A Stratified Diagnosis of the Indian Monsoon – Eurasian Snow Cover Relationship

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Abstract

This study is aimed at reconciling inconsistencies between modeling studies of the Indian monsoon-Eurasian snow cover relationship, which support the Blanford (1884) hypothesis, and recent diagnostic studies, which have largely failed to show its existence. Recently released Version 2 NESDIS/NOAA satellite-based retrievals of snow cover are used. A focus is given to diagnosing a) spatial and temporal complexity in the Eurasian snow cover distribution, b) the role of ENSO in modulating the snow cover-All India Rainfall (AIR) relationship, and c) the spatial distribution of the rainfall association within India.

With these goals in mind, the climatological distribution of snow cover and its interannual variability are first assessed. While snow cover is largest in northern Eurasia, its variability is most pronounced in southwestern Asia between the Black and Caspian Seas, and across the northern Indian, Himalayan, and Tibetan Plateau (NIHT) region. In regions of large variability and for Eurasia as a whole, AIR is found to exhibit a very weak correlation with both December, January, February (DJF) and March, April, May (MAM) snow cover when considered across the available data record.

Patterns of snow cover anomalies associated with both ENSO and anomalous monsoon seasons are then examined in a composite analysis. Spatial complexity in snow cover anomalies during both anomalous monsoon years and ENSO events is shown to be large. As the association between ENSO and snow cover is found to be strong across much of Eurasia, ENSO's influence on the monsoon-snow cover relationship over the climatological record is strongly suggested. Moreover, the composites suggest that many idealized simulations of the monsoon snow-cover interaction are based on forcings that are not generally reflective of variations in nature.

When correlations between snow cover and monsoon intensity are calculated for regions neighboring India during anomalous monsoon seasons in which ENSO is weak (AM-neutral years), robust and statistically significant negative correlations are found, in support of the Blanford hypothesis. Specifically, snow cover in both the Southwest Asian and NIHT regions are found to correlate strongly with AIR during spring and winter, respectively. While snow cover over the entirety of Eurasia is also found to exhibit a modest correlation with AIR during AM-Neutral years, the correlation results largely from anomalies in northern Eurasia that are distant from India and are therefore probably unrelated to the Blanford hypothesis.

The spatial pattern of rainfall anomalies within India is also investigated. It is found that correlations between district rainfall and snow cover in the SW Asia and NIHT regions during ENSO are largely insignificant while during AM-Neutral years, significant negative correlations are found across central and northern India, in modest agreement with model simulations that show the strongest rainfall response in northern India. Together, the findings support the existence of the Blanford mechanism while suggesting that the influence of the land surface can be overwhelmed by ENSO. A new conceptual model of the monsoon-snow cover relationship that builds on the Blanford hypothesis is thus proposed to better explain its apparent absence from diagnostic studies that have used mean Eurasian snow cover over the entire data record.

1. Introduction

Year-to-year variations in Indian summer monsoon rainfall directly impact the livelihoods of over a billion people (e.g. Parthasarathy et al. 1988, Gadgil 1996). Moreover, as the monsoon is itself associated with the greatest diabatic heating of the atmosphere during boreal summer, its influence extends a great distance from the Asian continent (e.g. Walker 1923, Webster et al. 1998, Liu and Yanai 2001). Understanding and predicting variability in the monsoon thus exist as key science objectives. As continental snow cover is believed to comprise one of the few sources of seasonal persistence in the Asian region, and thus may potentially be used as an empirical predictor, the monsoon-snow cover relationship is particularly compelling.

Blanford (1884) first suggests that the varying extent and thickness of continental snow cover exerts an influence on the land surface's thermal characteristics and, in turn, influences the onset of the Asian summer monsoon. Blanford cites the mechanism as being responsible for a decrease in rainfall over the plains of western India during years of large winter snow cover in the Himalayas. Building on Blanford's early speculations (hereafter termed the Blanford hypothesis), Walker (1910) finds a negative correlation between Himalayan snow depth at the end of May and the amount of summer monsoon rainfall over India during the period 1876-1908. Walker subsequently establishes Himalayan snow cover as a key predictor of monsoon intensity and, for several decades thereafter, the British and Indian Meteorological Services use snow cover as a predictor of the advance of the southwest monsoon. In the early conceptual model of Blanford, the spatial distributions of the rainfall and snow cover fields are not explicitly stated. Rather, the model is largely qualitative, associating spring seasons of excess or scanty snow cover near India with summers of excessively dry (i.e. weak monsoons) or wet (i.e. strong monsoons) conditions in India, respectively.

The conclusions drawn by Blanford and Walker were not to withstand scrutiny, however, and in subsequent decades the monsoon-snow cover association was shown to be invalid during some years. Following an extended period of poor monsoon-snow cover correspondence, the Indian Meteorological Department removed snow accumulation from its list of predictors of monsoon intensity in the 1960's. Only following the study of Hahn and Shukla (1976), in which an inverse relationship between Eurasian mean snow cover for December, January, February (DJF) and March and monsoon strength is shown in a nine-year record of photographically interpreted satellite imagery during the late 1960's and early 1970's, has the monsoon-snow cover relationship received new interest. In the Hahn and Shukla study, and in numerous subsequent studies, the monsoon-snow cover relationship is assessed broadly over Eurasia rather than the regions neighboring India that were cited by Blanford and Walker as key. Dey and Bhanu Kumar (1982), Dey and Bhanu Kumar (1983), Dickson (1984), Ropelewski et al (1984), Yang (1996), SankarRao et al. (1996), and Matsuyama and Masuda (1998) also find negative correlations between mean Eurasian snow cover and monsoon intensity, in support of the Hahn and Shukla (1976) results. However, due to brevity of available data records, many of the studies achieve results that whose statistical significance is marginal and many rely on data records of a decade or less. It has yet to be established that such records are adequate to examine fully the monsoon-snow cover relationship, which may be temporally complex. Moreover, the relevance of Eurasian mean snow cover to the Blanford hypothesis has yet to be established.

Nevertheless, the physical basis for the monsoon-snow cover interaction has been studied extensively in models (Hahn and Manabe 1975, Barnett et al 1989, Yasunari et al. 1991, Zwiers 1993, Vernekar et al. 1995, Douville and Royer 1996, Yang and Lau 1996, Dong and Valdes 1998, Ferranti and Molteni 1999, Bamzai and Marx 2000). The net effect of elevated snow cover, usually imposed in central and southern Eurasia, is to lessen the land-sea temperature contrast, displace the springtime midtropospheric ridge near India, and decrease the strength of the monsoon (e.g. Meehl 1994a, b, Chandrasekar 2002). The studies have shown rainfall in Southeast Asia to be particularly sensitive to surface heating fluctuations in southern Asia (Zhao and Chen 2001). Of the studies, only Zwiers (1993) fails to reproduce a strong monsoon-snow cover relationship, an outcome cited by the author as the possible result of errors in model snow cover. Thus as a whole, the simulations overwhelmingly support the Blanford hypothesis all cite albedo and surface hydrologic processes in southern Asia as key. Modulation of the summertime mid-tropospheric meridional temperature gradient across the

Indian peninsula is shown to link surface thermal forcing and the large-scale circulation, a finding that is echoed in process studies (Dey and Bhanu Kumar 1982, Fu and Fletcher 1985, Hahn and Kathuria 1986, Meehl 1994a, Li and Yanai 1996). Moreover, the model simulations provide a quantitative description of rainfall anomalies with a maximum response in rainfall in northern India (e.g. Barnett et al. 1989, Vernekar et al 1995, Dong and Valdes 1998) and, often, an opposing response in southern India (e.g. Bamzai and Marx 2000). Implicit in the conclusions of the modeling and process studies is that variability in snow cover remote from southern Asia is of secondary or negligible importance in instigating the monsoon-snow cover relationship. Despite the successes of model studies, however, a major caveat remains as the realism of both the mean state and variability of model snow cover fields variability remains largely unverified.

In contrast to model studies, recent diagnostic studies have contradicted the Blanford hypothesis. Liu and Yanai (2001) find significant positive correlation between AIR and March, April, and May (MAM) upper tropospheric temperature in Western Europe, remote from the NIHT region. Moreover, land surface temperatures, which presumably should be central to the monsoon-snow cover relationship, are found to be largely uncorrelated with AIR. Using surface snow cover, soil moisture, and air temperature observations from 1870 to 2000, Robock et al. (2003) find monsoon rainfall and snow cover anomalies over Eurasia to be positively correlated. Kripalani and Kulkarni (1999) show the spatial structure of the snow cover monsoon relationship to be complex in northern Eurasia with negative correlation in western Eurasia and positive correlation in eastern Eurasia. Kripalani et al (2003) document the association between monsoon rainfall, snow cover, and snow melt over two northern Indian districts using data from INSAT, finding a positive relationship between snow cover and monsoon strength. In addition, while high latitude associations with monsoon strength have been found (Klassen et al 1994, Rajeevan 2002), they may be symptomatic of the larger-scale shift in the midlatitude jet streams rather than its root cause (e.g. Meehl 1997). The lack of a strong monsoon-snow cover relationship in observations has been interpreted by some as a delinking of the monsoon from the Eurasian continent in a warming climate (Kripalani et al. 2001, 2002). Both the spatial complexity of the Eurasian snow cover distribution and the role of ENSO are not generally addressed in these studies, however.

Few studies have examined the association between ENSO, the Eurasian snow cover distribution, and the monsoon. Using satellite and station data during the 1970's and 1980's, SankarRao et al. (1996), Yang (1996), Matsuyama and Masuda (1998), and Kitoh et al. (1999) show that the relationship between Eurasian mean snow cover and the monsoon is diminished during ENSO years. Moreover, Eurasian mean snow cover is found to be highly variable, correlating with monsoon intensity in some years while acting independently in others. In identifying multiple low-frequency modes of variability interacting with the snow cover distribution, the studies thus suggest that data records of a decade or less are probably insufficient to resolve fully the monsoon-snow cover relationship. In a model study, Becker et al. (2000) shows an association between high snow cover over western Eurasia and La Niña events. Moreover, the model study of Yang and Lau (1998) shows that the remote forcing of ENSO can overwhelm local monsoon-land surface interactions, thus cautioning against assessing the interactions simultaneously during both ENSO and non-ENSO conditions. In light of the strong influence of ENSO on the monsoon environment, the causal role of snow cover anomalies has also been questioned (e.g. Meehl 1997) however; recent model studies reaffirm an active role for the Blanford mechanism (Ferranti and Molteni 1999). The association between Eurasian snow cover and monsoon intensity during years of neutral tropical SST anomalies remains to be shown, however.

Studies also have yet to examine extensively the spatial structure of the monsoon-snow cover interaction. Bamzai and Shukla (1999) and Ye and Bao (2001) assess the climatological mean correlation of snow cover with monsoon rainfall as a function of location across Eurasia. An important conclusion of the studies is that, in fact, spatial variability of Eurasian snow cover is large, with zonal asymmetry in the monsoon-snow cover correlation centered near 80^{o}E. However, in the mean, the studies find negative correlations between snow cover and monsoon intensity to be confined to eastern Europe and western Asia, regions that are probably not relevant to the Blanford mechanism. Perhaps more surprisingly, the correlations in regions neighboring India are found to be marginally positive. Among the few recent studies to identify a monsoon-snow cover relationship consistent with the Blanford hypothesis is the recent study of Wu and Qian (2003), which examines snow cover and depth over the Tibetan Plateau and its relationship to monsoon anomalies from 1960 to 1998. Anomalies in snow cover are found to be both spatially and temporally complex across the Plateau with anomalies in southwest portions of the Plateau often out of phase with those in the central and eastern Plateau. Nonetheless, a mean negative correlation is found between wintertime snow cover and subsequent monsoon rainfall.

Science Questions

In the context of both the disagreements that exist between modeling and diagnostic studies of the monsoon-snow cover relationship, the large and direct role played by snow cover in modifying thermal characteristics of the land surface, and the strong influence of ENSO in the monsoon environment, a number of open questions remain including:

- Given its limited relevance to the Blanford mechanism, is Eurasian mean snow cover a suitable index with which to diagnose the monsoon-snow cover relationship?
- Given the relatively strong influence of ENSO on the monsoon environment (Yang and Lau 1998), what is the role of ENSO in masking the Blanford hypothesis in studies that consider together both ENSO and non-ENSO years?
- Is it likely that snow cover, which has a significant impact on surface radiative and thermal properties, can be unrelated to the development of the monsoon thermal low and monsoon intensity as suggested by Bamzai and Shukla (1999), and Ye and Bao (2001)? If not, why is the Blanford hypothesis not apparent?
- What are the spatial structures of Eurasian snow cover anomalies associated with both ENSO events and anomalous monsoon years? Does snow cover play a role in communicating the ENSO-monsoon interaction? Have models used realistic forcing fields in simulating the monsoon-snow cover interaction?
- For years in which ENSO is not strong, what is the observed monsoon-snow cover association and is it consistent with the Blanford hypothesis?

The present study addresses the above questions using a recently available satellite record of snow cover from 1967 to 2001. Section 2 discusses the data and analysis method while Section 3 presents attributes of the climatological mean springtime snow cover distribution and its interannual variability. Section 4 assesses associations between snow cover, AIR, and ENSO across the entire data record and discusses characteristics of the snow cover distribution for both DJF and MAM. Large-scale composite associations between ENSO, the monsoon, and Eurasian snow cover that quantify the spatial complexity of the monsoon-snow cover relationship are presented in Section 5. Stratified diagnoses of the large-scale distributions are then discussed in Section 6 and Indian district-based rainfall's association with snow cover near India is assessed in Section 7. A conceptual model that summarizes the salient associations found between snow cover, Indian rainfall, and ENSO is then developed in Section 8.

2. Data and Method

The recently released National Oceanic and Atmospheric Administration (NOAA)/National Environmental Satellite, Data and Information Service (NESDIS) Version 2 dataset, spanning from October 1966 to June 2001 at weekly intervals (Armstrong and Brodzik 2002), is used. Each grid cell contains one bit of information for each week indicating the absence or presence of snow cover and is reported on a 25 km equal-area (EASE) grid that spans the northern hemisphere. Snow cover extent is based on the digital NOAA-NESDIS Weekly Northern Hemisphere Snow Charts, revised and regridded to the EASE-Grid. The original NOAA-NESDIS weekly snow charts are derived from the manual interpretation of AVHRR, GOES, and other visible-band satellite data. Unlike the daily data, microwave retrievals have not been incorporated, at any time, in the snow cover estimates. The data have been regridded for the purposes of this study to percent snow cover on a 1ox1o weekly grid. Version 2 of the NESDIS dataset represents the latest improvements and extension of snow cover reanalysis and snow chart research that comprise a substantial improvement over Version 1 of the NESDIS dataset released in 1995 (Robinson et al. 2001). Data gaps exist in the dataset during July 1968, June through Oct. 1969 and, July through 26 Sept. 1971, however, as a focus is given in this study to weeks beginning in DJF and MAM the data gaps do not affect the present analysis. Finally, special efforts have been taken in compiling the Version 2 product to ensure data quality in the 1967 to 1972 interval, which has been cited as a period of deficiencies in other data records (e.g. Kripalani et al. 1996).

Monsoon intensity is gauged from the All-India summer monsoon rainfall index (AIR), which is calculated from the area-weighted rain gauge reports from stations distributed over India from 1871 to 2001 (Mooley and Parthasarathy 1984; Parthasarathy et al. 1994). Data from 1967 to 2001 are used here. In addition to the All-India index, rainfall estimates are complied from area-weighted averages of the station data for each of India's 29 districts. Rainfall estimates are reported at monthly intervals, however, for the calculations here, only averages for the summer monsoon season from June through September (JJAS) are used. The intensity of the El Niño – Southern Oscillation (ENSO) is gauged from SST anomalies in the Niño3 region (5 ^{o}S : 5 ^{o}N, 150 ^{o}W : 90 ^{o}W). Prior to 1982, SST from the Reconstructed Reynolds product is used (Smith and Reynolds 1994) after which time Reynolds SST is used (Reynolds and Smith 1996).

B) Method of Analysis

Monsoon and ENSO conditions are declared for each year from 1967 to 2001, based on anomalies in JJAS rainfall exceeding 10% and JJAS SST exceeding 0.7^{o}C. The identification is objective, characterizes the state of ENSO during the monsoon season, and is largely consistent with definitions by Kiladis and Diaz (1989), the Center for Ocean-Atmosphere Interaction Studies (COAPS) and the Climate Prediction Center (CPC). Moreover, the results of the study are found to be generally robust to alternative seasonal ENSO classifications. Table 1 summarizes the declaration of monsoon seasons and ENSO events by year. ENSO events and anomalous monsoon seasons are not significantly biased towards either end of the data record though anomalous monsoon seasons have become less frequent, and ENSO events have become more frequent, in recent years (e.g.

Table 1: Declaration of monsoon season strength and ENSO phase are shown. Monsoon and ENSO years in bold are associated with anomalous ENSO and monsoon conditions, respectively. The year 1990 has been added to the strong AM-Neutral grouping due to a scarcity of such events as it is the next strongest monsoon season (+7%) in which Niño-3 SST anomalies are small (<0.2^{o}C, see text).

Monsoon Strength			ENSO (JJAS)		
Strong	Normal	Weak	Warm	Normal	Cold
1970	1967	1968	1969	1967	**1970**
1975	**1969**	**1972**	**1972**	**1968**	1973
1983	1971	1974	1976	1971	**1988**
1988	**1973**	1979	**1982**	**1974**	1999
1990*	**1976**	**1982**	**1983**	**1975**	
1994	1977	1986	**1987**	1977	
	1978	**1987**	1991	1978	
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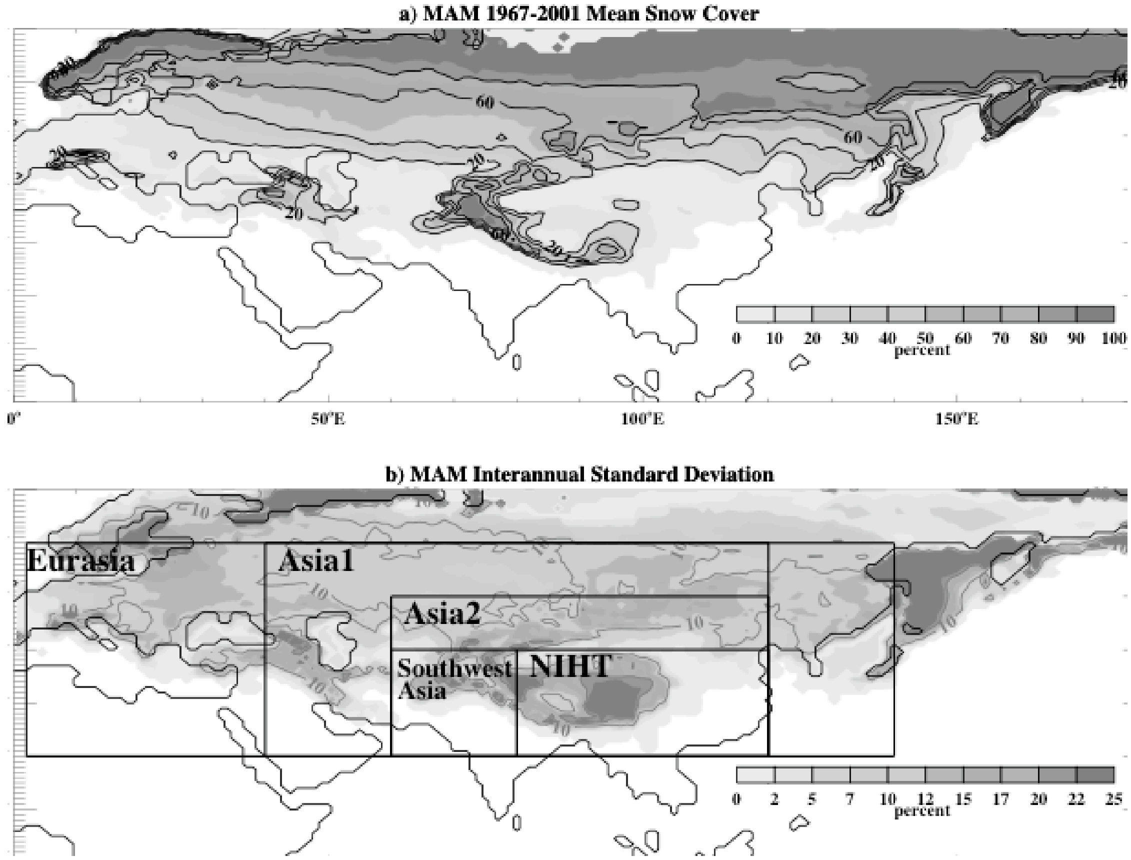

Figure 1: a) The mean springtime (MAM) snow cover distribution from 1967-2001 based on the Version 2 NESDIS product. For clarity the 20%, 40% and 60% levels have been outlined. b) The standard deviation of interannual variations in MAM snow cover from 1967 to 2001 is shown. Outlined regions correspond to the Eurasian, Asia1, Asia2, SW Asian, and NIHT regions used in subsequent discussion and analysis. The 10%, 20% and 30% levels have been outlined.

Fasullo and Webster 2002). Based on these declarations, several categories of years will be considered in subsequent analyses including:

- ENSO Years (La Niña and El Niño years),
- Anomalous monsoons with normal ENSO conditions or AM-Neutral years (weak monsoon / normal SST years and strong monsoon / normal SST years)
- ENSO Years accompanying anomalous monsoons (AM-ENSO years: La Niña/strong monsoon years and El Niño/weak monsoon years)

Due to the scarcity of AM-Neutral years corresponding to strong monsoon conditions, the next strongest monsoon year in which Niño-3 SST anomalies were less than 0.7 ^{o}C has also been added to the grouping. In 1990, the monsoon rainfall anomaly was 7% and SST anomalies were less than 0.2^{o}C. The inclusion of 1990 does not alter the results of the study but merely bolsters their significance. Based upon these groupings, the snow cover-ENSO-monsoon associations will be assessed.

3. Climatological Springtime Snow Cover

Figure 1 shows the mean MAM snow cover distribution in Eurasia and the standard deviation of its interannual variability based on NESDIS snow cover data from 1967 to 2001. In general, the springtime snow cover distribution is characterized by dense snow cover (> 60%) in northern Eurasia and moderate snow cover (20% to 40%) in central Eurasian. Comprising one of the few subtropical regions in which significant snow cover is present, the elevated area of northern Pakistan, northern India, Nepal, Bhutan, and China also exhibit modest snow cover (>20%) on average. The interannual variability of snow cover by location is shown in Fig. 2b.

Table 2: Correlations between MAM snow cover and JJAS All India Rainfall are shown. Values equal to or exceeding the 80% and 85% confidence levels are shown in italic and bold type, respectively. Also shown are correlations between DJF and subsequent MAM snow cover for each region.

	Correlation (1967-2001)		Persistence r(DJF,MAM)
	DJF	MAM	
Eurasia	-0.21	-0.15	-0.08
Asia1	-0.07	-0.12	-0.01
Asia2	-0.05	0.02	**0.25**
SW Asia	0.07	-0.18	0.14
NIHT	-0.09	0.18	**0.50**

Largest variability (>15%) exists generally along the southern fringe of the snow cover distribution including southern Europe and the Caucus Mountains between the Caspian and Black Seas. Much of the Himalaya mountain range and Tibetan Plateau also experience pronounced interannual variability (>15%) over large spatial domains and fluctuations through much of Mongolia and southern China are large. The marked interannual variability in the regions neighboring northern India thus satisfies a prerequisite of the Blanford hypothesis as variability in snow cover exists and is sizable. Moreover, the distribution of snow cover and its interannual variability are similar to those shown by studies using other datasets (e.g. Bamzai and Shukla 1999).

For the purposes of subsequent analyses, several regions are now identified to successively isolate the relationship between the monsoon and regions in which snow cover variance is large (Fig. 2a). The regions include:

- Eurasia (0 ^{o}E : 140 ^{o}E, 20 ^{o}N : 60 ^{o}N)
- Asia1 (40 ^{o}E : 120 ^{o}E, 20 ^{o}N : 60 ^{o}N)
- Asia2 (60 ^{o}E : 100 ^{o}E, 20 ^{o}N : 50 ^{o}N)
- Southwest Asia (60 ^{o}E : 80 ^{o}E, 20 ^{o}N : 40 ^{o}N)
- NIHT (80 ^{o}E : 120 ^{o} E, 20 ^{o}N : 40 ^{o}N)

The Eurasian region is defined to correspond to regions used in previous studies of the monsoon-snow cover relationship (e.g. Hahn and Shukla 1976, Yang 1996) while the Asian regions are defined to progressively isolate the monsoon-snow cover relationship near India. The Southwestern Eurasian and NIHT regions are delineated in order to isolate important

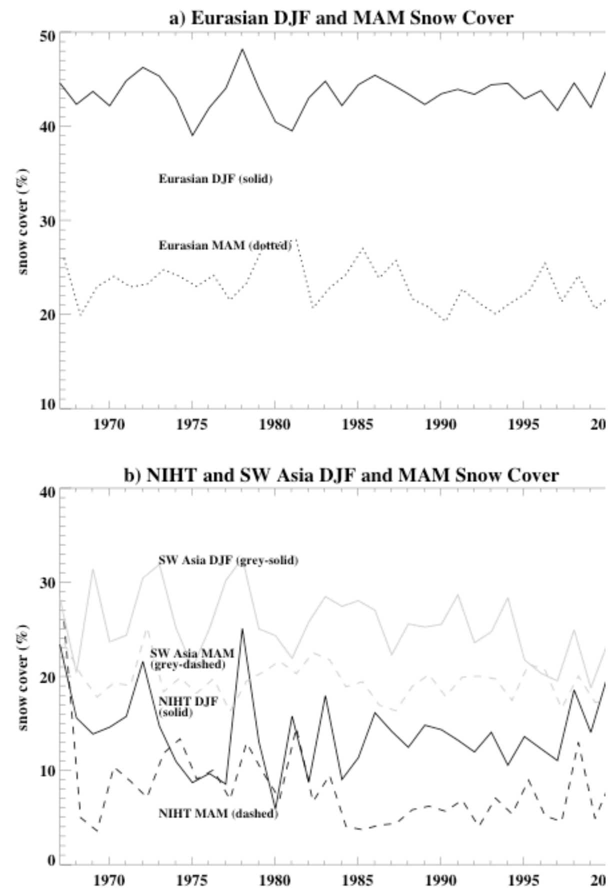

Figure 2: Timeseries are shown for DJF (solid) and MAM (dashed) a) Eurasian, and b) SW Asian (grey) and NIHT (black) snow cover for the NSIDC data record.

Table 3: Correlations are shown for both DJF and MAM snow cover and subsequent JJAS All India Rainfall. Correlations exceeding the 80% and 90% confidence levels are in italics and bold type, respectively.

Correlations	DJF (ENSO / AM-Neutral / AM-ENSO)	MAM (ENSO / AM-Neutral / AM-ENSO)
Eurasia	-0.32 / -0.45 / -0.75	-0.06 / -0.53 / -0.39
Asia1	-0.17 / -0.24 / -0.53	-0.09 / -0.49 / -0.52
Asia2	-0.17 / -0.09 / -0.53	0.04 / -0.31 / 0.19
SW Asia	-0.02 / 0.00 / -0.08	-0.30 / -0.58 / -0.08
NIHT	-0.17 / -0.58 / -0.32	0.42 / -0.20 / 0.55

differences in snow cover variability that will be shown in Sections 5 and 6.

4. Climatological Relationships

Figure 2 shows the evolution of snow cover for the Eurasian, SW Asian, and NIHT regions based on DJF and MAM averages while Table 2 summarizes their persistence through spring and correlations with AIR. Notably, over all regions correlations between snow cover and AIR fail to achieve 80% statistical significance. Eurasian snow cover averages 44% during DJF and falls to 23% during MAM, however the corresponding interannual standard deviation increases from 1.8% to 2.2%. Correlation of snow cover with AIR is –0.21 for DJF and –0.15 for MAM. For the Asia1 and Asia2 regions, whose timeseries are not shown in Fig. 2, correlations with AIR are negligible at –0.07 and –0.05 in DJF and –0.12 and 0.02 in MAM, respectively. Over SW Asia, snow cover averages 25% and 19% in DJF and MAM, with standard deviations of 3.5% and 2.1%, respectively. Correlations with AIR are again small at 0.07 and –0.18 for DJF and MAM, respectively. NIHT snow cover averages 14% for DJF and 8% in MAM with a standard deviation of 4.2% during both seasons. Correlations with AIR are also small at –0.09 for DJF and 0.18 for MAM. Persistence of anomalies through boreal spring is small. Lagged correlations are negative in the Eurasian and Asia1 regions, less than 0.26 in the Asia2 and SW Asia regions, and modest in the NIHT region at 0.50. Thus while diagnostic studies have used both DJF and MAM snow cover as an index in assessing the Blanford hypothesis which cites May snow cover, the assumption of strong persistence across boreal spring is not valid generally. Moreover, consistent with assessments by Bamzai and Shukla (1999) and Ye and Bao (2001), the

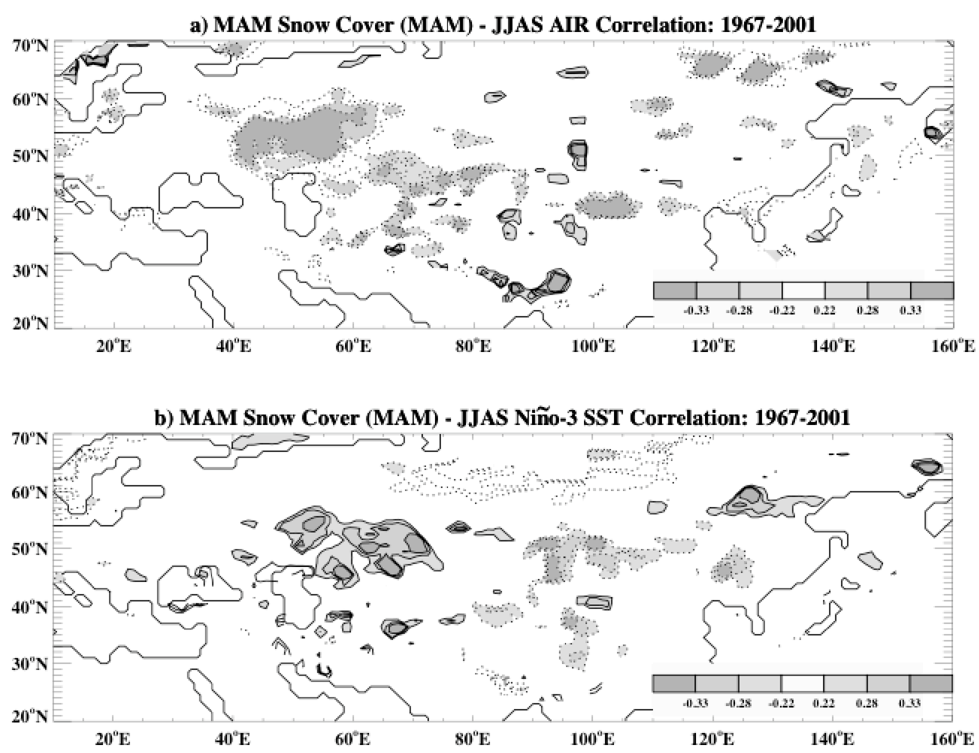

Figure 3: Correlations of a) JJAS All India rainfall (AIR) and b) Niño-3 SST with MAM snow cover are shown as a function of location from 1967 to 2001. Contours are at the 80%, 90% and 95% significance levels.

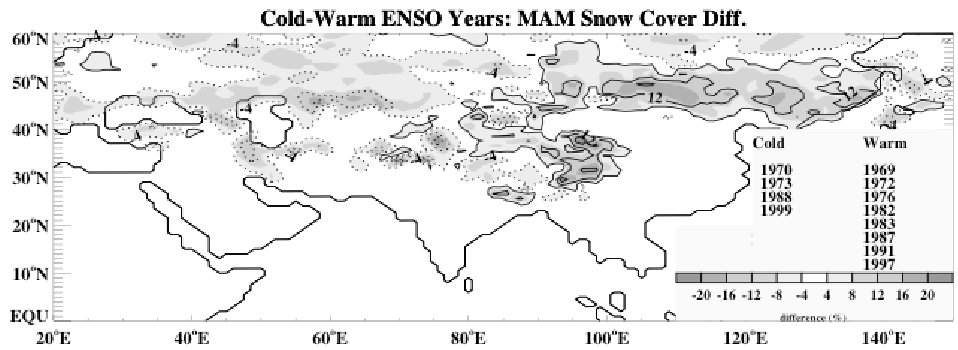

Figure 4: Difference in MAM snow cover between La Niña and El Niño years.

negative correlation between DJF Eurasian snow cover and AIR results largely from variability in Northwestern Asia as the correlations near India are weak, and in instances, positive. The negative correlation between AIR and Eurasian snow cover may therefore correspond to fluctuations that are not causally related through the Blanford mechanism (e.g. Bamzai and Shukla 1999).

5. Large-Scale Spatial Associations

To investigate the spatial distribution of the snow cover – monsoon association responsible for the correlations presented in Table 2, the large-scale spatial correlations between monsoon strength, ENSO, and snow cover are assessed. Figure 3a shows the correlation coefficient between JJAS AIR and MAM snow cover as a function of location in Eurasia. Contour levels are chosen to correspond to the 80%, 90%, and 95% confidence intervals. While AIR and snow cover in most regions share less than 10% of their total variance, statistically significant associations are found nonetheless. Negative correlations are particularly strong and widespread in western Asia, to the north and east of the Caspian Sea, and are scattered in northeastern Siberia and Mongolia. Positive correlations are scattered in the mountainous Himalaya region and through central Asia at 95°E. The lack of strong negative correlations near India in Fig. 3a confirms the results of Bamzai and Shukla (1999) and Ye and Bao (2001). Moreover, the spatial distribution of the snow cover and AIR relationship suggested in Table 2 is confirmed to be at odds with the Blanford hypothesis, which suggests the existence of strong associations near India.

To gain further insight into the role of ENSO in the monsoon-snow cover relationship, Fig. 3b shows the correlation between MAM snow cover and JJAS SST anomalies in the Niño-3 region with contours again indicated at the 80%, 90% and 95% confidence intervals. The distribution of correlations in western Eurasia is, in some ways, a mirror image of the salient features already discussed in Fig. 3a with widespread positive correlations north and east of the Caspian Sea. In eastern Eurasia, negative correlations exist across much of Mongolia and China with positive correlations in eastern Siberia. Correlations near India west and east of 80°E are generally positive and negative, respectively, though the correlations are not generally strong or widespread. The apparent zonal asymmetry of the correlations about 80°E, however, serves as an initial motivation for delineation between the SW Asia and NIHT regions (Fig. 1).

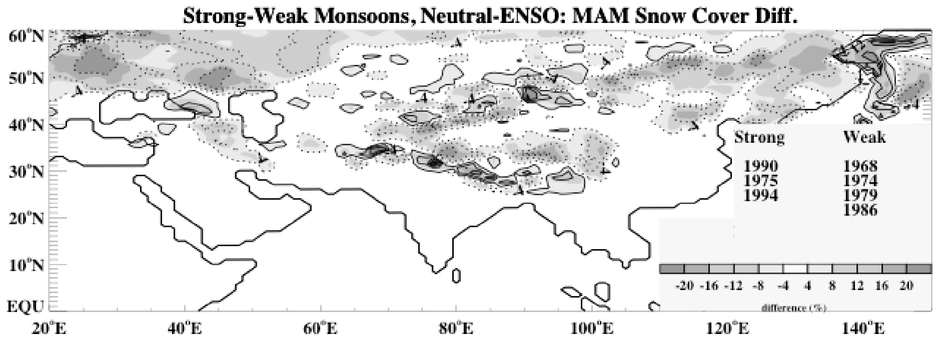

Figure 5: Difference in MAM snow cover between strong and weak monsoon seasons in which ENSO conditions are neutral.

Though the causal associations between snow cover, the monsoon, and ENSO cannot be determined in a diagnostic study, some important remarks can nonetheless be made. First, given the well-established inverse relationship between monsoon strength and ENSO (e.g. Walker 1923), the similarity between the fields in Fig. 3a and 3b in eastern Eurasia may be interpreted initially as a logical residual of the monsoon-ENSO relationship in the snow cover field. However, as ENSO and AIR share only a quarter of their total variance over the assessed period, with a correlation of –0.54, the similarity of the spatial distributions is not required based on the monsoon-ENSO interaction alone.

Moreover, in conjunction with Table 2, Fig. 3 raises some compelling questions. Does ENSO influence the spatial distribution of the climatological AIR-snow cover association (Fig. 3a)? Is snow cover a mechanism by which ENSO and the monsoon interact or does ENSO otherwise influence the observed monsoon-snow cover relationship? A focus is therefore given to examining the spatial distribution of the monsoon-snow cover relationship, both for years in which the influence of ENSO is strong and for years in which it is weak.

6. Stratified Diagnoses

Figures 4,5 and 6 show the differences between snow cover for the various groupings of ENSO and monsoon years already defined (Table 1) while Table 3 summarizes basic statistics relevant to the associations between ENSO, the monsoon, and snow cover. Together, the findings show that assessments averaged over Eurasia and the climatological record mask important associations that exist as a function of time and location. Figure 4 shows the difference field for ENSO years. Most simply, the field can be described as a zonally asymmetric distribution centered near 80^{o}E with positive (negative) differences of 4% to 10% in most of the Eastern (Western) Eurasian regions in which snow cover is present in the mean (Fig. 1). Notably the regions north and east of the Caspian Sea that correlate strongly with AIR (Fig. 3a), are also strongly associated with ENSO phase. Differences in snow cover are particularly pronounced in the Northeastern Eurasia with values exceeding 12% in some areas. As with the correlation fields of Fig. 3, the zonal asymmetry about 80^{o}E serves as a basis for the selection of domains in Fig. 1.

In addition, Fig. 4 shows that the assumption of a normally distributed Eurasian snow cover anomaly in central and southern Asia used in many model simulations is not generally valid for ENSO years. Moreover, Fig. 4 suggests that evaluation of the AIR - Eurasian snow cover association with data that are strongly biased towards the eastern or western Eurasian regions (e.g. Matsuyama and Masuda 1998) are highly subject to variability associated with ENSO. The correlation between AIR and snow cover for ENSO years is shown in Table 3. Though failing to reach the 80% confidence level, the correlation is strongest over Eurasia during DJF, at –0.32, but falls to –0.06 during MAM. Other strong correlations during ENSO years are apparent near India in the SW Asia and NIHT regions, where correlations are –0.30 and 0.42, respectively. Interestingly, the positive correlation between NIHT snow cover and AIR during ENSO years, which acts counter to the Blanford hypothesis, is the only correlation to exceed the 80% confidence interval. The

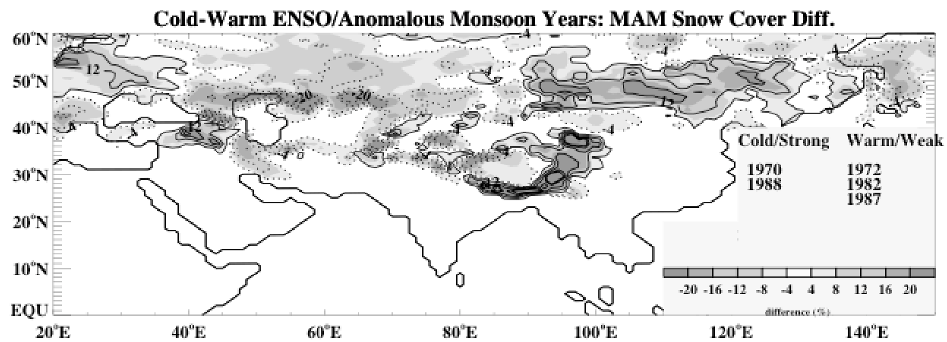

Figure 6: Difference in MAM snow cover between strong and weak monsoon seasons associated with ENSO.

association during ENSO events thus plays a large role in masking the Blanford hypothesis over the climatological record in the NIHT region.

Figure 5 shows the difference in snow cover between strong and weak monsoon years in which ENSO forcing is weak or absent (AM-Neutral years). While the difference field is mixed in the southern Himalaya, large areas of the Tibet Plateau and northeastern and northwestern Eurasia experience less snow cover during strong years than during weak years. The spatially mixed association between AIR and snow cover over the Tibetan Plateau has also been shown to be a characteristic of surface observations in the region (Wu and Qian 2003). The complex spatial structure of the snow cover difference field, with scattered differences in central Eurasia and large anomalies in northwestern and northeastern Eurasia, again points to shortcomings in the fields used in many model simulations of the snow cover relationship. Nonetheless, the AIR-snow cover association over Eurasia acts largely in accordance with the Blanford hypothesis, with reduced and enhanced Eurasian snow cover associated with anomalously strong and weak monsoons, respectively. Interestingly, regions east of the Caspian Sea that correlate negatively in the data record (Fig. 3a) do not generally show a strong association with anomalous monsoon seasons in which neutral ENSO conditions exist, suggesting that the correlations with AIR found in such regions over the climatological record are due to their association with ENSO. Table 3 summarizes the regional associations. During AM-Neutral years, significant negative correlations exist between AIR and DJF NIHT and MAM SW Asian snow cover. Surprisingly however, significant negative correlations also are found for the Asia1 region in MAM and Eurasian region during both DJF and MAM. However, as the correlations are stronger than those for the Asia2 region, variability in northern Eurasia must play a key role in establishing the strong negative Eurasian correlations with AIR.

Figure 6 shows the difference in MAM snow cover for ENSO years associated with anomalous monsoons (AM-ENSO years). Large negative and positive differences exist in northwestern and northeastern Eurasia, respectively. Near India, snow cover's difference field is spatially complex, with positive differences in the eastern Tibetan Plateau and negative differences across the western Plateau, northern India, and Pakistan. Regional correlations between AIR and snow cover in SW Asia (Table 3) are not significant while, in the NIHT region, they are negative for DJF and positive for MAM. The inconsistency in the association between ENSO, AIR, and snow cover, obscures any simple causal role that snow cover may play in communicating the monsoon-ENSO coupling.

Comparison of Figs. 4-6 also reveals a number of notable features. For example, the difference field during AM-ENSO years (Fig. 6) is spatially similar, yet significantly more intense than for ENSO years as a whole (Fig. 4), suggesting that the influence of ENSO across the Eurasian continent may be more intense during AM-ENSO years. Moreover, for AM-ENSO years (Fig. 6), differences in northeastern Asia are very large and positive, while for AM-Neutral years, the differences are large and negative (Fig. 5). Thus, in some large-scale

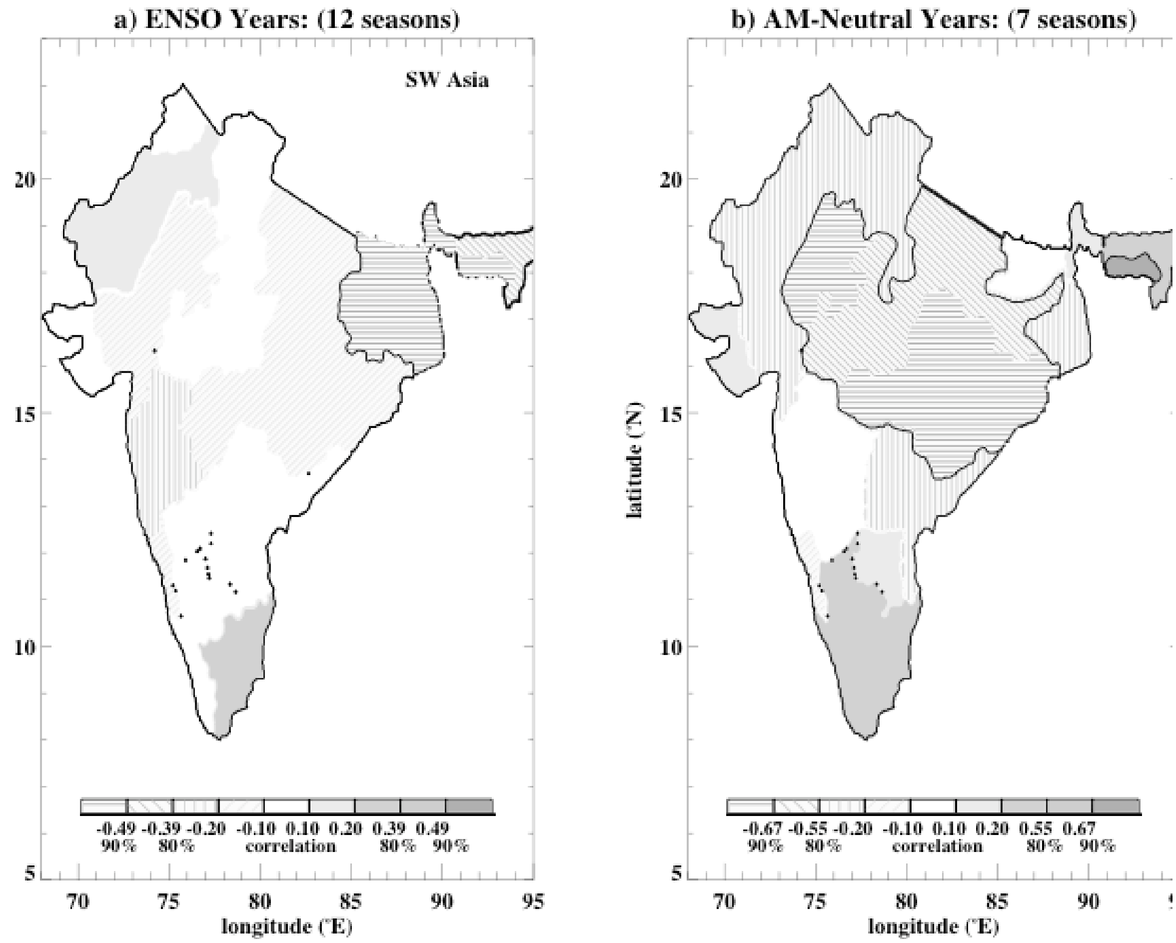

Figure 7: District-wide correlations of JJAS rainfall with MAM snow cover in the SW Asia region for a) ENSO years and b) AM-Neutral years. Shading and stippling of the regions corresponds to the 80%, 90%, and 95% confidence levels of positive and negative correlations, respectively. Contour lines correspond to correlations exceeding the 80% confidence level.

regions, the monsoon-snow cover association can be strong yet change sign based on the presence of ENSO.

7. Regional Relationships within India

Finally, the spatial distribution of the Indian rainfall association with snow cover in neighboring regions is investigated. Figures 7 and 8 show correlations between snow cover in the SW Asia and NIHT regions and rainfall in individual Indian districts for both ENSO and AM-Neutral years. During ENSO, correlations across India using both SW Asian and NIHT snow cover are mixed and in most districts fail to exceed the 80% confidence interval. However, during AM-Neutral years, correlations with SW Asian snow cover are strong and surpass the 80% confidence interval across much of central and northern India (Fig. 7b). A significant positive correlation is found in southern India. NIHT snow cover is negatively correlated with snow cover over more than 90% of the country with the 80% confidence interval exceeded in districts along India's western coast and northern boundary. The rainfall associations shown in Figs. 7, 8 are thus largely consistent with the response shown in models, which simulate greatest responses in rainfall across northern India (e.g. Barnett et al. 1989) and, in instances, an opposing response in southern India (e.g. Bamzai and Marx 2000).

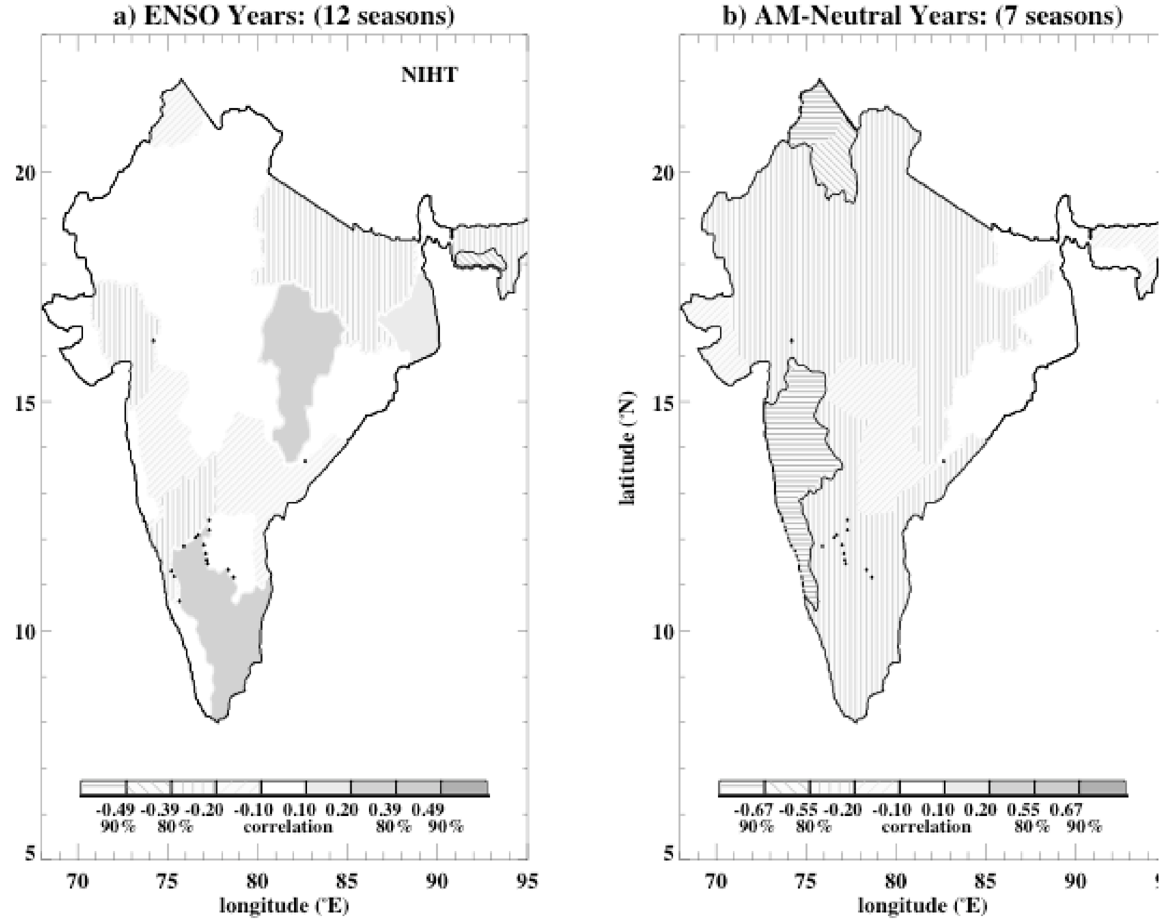

Figure 8: District-wide correlations of JJAS rainfall with MAM snow cover in the NIHT region for a) ENSO years and b) AM-Neutral years. Shading and stippling of the regions corresponds to the 80%, 90%, and 95% confidence levels of positive and negative correlations, respectively. Contour lines correspond to correlations exceeding the 80% confidence level.

8. A Revised Conceptual Model

As the stratified analysis of satellite data suggests that the monsoon-snow cover relationship is both strongly influenced by ENSO and exists as a function of location, a revised conceptual model that builds upon the Blanford hypothesis is shown in Figure 9. The revised conceptual model is not intended to address all interactions that may exist between ENSO, the monsoon, and snow cover. Rather, only those associations found to be both strong, and relevant to the Blanford hypothesis are included. To address both the role of ENSO and the spatial complexity of the monsoon-snow cover relationship, the hypothesis' basic components include:

- DJF snow cover in the NIHT region,
- MAM snow cover in the SW Asian region,
- JJAS Indian rainfall – which exists as a function of both district and time,
- JJAS Niño-3 SST – whose association with both Eurasian snow cover and JJAS monsoon intensity can be strong.

Together, the associations between the components better explains intricacies of the observed monsoon-snow cover relationship, such as the strongly positive correlation between district rainfall and NIHT snow cover during ENSO years (Fig. 6a) and the weak correlation that exists in the mean between snow cover near India and monsoon intensity.

When ENSO events do not accompany the monsoon (AM-Neutral years), negative correlations between AIR and both DJF snow cover in the NIHT region and MAM snow cover in SW Asia, are found (Fig. 5, Table 3). However, when ENSO events occur, they accompany associations between AIR and SW Asian and NIHT snow cover that are weak or exist in direct opposition to the Blanford hypothesis, respectively. Thus, across the entire data record, which encompasses both AM-Neutral and ENSO years, insignificant correlations are found between AIR and snow cover in southern Asia (Fig. 3a).

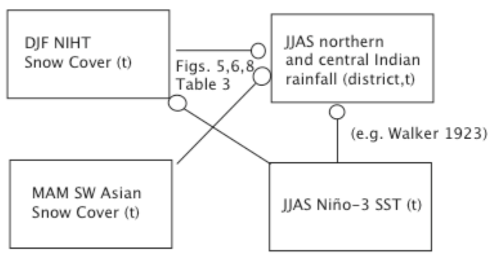

Figure 9: A revised conceptual model of the monsoon-snow cover relationship is shown that builds on the Blanford hypothesis and is consistent with both observations and model studies. Open arrows correspond to inverse relationships between the connected components.

9. Summary

The association between monsoon intensity and Eurasian snow cover has been assessed using satellite retrievals from 1967 to 2001. Among the key findings is that ENSO is itself significantly associated with the snow cover distribution in some regions. Moreover, given the complex relationships that are shown to exist between snow cover, AIR, and ENSO, Eurasian mean snow cover, is judged as a poor index with which to assess the Blanford hypothesis. In addition, given the ENSO-monsoon relationship and the strong associations that are found to exist between ENSO and snow cover, an evaluation of the Blanford hypothesis during strong ENSO events is probably not ideal.

Rather, it is argued that the Blanford hypothesis is best evaluated in a stratified analysis that differentiates between periods of strong and weak ENSO influence and isolates snow cover variability near India, rather than over the entirety of Eurasia. Here, in a composite assessment of the snow cover field during ENSO, AM-Neutral, and AM-ENSO years, it is found that the spatial pattern of interannual variability in the snow cover distribution is complex, with large zonal and meridional structure. The idealized snow cover anomalies imposed in many model studies are therefore not generally reflective of variations in nature. Moreover, snow cover in the NIHT and SW Asian regions exhibits a significant negative correlation with AIR during winter and spring of AM-Neutral years, respectively, in support of the Blanford hypothesis. The correlations exceed the 90% confidence limit despite the relatively limited sample of AM-Neutral events.

District rainfall correlations with snow cover in the SW Asian and NIHT regions have also been explored for both ENSO and AM-Neutral years. During ENSO, correlations between both SW Asian and NIHT snow cover and district rainfall are generally small and insignificant. In contrast, negative correlations during AM-Neutral years are significant and widespread across central, western, and northern India while being mixed in southern India. The spatial distribution of correlations within India supports generally model simulations, which show the greatest snow cover-rainfall association in northern India and, in instances, an opposing response in southern India. Based on the observed associations, a conceptual model is developed that builds upon the Blanford hypothesis and is consistent with the observed ENSO-monsoon-snow cover interaction. Future work in understanding the monsoon-snow cover relationship will include the simulation of monsoon variability in the presence of a realistically varying surface snow cover distribution. In addition, given the strong association observed between snow cover in northern Eurasia and the monsoon that is unaccounted for by the Blanford hypothesis (Fig. 5), mechanisms that link high latitude snow cover to the monsoon may remain to be explored.

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