

Characteristics of Eurasian snow depth with respect to Indian summer monsoon rainfall

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Abstract Earlier studies show a strong negative relationship between Eurasian snow cover/depth and Indian summer monsoon rainfall (ISMR). In such studies, both the parameters snow and rainfall are seasonally averaged over large areas. Indian summer monsoon has its own characteristics of evolution such as onset, active, break and withdrawal phases which have been studied extensively. However, the evolution of Eurasian snow is yet to be examined. Further, it is interesting to explore the characteristics of evolution of snow over the different regions of Eurasia and their relationship with the evolution characteristics of summer monsoon. In this paper, a detailed examination has been done on the starting and the ending dates of snowfall over different regions of Eurasia and attempts have been made to explore any relationship with onset of ISMR. It is observed that the regions where snowfall started early, it also ended late. Further, in those regions maximum snow depth also occurred late. In some years, more snowfall in East Eurasia is followed by less snowfall in West Eurasia. Also snow depths particularly in the northernmost and southwest regions of East Eurasia are opposite in phase. The results of this study indicate a weak relationship between snow starting dates in Eurasia and summer monsoon onset dates in the Kerala coast. However, the relationship between the northernmost Eurasian snow

depth and the summer monsoon precipitation in the Peninsular India is significant.

1 Introduction

South Asian monsoon is expected to be driven by seasonal variations in land–sea temperature contrast between Asian landmass and adjacent ocean. Next to the sea surface temperature (SST), snow cover/depth is the most important surface condition to affect the Indian summer monsoon rainfall (ISMR). However, the accurate measurements of snow cover and depth are the critical issues so far as their use in forecasting is concerned. Along with the temperature of snow surface, sensible heat flux and latent heat flux are the important factors that define surface energy balance. Albedo and related sensible heat flux are associated with snow cover while snow depth significantly affects both sensible and latent heat flux. There is weakening of sensible heat flux due to high albedo from large areal extent of snow cover that leads to reflect more solar radiation while moisture content of soil from snow melt utilises some amount of solar energy in evaporation (latent heat flux) process. Thus, when there is more snow cover/depth, relatively a small part of solar energy is utilised in heating continental landmass during summer prior to monsoon. The sensible heat flux at the higher altitude like in the case of the Tibetan Plateau is one of the important factors in land–sea heating contrast. It is further enhanced due to the latent heat released in the troposphere. Excessive snowfall during the winter delays melting of snow in spring and consequently furthers delay in buildup of land–sea temperature contrast which drives the monsoon.

Long back Blanford (1884) based on the study of weather reports suggested negative influence of Himalayan

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snow on the summer monsoon of India and Burma. Zwiers (1993) and Vernekar et al. (1995) using global climate models and Dash et al. (2006a) using regional climate model RegCM3 demonstrated the negative influence of Tibetan snow depth in spring on the next summer monsoon rainfall. Luo and Yanai (1984), He et al. (1987) and Murakami (1987) summarised that the high elevated Tibetan Plateau acts as a heat source in summer and heat sink in winter, in addition to its acting as a mechanical barrier that affects flow pattern around it. Further, in summer a temperature gradient develops in the upper troposphere between Tibetan Plateau and equatorial Pacific which is further associated with the onset of South Asian summer monsoon (He et al. 1987; Li and Yanai 1996; Shaman and Tziperman 2005; Yanai and Wu 2006). Zhang et al. (2004) observed interdecadal increase in spring snow depth in Tibetan Plateau after late 1970s in his study of the period 1962–1993. This excessive snowfall is concurrent with excessive precipitation over northern India, northwestern China and Western Asia and with drought over Central Asia during March–April. The increase of the snow depth is also related to the excessive summer rainfall over the Yangtze River valley and the drought conditions in southeastern and northeastern China and the Indochina peninsula.

The negative relationship between Tibetan snow and ISMR has been extended to that between Eurasian snow cover/depth and ISMR. Studies of Hahn and Shukla (1976), Dey and Bhanu Kumar (1982), Dickson (1984), Barnett et al. (1989) and Sankar-Rao et al. (1998) based on observational data have inferred the negative relationship between Eurasian snow cover and ISMR. Bamzai and Shukla (1999) and Kripalani and Kulkarni (1999) reexamined the relationship and found significant inverse correlation for West Eurasian region while positive correlation for East Eurasian region. Using Historical Soviet Daily Snow Depth (HSDSD) version-1 dataset, Kripalani and Kulkarni (1999) studied the monthly climatology and variability of snow depth and its interaction with ISMR. Instead of taking Eurasia as whole as in earlier studies, they converted the monthly snow depth data for 284 stations into 70 uniform blocks and correlated it with ISMR time series. Whereas Bamzai and Shukla (1999) using satellite-derived snow cover data for 22 years (1973–1994) studied the frequency of occurrence of snow at grid points over Eurasia and correlated December, January, February and March mean snow cover anomalies for four regions with the subsequent ISMR. Bamzai and Shukla (1999) after analyzing areal extent of snow concluded that winter and spring snow covers of southern Eurasia and the Himalayas have high interannual variability and are poorly correlated with the subsequent monsoon rainfall. Kripalani and Kulkarni (1999) conjectured the existence of a mid-latitude

long wave pattern with an anomalous ridge (trough) over the Eastern Siberia during the winter prior to a strong (weak) monsoon. They also identified reversal in correlations between pre-monsoon and post-monsoon months over West and East Eurasia. This reversal in correlation could be associated with mid-latitude circulation pattern and support the theory proposed by Meehl (1997) that monsoon plays an active part in the tropospheric biennial oscillation. Meehl (1997) further inferred that snow cover anomaly may be an artifact of the mid-latitude circulation pattern associated with convective heating anomalies, rather than an independent forcing. The physical mechanism behind the snow-monsoon relationship has also been examined by several other authors (Liu and Yanai 2002; Ueda et al. 2003; Yasunari 2006). A study by Liu and Yanai (2002) has examined the large scale mid-latitude circulation pattern associated with Eurasian snow cover/depth and Asian summer monsoon. They observed northerly wind anomaly during the high snow year leading to weaker monsoon over East Asia. During heavy spring snow cover in northwestern Eurasia, the cooling centre of the cyclonic anomaly in the lower troposphere leads to a Rossby-wave-train-like circulation response. That makes atmospheric disturbances to propagate from Europe to Asia. Another study by Ueda et al. (2003) based on northern Eurasia spring snow cover variations and its relation with atmospheric circulation mechanism identified that retreat of snow in spring is controlled by winter-spring circulation anomalies along with northward warm advection anomalies. As discussed by several scientists, India summer monsoon circulation is initiated basically due to land–sea heating contrast. Cooling due to the excess snow reduces this differential heating and hence the monsoon. Fasullo (2004) using satellite observations shows that the areas with larger variability in snow cover in southwestern Asia, Himalayan and Tibetan Plateau and Eurasia as a whole have weak correlation with all India rainfall. However, during weak El Niño southern oscillation (ENSO) years this negative correlation is strong in southwestern Asia, Himalayan and Tibetan regions. During an El Niño event, the perturbation to the development of troposphere temperature anomalies over the southern Eurasia is observed in a study by Xavier et al. (2007). This remote climatic phenomenon over the Eurasia region may also influence ISMR.

In addition to the studies concerning snow cover and snow depth, Dash et al. (2004) examined the number of days with different snow depths and found those with 5–50 cm in the months of winter and spring in West Eurasia (East Eurasia) having significant negative (positive) correlation with ISMR. Further using HSDSD-II data set, Dash et al. (2005) statistically examined the empirical relationship between the anomalies in winter/spring snow depth over west (25–70°E, 35–65°N) and east (70–140°E,

35–65°N) Eurasia and ISMR for the period 1951–1994. Their results show that 57% of heavy snow events and 24% of light snow events over West Eurasia are followed by deficient and excess ISMR, respectively. They concluded that large scale changes in mid latitude circulation pattern arising due to West Eurasian snow anomaly could be used as indicators of weak/strong monsoon circulation and deficient/excess ISMR. A study in the recent past, Ye et al. (2005) used HSDSD-II data set along with monthly gridded global precipitation and statistically analysed the connection between the early snow onset dates over northern Eurasia and the following year's summer monsoon over Southeast Asia. They undertook and reported that when the onset of snow in the northeastern Siberia is earlier than normal, there is more snow cover during the early season, more moisture coverage, higher prevalence of southwesterly monsoon winds and late monsoon withdrawal over Southeast Asia.

Different numerical modelling experiments have also been conducted to analyse the snow-monsoon relationship. Sensitivity studies with general circulation models (GCMs) such as those of Barnett et al. (1989) and Vernekar et al. (1995) have shown that when large, spatially coherent, positive snow anomalies are imposed over Eurasia in winter/spring, the monsoon circulation in the following summer is weaker than average in Southeast Asia. Vernekar et al. (1995) after conducting model experiments concluded that February snowfall results deficient rainfall in the following Indian summer monsoon months. Dash et al. (2006b) used observed Eurasian snow depth values as one of the boundary conditions in a spectral GCM and integrated the model for 6 months to examine the influence of Eurasian snow depth on the monsoon circulation. They designed the model experiments for contrasting years of snow depth values of April over Eurasia followed by contrasting ISMR years. The model-simulated mean monsoon circulation features for high and low snow depth years were compared with the corresponding years of NCEP/NCAR reanalysed fields. In their study, the evolution of weak/strong monsoon circulation from the mid-latitude circulation in response to high/low Eurasian snow depth in April was indicated. Turner and Slingo (2010) using a coupled climate model HadCM3 reexamined the negative relationship to monsoon rainfall exists from both northern West Eurasia and Himalayan/Tibetan Plateau in the absence of ENSO conditions. They demonstrated that in this model forcing from Himalayan region dominates and reduce the heating of the troposphere over the Tibetan Plateau. Using historical coupled ocean-atmosphere simulations of the coupled model intercomparison project3 (CMIP3) database and observations of snow cover and snow depth data, Peings and Douville (2010) further reexamined the snow-monsoon relationship. They found

the East–West dipole pattern of snow cover anomalies over Eurasia using observational data which is not confirmed by model simulations. Some models which indicate strongest snow-monsoon relationship also show an unrealistic impact of ENSO on both winter snow cover and summer monsoon.

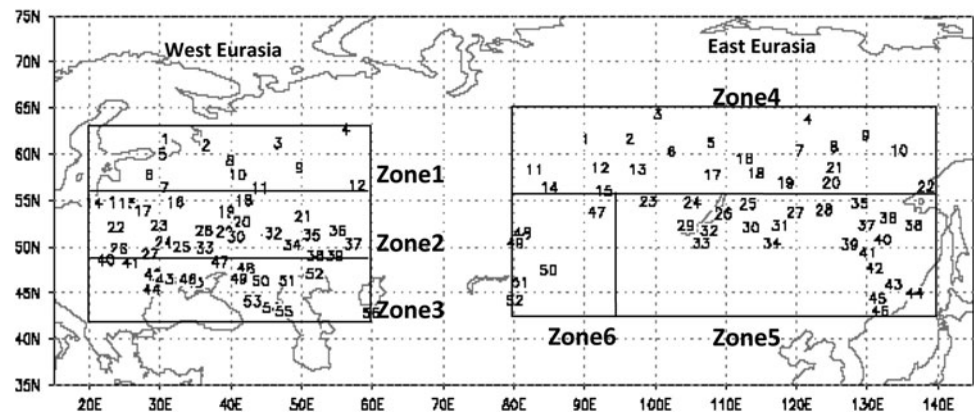
In the light of the above studies, it is necessary to examine whether there is any relationship between the evolutions of winter/spring Eurasian snow and Indian summer monsoon. It is also essential to know the detailed temporal and spatial distributions of snow depth over Eurasia and precipitation over Indian landmass in order to make use of these findings in long range monsoon prediction. In this study, the snow depth distribution and its variation over different sectors of Eurasia will be examined in detail. An attempt has been made here to analyse the starting and ending dates of snowfall along with its seasonal evolution. In this paper, Sects. 2 and 3 describe the sources of data used and the applied method, respectively. Characteristics of snow depth in different zones of Eurasia are explained in Sect. 4 whereas starting and ending dates of snowfall are discussed in Sect. 5. In Sect. 6 we examine the relationship of snow depth in different regions of Eurasia with those of ISMR. Finally conclusions are summarised in Sect. 7.

2 Description of data used

The HSDSD-II dataset for the period 1951–1994 is used in this study. It is a long-term climatological snow depth dataset (1881–1995) prepared by National Snow and Ice Data Center (NSIDC) on CDROM. The HSDSD data were extracted from the Soviet meteorological archive, which contains daily data from Russian (USSR) World Meteorological Organisation (WMO) stations. At each WMO station, HSDSD data have been prepared on the basis of data quality control flags and eight conditions which include snow cover percentage, snow cover characteristic, snow cover quality, location characteristic, location quality, snow depth, snow depth characteristic and snow depth quality. Based on the daily snow depth variations, it is inferred that the snowfall period lies between October and May, particularly for West Eurasia. Here snowfall continues from the first half of October up to the second half of May. While in East Eurasia at some eastern stations, snowfall process starts from the end of September up to early part of June. The current study is based on the period 1 October to 31 May.

In the period October–May, 56 out of 78 WMO stations are selected for West Eurasian region while 52 out of 94 stations are selected for East Eurasian region based on maximum daily data availability (>90%) for the period 1951–1994. Selected stations are shown in Fig. 1. The data

Fig. 1 Division of West and East Eurasia into different zones and the selected stations there in (marked by numbers) where HSDSD-II data are considered in this study



filling at a particular station is based on its climatological average and also on the snow depth variations in nearby stations during that year.

The high resolution ($1^\circ \times 1^\circ$ lat./long.) gridded daily rainfall version-2 data (Rajeevan et al. 2006) are used in this study to analyse the monsoon rainfall for the period 1952–1995. India Meteorological Department (IMD) has considered 2,140 rain gauge stations with minimum 90% of data availability and then converted this data set by grouping the station data into 1° lat./long. grid boxes. Rajeevan et al. (2006) used interpolation scheme in which values are computed from a weighted sum of observations using Shepard's method. This procedure has made the data smoother than the individual station data. These smoother gridded rainfall data are found to be convenient for further calculations. This gridded dataset has subsequently been used in studies of Rajeevan et al. (2006), Goswami et al. (2006) and Dash et al. (2009). Also the time series of ISMR onset dates over Kerala coast by Joseph et al. (2006) are used here. These onset dates over Kerala are determined by subjective estimates primarily using daily rainfall reports from rain gauge stations of the synoptic network.

3 Methods

The daily climatologies of all the selected stations (56 for West Eurasia and 52 for East Eurasia) have been prepared for the months October–May. As mentioned earlier, the period 1951–1994 is selected since snow depths for maximum numbers of stations are available in this period. The categorisation of West and East parts of Eurasia is based on the strong negative (positive) correlation between December, January and February West Eurasian (East Eurasian) snow depth and ISMR (Dash et al. 2005). West Eurasia ($42\text{--}63^\circ\text{N}$ and $20\text{--}60^\circ\text{E}$) has been divided into three sub domains based on latitudes such as the northernmost ($56\text{--}63^\circ\text{N}$ and $20\text{--}60^\circ\text{E}$), middle ($49\text{--}56^\circ\text{N}$ and $20\text{--}60^\circ\text{E}$) and southernmost ($42\text{--}49^\circ\text{N}$ and $20\text{--}60^\circ\text{E}$). Similarly, East

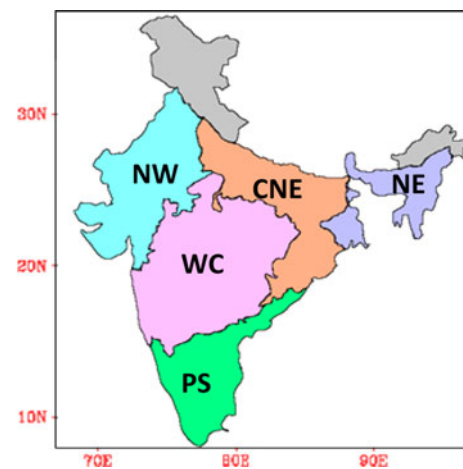


Fig. 2 Indian homogeneous monsoon regions (based on source available at <http://www.tropmet.res.in>) Northwest (NW), Central Northeast (CNE), Northeast (NE), West Central (WC) and Peninsular (PS)

Eurasia ($43\text{--}65^\circ\text{N}$ and $80\text{--}140^\circ\text{E}$) is divided into north ($56\text{--}65^\circ\text{N}$ and $80\text{--}140^\circ\text{E}$) and south. Again southern region is divided into eastern ($43\text{--}56^\circ\text{N}$ and $80\text{--}95^\circ\text{E}$) and western ($43\text{--}56^\circ\text{N}$ and $95\text{--}140^\circ\text{E}$) parts. These zones are sketched in Fig. 1. For rainfall analysis, the five homogeneous monsoon regions, Northwest, Central Northeast, Northeast, West Central and Peninsular are shown in Fig. 2. These regions are defined by the Indian Institute of Tropical Meteorology (IITM), Pune (<http://www.tropmet.res.in>) on the basis of spatial and temporal variations of precipitation across the entire country using statistical techniques. The details are given by Parthasarthy et al. (1995).

In this study, the starting date of snowfall (SDS), ending date of snowfall (EDS) and maximum snowfall date (MSD) are identified and analysed at the selected stations based on their 1951–1994 climatological time series for the months October–May. There is no established procedure to declare onset of snowfall as in case of summer monsoon over India. Procedure adapted by the IMD for declaring monsoon onset over Kerala coast is based on subjective estimates by the forecasters (Rao 1976). Based on the

information in 14 available meteorological stations, if around 60% of them after 10th May receive 2.5 mm or more rainfall for two consecutive days, the onset over Kerala is declared provided the criteria based on wind field and outgoing wave radiation are satisfied (<http://www.imd.gov.in/section/nhac/dynamic/MOK.htm>). In this study, SDS is declared when lying snow starts increasing day-by-day at the beginning of the season while EDS is identified when snow depth goes below 1 cm at the end of the season. Further, SDS is related to the monsoon onset dates prepared by IMD (Joseph et al. 2006). The snow depths in the selected regions of Eurasia are also examined with respect to the area weighted precipitation over five homogeneous monsoon regions of India.

Ye et al. (2005) identified that early season snow onset leads to more snow coverage in northeastern Siberia and that is significantly associated with summer monsoon rainfall over Southeast Asia. In their study, snow onset dates at different stations of Eurasia are identified based on the starting dates when snowfall process continuously occurs for a longest period. However, in our study we consider that even when there are few days without snowfall, all the earlier snow might not have melted completely and hence it can have still the cooling effect in the atmosphere. Hence in this study, SDS is defined as the day since when there is increase in the magnitude of snow depth is observed. During the initial days of snowfall if break in snowfall process is >4 days before any continuous rise, SDS is declared when snow depth at least for three continuous days remains more than 4 cm or 10% of the maximum snow depth in that year whichever is less.

4 Characteristics of snow depth in different zones of Eurasia

As mentioned earlier, daily climatologies of snow depths in each zone reported at 108 selected stations in the West and East Eurasia are prepared and examined here. In order to calculate the zone average of snow depth, we have divided each zone into grid boxes of 5° × 3.5°

(longitude × latitude) site. The number of stations varies from box to box. The average of snow depths over all the stations in a box represents the snow depth of that box. There are also few blank boxes. The HSDSD-II dataset does not contain continuous time series of snow depth in these stations. Hence we have done some approximation so that the average snow depths in these vacant boxes are considered to be equal to the mean of other remaining boxes in a zone, without loss of any generality. This approach is adopted since the maximum of the vacant boxes are originally having stations but those stations are not considered in this study due to the unavailability of long series of continuous data. As shown in Fig. 3a, maximum snow depth in West Eurasia occurs in zone 1 and minimum in zone 3. This pattern in snow depth may be attributed to the geographical location with respect to the latitude. East Eurasia results indicate similar kind of pattern as shown in Fig. 3b. Comparison shows that zone 4 in East Eurasia has maximum snow depth than the rest of Eurasia while zone 3 in West Eurasia has minimum. In Fig. 3a, b, climatological time series of daily mean snow depths in each zone indicate that zones where snowfall starts relatively early, more snow falls in those zones and also MSD and EDS occur relatively late.

Figure 3a depicts that the MSD in zone 3 in West Eurasia occurs in the first week of February while in zones 1 and 2, it occurs between end of February and beginning of March. As shown in Fig. 3b, MSD in zones 5 and 6 occurs in the third week of February while in zone 4 it occur in third week of March. The maximum values of mean snow depth in northern regions (zones 1 and 4) are about three times more than those in the respective southern regions.

It is well known that northern zones have more snow depth than southern zones. Statistical analysis of snow depths in all the six zones of West and East Eurasia is summarised in Fig. 4. Daily snow accumulated on ground is the combination of old snow and new snow. Due to the unavailability of information to determine old snow, here in our study, we have considered that old snow is either melted or measure of its depth is reduced by densification.

Fig. 3 Climatologies of daily mean snow depths over the period 1951–1994 in three zones of **a** West Eurasia (WE) and **b** East Eurasia (EE) as defined in Fig. 1

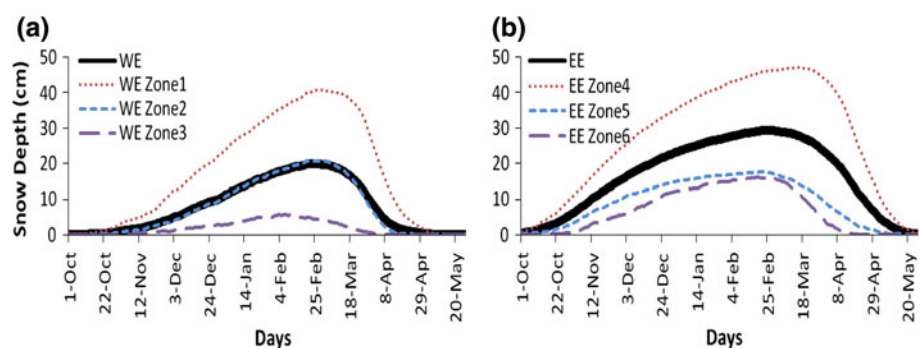
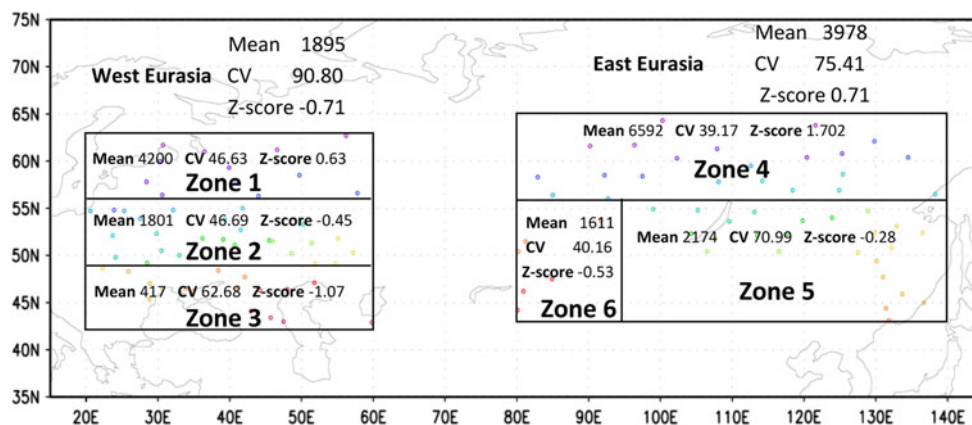


Fig. 4 Mean (cm), coefficient of variation (%) and standardised score (Z score) of snow depths in all the six Eurasian zones. The mean is over the period 1951–1994 and it is the sum of all the values in a season between October and May



Total snow depth in a season, averaged over 44 years (1951–1994) is calculated for each zone. Figure 4 shows that the mean snow depth in zone 4 is three times more than that in zone 5 and four times of that in zone 6. Similarly in West Eurasia, zone 1 mean snow depth is nearly twice than that in zone 2 while it is ten times of snow depth in zone 3. The variation in snow depth is the least in zone 4 in East Eurasia while it is maximum in zone 3 in West Eurasia. Zones 1 and 2 in West Eurasia have nearly the same variations.

Z score transformation is the way to standardised the data. It is the number of standard deviation from the mean. The Z scores or standardised scores indicate that snow depth in zone 4 is +1.7 standard deviation and in zone 1 it is +0.63 standard deviation above the value averaged over whole of Eurasia while in rest of the zones these are below the climatological value of total snow depths in a season. In zones 2 and 3, the standardised values of snow depths are -0.45 and -1.07 , respectively while in zones 5 and 6 these are -0.28 and -0.53 , respectively.

Percentage of coefficient of variation (CV) of snow depths given in Fig. 5 is a dimensionless number which is the product of 100 and the ratio of standard deviation to the respective mean value. The shaded plots are prepared using

the GrADS software function, oacres (<http://www.iges.org/grads/gadoc/gadocindex>). According to the GrADS documentation, to obtain the grid values, operational objective analysis system by Cressman (1960) is used. The interpolation method applied here is based on distance weighted formula. CVs show that in less snow regions, the variations are relatively high and reverse happens in more snow regions. In the case of ISMR also, there is less variation in more seasonal rainfall regions and more variation in less seasonal rainfall regions (Dash et al. 2002). Thus, break of few days in snowfall process during a season often occurs in the southern and southwestern regions particularly in the southern regions in West Eurasia. Snowfall process is relatively continuous in north of East Eurasia. This is also confirmed after analysing the dataset manually.

Yearly standardised anomalies of total snow depth for October–May during the period 1952–1994 are shown in Fig. 6 for each zone in West and East Eurasia. Figure 6a indicates that snow depth anomalies in zones 1 and 2 are in concert with those in the West Eurasia as a whole. However, there are exceptions in the years 1966, 1967, 1981, 1982, 1985 and 1987 where zone 1 snow depth anomalies are opposite in phase with those of West Eurasia. Also, the anomalies in zone 4 are nearly similar to those observed in

Fig. 5 Coefficients of variation (%) of snow depth for October–May in the period 1952–1994

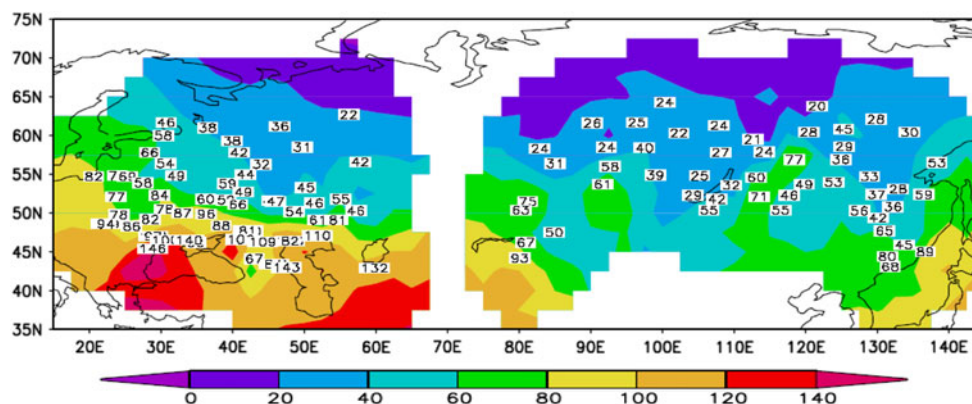
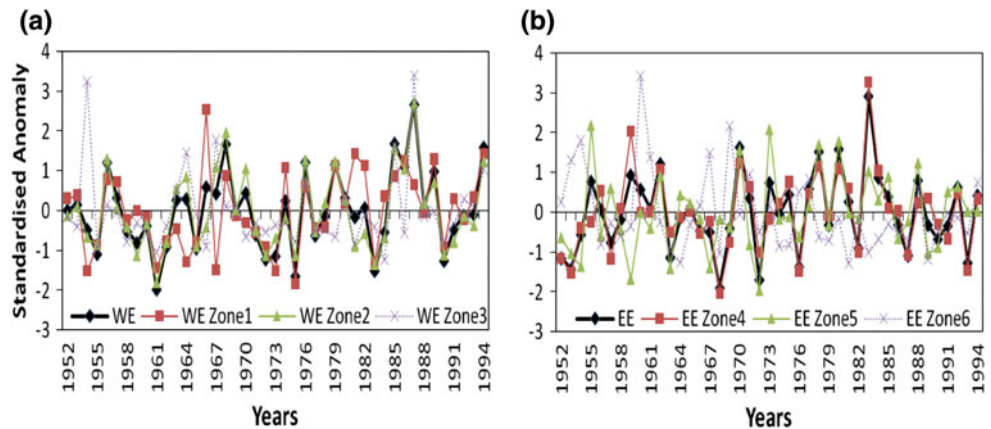


Fig. 6 Standardised snow depth anomalies in all the six zones of **a** West Eurasia (WE) and **b** East Eurasia (EE) for the months October–May in the period 1952–1994



the whole of East Eurasia. There are some years when relatively more season snowfall in East Eurasia is accompanied by less snowfall in West Eurasia. In some years, the reverse also happens. It is found that the correlation coefficient between West and East Eurasia total snow depth anomalies is -0.35 with 95% confidence level. Figure 6a indicates that changes in snow depths in zones 1 and 3 in West Eurasia differ considerably from each other. Similar, but more persistent difference is observed between zones 4 and 6 in East Eurasia. As shown in Fig. 6b, zones 4 and 6 seem to be opposite in phase. Early arrival of snow provides longer period of snowfall and could lead to relatively more snowfall in northernmost regions and subsequently less snow in southernmost regions. This aspect needs further studies to verify and understand the physical mechanisms behind it.

5 Starting and ending dates of snowfall

Figure 7 depicts the variations in SDS and EDS. Here number 1 represents 1 October and successive days are counted in increasing order. Negative numbers indicate that dates are counted backward. Variations in SDS suggest that snowfall begins in the northernmost regions of East and West Eurasia. Arrows in Fig. 7 schematically indicate the directions of seasonal evolution of snowline as the days proceed. In north of East Eurasia, SDS generally occurs few days before 1 October and gradually proceeds towards south and northwest regions. Snow arrives in southwest region of West Eurasia mostly in November end. Similarly, EDS shows that the melting of snow starts from the southern zones and gradually proceeds towards northern zones in the last week of May. However, at some stations in the north of East Eurasia, snow disappearance takes place in initial days of June also. The details of SDS, EDS and MSD period are listed in Table 1.

6 Relationship of Eurasian snow depths with ISMR

6.1 SDS and summer monsoon onset dates

In this study, SDS of different zones are further related with the onset dates of Indian summer monsoon in Kerala. Based on the progress of snowfall over different zones (discussed earlier), zones 1 and 4 are considered for onset date analysis. SDS of selected stations in zones 1 and 4 are found from daily mean snow depths in each year and these are related with the monsoon onset dates in the following year. Generally, summer monsoon onset dates occur in late May and early June. In Eurasia, as stated earlier, snow fall process begins mostly in October month particularly in the West Eurasia while at some stations in the East Eurasia it starts few days earlier.

Here, we have identified the years (Fig. 6) in which high/low snow depths in southernmost zones 3 and 6 are followed by low/high snow depths in northernmost zones 1 and 4, respectively. Relatively low snow depths in southern regions of Eurasia would lead to more north–south temperature gradient between Indian landmass and Eurasia and thus may lead to earlier onset of summer monsoon. As discussed in Sect. 3, 10% of maximum value of mean snow depth in zone 1 in West Eurasia is 4 cm as shown in Fig. 3a. Similarly, Fig. 3b shows the 10% of maximum value is 4.7 cm in East Eurasia zone 4. Although few break periods are observed in West Eurasia, there is significant continuity in the snowfall days in East Eurasian zones.

SDS of East and West Eurasia in the period 1951–1994 are related with the following summer monsoon onset dates in the period 1952–1995 as shown in Fig. 8. Further, SDS of six northernmost stations in West and East Eurasia are also considered for detailed analysis (Fig. 9). Stations 3, 4 and 8 in West Eurasia and 3, 4 and 5 in East Eurasia as indicated in Fig. 1 are selected for the onset date analysis. As mentioned earlier, we are interested in identifying the

Fig. 7 **a** Starting date of snowfall and **b** ending date of snowfall at selected stations in Eurasia

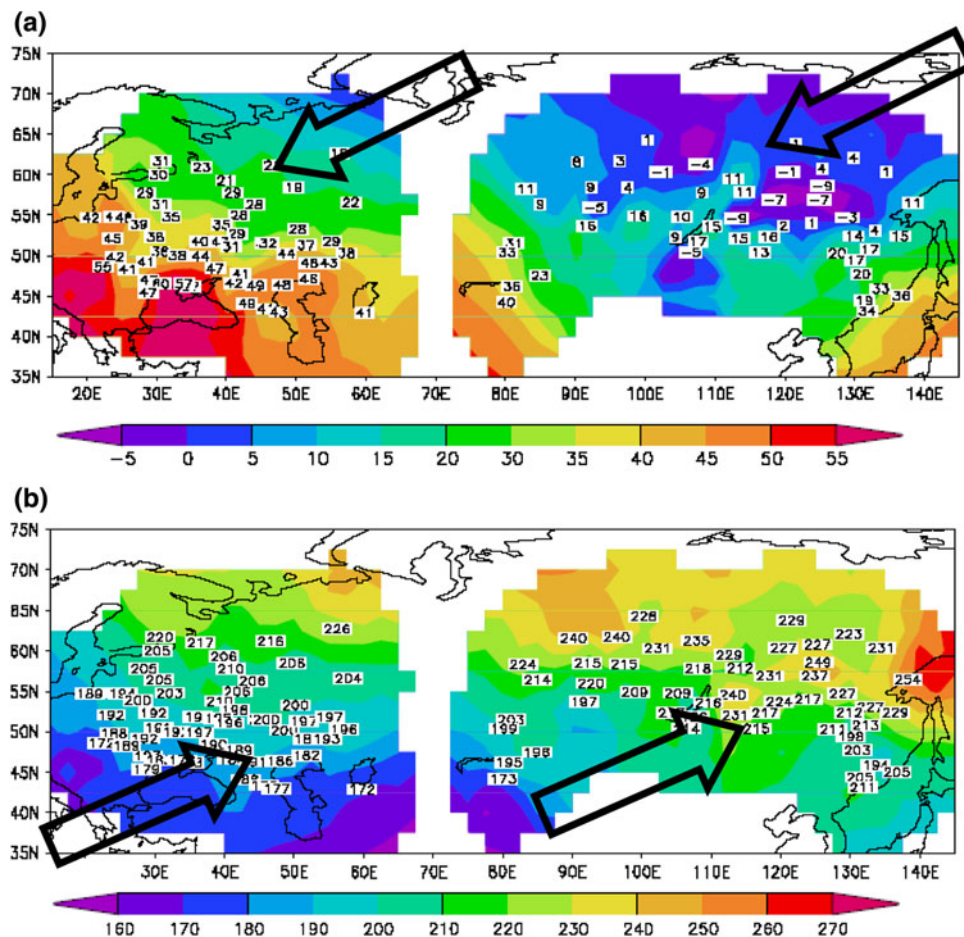


Table 1 Ranges in SDS, EDS and MSD for six Eurasian zones

Eurasian regions	Range in SDS	Range in EDS	Range in MSD
East zone 4	21 Sep–11 Oct	29 Apr–10 Jun	24 Feb–9 Apr
East zone 5	21 Sep–5 Nov	3 Apr–27 May	31 Dec–23 Mar
East zone 6	16 Oct–9 Nov	21 Mar–20 Apr	28 Jan–8 Mar
West zone 1	15 Oct–31 Oct	21 Apr–13 May	20 Feb–17 Mar
West zone 2	28 Oct–18 Nov	5 Apr–27 Apr	8 Feb–7 Mar
West zone 3	10 Nov–29 Nov	20 Mar–8 Apr	24 Jan–22 Feb

dates of arrival of snow in West and East Eurasia. Since the onset dates of different stations are widely separated, in our study we have selected few northernmost stations. The selection of these stations is based on their relatively low variation in snow depth and earlier SDS. These stations are located in the same latitude belt and also cover larger area. The onset date is declared when snow covers all these three stations. Rest of method is the same as described in the previous paragraph. At individual stations, there is possibility of more breaks in snowfall process which is normally filtered when we consider zone average. We have neglected those break periods during the initial days when snowfall begins in station and day-by-day snow depth value is more

than 20% of the maximum snow depth value during that year.

As depicted in Fig. 8, significant correlations are not found between SDS of northernmost zones in both West and East Eurasia and monsoon onset dates. However, SDS of six selected stations (Fig. 9) in West and East Eurasia have some relationships with following monsoon onset dates with correlation coefficient of 0.3 (at 90% confidence level) over the period 1960–1995. However, for the period 1952–1960 the correlations are weaker or we can say that correlations are in general weak.

It is difficult to explain physical connection between snow and monsoon onset dates. There could be some mid-latitude circulation associated with this relationship. A study by Meehl (1997) on tropospheric biennial oscillation using global coupled ocean atmospheric GCM had suggested the involvement of SST, temperature anomalies by large scale atmospheric circulation in tropics and tropical mid-latitude interactions in the northern hemisphere with monsoon rainfall over South Asia. The association of atmospheric–ocean mechanism would be the forcing that alters mid-latitude circulation in such a way to maintain the surface temperature anomalies over

Fig. 8 Standardised anomalies of starting date of snowfall (SDS) in northernmost zones of **a** West Eurasia **b** East Eurasia and onset dates of Indian summer monsoon

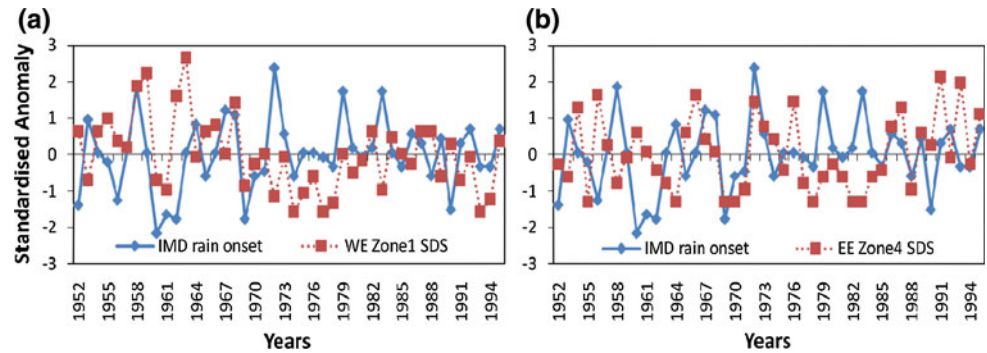
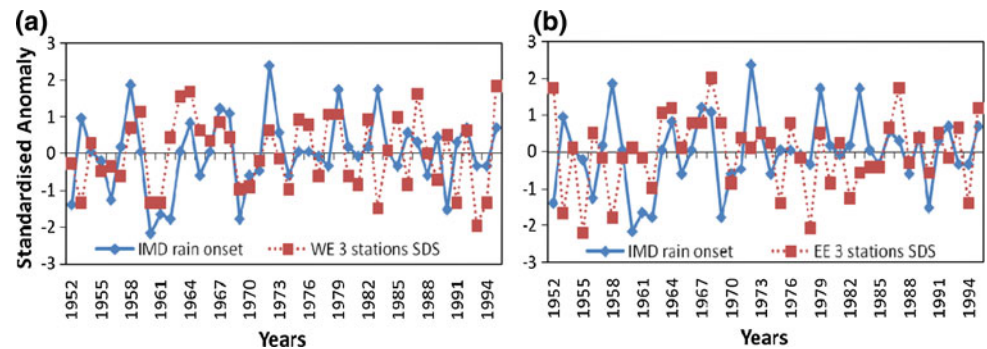


Fig. 9 Standardised anomalies of starting date of snowfall (SDS) at three northernmost stations of **a** West Eurasia (stations 3, 4 and 8) and **b** East Eurasia (stations 3, 4 and 5) and onset dates of Indian summer monsoon



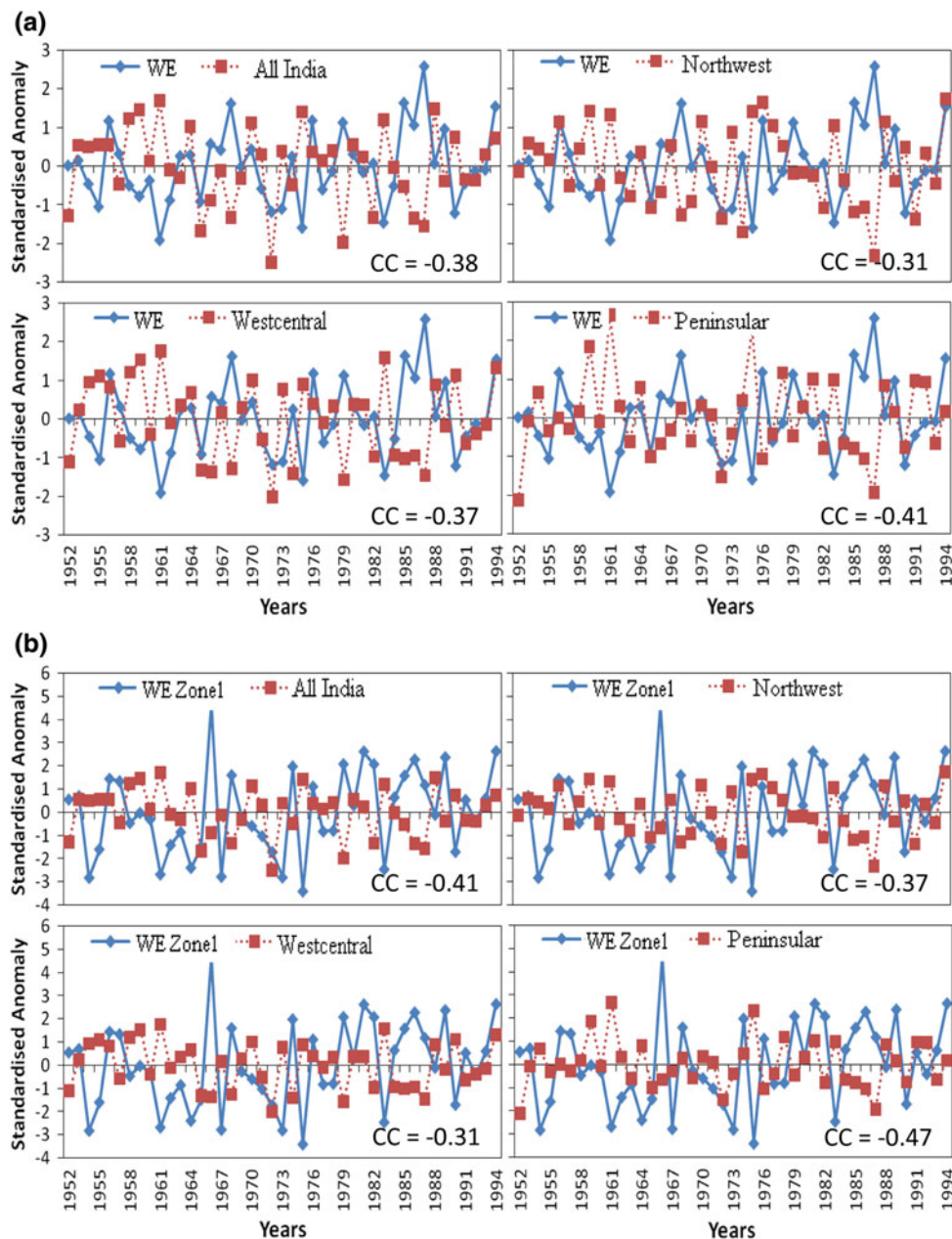
South Asia. This shows the complex connection of snow with monsoon.

6.2 Zone average of snow depths and summer monsoon rainfall

In this study, attempts have been made to relate snow depths in different zones of Eurasia with summer monsoon rainfall in five homogeneous regions in India. The rainfall zones are Northwest, Central Northeast, Northeast, West Central and Peninsular India (Fig. 2). Station averages of total snow depths in the months October–May in each of the six zones in Eurasia are correlated with the area weighted rainfall in five homogeneous monsoon regions of India. In fact, standardised anomalies of total snow depth and rainfall are used for this purpose. The correlation coefficient of snow depth anomaly in zone 2 in West Eurasia with rainfall anomaly in Peninsular India is -0.37 at 98% confidence level. Correlation coefficients between the other zones are relatively weak. In another detailed study by Fasullo (2004), the climatological distribution and interannual variability in snow cover over Eurasia were analysed using version 2 NOAA/NESDIS satellite-based data. He found that the winter and spring snow cover over the whole Eurasia and southern regions of Eurasia with large variability, exhibit weak correlation with ISMR. Only significant correlations along with the confidence levels are shown in Figs. 10, 11 and are also listed in Table 2.

These results suggest strong relationships between snow depth anomalies in northern zones with the rainfall in Peninsular India. The correlation coefficient of Peninsula rainfall with preceding season West Eurasian zone 1 snow depth is -0.47 and with East Eurasian zone 4 snow depth is 0.51 . This could be explained based on the fact that climatologically snow depths in the northern zones are several times more than those in the southern zones. Further, the snowfall in the northern zones is for longer period and hence there snow depths persist for relatively longer period than in the southern regions. Higher snow depths and their longer persistence in the zones 1 and 4 make their effects on Peninsular India rainfall stronger than those in the southern zones. It may be noted that Peninsular India with the exception of some areas of Tamilnadu receives maximum rainfall during southwest monsoon. This could explain relatively stronger connection of snow depth anomalies in the northern zones in Eurasia with rainfall in Peninsular India. The recent study by Ye et al. (2005) reflects similar view. They observed that thicker snow accumulation over northeast Siberia leads to more summer rainfall over India. As proposed by Kripalani and Kulkarni (1999), the anomalous anticyclonic circulation over Russian region before a strong monsoon advects warm air from the south to reduce snow depth, and cold air from the north to preserve deep snow. Also the anomalous cooling over southern Eurasia weakens the land–sea temperature

Fig. 10 Standardised anomalies of October–May snow depths in **a** West Eurasia (WE) and **b** WE-zone 1 and summer monsoon rainfall in All India, Northwest, West Central and Peninsular during 1952–1994, also correlation coefficients (CC) are shown in figures



contrast in the troposphere which may lead to the reduction of the southwesterly monsoonal flow. It has also been observed in this study that there are a number of cases when more snow over northern region is followed by less snow in southern region. Further study and modelling experiments are required to verify and understand the mechanisms associated with it.

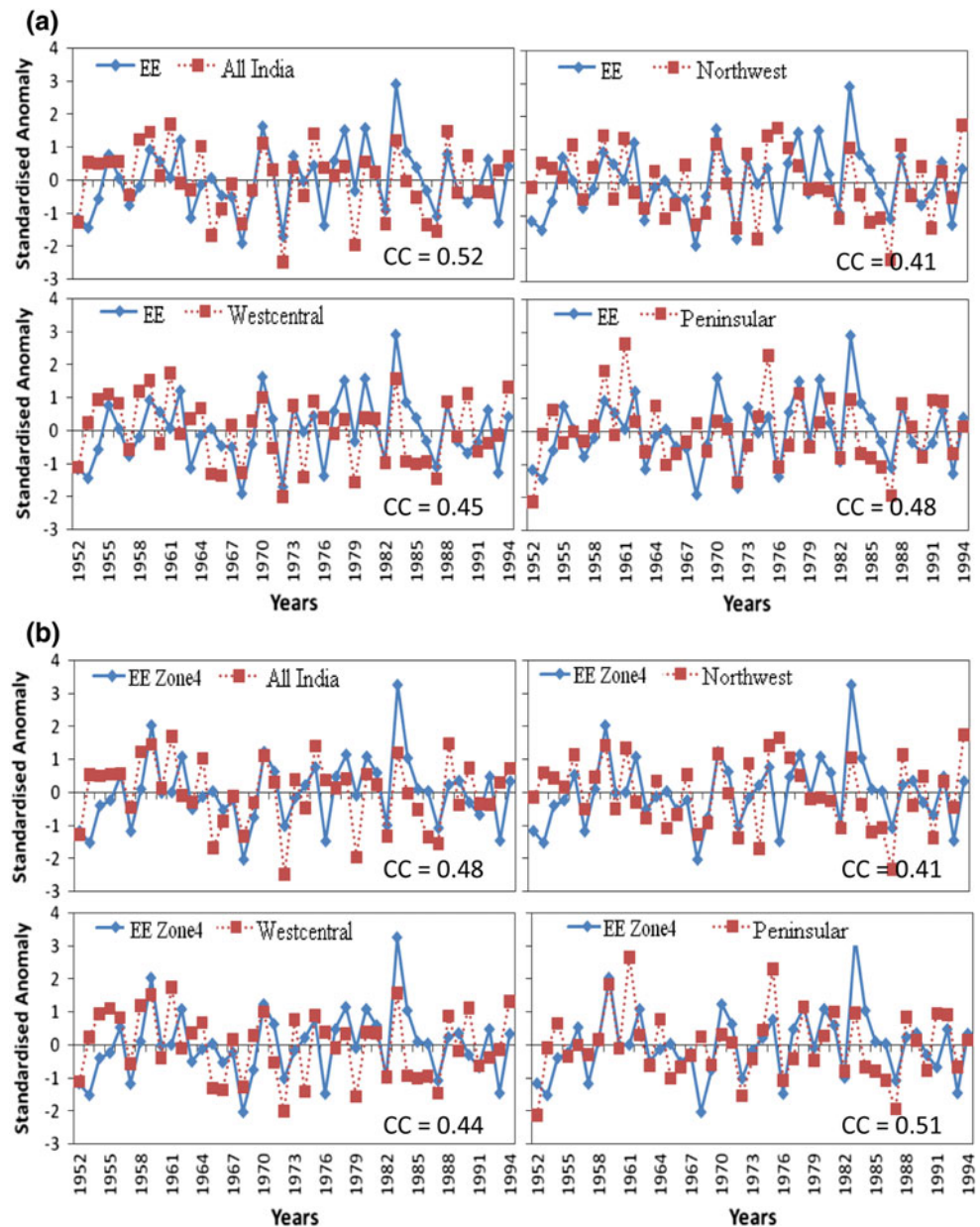
7 Conclusions

Results of this study show that climatologically snow depths in the northernmost zones of East and West Eurasia are more than those averaged over the whole of Eurasia

while in other regions those are less than the mean. The Z scores or standardised scores indicate that snow depth in the northern zone of East Eurasia is +1.7 standard deviation and in the northern zone of West Eurasia it is +0.63 standard deviation above the value averaged over whole of Eurasia while in rest of the zones these are below the mean. In zones 2 and 3, the standardised values of snow depths are -0.45 and -1.07, respectively while in zones 5 and 6 these are -0.28 and -0.53, respectively.

Analysis shows that snow starts falling at stations located in the northeast of Eurasia and gradually it propagates towards southwest. Also stations with early starting date of snowfall have late ending dates and also have late occurrence of maximum snow depth. In both East and West

Fig. 11 Standardised anomalies of October–May snow depths in **a** East Eurasia (*EE*) and **b** EE-zone 4 and summer monsoon rainfall in All India, Northwest, West Central and Peninsular during 1952–1994, also correlation coefficients (*CC*) are shown in figures



Eurasia, the maximum values of mean snow depths in the northernmost zones are about three times more than those in the respective southern zones. The duration of snowfall in the northern zones is longer and hence there snow depths persist for relatively longer period than in the southern zones.

Snow depth varies to a great extent over different stations in West and East Eurasia. Relatively high coefficients of variation in the snow depths are observed in south and southwest stations in West Eurasia than in any other station. The coefficients of variation in zones 1 and 2 in West Eurasia are 46.63 and 46.69%, respectively, while in zone 3 it is 62.68%. Zones 4, 5 and 6 in East Eurasia have CV of 39.17, 70.99 and 40.16%, respectively.

In some years, more snowfall in East Eurasia is accompanied by less snowfall in the West Eurasia and visa versa. The correlation coefficient between the snow depth anomalies in West and East Eurasia is -0.35 at 95% confidence level. Also, in some years snow depths in the northernmost and southwest zones in East Eurasia are opposite in phase.

The relationship between snow starting dates in Eurasia and onset dates of summer monsoon is weak. However, the northernmost zones of East and West Eurasia have significant correlations with seasonal summer rainfall in Northwest, West Central and Peninsular India. The most robust relationship is with the Peninsular India. Zones 1 and 4 have correlation coefficients of -0.47 and 0.51 ,

Table 2 Correlation coefficients between snow depths anomalies in different zones of Eurasia in October–May with the following summer monsoon rainfall anomalies in homogeneous zones in India

Indian regions	All India	Northwest	West central	Peninsular
Eurasian regions				
WE whole	−0.38 (98%)	−0.31 (95%)	−0.37 (98%)	−0.41 (99%)
WE zone 1	−0.41 (99%)	−0.37 (98%)	−0.31 (95%)	−0.47 (99%)
EE whole	0.52 (99%)	0.41 (99%)	0.45 (99%)	0.48 (99%)
EE zone 4	0.48 (99%)	0.41 (99%)	0.44 (99%)	0.51 (99%)

Level of confidence is given in each bracket

respectively, at 99% confidence level with Peninsular India rainfall while with the other regions in India the correlations are less. Climatologically snow depths in the northern zones of Eurasia are around three times more than those in the southern zones and also snow persists in those northern zones for longer duration. Also Peninsular India except some areas of Tamilnadu receives rainfall mainly due to the dominant weather systems during southwest monsoon compared to those in the rest of India. The above facts may explain the strong relationship between snow depth anomalies in zones 1 and 4 in Eurasia and Peninsular India summer monsoon rainfall.

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