop during El Niño events, though recently this relationship has broken down (Krishna Kumar et al., 1999a).

For Bangladesh, local wetting of the land surface, due to flooding, could also play a role in determining the strength of the monsoons. GCM simulations have found that land-based precipitation is partially controlled by land surface evaporative rates (Koster and Suarez, 1995; Reale and Dirmeyer 2001a,b; Hong and Kalnay, 2000) and that precipitation variability over land is controlled in part by land surface evaporative variability (Dirmeyer, 2001). No doubt, the extent of land surface flooding partly determines land surface evaporative rates over Bangladesh. Local river runoff levels (in addition to rainfall and storm surge) are an important indicator of this local flood potential. In fact, the seasonal flooding of the Bangladesh land surface may be of large enough scale to function as a catalyst, inducing the landfall of low-pressure systems from the Bay of Bengal. Yasunari et al. (1991) found evidence in a GCM experiment of such interactions at mid-latitudes.

2. Data and Methods

Snow Depth Data. Both model and observational studies have shown that snow volume, or depth, is a better predictor of monsoon intensity than snow coverage (Barnett et al. 1989; Kripalani and Kulkarni 1999; Ye and Bao 2001). In this study we restrict our analyses with snow to estimates of snow depth from Nimbus 7. This satellite sensor was in operation from November 1978 through August 1987, after which it began showing signs of failure. Its passive microwave data can be used to measure snow extent and calculate snow depth on an areal basis using the difference between brightness temperatures in the 18 and 37 GHz channels (Chang et al., 1987). This algorithm has been shown to be as accurate as more recent Nimbus 7 SMMR algorithm estimates of April and May snow depth over Eurasia (Foster et al. 1997).

We focus principally on Himalayan snow pack depth during the northern hemisphere spring season. Given Blanford's hypothesis, the inverse snow-monsoon relationship should be most strongly associated with spring snows, which delay the end of winter (Ramage, 1983). This postulant is further supported by model studies, which have shown that the largest variability of Eurasian snow mass occurs in April (Dong and Valdes 1998). Average monthly snow depth anomalies for the area 25N-35N and 75E-100E (the Himalayas and Tibetan Plateau) were determined and used.

River Data. Monthly river discharge data is from the Bahadurabad Transit station site (SW46.9L) on the Brahmaputra River for 1979-1987. Data for June 1983 is missing. Monthly anomalies were calculated.

ENSO Data. NINO3 (5N-5S, 150W-90W) was the index of ENSO used for this study (Kaplan et al. 1998).

Rainfall Data. Two time series measuring Bangladesh monsoon rainfall (BMR) were employed. 1) We averaged monthly rainfall data from all NCDC Global Historical Climatology

Network (GHCN) stations between 21N-26N and 87E to 93E for 1900 through 2000. Monthly and seasonal anomalies were then constructed based on this record length. 2) Optimally interpolated (OI) monthly rainfall was also used. These data were constructed by reduced space optimal interpolation of the raw GHCN station data. The method is similar to the sea level pressured analysis presented in Kaplan et al. (2000). The OI data are gridded at 4x4 degree resolution (Kaplan et al. 2001). Monthly and seasonal anomalies for 1900-2000 from the grid box centered at 24N and 90E were employed for this study.

For purposes of comparison we also employed the All-India Monthly Rainfall data of the Indian Institute of Tropical Meteorology (Parthasarathy et al. 1995) and compiled these data for JJAS, 1900-2000 as seasonal anomalies. Four of the 29 subdivision employed in the construction of this index lie partially or wholly within the domain of the GHCN BMR.

3. Results

Table 1 provides correlations among NINO3, OI BMR, GHCN BMR, and the All India Monsoon Index for JJAS for 1900-2000. For this 101-year time period, the Bangladesh rains are positively associated ($p < 0.05$) with NINO3, whereas the All-India rains are more strongly negatively correlated with NINO3 ($p < 0.001$). Thus, within the region, there seem to be differing responses to events in the Pacific: IMR is suppressed during an El Niño event, but BMR increases. The OI BMR rains are also weakly negatively correlated with the All-India rains, though not at statistically significant levels.

Table 2 shows correlation coefficients between BMR (for JJAS) and monthly snow depth anomalies in the preceding April, the concurrent NINO3 index, and concurrent or earlier river

discharge levels. The Nimbus 7 snow data and Brahmaputra discharge data records are of limited length (9 and 8 years respectively), so these findings must be considered provisional.

April snow depth is positively correlated with JJAS NINO3 but negatively correlated with both BMR indices and June Brahmaputra discharge. In the 101-year record NINO3 is positively associated with both BMR indices. Of particular interest, NINO3 and April snow are positively associated, but their effects on BMR differ. In addition, June Brahmaputra discharge is highly negatively correlated with April snow, but positively associated with BMR.

Using the data from the preceding analyses, we developed models of BMR using multiple regression analysis. Per stepwise regression, we accepted a predictor when the correlation between residuals was significant. Regressing June-September BMR on April snow and JJAS NINO3, we found that both explanatory variables are statistically significant (at $p < 0.002$ for OI BMR; $p < 0.05$ for GHCN BMR), and these regression models explain 72% (GHCN) and 87% (OI) of BMR variance. Given the limited data set (9 years), these model fittings were further examined by leave-one-out ordinary cross validation (OCV). Correlations among the omitted data points and OCV regression equations were significant for the OI BMR ($r=0.85$, $p<0.002$) and near significant for the GHCN BMR ($r=0.56$, $p=0.08$). Figure 1 shows a plot of the normalized OI BMR and the values predicted by OCV. We also subjected the rainfall, snow depth and ENSO data to an EOF analysis and confirmed that the BMR predominantly lies in the plane delineated by April Tibetan Plateau snow depth and JJAS NINO3 (93% of variance). These analyses indicate that our statistical findings are consistent and robust, and that though the record length is short, it would be extremely unlikely for the association between BMR, April snow depth and JJAS NINO3 to have occurred solely by chance.

We also calculated the regression of BMR rain for June-September on April snow, concurrent NINO3 and June Brahmaputra discharge (only eight years). The inclusion of June Brahmaputra discharge is statistically significant only for the OI BMR ($p < 0.05$). Both April snow depth and JJAS NINO3 remain significantly associated with both the OI BMR ($p < 0.002$) and the GHCN BMR ($p < 0.05$). 96% of OI BMR variance is accounted for with this three-variable regression model. These model fittings were again confirmed by OCV. Correlations among the omitted data points and OCV regression equations were significant for both the OI and GHCN BMR data sets ($r = 0.91$, $p < 0.001$; $r = 0.67$, $p < 0.05$, respectively).

Figure 2 deconstructs the regression model fit for the OI BMR. Regression values are shown with April snow alone, April snow and JJAS NINO3, and all three variables; also shown are the OI BMR anomaly values.

4. Discussion

Our findings show that the All-India monsoon index and BMR are not well correlated; if anything they vary inversely, though not at statistically significant levels. This result is similar to findings of Kripalani et al. (1996), showing that monsoon season rainfall at individual stations in Bangladesh had no significant relationship with All India Monsoon Rainfall (Kripalani and Singh, 1993).

The correlation between NINO3 and BMR is positive, contrary to the conventional wisdom that El Niño conditions suppress South Asian monsoon rainfall. A possible explanation is that BMR is more directly affected by land surface hydrologic processes, both Himalayan snow pack size directly to the north and seasonal land surface flooding due to meltwater

discharge, monsoon rainfall and storm surge. Specifically, the correlation analysis shows NINO3 for JJAS to be positively associated with April Himalayan snow pack depth estimates. Although not significant at 95%, a positive association also holds true for April NINO3 ($r=0.49$, $n=9$). These correlations suggest that Himalayan snow pack depth is tied to conditions in the Pacific, and, consistent with Blanford's hypothesis, that increased Himalayan snow pack depth decreases BMR. (This is true both for the simple correlation and within the regression model.) However, within the multiple regression model, in which the common effects of Himalayan snow pack depth are removed, BMR and NINO3 are significantly and positively associated. It thus appears that ENSO indirectly suppresses BMR through links with Himalayan snow pack depth, but directly, or through other yet unidentified mechanisms, enhances BMR.

The empirical regression model suggests that knowledge of April snow depth on the Tibetan plateau and forecast of JJAS conditions in the equatorial Pacific could provide a good predictive model of seasonal BMR. Inclusion of June river discharge levels can further tune such forecasts for the remainder of the monsoon season. However, given the short records lengths of the Nimbus 7 SMMR snow depth estimates and the Brahmaputra discharge, these results must be considered preliminary.

We also explored using the longer National Snow and Ice Data Center (NSIDC) snow cover data in place of the satellite estimates of snow depth (data not shown). However, the NSIDC snow cover data had a low correlation ($r=0.40$) with the Nimbus 7 snow pack depth estimates for the coincident period of record (1979-1987). The NSIDC data did not possess the same interannual variability, as much of the Himalayas is snow covered year-round. Regression models developed using the NSIDC Himalayan snow cover data were not statistically significant.

5. Conclusions

By virtue of its location at base of Himalayas and on the floodplain of the Meghna, Ganges, and Brahmaputra rivers, Bangladesh is an area greatly affected by hydrologic processes, both land-atmosphere and ocean-atmosphere. Monsoon rainfall over Bangladesh is not significantly correlated with the All India Monsoon Index. We find that a large percentage of the interannual variability of BMR is explained by a simple multiple regression model using satellite estimates of April Himalayan snow pack depth, an ENSO index and June Brahmaputra river discharge. Because of the short time record examined, these results should be viewed as preliminary. Future operational satellite estimates of snow depth (e.g. MODIS) will offer the opportunity to test these findings further.

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Figure 1. Time series plot of normalized OI BMR and OCV predicted values. Error bars (plus or minus 2 standard error), estimated from each OCV regression are also presented.

Figure 2. Reconstruction of the OI BMR from a regression model with 3 explanatory variables. Regression model values are shown with April Tibetan snow depth alone, April Tibetan snow depth and concurrent NINO3, and all three variables; also shown are the OI BMR anomaly values.

Table 1. Correlation coefficients among NINO3, BMR, and Indian monsoon rainfall indices, 1900-2000. * p<0.05; ‡ p<0.001

	NINO3	OI BMR	GHCN BMR	All-India
NINO3	1.00	0.20*	0.19*	-0.53‡
OI BMR	0.20*	1.00	0.79‡	-0.12
GHCN BMR	0.19*	0.79‡	1.00	0.00
All-India	-0.53‡	-0.12	0.00	1.00

Table 2. Correlation Coefficients among April Tibetan snow depth anomalies, NINO3, OI and GHCN BMR, and June Brahmaputra Discharge. All correlations are for the 9-year period 1979-87, except those with June Brahmaputra for which 1983 is missing. * p<0.05

	April	NINO3	OI Rain	GHCN	June
	Snow			Rain	Brahmaputra
	Depth				Discharge
April Snow	1.00	0.61*	-0.43	-0.28	-0.76*
Depth					
NINO3	0.61*	1.00	0.40	0.47	-0.30
OI Rain	-0.43	0.40	1.00	0.94*	0.31
GHCN Rain	-0.28	0.47	0.94*	1.00	0.17
June	-0.76*	-0.30	0.31	0.17	1.00
Brahmaputra					
Discharge					

Figure 1.

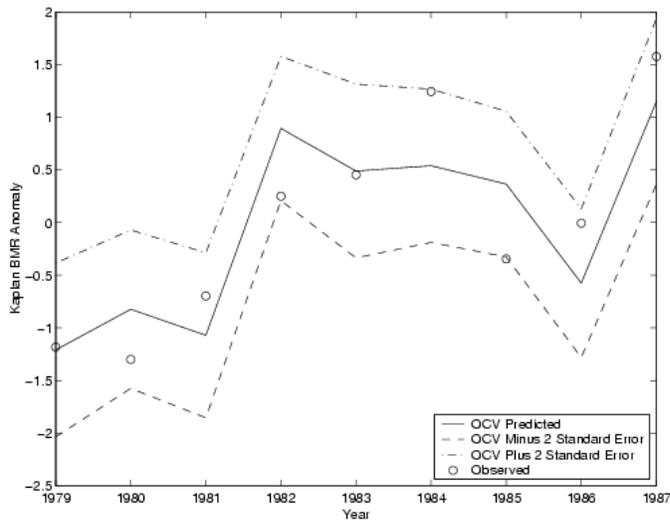


Figure 2.

