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The relationship between tibetan snow depth, ENSO, river discharge and the monsoons of Bangladesh

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Using satellite estimates of snow depth, we examine the interannual variability of the monsoon rains of Bangladesh, an area greatly affected by land surface hydrological processes including Himalayan snowpack size, snowmelt river flooding, and Bay of Bengal storm surge. For the twentieth century, we found Bangladesh monsoon rainfall (BMR) to be uncorrelated with the All-Indian Monsoon Index. This result is consistent with previous findings for shorter time records. We next used a short 9-year record of 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 the empirical model representation of BMR for June–September. These results, though with a limited length satellite record, suggest that BMR interannual variability is constrained by concurrent ENSO conditions, spring Himalayan snowpack size and land surface flooding. The same results could not be obtained from analyses using satellite estimates of snow cover. These findings stress the need for development of a quality longer record of satellite estimated snow depth. The twentieth-century analysis also indicates that BMR should be considered independently of Indian monsoon rainfall.

1. Introduction

The impact of Eurasian snow cover and land surface hydrological processes on the monsoons of South Asia has been studied for over a century. Blanford (1884) first suggested that climate conditions over India could be affected by the size of the Himalayan snow pack. Differences in the extent of this snowpack 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.

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The most intense south Asian monsoon rains occur over Bangladesh and the adjacent eastern portions of India (e.g. Assam). 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 to the exclusion of Bangladesh. In fact, the Indian monsoon is often used as a 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 hydrological 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 was not significantly correlated with Indian monsoon rainfall during 1901–1977 (Kripalani *et al.* 1996a) and that monsoon rainfall in neighbouring Assam was not significantly correlated with All-Indian Summer Monsoon Rainfall during 1951–1980 (Krishna Kumar *et al.* 1995). In this study we examined the effect of three variables on the monsoons of Bangladesh: Himalayan snowpack size, El Niño–Southern Oscillation (ENSO) conditions and river discharge levels.

1.1 *Snow and the South Asian monsoons*

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 modelled (Barnett *et al.* 1989, Meehl 1994, 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. (In addition, more energy is required to evaporate surface wetness; the specific heat of ice and land are about the same, but the specific heat of water is double that amount.) These thermodynamic 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). A number of studies have compared satellite estimates of snow depth with monsoon rainfall. Kripalani *et al.* (1996b) 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).

In model simulations, Eurasian snow cover has been shown to affect both albedo and rates of latent heat transfer. Barnett *et al.* (1989) found that heavy Eurasian snow increased evaporative rates and reduced land and overlying atmospheric temperatures. This reduction of the land–ocean contrast inhibited monsoon activity. In a prior study Barnett *et al.* (1988) ran the European Centre for Medium-range Weather Forecast (ECMWF) general circulation model (GCM) with double and half snow over Eurasia and found that these runs mimicked weak and strong monsoons respectively. Because the model Indian Ocean SSTs changed little, these GCM simulations supported Blanford's hypothesis that the land–sea thermal gradient is controlled by Eurasian snow amount. Similar model results have since been demonstrated by Vernekar *et al.* (1995), Douville and Royer (1996) and Dong and Valdes (1998).

1.2 *ENSO and the South Asian monsoons*

The covariability of the Indian monsoons and El Niño–Southern Oscillation (ENSO) conditions has been explored in numerous studies (Walker 1924, Rasmusson and Carpenter 1983, Ropelewski and Halpert 1987, Webster and Yang 1992, Mehta and Lau 1997, Webster *et al.* 1999). A clear explanation for this association has yet to be established. The canonical view is that during an El Niño event, subsidence over South Asia 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). In a recent model study, Dong and Valdes (1998) found evidence that El Niño conditions lead to increased snow mass on Eurasia.

1.3 *Land surface evaporative feedbacks*

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), that precipitation variability over land is controlled in part by land surface evaporative variability (Dirmeyer 2001) and that improved land surface modelling improves forecasting of climate anomalies (Dirmeyer *et al.* 2000). 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, first reducing the vertical moist stability over Bangladesh and allowing the development of local convection, which then enables 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. Such dynamics over Bangladesh, resulting from river flow and flooding, may induce the seasonal northward migration of the intertropical convergence zone (ITCZ), which provides an alternative hypothesis describing the monsoon activity (Gadgil 2003). For these reasons we have included the effects of late spring river discharge in our analysis.

2. Data and methods

2.1 *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). This finding follows from the simple thermodynamic considerations discussed in section 1, through which changes in Eurasian snow depth can affect the meridional temperature gradient that drives the South Asian monsoons.

In this study we focus specifically on Himalayan snowpack depth during the Northern Hemisphere spring season. This plateau region (the Himalayas and Tibetan plateau) lies directly north of Bangladesh and supports a summertime high-pressure ridge and the warmest summertime upper tropospheric temperatures on the planet (Li and Yanai 1996). The upper tropospheric temperature gradient between the Himalayas and the Indian Ocean and the summertime heating of the Tibetan plateau has been shown to be associated with the onset of the South Asian monsoons (Luo and Yanai 1984, He *et al.* 1987, Yanai *et al.* 1992, Yanai and Li 1994, Li and Yanai 1996). Furthermore, the temperature gradient between the Tibetan plateau and equatorial Pacific has been shown to be associated with Indian monsoon rainfall (Fu and Fletcher 1985). We therefore anticipated that the strength of this upper troposphere high-pressure ridge and of the summer meridional upper troposphere temperature gradient between the Himalayas and the Indian Ocean, and thus monsoon rainfall over Bangladesh, would be sensitive to spring snowpack size. It has also been suggested that 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).

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 to 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). The accuracy of this data is unknown and the error may be large (Chang *et al.* 1990); however, the SMMR data set remains the only source of monthly snow volume available for Eurasia. The algorithm used here has been shown to be more accurate than more recent Nimbus 7 SMMR algorithm estimates of April and May snow depth for Eurasia when compared with snow depth climatology (Foster *et al.* 1997).

Average monthly spring season snow depth anomalies for the area 25° N–35° N and 75° E–100° E (the Himalayas and Tibetan plateau) were therefore determined and used. The time series of 1979–1987 April snow depth anomalies is shown in figure 1.

2.2 *River data*

Monthly river discharge data are from the Bahadurabad Transit station site (SW46.9L) on the Brahmaputra river for 1979–1987. The accuracy of these discharge measurements is not known; however, typical river gauging is accurate to within 10%. Data for June 1983 are missing. Monthly anomalies were calculated,

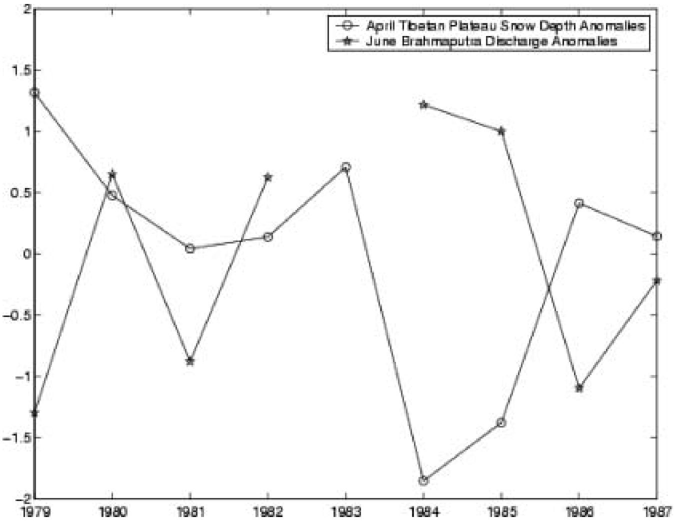

Figure 1. Time series plot of 1979–1987 April Tibetan plateau snow depth anomalies as calculated from Nimbus 7 SMMR satellite measurements and 1979–1987 June Brahmaputra river discharge anomalies. All records are shown in normalized units of standard deviations.

and the 1979–1987 June monthly anomalies are shown in figure 1. These anomalies appear negatively correlated with the April snow depth anomalies. This association is consistent with a cooling of the Tibetan plateau caused by an increased snowpack, which delays snowmelt and reduces June river flow.

2.3 *ENSO data*

NINO3 (5° N–5° S, 150° W–90° W) was the index of ENSO used for this study (Kaplan *et al.* 1998). A time series of JJAS (June, July, August, September) seasonal anomalies is shown in figure 2(*a*). The 99.7% confidence interval estimates place the true value within ± 0.5K of the index during the twentieth century.

2.4 *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 22° N–26° N and 88° E–92° E for 1900 to 2000. Monthly and seasonal anomalies were then constructed based on this record. (2) Optimally interpolated (OI) monthly rainfall was also used. These data were constructed by reduced space optimal interpolation of the GHCN station data anomalies binned and averaged on a 4° resolution grid. The method of reduced space OI is similar to the sea level pressure analysis presented in Kaplan *et al.* (2000). Monthly and seasonal anomalies for 1900–2000 from the grid box centered at 24° N and 90° E were employed for this study. Times series of these BMR records is presented in figure 2(*b*). The increased variability evident in the GHCN record during the last decade, due to changes in the number and location of stations in operation, is reduced by the optimal interpolation. The spatial variability of station-measured rainfall within the BMR grid box indicates an error around 25 mm per-month for most of the twentieth century.

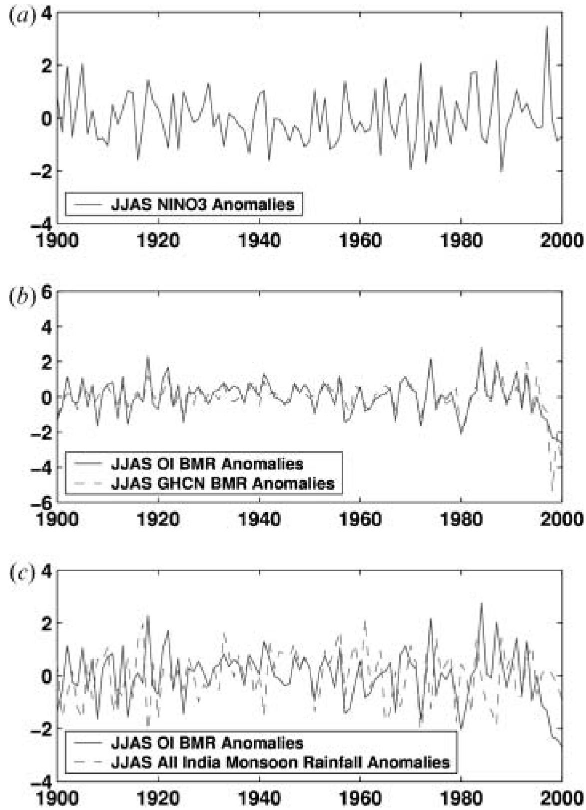

Figure 2. Time series plots of 101-year index records. (*a*) JJAS NINO3 anomalies; (*b*) JJAS OI and GHCN BMR rainfall anomalies; (*c*) JJAS OI BMR and All-India Monsoon Rainfall anomalies. All records are shown in normalized units of standard deviations.

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 (figure 2(*c*)). Four of the 29 subdivisions employed in the construction of this index lie partially or wholly within the domain of the GHCN BMR.

2.5 *Statistical analysis*

Simple correlation and multiple regression analyses were performed. Statistical significance of the correlations was assessed using Student's *t*-test. Multiple regression model significance was assessed using the *F*-test. Because of the short satellite snow depth and river discharge records (9 years), the multiple regression models of BMR potentially possess artificially high skill. Therefore, the data were further tested by cross-validation (von Storch and Zwiers 2001). Specifically, leave-one-out ordinary cross validation (OCV) was performed in which the multiple regression analysis was repeated for the 1979–1987 record minus one year's data. The regression model was then used to estimate BMR for the omitted year. This process was repeated for each year. The time series of estimated BMR from the leave-one-out OCV was then correlated with the actual BMR. Significant correlation among these time series provides evidence that the multiple regression model skill is not artificially high, in spite of the short record length. In addition, the covariability of the ENSO, snow depth and BMR records were assessed using empirical orthogonal function (EOF) analysis, and the order of the multiple regression models was analysed using the Akaike Information Criterion (von Storch and Zwiers 2001). This analysis was used as further corroboration that the skill of the multiple regression models was not inflated.

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 not associated with NINO3, whereas the All-India rains are 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 is not significantly affected. The OI BMR rains are also not correlated with the All-India rains.

Table 2 shows correlation coefficients for 1979–1987 between BMR (for JJAS) and monthly snow depth anomalies in the preceding April, the concurrent NINO3 index, and June Brahmaputra 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.

For this short period of record, April snow depth is significantly negatively correlated with June Brahmaputra discharge. This correlation corroborates the figure 1 graphic and again indicates that increased spring snow on the Tibetan plateau delays snow melt and reduces June Brahmaputra discharge. The BMR records are not associated with any of the other measures at statistically significant levels; however, the tendencies of the BMR correlations are intriguing. Both BMR indices are negatively correlated with April snow depth but positively correlated with JJAS NINO3. While the correlations of April snow depth and JJAS NINO3 with BMR are inverse, JJAS NINO3 and April snow depth are themselves positively associated. Thus, April snow depth and JJAS NINO3 could be masking each other's effects on BMR so that simple correlation analysis may be inadequate for revealing their effect on BMR. We therefore developed models of BMR using multiple regression analysis. In such analysis, we accepted a predictor when the correlation between residuals was significant.

3.1 *Multiple regression model*

Regression of BMR rain for June–September on April snow and concurrent NINO3 accounts for 54% (GHCN) and 77% (OI) of BMR variance. For the OI BMR model

Table 1. Correlation coefficients among NINO3, BMR and Indian monsoon rainfall indices, 1900–2000.

	NINO3	OI BMR	GHCN BMR	All-India
NINO3	1.00	−0.02	−0.02	−0.53*
OI BMR	−0.02	1.00	0.80*	−0.06
GHCN BMR	−0.02	0.80*	1.00	0.01
All-India	−0.53*	−0.06	0.01	1.00

*$p < 0.001$.

Table 2. Correlation coefficients among April Tibetan snow depth anomalies, NINO3, OI and GHCN BMR, and June Brahmaputra discharge.

	April snow depth	NINO3	OI rain	GHCN rain	June Brahmaputra discharge
April snow depth	1.00	0.61	−0.58	−0.39	−0.76*
NINO3	0.61	1.00	0.18	0.26	−0.30
OI rain	−0.58	0.18	1.00	0.92*	0.35
GHCN rain	−0.39	0.26	0.92*	1.00	0.20
June Brahmaputra discharge	−0.76*	−0.30	0.35	0.20	1.00

All correlations are for the 9-year period 1979–1987, except those with June Brahmaputra for which 1983 is missing.
*$p < 0.05$.

both explanatory variables are statistically significant (each variable at $p < 0.02$). Within these multiple regression models increased April snow leads to decreased BMR, and increased JJAS NINO3 SSTs result in increased BMR. These tendencies are consistent with the results presented in table 2 for simple correlation; however, unlike the results for simple correlation, both April snow depth and JJAS NINO3 are statistically significant in the multiple regression model. This statistical significance is the correct consequence of the multiple regression analysis, which considers the orthogonal contribution of each explanatory variable. Because April snow and JJAS NINO3 are themselves positively correlated but their effects on BMR are opposite, each masks the other's effect when subjected to simple correlation with BMR; however, when these explanatory variables are considered in conjunction within the multiple regression model they are both shown to be statistically significant.

Given the limited data set (9 years), these model fittings were further examined by leave-one-out OCV. Correlations among the omitted data points and OCV regression equations were significant by the *F*-test for the OI BMR ($r = 0.66$, $p < 0.05$). Figure 3 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 (95% of variance). These analyses indicate that our statistical findings are consistent and robust, and that though the record length is short, it would be unlikely for the association between BMR, April snow depth and JJAS NINO3 to have occurred by chance.

We also performed multiple regression of the OI BMR for June–September on April snow, concurrent NINO3 and June Brahmaputra discharge (only 8 years). The inclusion of June Brahmaputra discharge is not statistically significant by the *F*-test; however, its presence in the regression model is favoured by the Akaike Information Criterion. Both April snow depth and JJAS NINO3 remain significantly explanatory variables ($p < 0.05$), and 88% of OI BMR variance is accounted for with this three-variable regression model.

Figure 4 deconstructs this regression model fit for the OI BMR. Using the parameter estimates from the multiple regression model, the BMR anomaly is predicted with April snow alone, April snow and JJAS NINO3, and all three variables. Also shown are the OI BMR anomaly values. This deconstruction

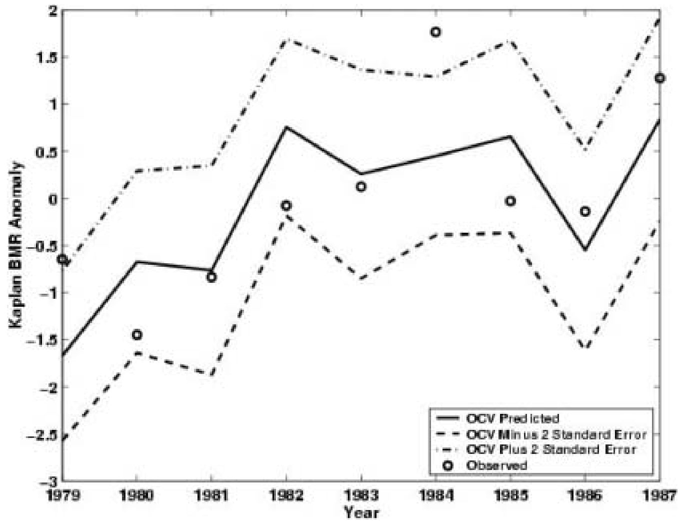

Figure 3. Time series plot of normalized OI BMR and OCV predicted values. Error bars (± 2 standard error) estimated from each OCV regression are also presented.

highlights the additional corrections of JJAS ENSO and June Brahmaputra discharge to the model estimate of BMR. With April snow alone, the BMR anomaly predictions are of the correct sign for 6 of the 8 years. With both April snow and JJAS ENSO, the BMR anomaly predictions are again of the correct sign for 6 of the 8 years but are much closer to the observed anomalies. With all three explanatory variables, the BMR anomaly predictions are most closely matched.

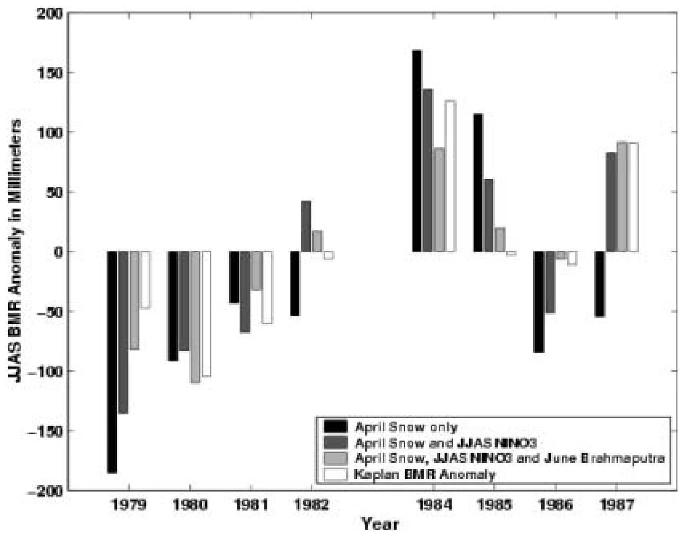

Figure 4. Reconstruction of the OI BMR from a regression model with three explanatory variables. Regression model values are shown with April Tibetan snow depth alone, April Tibetan snow depth and concurrent NINO3, and all three variables; also shown are the OI BMR anomaly values (predictand).

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 the findings of Kripalani *et al.* (1996a), which showed 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, but negative between NINO3 and the All-India Monsoon Rainfall. Furthermore, the correlation analysis shows NINO3 for JJAS to be positively associated with April Himalayan snowpack depth estimates, and, although not significant at 95%, a positive association also holds true for April NINO3 ($r = 0.49$, $n = 9$). These correlations suggest that Himalayan snowpack depth is tied to conditions in the Pacific, and that increased Himalayan snowpack 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 snowpack depth are removed, BMR and NINO3 are significantly and positively associated. It thus appears that ENSO indirectly suppresses BMR through links with Himalayan snowpack depth, but directly, or through other yet unidentified mechanisms, enhances BMR.

The indirect suppression of BMR by ENSO through links with Himalayan snowpack depth may be the result of an atmospheric teleconnection. Recent research has provided evidence that changes in Northern Hemisphere wintertime convection over the equatorial Pacific Ocean associated with an El Niño event excite large-scale atmospheric waves (stationary barotropic Rossby waves) that propagate eastward over the Atlantic Ocean and enter the North African-Asian jet. These Rossby waves are associated with increased wintertime storm activity above the Tibetan plateau and increased snow accumulation. The increased snowpack then persists through the spring and summer, reduces the thermal contrast between the Indian Ocean and the Asian land mass, and weakens the intensity of the South Asian summer monsoons (Shaman and Tziperman 2005a).

Further evidence suggests that direct enhancement of BMR may also be mediated by atmospheric Rossby waves. During Northern Hemisphere summertime El Niño events, reduced convection over Indonesia produces a baroclinic atmospheric response (westward-propagating stationary baroclinic Rossby waves) within the tropics (Gill 1980). These waves reduce subsidence and favour monsoon rainfall over Bangladesh and Myanmar, but do not extend far enough west to affect monsoon rainfall over peninsular India (Shaman and Tziperman 2005b). This mechanism may explain the different correlations of BMR and IMR with Northern Hemisphere summertime El Niño conditions.

The empirical regression model presented here 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 may 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. However, the NSIDC snow cover data had a low correlation ($r = 0.403$) with the Nimbus 7 snowpack depth estimates for the coincident period of record (1979–1987). The NSIDC data did not possess the same interannual variability, and regression models developed using the NSIDC Himalayan snow cover data were not statistically significant. The poor correlation between the snow depth and snow cover data sets exists because the snow cover measurements make no distinction among differing snow depths (i.e. of 1 cm and 1 m); rather snow cover only identifies the percentage area covered with snow. In an area of year-round snow cover, snow depth variability is presumed to have a larger effect on the local energy balance than snow cover variability. A deep snowpack not only reduces incident solar radiation by increasing land surface albedo, but more absorbed radiation is also used to melt snow rather than heat the land surface. In addition, the wetter land surface has a higher specific heat than dry land and evaporation of surface moisture keeps the land and overlying air column cool.

Our findings suggest that analysis of the regional variability of rainfall throughout all of South Asia is warranted. In addition, an examination of the moist energy budget for Bangladesh might be highly revealing. Finally, the conclusiveness of our analysis was limited by the short record length of available satellite snow depth estimates. Future operational satellite estimates of snow depth (e.g. MODIS) will offer the opportunity to test these findings further. Given the promising preliminary results presented here, which indicate that accurate statistical forecasts of BMR are possible using satellite snow depth estimates, it is extremely important that this record be extended in the coming years.

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References

BAMZAI, A.S. and MARX, L., 2000, COLA AGCM simulation of the effect of anomalous spring snow over Eurasia on the Indian summer monsoon. *Quarterly Journal of the Royal Meteorological Society*, **126**, pp. 2575–2584.

BAMZAI, A.S. and SHUKLA, J., 1999, Relation between Eurasian snow cover, snow depth, and the Indian summer monsoon: an observational study. *Journal of Climate*, **12**, pp. 3117–3132.

BARNETT, T.P., DUMENIL, L., SCHLESE, U. and ROECKNER, E., 1988, The effect of Eurasian snow cover on global climate. *Science*, **239**, pp. 504–507.

BARNETT, T.P., DUMENIL, L., SCHLESE, U., ROECKNER, E. and LATIF, M., 1989, The effect of Eurasian snow cover on regional and global climate variations. *Journal of the Atmospheric Sciences*, **46**, pp. 661–685.

BLANFORD, H.F., 1884, On the connexion of Himalayan snowfall and seasons of drought in India. *Proceedings of the Royal Society of London*, **37**, pp. 3–22.

CHANG, A., FOSTER, J.L. and HALL, D.K., 1987, Nimbus-7 derived global snow cover parameters. *Annals of Glaciology*, **9**, pp. 39–45.

CHANG, A., FOSTER, J.L. and HALL, D.K., 1990, Satellite sensor estimates of northern hemisphere snow volume. *International Journal of Remote Sensing*, **11**, pp. 167–171.

DICKSON, R.R., 1984, Eurasian snow cover versus Indian monsoon rainfall: an extension of the Hahn-Shukla results. *Journal of Climate and Applied Meteorology*, **23**, pp. 171–173.

DIRMEYER, P.A., 2001, An evaluation of the strength of land–atmosphere coupling. *Journal of Hydrometeorology*, **2**, pp. 329–344.

DIRMEYER, P.A., ZENG, F.J., DUCHARNE, A., MORRILL, J.C. and KOSTER, R.D., 2000, The sensitivity of surface fluxes to soil water content in three land surface schemes. *Journal of Hydrometeorology*, **1**, pp. 121–134.

DONG, B.W. and VALDES, P.J., 1998, Modelling the Asian summer monsoon rainfall and Eurasian winter/spring snow mass. *Quarterly Journal of the Royal Meteorological Society, Part B*, **124**, pp. 2567–2596.

DOUVILLE, H. and ROYER, J.F., 1996, Sensitivity of the Asian summer monsoon to an anomalous Eurasian snow cover within the Meteo-France GCM. *Climate Dynamics*, **12**, pp. 449–466.

FOSTER, J.L., CHANG, A.T.C. and HALL, D.K., 1997, Comparison of snow mass estimates from prototype passive microwave snow algorithm, a revised algorithm and a snow depth climatology. *Remote Sensing of Environment*, **62**, pp. 132–142.

FU, C. and FLETCHER, J.O., 1985, The relationship between Tibet–tropical ocean thermal contrast and the interannual variability of Indian monsoon rainfall. *Journal of Climate and Applied Meteorology*, **24**, pp. 841–847.

GADGIL, S., 2003, The Indian Monsoon and its variability. *Annual Reviews of Earth and Planetary Sciences*, **31**, pp. 429–467.

GILL, A.E., 1980, Some simple solutions for heat-induced tropical circulation. *Quarterly Journal of the Royal Meteorological Society*, **106**, pp. 447–462.

HAHN, D.G. and SHUKLA, J., 1976, Apparent relationship between Eurasian snow cover and Indian monsoon rainfall. *Journal of the Atmospheric Sciences*, **33**, pp. 2461–2462.

HE, H., MCGINNIS, J.W., SONG, Z. and YANAI, M., 1987, Onset of the Asian monsoon in 1979 and the effect of the Tibetan Plateau. *Monthly Weather Review*, **115**, pp. 1966–1995.

HONG, S.Y. and KALNAY, E., 2000, Role of sea surface temperature and soil-moisture feedback in the 1998 Oklahoma–Texas drought. *Nature*, **408**, pp. 842–844.

KAPLAN, A., CANE, M., KUSHNIR, Y., CLEMENT, A., BLUMENTHAL, B. and RAJAGOPOLAN, B., 1998, Analyses of global sea surface temperature 1856–1991. *Journal of Geophysical Research*, **103**, pp. 18567–18589.

KAPLAN, A., KUSHNIR, Y. and CANE, M.A., 2000, Analysis of historical sea level pressure 1854–1992. *Journal of Climate*, **13**, pp. 2987–3002.

KAPLAN, A., EVANS, M.N., REICHERT, B.K. and CANE, M.A., 2003, Constraints from the instrumental and paleo data on nineteenth century climate. In *EOS, Transactions, AGU*, *82*(47) Suppl. Abstract GC21A-07, accessed via online abstract database (http://www.agu.org/meetings/waisfm01.html), July 2003.

KOSTER, R.D. and SUAREZ, M.J., 1995, Relative contributions of land and ocean processes to precipitation variability. *Journal of Geophysical Research*, **100**, pp. 13775–13790.

KRIPALANI, R.H. and KULKARNI, A., 1999, Climatology and variability of historical Soviet snow depth data: some new perspectives in snow—Indian monsoon teleconnections. *Climate Dynamics*, **15**, pp. 475–489.

KRIPALANI, R.H. and SINGH, S., 1993, Large-scale aspects of India–China summer monsoon rainfall. *Advances in Atmospheric Sciences*, **10**, pp. 71–84.

KRIPALANI, R.H., INAMDAR, S. and SONTAKKE, N.A., 1996a, Rainfall variability over Bangladesh and Nepal: comparison and connections with features over India. *International Journal of Climatology*, **16**, pp. 689–703.

KRIPALANI, R.H., SINGH, S.V., VERNEKAR, A.D. and THAPLIYAL, V., 1996b, Empirical study on Nimbus-7 snow mass and Indian summer monsoon rainfall. *International Journal of Climatology*, **16**, pp. 23–34.

KRISHNA KUMAR, K., SOMAN, M.K. and RUPA KUMAR, K., 1995, Seasonal forecasting of Indian summer monsoon rainfall: a review. *Weather*, **50**, pp. 449–467.

Krishna Kumar, K., Kleeman, R., Cane, M.A. and Rajagopalan, B., 1999a, Epochal changes in Indian monsoon-ENSO precursors. *Geophysical Research Letters*, **26**, pp. 75–78.

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

Li, C. and Yanai, M., 1996, The onset and interannual variability of the Asian summer monsoon in relation to land–sea thermal contrast. *Journal of Climate*, **9**, pp. 358–375.

Luo, H. and Yanai, M., 1984, The large-scale circulation and heat sources over the Tibetan Plateau and surrounding areas during the early summer of 1979. Heat and moisture budgets. *Monthly Weather Review*, **112**, pp. 966–989.

Meehl, G.A., 1994, Coupled Land–ocean–atmosphere processes and South Asian monsoon variability. *Science*, **266**, pp. 263–267.

Mehta, V.M. and Lau, K.M., 1997, Influence of solar irradiance on the Indian monsoon–ENSO relationship at decadal–multidecadal time scales. *Geophysical Research Letters*, **24**, pp. 159–162.

Parthasarathy, B., Munot, A.A. and Kothawale, D.R., 1995, All India monthly and seasonal rainfall series: 1871–1993. *Theoretical and Applied Climatology*, **49**, pp. 217–224.

Ramage, C.S., 1983, Teleconnections and the siege of time. *Journal of Climatology*, **3**, pp. 223–231.

Rasmusson, E.M. and Carpenter, T.H., 1983, The relationship between eastern equatorial Pacific sea–surface temperatures and rainfall over India and Sri-Lanka. *Monthly Weather Review*, **111**, pp. 517–528.

Reale, O. and Dirmeyer, P.A., 2001a, *Modeling the Effect of Land-Surface Variability on Precipitation Variability.* Part I. *General Response* (Calverton, MD: Center for Ocean-Land-Atmosphere Studies).

Reale, O., Dirmeyer, P.A. and Schlosser, A., 2001b, *Modeling the Effect of Land-Surface Variability on Precipitation Variability.* Part II. *Spatial and Time-Scale Structure* (Calverton, MD: Center for Ocean-Land-Atmosphere Studies).

Ropelewski, C.F. and Halpert, M.S., 1987, Global and regional scale precipitation patterns associated with the El-Niño Southern Oscillation. *Monthly Weather Review*, **115**, pp. 1606–1626.

Ropelewski, C.F. and Halpert, M.S., 1989, Precipitation patterns associated with the high index phase of the Southern Oscillation. *Journal of Climate*, **2**, pp. 268–284.

Sankarrao, M., Lau, K.M. and Yang, S., 1996, On the relationship between Eurasian snow cover and the Asian summer monsoon. *International Journal of Climatology*, **16**, pp. 605–616.

Shaman, J. and Tziperman, E., 2005a, The effect of ENSO variability on Tibetan Plateau snow depth: a stationary wave teleconnection mechanism and implications for the South Asian monsoons. *Journal of Climate*, pp. 2067–2079.

Shaman, J. and Tziperman, E., 2005b, The direct effect of summertime ENSO conditions on the South Asian monsoons: barotropic and baroclinic teleconnection mechanisms. In review.

Vernekar, A.D., Zhou, J. and Shukla, J., 1995, The effect of Eurasian snow cover on the Indian monsoon. *Journal of Climate*, **8**, pp. 248–266.

Von Storch, H. and Zwiers, F.W., 2001, *Statistical Analysis in Climate Research* (Cambridge: Cambridge University Press).

Walker, G.T., 1924, Correlation in seasonal variations of weather. IV. A further study of world weather. *Memoirs of the Indian Meteorological Department*, **24**, pp. 275–332.

Webster, P.J., Moore, A.M., Loschnigg, J.P. and Leben, R.R., 1999, Coupled ocean–atmosphere dynamics in the Indian ocean during 1997–98. *Nature*, **401**, pp. 356–360.

Webster, P.J. and Yang, S., 1992, Monsoon and ENSO. selectively interactive systems. *Quarterly Journal of the Royal Meteorological Society*, **118**, pp. 877–926.

YANAI, M. and LI, C., 1994, Mechanism of heating and the boundary layer over the Tibetan Plateau. *Monthly Weather Review*, **122**, pp. 305–323.

YANAI, M., LI, C. and SONG, Z., 1992, Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon. *Journal of the Meteorological Society of Japan*, **65**, pp. 81–102.

YASUNARI, T., KITOH, A. and TOKIOKA, T., 1991, Local and remote responses to excessive snow mass over Eurasia appearing in the northern spring and summer climate: a study with the MRI.GCM. *Journal of the Meteorological Society of Japan*, **69**, pp. 473–487.

YE, H.C. and BAO, Z.H., 2001, Lagged teleconnections between snow depth in northern Eurasia, rainfall in Southeast Asia and sea-surface temperatures over the tropical Pacific Ocean. *International Journal of Climatology*, **21**, pp. 1607–1621.