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Seasonal predictability of the Indian Summer Monsoon : What role do land surface conditions play?

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This paper is dedicated to the memory of M.K.Soman, good friend and colleague who inspired my lasting interest in the Indian summer monsoon (IMS).

सार - यूरेशिया में वसंत ऋतु के समय अनियमित हिमपात धरातल की ऊर्जा और नमी को प्रभावित करने के कारण जलवायु प्रणाली पर अपनी दीर्घ अवधि छाप बनाए रखता है। इस प्रकार से हिमपात की अनियमितताओं से उत्पन्न हुई धरातलीय विषमताएँ मानसून वर्षा की परिवर्तनशीलता को प्रभावित करती हैं। इस शोध-पत्र में पश्चिमी यूरेशिया के धरातल की स्थितियों के प्रभाव से प्रभावित मानसून की परिवर्तनशीलता और विशेष रूप से इस प्रकार से प्रभावित भारतीय ग्रीष्मकालीन मानसून के पूर्वानुमान की व्याख्या करने के लिए मौसम पूर्वानुमान समुच्चय कार्यक्रम से प्राप्त हुए परिणामों का उपयोग किया गया है। पश्चिमी यूरेशिया में वसंत ऋतु के समय धरातल की इस तरह की स्थितियों को और विशेषकर हिमपात की मात्रा को निर्धारित करने वाले महत्वपूर्ण कारकों की भी जाँच की गई है।

इस जाँच से प्राप्त हुए परिणामों से यह पता चला है कि पश्चिमी यूरेशिया में अधिक हिमपात ला निना से प्रभावित है। अतः इस शोधपत्र में यह सुझाव दिया गया है कि एल निनो/दक्षिणी दोलन (ई.एन.एस.ओ.) का प्रभाव यूरेशिया की शीतकालीन जलवायु पर पड़ता है। हिम की मात्रा से उत्पन्न इन असामान्यताओं का प्रभाव ग्रीष्म ऋतु में मृदा की नमी और धरातल के तापमानों में परिवर्तनों के रूप में देखा जाता है। धरातल की इन असामान्य स्थितियों के मानसून वर्षा की परिवर्तनशीलता पर पड़ने वाले प्रभाव की जाँच करने के लिए जलवायविक समुद्र सतह तापमान वाले ग्रीष्मकालीन समाकलनों के समुच्चयों का उपयोग किया गया है। इन परिणामों से यह पता चला है कि पश्चिमी यूरेशिया में हिमपात की सामान्य से अधिक मात्रा के संयोग से मानसून परिसंचरण काफी कमज़ोर पड़ जाता है जबकि अखिल भारतीय स्तर पर वर्षा में थोड़ी सी वृद्धि हो जाती है। प्रेक्षित समुद्र सतह तापमान और समांतर समुच्चय से प्राप्त हुए परिणामों से अखिल भारतीय वर्षा में विपरीत प्रतिक्रिया का पता चलता है, जिससे यह संकेत मिलता है कि समुद्र सतह तापमान की विसंगतियों का प्रभाव, मानसून वर्षा की अंतः वार्षिक परिवर्तनशीलता पर प्रछन्न रूप से प्रबल रहता है।

इन परिणामों से यह सिद्ध हो जाता है कि धरातल की स्थितियों का मानसून के बड़े पैमाने पर परिसंचरण पर महत्वपूर्ण और भारतीय ग्रीष्मकालीन मानसून वर्षा पर कम प्रभाव पड़ सकता है। यद्यपि इससे संबंधित प्रक्रिया का अभी पता लगाया जाना है। ऐसा माना गया है कि मध्य अक्षांशीय परिसंचरण और मानसून के परस्पर संबंध यूरेशिया की धरातल की स्थितियों और मानसून की परिवर्तनशीलता को समझने में प्रमुख भूमिका निभा सकते हैं। यदि ऐसी स्थिति उत्पन्न होती है तो मध्य अक्षांशीय परिसंचरण की उच्च आंतरिक विभिन्नताओं के कारण उक्त संबंध की प्रागुक्ति के सीमित रहने की संभावना है।

ABSTRACT . Anomalous springtime snow amounts over Eurasia may provide long term memory to the climate system by affecting the land surface energy and moisture budgets. In turn the anomalous land surface conditions introduced by snow anomalies may influence monsoon variability. In this paper, results from a programme of seasonal forecast ensembles are used to address, specifically, the influence of western Eurasian land surface conditions on the variability and hence predictability of the Indian summer monsoon. The factors that are important for establishing spring time land surface conditions over western Eurasia, particularly snow amounts are also investigated.

The results have shown that high snow amounts over western Eurasia are linked to La Nina, suggesting that the El- Nino/Southern Oscillation (ENSO) has an influence on the wintertime climate of Eurasia. The signature of these snow depth anomalies is carried through to the summer in terms of changes in soil wetness and surface temperatures. An ensemble of summer integrations with climatological sea surface temperature (SST) has been used to investigate the impact of these anomalous land surface conditions on monsoon variability. The results have shown that the monsoon circulation is substantially weakened in association with above normal snow amounts over western Eurasia, whilst All India Rainfall is slightly increased. Results from a parallel ensemble with observed SSTs show an opposite response in All India Rainfall, suggesting that the forcing by SST anomalies is potentially dominating the monsoon's interannual variability.

The results have demonstrated that land surface conditions can have a significant impact on the large scale monsoon circulation and to a lesser extent on Indian Summer Monsoon rainfall, although the mechanisms involved have yet to be identified. It is suggested that interactions between the mid-latitude circulation and the monsoon may hold the key to understanding the link between Eurasian land surface conditions and monsoon variability. If that is the case then predictability of this relationship is likely to be limited, due to the high level of internal variability of the mid-latitude circulation.

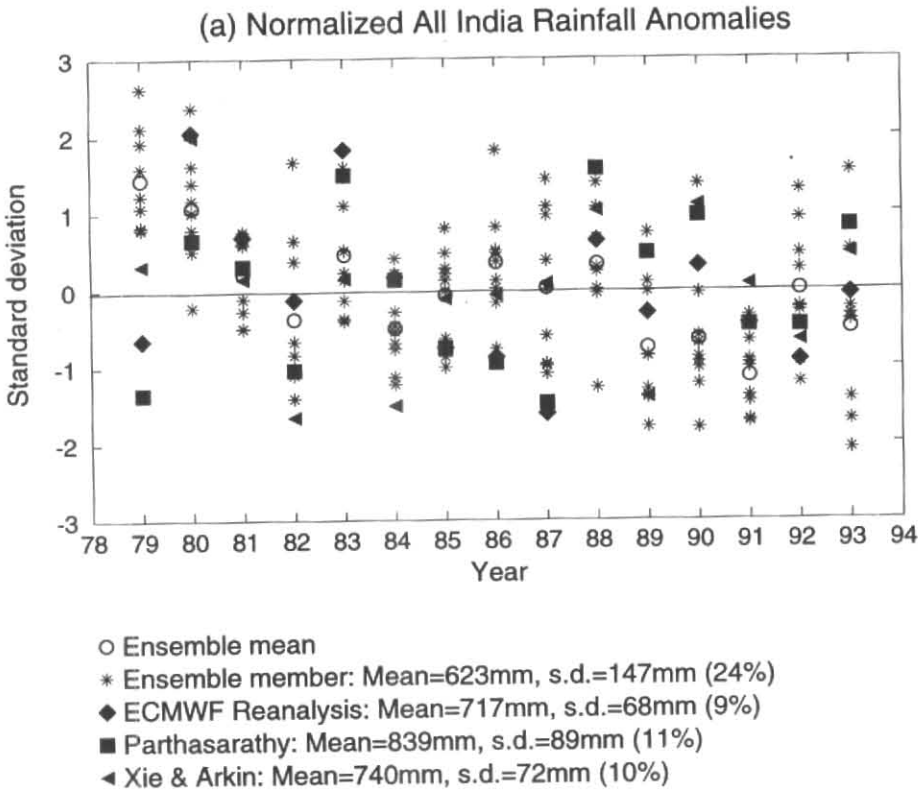
Key words – Indian summer monsoon, Eurasian snow cover, Predictability, Land surface processes.

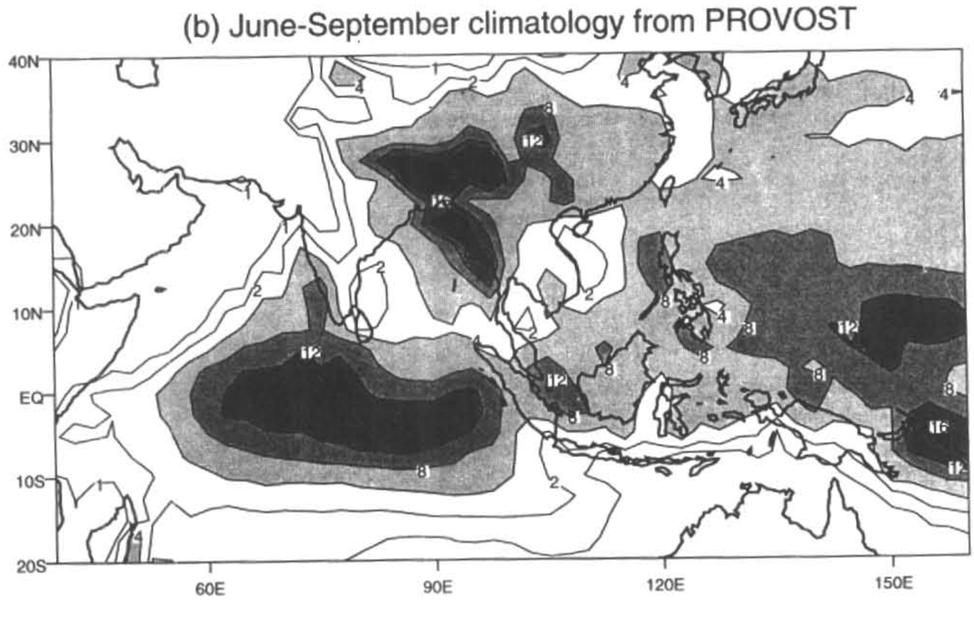
1. Introduction

The principal scientific basis for seasonal prediction is that lower boundary conditions, such as sea surface temperature (SST), are less chaotic and may therefore be, at least partially, predictable. Even though the atmosphere is chaotic, these lower boundary conditions can 'lend' predictability to the atmosphere. For over 120 years seasonal forecasting of Indian summer monsoon rainfall has been the goal of meteorologists. Currently, the Indian Meteorological Service relies upon statistical links among key variables around the globe for producing an official seasonal forecast (Krishna Kumar *et al.*, 1995). While statistical forecasts have been moderately successful, they are limited in that they do not provide details regarding the magnitude and spatial distribution of the prospective rainfall anomalies, nor can confidence bounds on the forecast be given. Using ensembles of simulations with numerical weather prediction models, dynamical seasonal prediction has the potential to provide probabilistic forecasts. Based on the dispersion of the ensemble members, it is possible to establish confidence thresholds on the forecast, and to gain some insight on the potential regionality of the rainfall anomalies and the likely incidence of extreme events. Dynamical seasonal forecasting of the Indian summer monsoon, if successful, would revolutionize the ability of governments and society to deal with the prospective impacts of a weak or strong monsoon.

To date, however, dynamical seasonal predictability of the Indian summer monsoon has not demonstrated a very high level of skill and is currently not as successful as the traditional statistical methods. Fig. 1(a) shows the seasonal All India Rainfall anomalies predicted by the ensembles of seasonal forecasts performed with the ECMWF model (Brankovic and Palmer 2000) as part of the EU Project on 'Prediction of Climate Variations on Seasonal to Interannual Timescales (PROVOST)'. These hindcast experiments used the observed SSTs and therefore could be considered as the best possible estimates of the current level of skill. In Figure 1(a), these hindcasts have been verified against various estimates of the observed anomalies. [For the Xie/Arkin climatology, the ECMWF reanalyzes, and the PROVOST data, only land points are used to compute the All India Rainfall for the domain 10°N-25°N, 70°E-95°E. The differing horizontal resolutions of the various datasets will mean that, effectively, the averaging has been done over slightly different areas. As noted by Annamalai *et al.* (1999), there are considerable discrepancies between these estimates from which they concluded that the rain gauge data of Parthasarathy *et al.* 1994, 1995 are still the most reliable for defining weak and strong monsoon years]. The PROVOST ensemble show considerable inter-ensemble and interannual variability in monsoon rainfall. Compared with the observed estimates, the model systematically underestimates the All India Rainfall, but overestimates the interannual standard deviation. In most years there is a large spread within the ensemble; those years where the spread is reduced (*e.g.*, 1981) are not necessarily years in which the boundary forcing by, for example, El Nino is strong. In several years the ensemble mean anomaly is of opposite sign to the observed signal, indicative of limited skill in the PROVOST simulations.

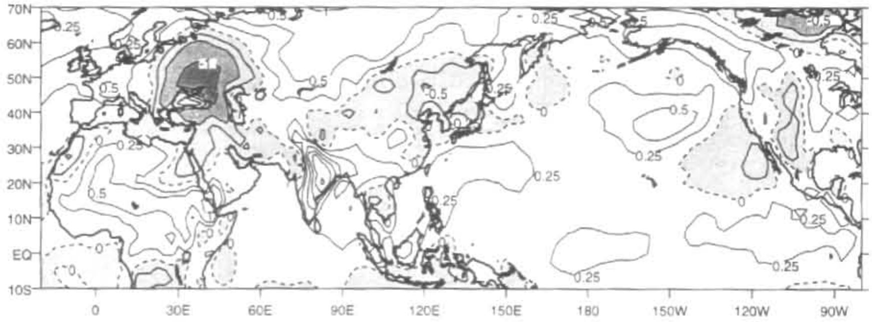
Two possible explanations for this lack of predictability have been postulated. The first is that model errors in the mean monsoon simulation are still substantial enough that the signal being sought is smaller than the systematic Dias. Fig. 1(b) shows the seasonal mean precipitation climatology from the PROVOST integrations



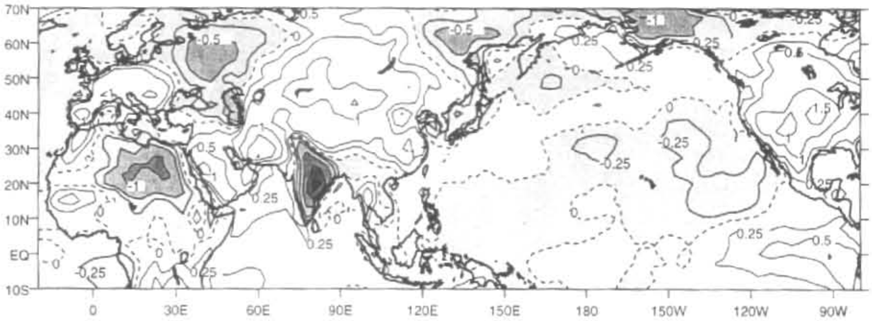


Figs. 1(a&b). (a) Standardized All India Rainfall anomalies for all ensemble members and all ensemble means over the summer season (June to September). Superposed are observations from Parthasarathy (1994, 1995), Xie-Arkin climatology (1996) and the ECMWF Reanalyses (ERA). (b) Seasonal mean (June to September) precipitation climatology (mm/day) from the PROVOST ensembles. Contours are drawn at 1, 2, 4 and every 4 mm/day thereafter, values in excess of 4 mm/day are shaded

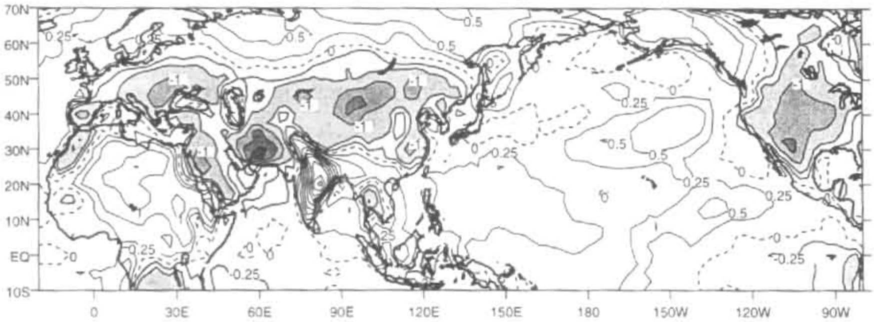
(a) Weak - Normal



(b) Strong - Normal



(c) Weak - Strong

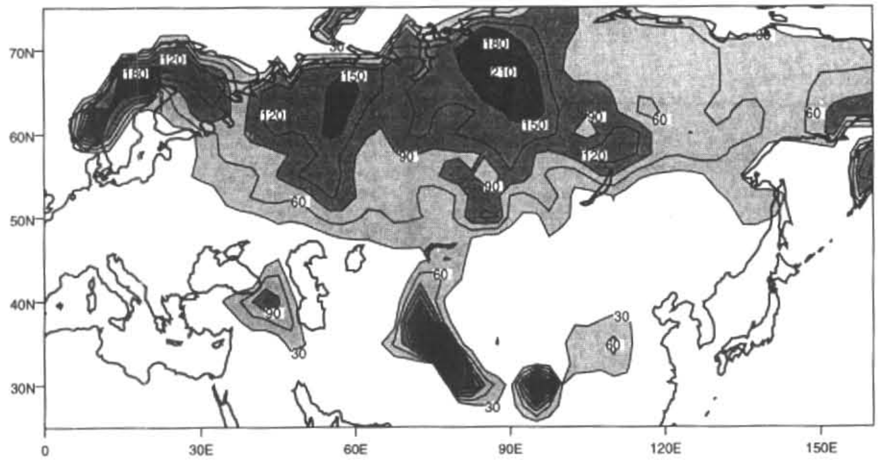


Figs. 2(a-c). Differrences in 2 metre temperature (K) for June-September between (a) strong vs. normal, (b) weak *vs*. normal and (c) weak *vs*. strong monsoon composites from the PROVOST ensembles. Contours are drawn at +/- 0.25 K and every 0.5 K thereafter, negative anomalies are shaded

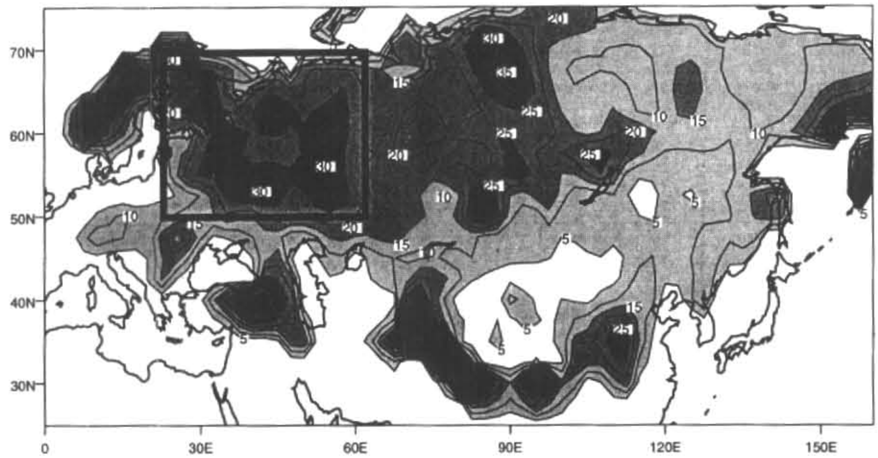
with the ECMWF model. Compared to the climatology of Xie and Arkin (1996) and the estimates from reanalyses (Annamalai *et al*. 1999; their Figure 3), the model substantially underestimates the rainfall over the Indian subcontinent and overestimates the precipitation over the equatorial Indian Ocean. This is a known systematic error of the ECMWF model (*e.g.*, Ferranti *et al*., 1997). Clearly these errors in the mean state of the model may affect its ability to provide skillful predictions for the Indian subcontinent.

The second possibility for the lack of skill is that, although the seasonal mean rainfall only varies by about 10%, subseasonal variations, associated with weather events and active/break cycles, can be large and may significantly affect the seasonal mean rainfall. If these subseasonal events are chaotic then they may limit the seasonal predictability. However, it has been suggested by, for example, Palmer (1994) and Webster *et al*. (1998) that slowly varying boundary conditions (*e.g*., SST) may predispose this chaotic subseasonal variability into preferred regimes, so lending predictability to the system on the seasonal time scale. This is an attractive idea but so far no observational evidence has been found to support this hypothesis (Sperber *et al*. 2000). Instead it seems likely that the low frequency boundary forcing

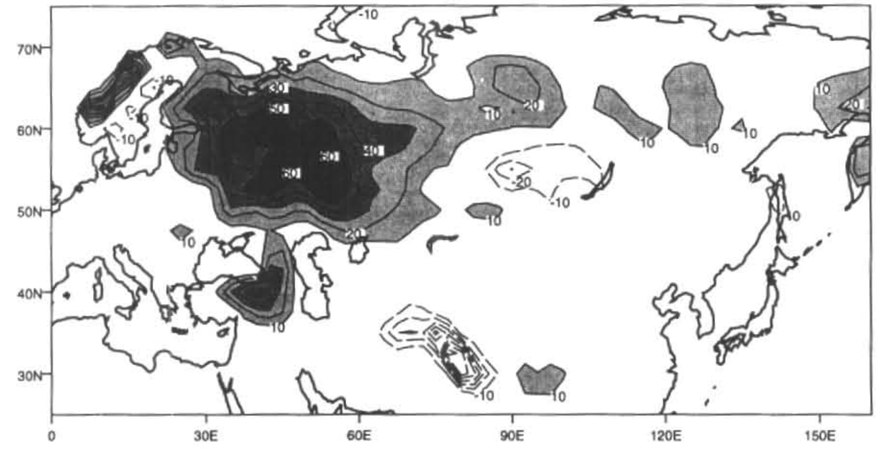
(a) Mean



(b) Standard deviation



(c) Difference: High - Low snow index



Figs. 3(a-c). (a) Ensemble mean and (b) standard deviation of March snow depth (cm) from PRISM-W. (c) Composite March snow depth anomalies (cm) for high versus low snow conditions based on the snow depth anomalies over western Eurasia in March from PRISM-W. The contour interval is 30 cm in (a) and 10 cm in (b) and (c); values in excess of 30 cm in (a) and 5 cm in (b) and (c) are shaded. Negative contours are dashed in (c) and no zero line is drawn predisposes the monsoon system towards a wet or dry state, as postulated by Charney and Shukla (1981); this suggests that predictability of the seasonal mean monsoon requires only that the effects of the slowly varying components of the climate system be correctly simulated. Thus, model improvements to reduce systematic errors in the mean simulation and in the model's response to low frequency boundary forcing may improve the prospects for dynamical seasonal prediction.

The oceans, with their much larger heat capacity, are generally considered to provide the long term memory of the climate system required for seasonal prediction. However, although a wide range of studies have confirmed the importance of tropical SSTs, particularly El Nino, (*e.g.*, Webster and Yang 1992; Ju and Slingo 1995), there is also evidence that the land surface conditions of the Eurasian continent may influence the monsoon (*e.g.*, Meehl 1994). Fig. 2 shows the anomalies in the 2 metre air temperature for composites of weak and strong monsoons from the PROVOST ensembles. Here strong/weak monsoons are defined in terms of All India Rainfall (AIR) anomalies exceeding ± 1 standard deviation (σ) as shown in Fig. 1(a). The strong/weak composites consist of 24/23 members. A set of normal monsoons, comprising 29 members, was constructed based on the criterion that the AIR anomalies differ by less than 0.25 σ from the mean. The 2 metre temperature is used as a proxy for the surface temperature which was not available from the PROVOST archive. The results show the expected response by the land surface of India in which drier (wetter) conditions in weak (strong) monsoon years are associated with warmer (cooler) temperatures. However, in the PROVOST ensembles the link between All India Rainfall and El Nino is rather tenuous with a suggestion that weak monsoons are associated with developing El Nino (Year 0, Webster and Yang 1992) and strong monsoons with mature El Nino (Year +1). The tendency for weak (strong) monsoons to occur in Year 0 (+1) of El Nino is also a feature of the observed behaviour (*e.g.*, Slingo and Annamalai, 2000).

The planetary scale anomalies in the land surface temperatures of Eurasia are a particularly striking aspect of Fig. 2. The results from the PROVOST ensembles suggest that weak and strong monsoons can be influenced by complex patterns in the boundary forcing in which the temperatures of the Eurasian continent appear to be an important factor. These land surface anomalies may be a consequence of anomalous snow amounts over Eurasia in the previous spring, which are generally considered to be instrumental in providing long term memory to the climate system (*e.g.*, Barnett *et al.* 1989). However, the links between the summertime land surface temperature anomalies, identified in Fig. 2, and the preconditioning factors in the preceding spring (such as snow amount) cannot be identified from the PROVOST integrations due to the experimental set up in which the integrations were initiated at the beginning of June. In response to these results a programme of seasonal ensemble experiments was developed to address, specifically, the role of the Eurasian land surface conditions, as distinct from SSTs, in influencing the predictability of the Indian summer monsoon. Known as PRISM (Predictability experiments for the Indian Summer Monsoon), the programme addresses two specific questions :

TABLE 1
Simulated All India rainfall

	Seasonal Mean (mm)	Standard Deviation (mm)	Standard Deviation as % of mean
PROVOST	623	147	24
PRISM-O	668	114	17
PRISM-C	686	80	12

(*i*) What factors (*e.g.*, SST forcing in winter) are important for establishing spring time land surface conditions over Eurasia, particularly snow amounts?

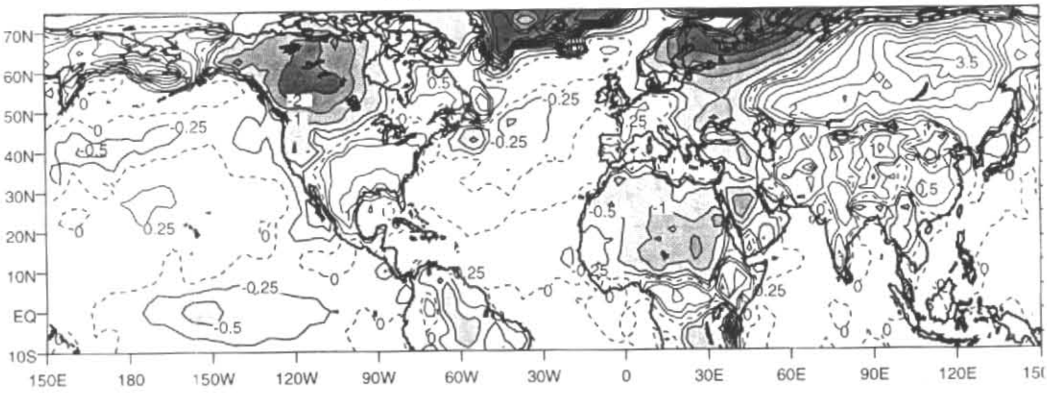
(*ii*) How do these land surface conditions influence the subsequent Indian summer monsoon and how important are they compared with SST forcing?

In this paper, the first question will be addressed briefly, but the main focus will be on the influence of Eurasian land surface conditions on the seasonal mean behaviour of the Indian summer monsoon. The experimental design of PRISM will be described in Section 2 and the results given in Section 3. Some tentative conclusions on the role of Eurasian land surface conditions in monsoon seasonal prediction will be given in Section 4.

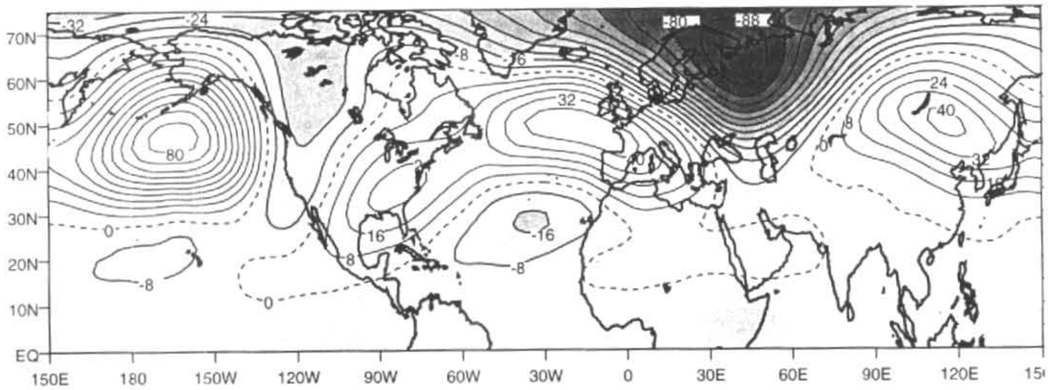
2. Experimental design

An ensemble of integrations is required to obtain a robust signal with regard to the impact of boundary forcing (*e.g.*, SST anomalies) on the seasonal time scale, where the size of the ensemble depends on the signal to noise ratio. For the Indian summer monsoon, the results of Brankovic and Palmer (1997) suggested that an

(a) Surface Temperature



(b) 500hPa Height



Figs. 4(a&b). Composite differences in (a) surface temperture (K) and (b) 500 hPa geopotential height (m) for January-March based on high versus low snow conditions using the snow depth anomalies over western Eurasia in March from PRISM-W. In (a), contours are drawn at +/- 0.25K and every 0.5K thereafter; negative anomalies are shaded. In (b), the contour interval is 8m and negative values are shaded

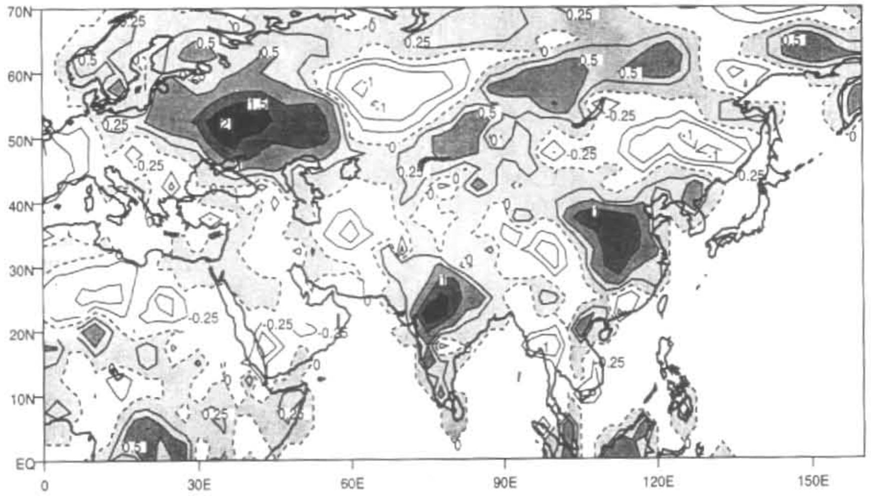
ensemble size of around 10 would be needed. Consequently three ensembles of integrations, each with 10 members, were set up as follows :

PRISM-W :	6 month integrations from 1-10 November to 1-10 April; observed SST's; initial conditions (atmosphere and land surface) from ECMWF Reanalyses (Gibson *et al.*, 1996, 1997).
PRISM-C :	6 month integrations from 1-10 April to 1-10 November; climatological SSTs; initial conditions (atmosphere and land surface) from PRISM-W ensemble.
PRISM-O :	6 month integrations form 1-10 April to 1-10 November; observed SST's; initial conditions (atmosphere and land surface) from PRISM-W ensemble.

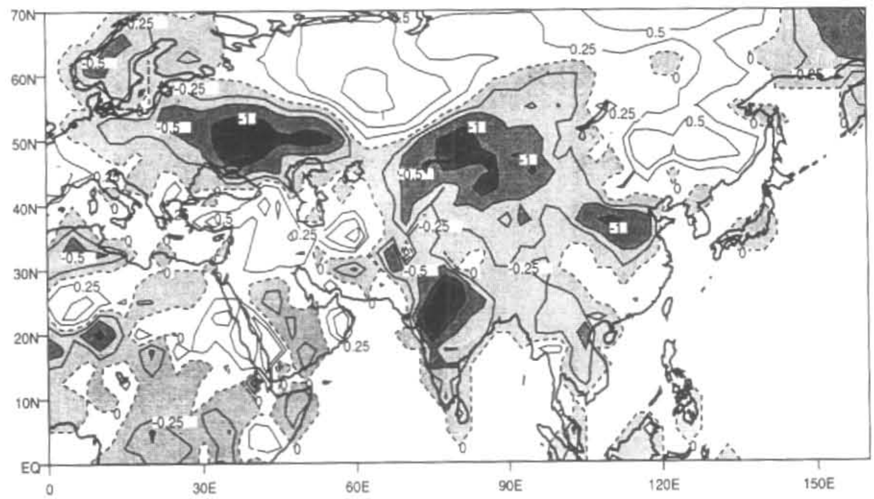
These ensembles were integrated for 8 different years (1982/83, 83/84, 84/85, 86/87, 87/88, 88/89, 91/92), chosen to cover a range of different phases of El Nino/La Nina. The PRISM-W ensemble was designed to provide a set of initial states at the end of March in which the land surface is in balance with the atmosphere and which reflects the range of possible states that might occur for the particular SST forcing during the preceding winter. It also enables the question of the relationship between Eurasian land surface conditions and SST forcing during winter to be addressed.

The range of land surface conditions generated by PRISM-W is used to initialize the two sets of summer ensembles. The results from PRISM-C, in which the interannual variability of the SSTs is suppressed, will enable the influence of land surface conditions on the monsoon to be detected in isolation from the effects of SST forcing. Comparison of PRISM-O with PRISM-C

(a) Soil wetness



(b) Surface temperature



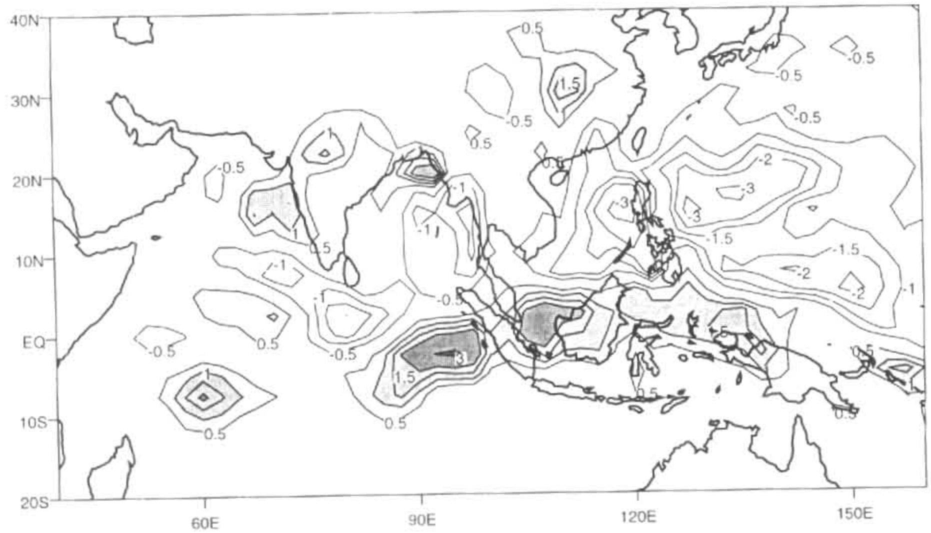
Figs. 5(a&b). Composite differences in (a) soil wetness (mm) and (b) surface temperature (K) for June-September from the PRISM-C integrations (climatological SSTs) for high versus low snow conditions based on the snow depth anomalies over western Eurasia in March. In (a) and (b), the contour interval is 0.5 with additional contours at +/- 0.25. Positive values are shaded in (a) and negative values in (b)

will then show how observed SSTs influence monsoon variability relative to the effect of land surface conditions.

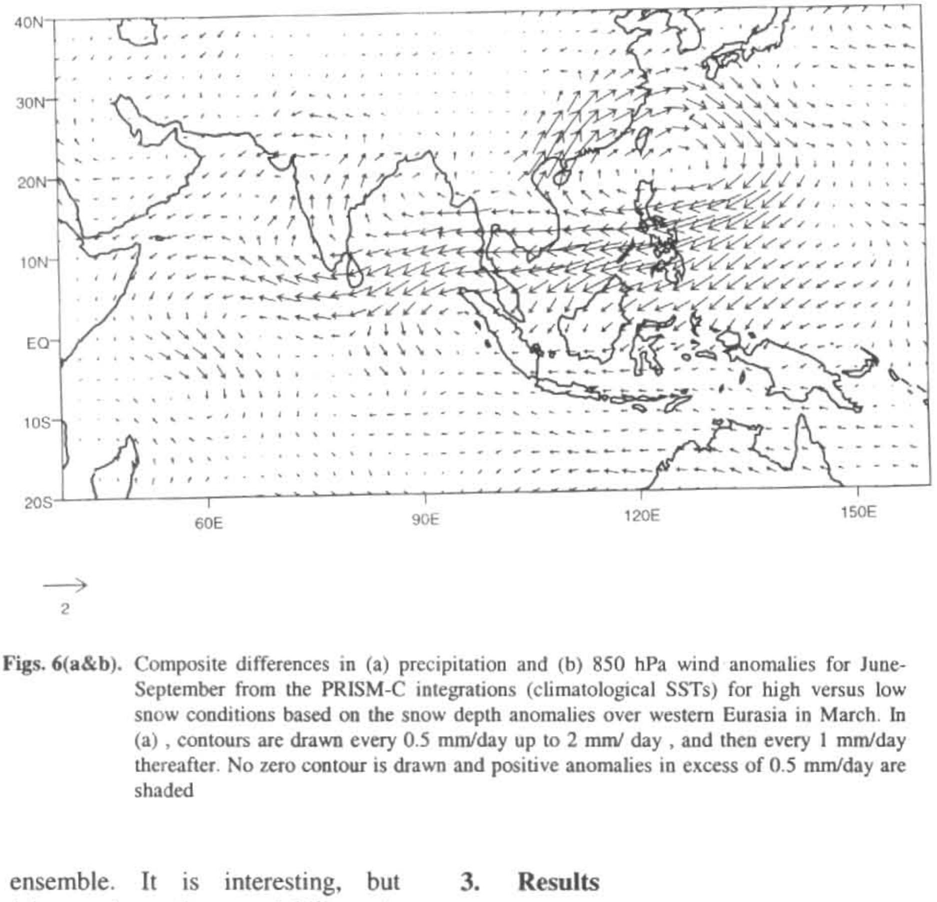
All the integrations were performed with the ECMWF Integrated Forecast System (IFS) model at a horizontal resolution of triangular truncation T63 (equivalent to 1.875°), and with 31 vertical levels. The model version, Cy16r2, operational in the latter half of 1997, was used for these experiments (Ritchie *et al.* 1995).

Although the PRISM experiments were run with a more recent version of the ECMWF model than that used for PROVOST, the basic simulation is very similar. The systematic errors remain generally unchanged (not shown), with excessive precipitation persisting over the equatorial Indian Ocean. Over the Indian subcontinent there has been a slight improvement compared with Fig. 1(b), with a decrease in rainfall along the foothills of the Himalayas and a slight increase over the central plains of India. The ensemble mean and standard deviation of the all India Rainfall from the PROVOST, PRISM-O and PRISM-C ensembles are given in Table 1. Although the seasonal mean rainfall remains substantially underestimated, the level of variability is much improved

(a) Precipitation



(b) 850hPa winds



Figs. 6(a&b). Composite differences in (a) precipitation and (b) 850 hPa wind anomalies for June-September from the PRISM-C integrations (climatological SSTs) for high versus low snow conditions based on the snow depth anomalies over western Eurasia in March. In (a) , contours are drawn every 0.5 mm/day up to 2 mm/ day , and then every 1 mm/day thereafter. No zero contour is drawn and positive anomalies in excess of 0.5 mm/day are shaded

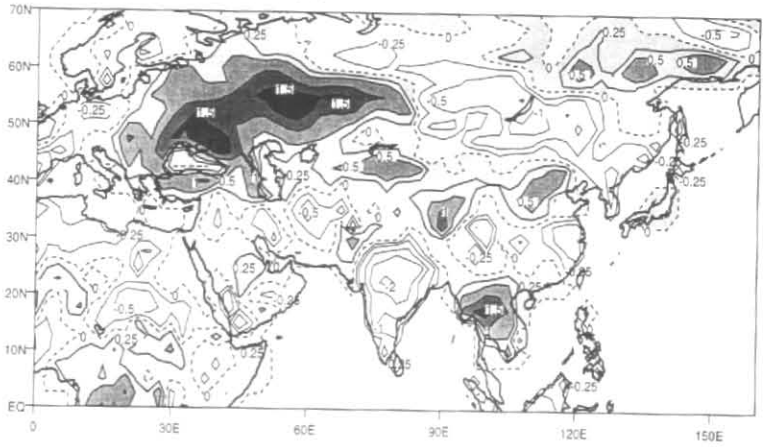
in the PRISM-O ensemble. It is interesting, but perhaps not surprising, that the variability is considerably lower in PRISM-C than in PRISM-O, suggesting that interannual variations in the observed SSTs have an impact on the degree to which the monsoon rains vary within the ensemble and from year to year.

3. Results

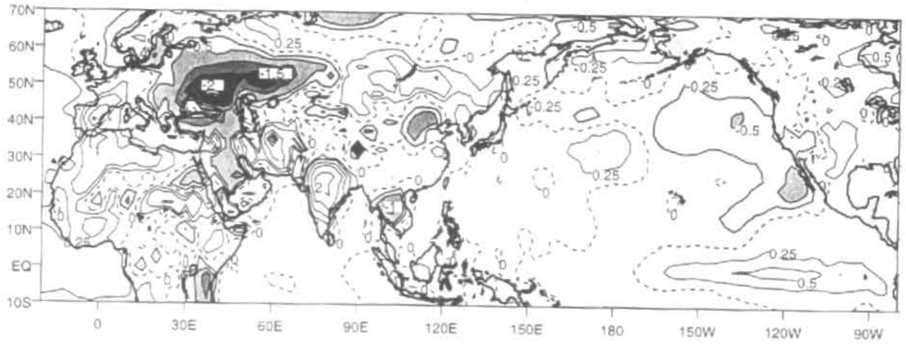
3.1. *Eurasian snow anomalies in March : Results from PRISM-W*

It is generally considered that anomalous springtime snow amounts over Eurasia are instrumental in providing

(a) Soil wetness



(b) Surface temperature



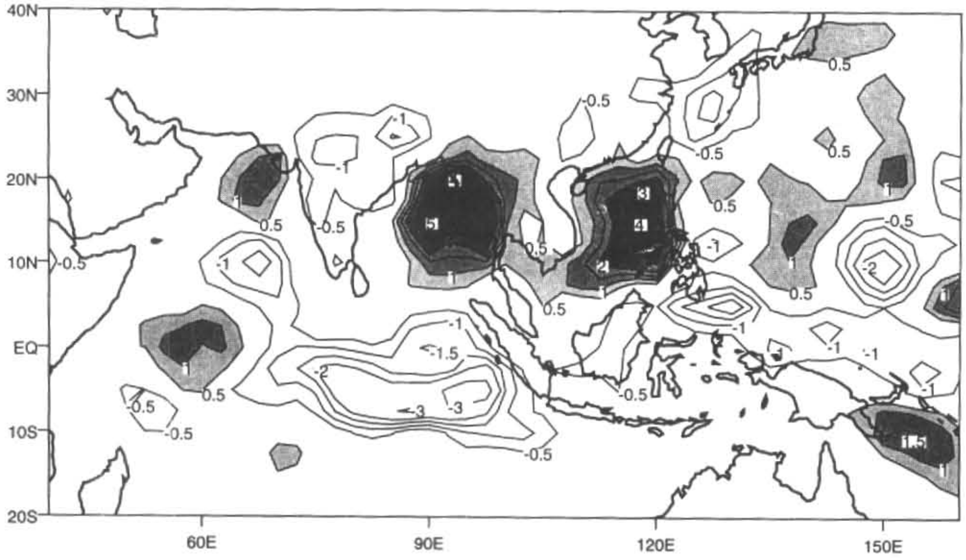
Figs. 7(a&b). Composite differences in (a) soil wetness (mm) and (b) surface temperature (K) for June-September from the PRISM-O integrations (observed SSTs) for high versus low snow conditions based on the snow depth anomalies over western Eurasia in March. Contours and shading as in Figure 5

long term memory to the climate system (*e.g.*, Barnett *et al.* 1989). Greater Eurasian snow affects the degree and timing of the summer continental warming in two ways. Firstly, the higher albedo reflects more solar radiation thus reducing the amount of energy available to warm the landsurface. Secondly, even after the snow has melted, the increased soil moisture means that more solar energy is used to evaporate the soil moisture rather than warming the land surface. As noted by Li and Yanai (1996), it is the sensible heating over land in spring that leads to a reversal in the meridional temperature gradient which drives the monsoon circulation. It follows therefore that sensible heat source may contribute to changes in the strength of the monsoon. So a heavier snow pack, which may reduce the land-ocean temperature differential, could delay the onset and weaken the monsoon. Conversely, less Eurasian snow may lead to a stronger monsoon.

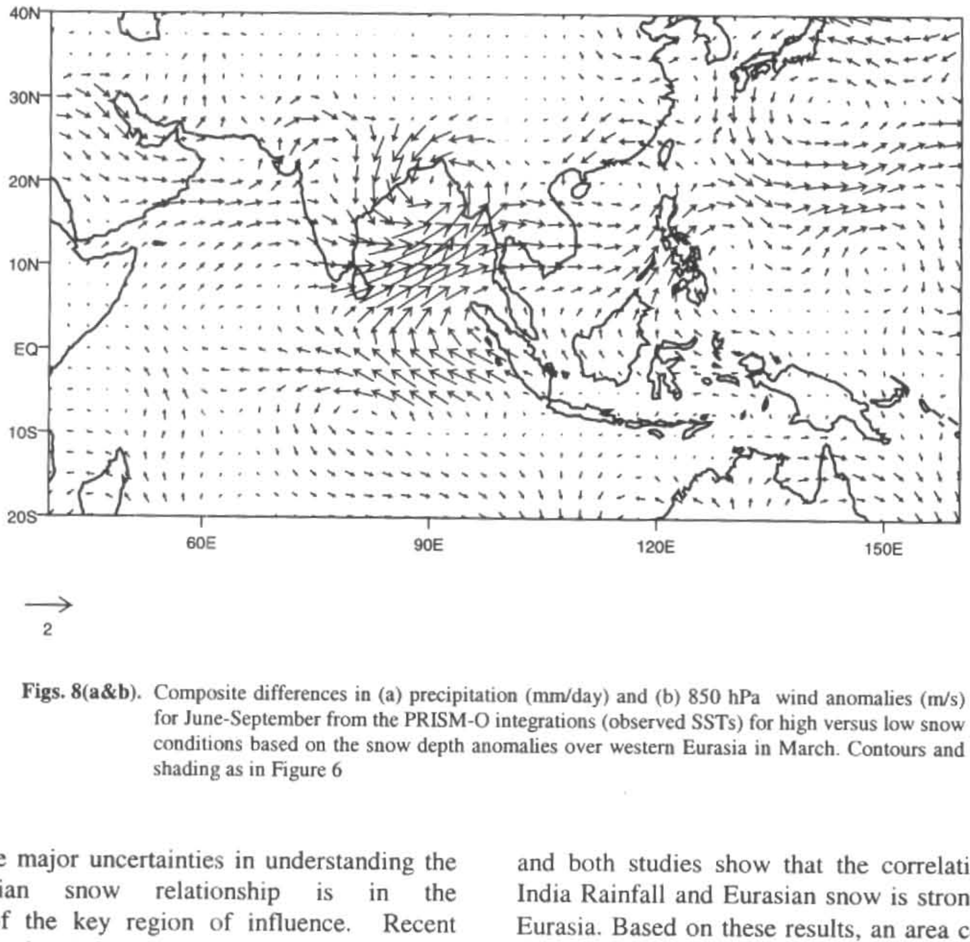
Fig. 3 (a) shows the March snow depth climatology from the PRISM-W integrations. The distribution is very similar to that given in Kripalani and Kulkarni (1999) based on the historical Soviet daily snow depth data. The simulated snow depths are generally higher than those given by Kripalani and Kulkarni (1999), but the model values are based on a snow density in which 1 cm of snow is equivalent to 1 mm of water. It is quite likely that for old snow, possibly more typical for March, the density is higher, thus giving smaller depths for the same water equivalent. Clearly, without knowing the observed snow density it is not possible to make a quantitative comparison of the simulated and observed values.

The variation of snow depths within the ensemble and between years from PRISM-W is shown in Fig. 3(b). Again there is reasonable agreement with the pattern of variability given in Kripalani and Kulkarni (1999), although the level of variability appears to be slightly lower in the model than observations, when normalized by the mean snow depth.

(a) Precipitation



(b) 850hPa winds



Figs. 8(a&b). Composite differences in (a) precipitation (mm/day) and (b) 850 hPa wind anomalies (m/s) for June-September from the PRISM-O integrations (observed SSTs) for high versus low snow conditions based on the snow depth anomalies over western Eurasia in March. Contours and shading as in Figure 6

One of the major uncertainties in understanding the monsoon-Eurasian snow relationship is in the identification of the key region of influence. Recent studies by Bamzai and Shukla (1999) and Kripalani and Kulkarni (1999) have emphasized the east-west character of the anomalous snow conditions over Eurasia, and both studies show that the correlation between All India Rainfall and Eurasian snow is strongest for western Eurasia. Based on these results, an area covering 50° N - 70° N and 20° E - 60° E [see box on Fig. 3(b)] was chosen to define a snow index against which to investigate the relationship between monsoon activity and Eurasian snow.

This area also encompasses the region of maximum variability over western Eurasia in the PRISM-W integrations.

Using this index, composites of high/low snow cases from PRISM-W have been constructed based on the snow depth anomaly exceeding ± 1 standard deviation. This gives 14 members in each category. Fig. 3(c) shows the difference in snow depth between high and low snow indices. The change in snow depth is substantial, particularly south of 60°N. In agreement with the results of Bamzai and Shukla (1999) and Kripalani and Kulkarni (1999), an east-west dipole in the snow depth anomalies is simulated by the model.

One of the aims of PRISM is to investigate the factors that influence Eurasian snow anomalies and hence their predictability. Fig. 4 shows the surface temperature and 500 hPa height anomalies for high versus low snow cases for the 3 month mean, January-March. The surface temperature anomalies[Fig. 4(a)] show coherent, large scale patterns which, over Eurasia, are consistent with the east-west structure of the snow anomalies [Fig. 3(c)]. There is also a clear indication that high snow amounts over western Eurasia are linked to La Nina, suggesting that the El Nino/Southern Oscillation (ENSO) has an influence on the wintertime climate of Eurasia.

The 500 hPa height anomalies[Fig. 4(b)] also show the signature of ENSO, with the characteristic Pacific North American (PNA) pattern. Over Eurasia, the pronounced trough-ridge pattern is consistent with the snow anomalies, with advection of cold air on the western side of the trough and warm air on the eastern side. These circulation changes are in agreement with those given in Bamzai and Shukla (1999) and Kripalani and Kulkarni (1999) for high snow cover/amounts over western Eurasia. The potential influence of ENSO is further supported by the anticyclonic anomalies over the North Atlantic. This pattern of anomalies was prevalent during the La Nina winter of 1998/99 and has been shown to be highly predictable in an ensemble of seasonal forecasts (Dong *et al.*,2000). It is notable that snow cover was above normal over the region 50°N - 60°N, 25°E - 40°E in March 1999 (Climate Diagnostics Bulletin, NOAA 1999).

Meehl (1997) suggested that Eurasian snow anomalies may be a manifestation of changes in the large scale, midlatitude circulation, possibly driven by ENSO. The results from PRISM-W give weight to the hypothesis that Eurasian land surface anomalies, particularly snow amounts, may be linked to ENSO and hence may be potentially predictable. Using the PROVOST integrations for northern winter (December - March), Corti *et al.*, (2000) also found a significant relationship between Eurasian snow depth anomalies and ENSO, and noted that the circulation regimes associated with the dominant mode of variability in Eurasian snow showed a high level of predictability.

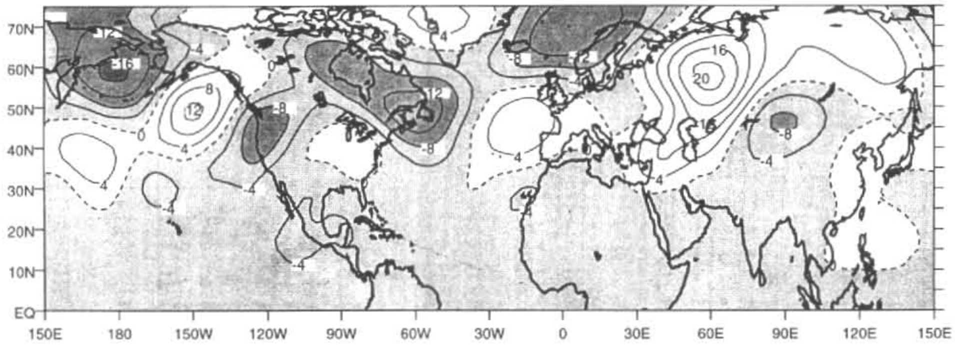
3.2. *Influence of Eurasian land surface conditions on monsoon variability*

The design of the PRISM-C experiments, in which climatological SSTs are used, should enable the effect on monsoon variability of persistent anomalies in Eurasian land surface conditions to be detected. It is assumed here that these persistent anomalies are set up during the preceding winter and spring, and are primarily associated with snow which influences the energy and moisture budget of the land surface over relatively long time scales. As discussed in Section 3.1, snow depth anomalies over western Eurasia have been linked to Indian summer monsoon rainfall in other studies (Bamzai and Shukla, 1999; Kripalani and Kulkarni, 1999) and will be the focus of discussion here.

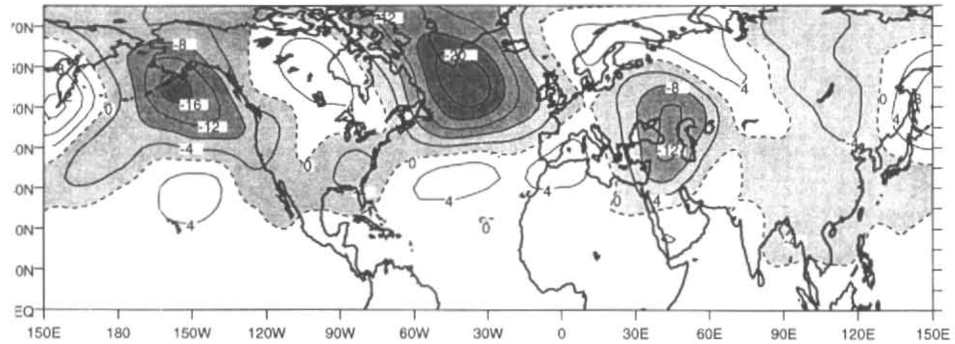
If snow depth anomalies in spring are able to influence the monsoon, then the signature of these anomalies must be carried through to the summer in the land surface conditions (*e.g.* soil wetness, temperature). Fig. 5 shows the soil wetness and surface temperature anomalies for June to September from PRISM-C, for the composites based on high *versus* low snow amounts in March over western Eurasia [Fig. 3(c)]. Here the soil wetness refers to the top layer (7 cm) of the soil, as defined in the land surface parameterization used in the ECMWF model (Viterbo and Belijaars 1995). The difference in soil wetness between the high and low snow composites exceeds 2 mm over western Eurasia in the region where the snow anomalies in March are large [Fig. 3(c)], in excess of 6 mm water equivalent. Wetter soil is associated with cooler surface temperatures since more of the incoming solar radiation is used for evaporation than for heating the soil; the close correspondence between the patterns of soil wetness and surface temperature anomalies is evident in Fig. 5.

With the diagnostics available from the PRISM integrations, it has not been possible to do a complete budget of the soil hydrology, nor to show unequivocally that the western Eurasian land surface anomalies in summer are directly related to differences in springtime snow amounts. It could be argued, due to the planetary scale nature of the anomaly patterns in Fig. 5, that they are simply a reflection of differences in the midlatitude circulation during the summer. However, it

(a) PRISM-C



(b) PRISM-O



Figs. 9(a&b). Composite differences in 500 hPa height anomalies (m) from (a) PRISM-C and (b) PRISM-O integrations for June-September from high versus low snow conditions based on the snow depth anomalies over western Eurasia in March. Contour interval is 4 m and negative values are shaded

will be shown later that these soil wetness and surface temperature anomalies in western Eurasia are also reproduced in the PRISM-O ensembles and coexist with very different midlatitude circulation regimes. This suggests that they are a signature of the snow anomalies in March which has been carried through into the summer season.

The impact of these anomalous land surface conditions on the Indian summer monsoon is shown in Fig. 6, where the seasonal mean (June-September) differences in precipitation and 850 hPa winds for high versus low snow amounts in March have been plotted. On the large scale, the results suggest that the Asian Summer Monsoon is weakened in association with above normal snow amounts over western Eurasia. The pattern of anomalies is very similar to the dominant mode of interannual variability for the Asian Summer Monsoon found in the ECMWF Reanalyses (Annamalai *et al.*, 1999) and in the ECMWF model, as identified by Ferranti *et al.* (1997). This mode basically describes a latitudinal shift in the Tropical Convergence Zone (TCZ) over the west Pacific and SE Asia. In association with this southwards movement of the TCZ, the monsoon westerlies are generally weaker than normal whilst the development of anticyclonic flow over the north west Pacific brings southerly winds and enhanced rainfall into China. Although on the large scale the monsoon is weaker than normal, over the Indian subcontinent itself, rainfall is increased, associated with enhanced southerly flow from the warm ocean and an anomalous cyclonic circulation over north west India. The change in All India Rainfall between the high and low snow composites is +43 mm, less than one standard deviation and therefore not a significant anomaly. This lack of correspondence between the strength of the monsoon circulation and All India Rainfall is well known (*e.g.* Ju and Slingo 1995; Wang and Fan 1999).

The results shown in Fig. 6 suggest that Eurasian snow anomalies in the spring preceding the monsoon can have an effect on the monsoon circulation and to a lesser extent on All India Rainfall. The weakening of the large scale monsoon circulation shown in Fig. 6(b) is, in simple terms, consistent with the continental scale cold surface temperature anomalies seen in Fig. 5(b) and hence a weakening of the land-sea temperature contrast and the meridional temperature gradient. However, for the Indian subcontinent, the sign of the relationship (above normal snow with enhanced rainfall) is opposite to that suggested by Bamzai and Shukla (1999) and by Kripalani and Kulkarni (1999) based on observed data. In a sensitivity experiment with a GCM, Bamzai and Marx (1999) also showed an opposite signal to that obtained in this paper; however, they used a different region for defining the snow anomaly, which extended across central Asia rather than focusing on western Eurasia. In all these studies, the effect of interannually varying observed SSTs are an integral part of the response, whereas in PRISM-C this is not the case.

To ascertain how much interannually varying SSTs affect the perceived relationship between Eurasian snow and monsoon variability, the results from PRISM-O have been analyzed in a similar manner. As for PRISM-C, composites of high and low snow cases have been constructed based on the snow depth anomalies over western Eurasia in March. Thus, the composites from PRISM-O have been constructed from sets of integrations which start with the same initial atmospheric and land surface conditions as used in PRISM-C, but which diverge due to the introduction of observed rather than climatological SSTs.

As for PRISM-C, the results from PRISM-O show that the signature of the springtime snow anomalies is carried through to the summer in terms of soil wetness and surface temperature anomalies (Fig. 7). Since PRISM-O used observed SSTs for each year, there are also surface temperature anomalies over the oceans for the high versus low snow cases. Fig. 7(b) shows that above normal snow amounts in spring over western Eurasia are coincident with El Nino conditions in the East Pacific in summer. This means that the response of the Indian summer monsoon to anomalous land surface conditions in the PRISM-O integrations is likely to be modified by the presence of ENSO forcing.

Fig. 8 shows the seasonal mean (June-September) differences in precipitation and 850 hPa winds for the PRISM-O composites based on high versus low snow amounts in March. In comparison with the results from PRISM-C (Fig. 6), the response of the monsoon to western Eurasian snow anomalies is substantially different. On the large scale, the monsoon circulation is strengthened and the rainfall over much of SE Asia is enhanced. The wind anomalies shown in Fig. 8(b) suggest a more complex regional response than was obtained with PRISM-C and the pattern of neither the precipitation nor the circulation anomalies resemble any of the dominant modes of monsoon interannual variability identified from reanalyzes (Annamalai *et al.* 1999, Sperber *et al.* 1999).

However, over the Indian subcontinent the precipitation is reduced, the All-India Rainfall difference between the high and low snow composites being 44 mm. Thus, in the PRISM-O integrations, the sign of the relationship (above normal Eurasian snow amounts with reduced rainfall) is now in agreement with observations (Bamzai and Shukla, 1999; Kripalani and Kulkarni, 1999). This suggests that SST variability may play an important part in modulating the relationship between monsoon variability and anomalies in Eurasian snow and land surface conditions. El Nino is known to predispose the Indian summer monsoon towards below normal rainfall (*e.g.*, Rasmusson and Carpenter 1983), and the results from PRISM-O (not shown) confirm that the model has successfully captured this link. As Fig. 7(b) shows, high snow cases tend to be coincident with El Nino conditions in the model so that the reduction in All India rainfall seen Fig. 8 could be as much a response to SST forcing as to anomalous land surface conditions.

4. Discussion and Conclusions

The results from the PRISM-C ensemble have demonstrated that land surface conditions can have a significant impact on the large scale monsoon circulation and to a lesser extent on Indian Summer Monsoon rainfall, although the mechanisms involved have yet to be identified. The location of the snow anomaly [Fig. 3(c)] and the resultant soil wetness and surface temperature anomalies (Figs. 5 & 7) make it unlikely that the mechanism involves simply a change in the land-sea temperature contrast, as has been suggested by earlier studies (*e.g.*, Dickson 1984) where the focus was on Himalayan or southern Eurasian snow cover. Also, the complex regional characteristics of the monsoon's response suggest that such a simplistic explanation is unlikely.

Comparison of the results from the PRISM-C and PRISM-O ensembles has enabled some conclusions to be drawn about the relative impacts of land surface conditions and SST anomalies on monsoon variability. The results from PRISM-C show that land surface anomalies, associated with spring snow amounts, can influence the monsoon. Therefore land surface conditions are an important part of the system which need to be predicted accurately. The mechanisms involved in the relationship between the monsoon and Eurasian land surface conditions are as yet unclear. However, the fact that the observed relationship between Eurasian snow and monsoon rainfall is opposite to that suggested by PRISM-C, and is then only correctly captured by the introduction of observed SSTs in PRISM-O, suggests that the forcing by SST anomalies is potentially dominating the monsoon's interannual variability. If that is the case then it may be difficult to unravel the processes involved in the relationship between land surface conditions and monsoon variability using observations.

A possible link between Eurasian land surface conditions and monsoon variability may lie in the response of the mid-latitude flow and its interactions with the monsoon circulation. It is well known that the monsoon is not isolated from the extratropics and that considerable interactions take place on a range of space and time scales. For example, in 1997 the northern part of the Indian monsoon was substantially affected by midlatitude westerly disturbances, particularly during June (Bell and Halpert, 1998). A series of large scale midlatitude troughs penetrated the upper troposphere over northern India giving rise to prolonged periods of cyclonic vorticity and enhanced activity along the monsoon trough. Dethof *et al.* (1999) have also demonstrated that interactions can occur between mid-latitude tropospheric cyclones and the upper-level monsoon anticyclone in which the anticyclone is substantially disrupted on synoptic time scales.

Fig. 9 shows the seasonal mean (June-September) anomalous 500 hPa height fields from the PRISM-C and PRISM-O composites based on high versus low March snow amounts. There is little correspondence between the two fields. This suggests that the anomalous land surface conditions over western Eurasia do not strongly influence the mid-latitude circulation, although in PRISM-C the ridge near 60° E and the downstream trough are correctly phase locked with the Eurasian soil wetness and surface temperature patterns shown in Fig. 5. In PRISM-C, the trough near 90° E may be conducive to greater penetration of mid-latitude cyclones into the upper troposphere over northern India, possibly contributing to the enhanced precipitation and cyclonic anomalies shown in Fig. 6.

In PRISM-O [Fig. 9(b)], the height anomalies over the Pacific/North American sector are consistent with El Nino forcing (PNA+ pattern). It is possible that any phaselocking of the midlatitude circulation with Eurasian land surface anomalies is disrupted in PRISM-O by upstream Rossby waves generated by El Nino forcing over the Pacific. This discussion must, however, be seen in the context of the chaotic nature of the mid-latitude circulation. If interactions with the extratropics hold the key to understanding the link between Eurasian land surface conditions and monsoon variability, then predictability of this relationship is likely to be limited. The hypothesis that the boundary forcing (either from SSTs or land surface conditions) may systematically alter the statistics of interactions between the monsoon and the extratropics needs to be tested using high frequency data and will be a future focus of research.

The results presented in this paper are by no means conclusive, but clearly support the need for further research into the role of land surface conditions in the seasonal predictability of the monsoon. The mechanisms involved in the relationship between Eurasian snow and monsoon variability remain elusive, but it is evident from the results described here that much can be learned through carefully designed sensitivity experiments. The application of ensemble techniques, as used in seasonal prediction, were found to be particularly appropriate. A major limiting factor of this study has been the quality of the basic monsoon simulation. There are still substantial errors, particularly on the regional scale, which means that focusing on All India rainfall, for example, may not provide a good measure of monsoon variability in the model. It is clear that this research needs to be revisited in the future with revised model versions and possibly with other models also. Although dynamical methods currently suggest that the potential predictability of the monsoon system is limited, this should be continually reassessed as models improve.

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