Impact of Climate Change on Spatial and Temporal Variability of Precipitation and Temperature in Western Himalayan Region

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ABSTRACT

The Himalayan region contains the most extensive and rugged high altitude areas on the earth. The region and its water resources play an important role in global atmospheric circulation, biodiversity, rainfed, irrigated agriculture, hydropower, as well as in the production of commodity exported worldwide. Though the Himalayas are the source of countless perennial rivers, paradoxically, people of mountain depend upon spring water for their sustenance. Himalayas like many places on the earth are experiencing rapid climate change which will have significant impact on ecosystem, biodiversity, agriculture and human well being. An attempt has been made in the present study to see impact of climate change in precipitation, and temperatures patterns in western Himalayan region. The climatic data of past 30 years (1980-2009) for different stations of Himalayan range particularly Himachal Pradesh and J&K were analysed to see the impact of climate variability in temperature and precipitation behaviour. The stations were selected with elevation ranging from 319-4784 meter above mean sea level. It has been observed that in case of annual maximum temperature an increasing trend was observed at all the stations except Kathua in outer Himalayan range. The highest increasing trend was observed at Shimla with 0.1 ºC per year. The seasonal analysis showed that winter as well as pre-monsoon seasons recorded increasing trends. During monsoon season few stations have recorded decreasing trend also. More or less similar trend were found in case of minimum temperature and the highest increasing rate in minimum temperature was noticed at Badharwaha in middle Himalayas with 0.12 ºC per year. The annual rainfall was found decreasing with few exceptions. The rainfall decreasing rate was as high as 11.9 mm per year at Badharwaha. On the other hand the seasonal analysis revealed that the monsoon period has recorded an increasing trend with few exceptions. The days with snowfall were also decreasing at all the stations and the highest decreasing rate was observed at Koukernag in middle Himalayas with 0.6 days per year followed by Gulmarg and Shimla. Preliminary analysis further indicates that there is a significant positive correlation between Winter North Atlantic Oscillation Index (NAO) with winter precipitation (December-February) in middle and greater Himalayas.

Keywords: Seasonal precipitation, Snowfall days, temperatures, Time series analysis, spatial correlation, Teleconnection

INTRODUCTION

The warming of the Earth–atmosphere system is likely to change temperature and precipitation, which may affect the quantity and quality of the freshwater resources. One of the most important impacts to society of future climatic changes is expected on regional water availability. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) dispelled many uncertainties about climate change. Warming of the climate system is now unequivocal. An increasing rate of warming has particularly taken place over the last 25 years, and 11 of the 12 warmest years on record have occurred in the recent past.

Over the next decades, it is predicted that billions of people, particularly those in developing countries, face shortages of water and food and greater risks to health and life as a result of climate change (UNFCCC, 2007). The annual variability of temperature and precipitation influences, strongly, the variability and productivity of agriculture. Climate variability and change will, therefore, have a significant impact on rural livelihoods at both local and a regional scale (Archer and Fowler, 2004).

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The vulnerability of the Indian subcontinent to the impact of changing climate is of vital importance because the major impact of climate change in this continent would be on the hydrology, affecting water resources and agricultural economy (Divya and Mehrotra, 1995). The major river systems of the Indian subcontinent, namely Brahamaputra, Ganga and Indus which originate in the Himalayas, are expected to be more vulnerable to climate change because of the substantial contribution from snow and glaciers into these river systems (Singh and Kumar, 1997). Trends in precipitation in the Greater Himalayas have been studied by many authors. Shrestha et al. (2000) found no distinct long term trends in precipitation in the Nepalese Himalayas although the regional series showed significant variability at annual and decadal time scale. However, further west in the Himalayan foothills, Borgaonkar et al. (1996) found significant decreasing trends in both winter and summer precipitation in a record at Shimla from 1876 to 1982, while Singh and Sen Roy (2002) observed a slight upward trend in winter rainfall and a slight downward trend in monsoon rainfall between 1964 and 1992 in the Beas catchment.

With respect to teleconnections, the Asian monsoon is one of the most important components in the coupled ocean-land-atmosphere system and significant links have been identified between Indian monsoon rainfall and a wide range of large scale features of the global climate, including El Nino Southern Oscillation (ENSO) (Yang, 1996) and Mediterranean pressure indices (Raicich at al., 2003). There is a connection between the Asian monsoon and ENSO, but it is not possible to predict the strength of the monsoon solely from the phase of ENSO, as these monsoon–ENSO correlations have variable lag-lead times (Webster and Yang, 1992) . During the 1997/98 El Niño events, the Indian rainfall remained essentially normal (Webster et al,. 1998; Torrence and Webster, 1999). Kumar et al. (1999) provided evidence of weakening of the ENSO-monsoon relationship in recent decades.

The inter-annual variability of winter precipitation in the north-western parts of South Asia is also influenced by(ENSO). The major northern hemisphere (NH) teleconnection patterns during NH winter were first recognized nearly three decades ago (e.g., Wallace and Gutzler 1981; Horel 1981; Barnston and Livezey 1987). Syed et al. (2006) investigated the effects of the ENSO on winter precipitation in Central Southwest Asia (CSWA) on the basis of observed climate data. A positive precipitation anomaly was found to correspond to the warm ENSO phase over a sub-region encompassing northern Pakistan, Afghanistan, Tajikistan and southern Uzbekistan and is shown in fig.1.

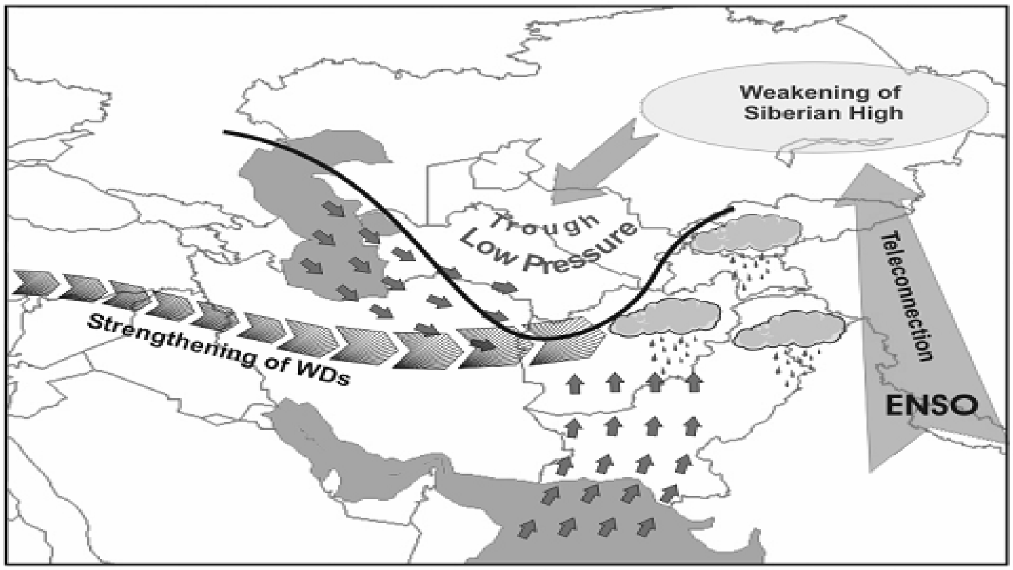

Fig.1. warm ENSO phase on the winter precipitation over CSWA.

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Source (Syed et al. (2006)

Winter precipitation in Himalayan region emanated from weather systems originated from Mediterranean or from Atlantic. Generally these weather systems which are known as western disturbances (WDs) reach South Asia they do not have well developed cold or warm fronts either at the surface or at the upper levels, most of them being at occluded stage (Pant and Rupa Kumar 1997). The different characteristics of these weather systems i.e western disturbances (WDs), including cyclogenesis, cyclolysis, climatology ,variability, frequency and track is influenced largely by global phenomenon known as North Atlantic Oscillation (NAO). The effect of the North Atlantic Oscillation (NAO) on winter precipitation over the Hindu Kush-Himalayan (HKH) region has also been investigated by Syed et al. (2006). A positive precipitation anomaly is found, corresponding to the Positive NAO phase over a sub-region encompassing northern Pakistan, Afghanistan, Tajikistan and southern Uzbekistan and is shown in fig.2.

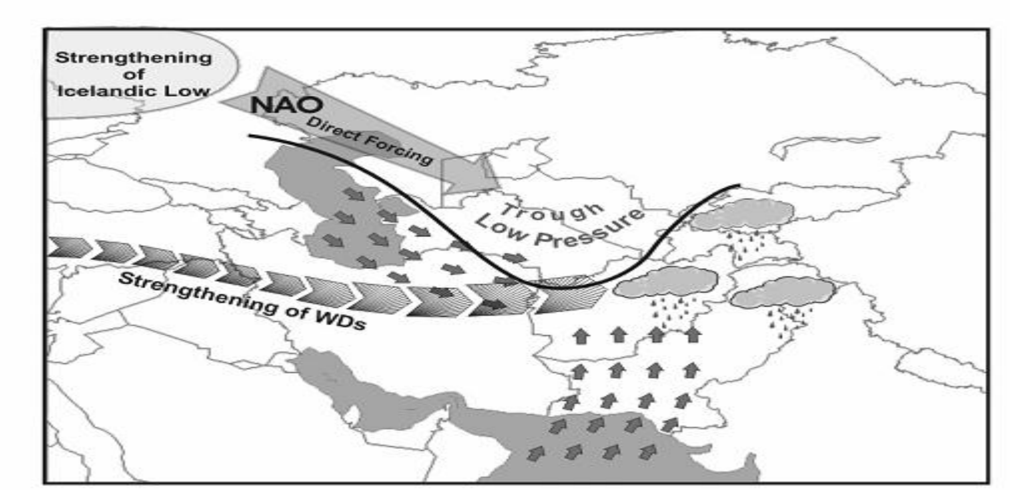
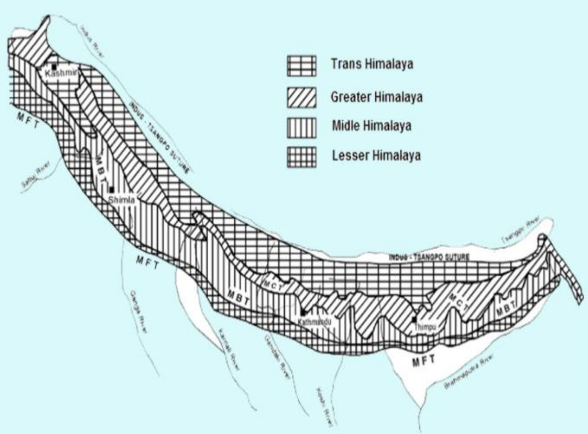


Fig.2 . Effect of positive NAO phase on winter precipitation over CSWA.
Source Syed et al. (2006)

In the present study an attempt has been made to analyze the impact of changing climate on precipitation and temperature patterns of the western Himalayan region representing Jammu and Kashmir , Himachal Pradesh also to see relate influence of Winter North Atlantic Oscillation Index(NAO) with precipitation in region selected for the study .

MATERIALS AND METHODS

The meteorological data for the period (1980-2009) from 17 stations in the range from 319-4784 in Jammu Kashmir and Himachal Pradesh representing the western Himalayan region for the study were collected from India Meteorological Department(IMD) as shown in fig.3.



Himalayan Range	Station	Elevation amsl (m)	Time period Temp/Rainfall	Snow
Greater Himalayan Range	Phalgam	4784		1980-2009
Midle Himalayan Range	Leh	3414		1961-69, 1978-89
	Kalpa	2960	1993-2009	-
	Gulmarg	2687	1980-2009	1975-2009
	Shimla	2202	1980-2009	1989-90 to 2010-11
	Koukernag	2148	1980-2009	1978-2009
	Quazikund	1739	1980-2009	1970-2009
	Banihal	1623	1980-2009	1962-2009
	Badharwaha	1613	1980-2009	1980-2009
	Srinagar	1588	1980-2009	1960-2009
	Batote	1528	1980-2007	1980-2009
	Dharamshala	1211	1980-2009	-
Lower Himalayan Range	Sundernagar	1150	1982-2009	-
	Bhuntar	1096	1980-2009	-
	Katra	618	1980-2009	-
	Jammu	448	1980-2009	-
	Kathua	319	1980-2009	-

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Only those meteorological stations which maintains the standard measurement practices as adopted by World Meteorological Organization and India Meteorological Department have been selected for the study. Daily temperatures, precipitation, snowfall days were taken from respective stations of IMD. Validation checks were carried out on the records to identify inconsistencies and records are thought to be consistent with standards meteorological measurement practices adopted by IMD. The spatial distribution of stations was among the lower, middle and upper Himalayan range. The stations were selected with elevation ranging from 319-4784 meter above mean sea level and are shown in Fig.4.

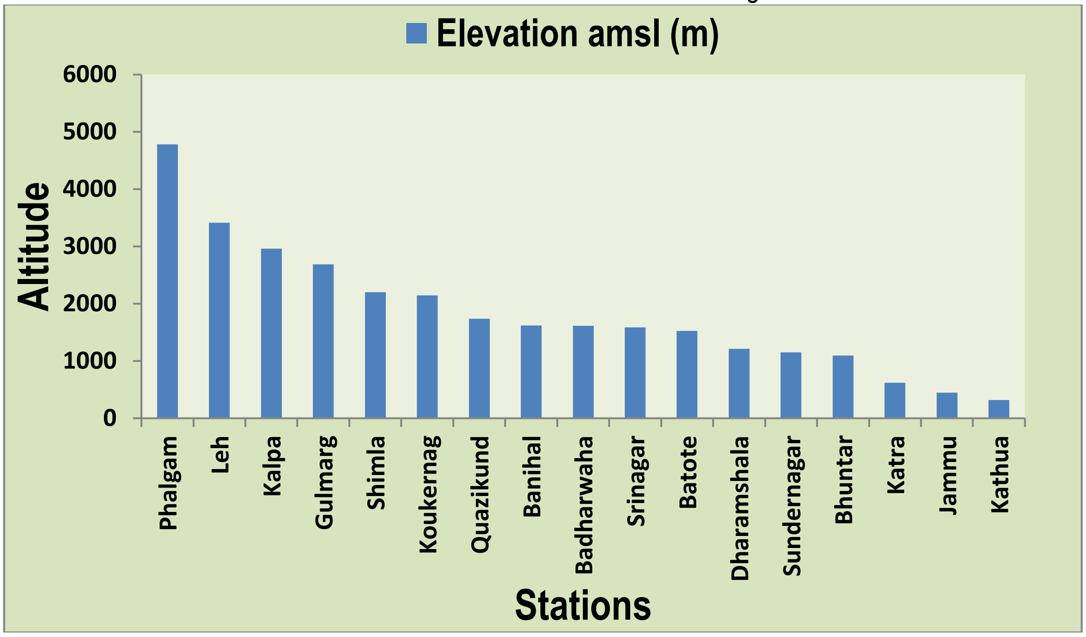

Fig.4

The temporal data set used for this study contains the maximum and minimum temperatures, precipitation for 30 years (1980-2009) for almost all the stations except for Leh wherein records are available upto 1990. Data for snowfall days are available only for 10 stations and period of data is also varies for these stations. Availability of snowfall data is 30 years or more for all the stations except for Leh, Kapla and Shimla. Data for Leh is irregular with gap years and availability of data is only from 1961-69,1978-89 . For Shimla data is available from 1989-2011, and no data is available for Kalpa. The annual and seasonal trend analysis for season viz premonsoon(March-May), Monsoon (June-September), Post monsoon (Oct-Dec) and winter (Jan-Feb) was carried out for temperature and precipitation over space and time and the rate of change of behavior of these parameters were worked out. As winter precipitation in Himalayan region are also influenced by variability of North Atlantic Oscillation Index(NAO) which is usually determined by normalized sea level pressure difference over Azores and Iceland(Jones etal.,1997). Attempt has also been made in this paper to correlate winter precipitation (Dec-Feb) of the seventeen stations under study for the period from 1990-2000 by using winter NAO index (Dec-Feb) average of normalized sea level pressure difference over Azore and Iceland(NAO-Dec-Feb) for the above period. Data for NAO index has been obtained online from http://www.cpc.ncep.noaa.gov/ .

RESULTS AND DISCUSSION

Seasonal Variability in Maximum Temperature

The seasonal average of maximum temperature for the period under study of different locations is presented in Table 1. The annual maximum temperature is lowest at Leh with 13.5 ºC and highest at Jammu with 29.7 ºC. Among the seasons i.e. Pre-monsoon (March-May), SW-monsoon (June-September), Post-monsoon (October-November) and Winter (Dec-

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February) the SW-monsoon season experienced the highest temperature. The trend analysis of annual seasonal maximum temperature (Table 2) showed that all the stations have the increasing trend since 1980 except Kathua. The highest warming rate was recorded at Shimla with 0.1 ºC/year followed by Koukernag and Kalpa. In case of pre-monsoon season, all the stations showed well marked increasing trend and the highest increasing rate was observed at higher elevations. The maximum temperature was increased in the range of 0.04-0.16 ºC/year. The SW-monsoon season is getting warmer in higher altitudes and vice-versa and Shimla recorded the highest warming rate with 0.6 ºC/year. The post-monsoon season followed the trend more or less similar to SW-monsoon season. In case of winter season all the stations have recorded increasing trend except Kathua. The highest increase was noticed at Srinagar and Shimla (0.13 ºC/year). Among all the stations the Shimla is getting warmer more rapidly as compared to others.

Table 1: Season wise Average of maximum temperature (ºC)

	Annual	Pre-monsoon	SW Monsoon	Post monsoon	Winter
Leh	13.5	13.4	25.1	12.3	2.6
Kalpa	16.1	16.4	22.3	16.4	7.3
Gulmarg	11.9	10.4	19.8	11.2	2.1
Shimla	18.8	20.3	22.8	18.4	12.1
Koukernag	18.0	18.3	26.5	16.9	6.7
Quazikund	19.3	19.4	27.3	19.2	8.3
Banihal	21.4	21.6	28.2	21.8	12.1
Badharwaha	22.6	23.0	29.8	22.5	13.9
Srinagar	20.1	20.4	28.7	18.5	8.7
Batote	20.7	21.2	26.8	20.7	11.9
Dharamshala	24.0	26.0	28.1	23.5	16.7
Sundernagar	26.9	29.5	31.3	26.4	19.0
Bhuntar	25.7	26.8	31.5	25.4	17.2
Katra	26.6	29.0	31.4	26.0	18.5
Jammu	29.7	32.4	34.9	29.0	20.5
Kathua	29.6	31.5	34.5	29.4	20.6

Table 2: Season wise linear trend and rate (ºC/year) of maximum temperature at different stations

Station	Annual		Pre-monsoon		SW Monsoon		Post monsoon		Winter	
	Trend	Rate	Trend	Rate	Trend	Rate	Trend	Rate	Trend	Rate
Kalpa	I	0.07	I	0.16	I	0.01	I	0.04	I	0.09
Gulmarg	I	0.01	I	0.10	I	0.00	I	0.09	I	0.02
Shimla	I	0.10	I	0.14	I	0.60	I	0.11	I	0.13
Koukernag	I	0.07	I	0.11	I	0.03	I	0.03	I	0.09
Quazikund	I	0.04	I	0.06	D	0.04	D	0.00	I	0.04
Banihal	I	0.06	I	0.12	I	0.01	I	0.05	I	0.10
Badharwaha	I	0.01	I	0.08	D	0.02	I	0.02	I	0.10
Srinagar	I	0.07	I	0.15	D	0.01	D	0.02	I	0.13
Batote	I	0.01	I	0.05	D	0.02	I	0.01	I	0.05
Dharamshala	I	0.06	I	0.09	I	0.00	I	0.05	I	0.10
Sundernagar	I	0.06	I	0.14	I	0.01	I	0.03	I	0.09
Bhuntar	I	0.03	I	0.07	D	0.02	D	0.00	I	0.06
Katra	I	0.01	I	0.08	D	0.04	D	0.02	I	0.03
Jammu	I	0.02	I	0.04	D	0.04	I	0.02	I	0.02
Kathua	D	0.02	I	0.10	D	0.06	D	0.05	D	0.04

I= increasing trend, D= decreasing trend

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Seasonal Variability in Minimum Temperature

The Table 3 shows the average minimum temperature of different locations for different meteorological seasons. The Leh being at highest altitude recorded lowest annual minimum temperature of -0.7 ºC and highest at Jammu with 17.8 ºC. During winter the spatial range of minimum temperature was from 8.8 to -12.4 ºC. The trend analysis of annual minimum temperature is presented in Table 4 which revealed that all the stations have the increasing trend except Kalpa. The highest increasing rate was recorded at Badharwaha with 0.12 ºC/year followed by Shimla and Jammu. The pre-monsoon season has also showed the similar trend. The SW-monsoon season is getting warmer at all the stations with few exceptions,

Table 3: Season wise normal minimum temperature (ºC)

	Annual	Pre-monsoon	SW Monsoon	Post monsoon	Winter
Leh	-0.7	0.1	11.1	-4.1	-12.4
Kalpa	4.4	3.7	11.1	2.4	-2.5
Gulmarg	3.0	1.9	10.5	1.4	-6.3
Shimla	10.5	11.2	15.4	9.4	4.0
Koukernag	6.6	6.3	14.0	4.2	-2.2
Quazikund	6.5	6.3	14.2	3.0	-1.6
Banihal	8.3	8.0	15.6	5.3	0.8
Badharwaha	7.4	6.9	14.9	4.7	-0.1
Srinagar	7.7	8.0	15.6	3.0	-0.8
Batote	9.8	9.8	16.7	8.1	2.3
Dharamshala	14.5	15.4	20.2	12.6	7.3
Sundernagar	12.5	13.0	20.4	9.2	3.8
Bhuntar	10.3	9.8	18.3	7.2	2.4
Katra	14.9	16.3	21.2	12.8	7.2
Jammu	17.8	19.0	24.7	15.5	8.8
Kathua	16.4	17.1	23.7	14.9	7.8

Table 4: Season wise linear trend and rate (ºC/year) of minimum temperature at different stations

Station	Annual		Pre-monsoon		SW Monsoon		Post monsoon		Winter	
	Trend	Rate	Trend	Rate	Trend	Rate	Trend	Rate	Trend	Rate
Kalpa	D	0.11	D	0.07	D	0.15	D	0.12	D	0.06
Gulmarg	I	0.05	I	0.10	I	0.04	I	0.08	I	0.08
Shimla	I	0.08	I	0.11	I	0.08	I	0.06	I	0.09
Koukernag	I	0.03	I	0.04	I	0.01	D	0.02	I	0.05
Quazikund	I	0.04	I	0.01	I	0.01	D	0.05	I	0.03
Banihal	I	0.04	I	0.05	I	0.04	I	0.01	I	0.05
Badharwaha	I	0.12	I	0.14	I	0.12	I	0.12	I	0.14
Srinagar	I	0.02	I	0.06	D	0.01	D	0.05	I	0.05
Batote	I	0.07	I	0.09	I	0.05	I	0.08	I	0.08
Dharamshala	I	0.03	I	0.03	I	0.01	I	0.01	I	0.07
Sundernagar	I	0.00	I	0.02	D	0.00	D	0.01	I	0.01
Bhuntar	I	0.02	I	0.03	I	0.01	I	0.04	I	0.01
Katra	I	0.07	I	0.10	I	0.04	I	0.07	I	0.09
Jammu	I	0.08	I	0.13	I	0.04	I	0.06	I	0.05
Kathua	I	0.05	I	0.09	I	0.03	D	0.04	D	0.04

I= increasing trend, D= decreasing trend

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whereas, the post-monsoon season showed a mixed response. In case of winter season all the stations have recorded increasing trend except Kathua and Kalpa. The highest increase among all the seasons was noticed at Badharwaha and on the other hand Kalpa showed a decreasing trend of minimum temperature.

Seasonal Variability in Rainfall

The seasonal average of rainfall for period under study for different locations for different season is depicted in Fig.5. The Dharamshala recoded the highest total rainfall (2622 mm) followed by Katra (2127 mm) and the lowest total rainfall was recoded at Leh (60 mm). The results of rainfall trend analysis are presented in Table 5 which showed that all the stations have the decreasing trend of annual rainfall except Kalpa, Shimla and Dharamshala. The Badharwaha has recoded the decreasing rate as high as 11.9 mm/year followed by Batote (10.8 mm/year) and Kathua and Koukernag (10.4 mm/year).

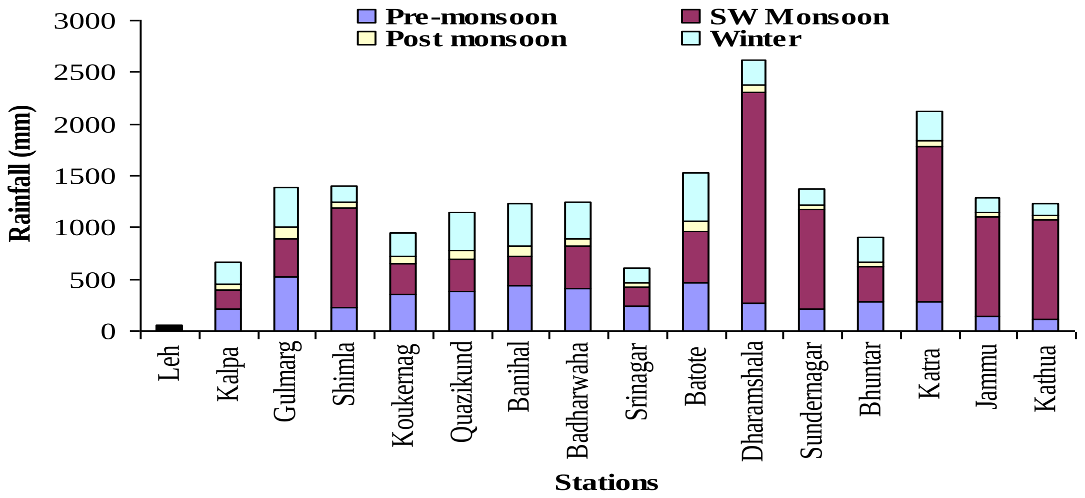

Fig 5: Seasonal rainfall (mm) at different stations

Table 5: Season wise linear trend and rate (mm/year) of rainfall at different stations

Station	Annual		Pre-monsoon		SW Monsoon		Post monsoon		Winter	
	Trend	Rate	Trend	Rate	Trend	Rate	Trend	Rate	Trend	Rate
Kalpa	I	1.05	D	0.75	I	4.51	D	1.9	D	0.79
Gulmarg	D	8.67	D	10.19	D	2.38	D	0.9	I	4.94
Shimla	I	9.58	I	0.28	I	8.41	D	1.4	I	2.30
Koukernag	D	10.37	D	7.96	I	0.13	D	1.8	D	0.37
Quazikund	D	8.15	D	6.73	I	0.28	D	1.5	D	0.22
Banihal	D	3.18	D	8.54	I	1.08	D	0.8	I	5.03
Badharwaha	D	11.93	D	10.14	I	0.86	D	1.1	D	1.32
Srinagar	D	2.55	D	5.00	I	0.08	D	0.4	I	2.77
Batote	D	10.79	D	11.09	I	0.38	I	0.4	D	0.52
Dharamshala	I	6.82	D	2.40	I	11.84	I	0.0	D	2.64
Sundernagar	D	6.21	D	3.61	I	2.95	D	1.1	D	4.48
Bhuntar	D	1.59	D	5.81	I	5.28	D	0.5	D	0.00
Katra	D	5.69	D	5.72	I	1.73	D	0.5	D	1.21
Jammu	D	0.82	D	2.94	I	3.36	D	0.1	D	0.50
Kathua	D	10.42	D	3.02	D	4.32	D	1.5	D	1.55

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The seasonal trend analysis showed that all the seasons have recorded decreasing trend in rainfall except SW-monsoon which showed an increasing trend with few exceptions. The rainfall increasing rate during SW-monsoon period was as high as 11.8 mm/year at Dharamshala followed by Shimla @ 8.4 mm/year.

Trend of snowfall days

The Fig. 6 depicts the average number of days on which the snow has occurred normally at different stations.

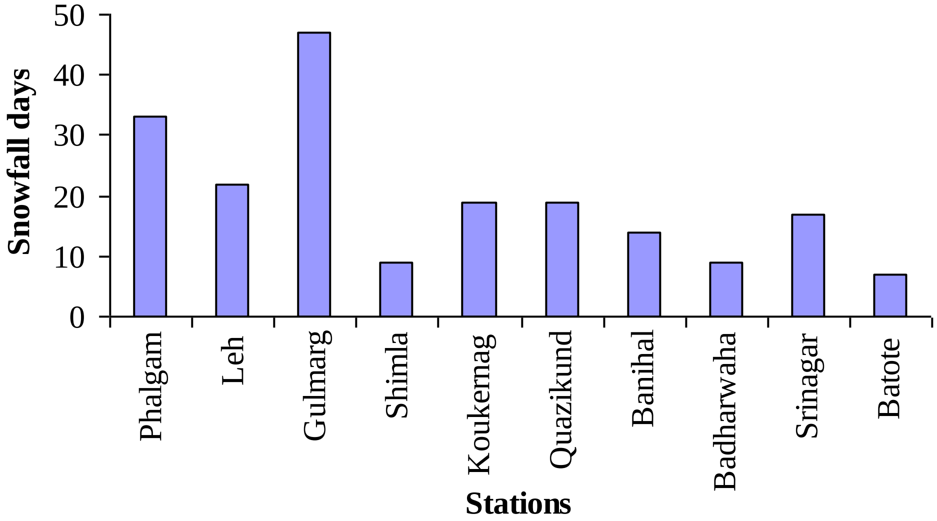
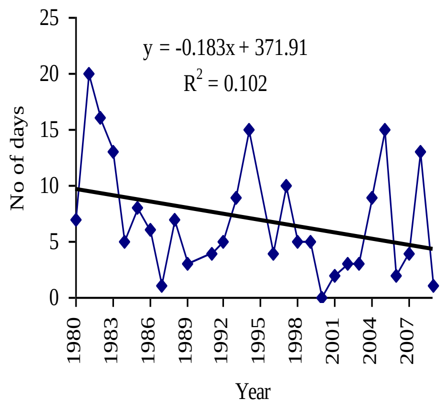


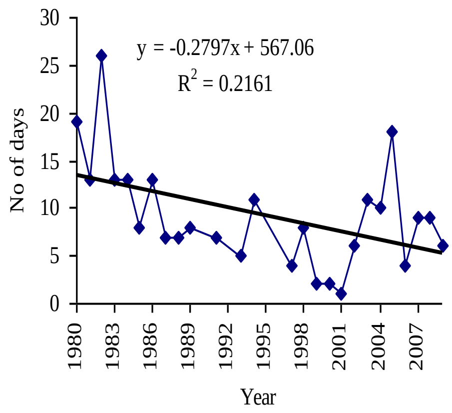
Fig 6: Average annual snowfall days

The highest snowfall days was recorded at Gulmarg with 47 days in the season followed by Phalgam and Leh with 33 and 22 snowfall days, respectively. The linear trend analysis showed a decline in snowfall days at all the stations and shown in fig.7 The highest decline was noticed at Koukernag @ 0.6 day/year followed by Gulmarg and Shimla with decreasing rate of 0.5 day/year.

Fig 7: Linear trend of snowfall days at different stations



Batote



Badharwaha

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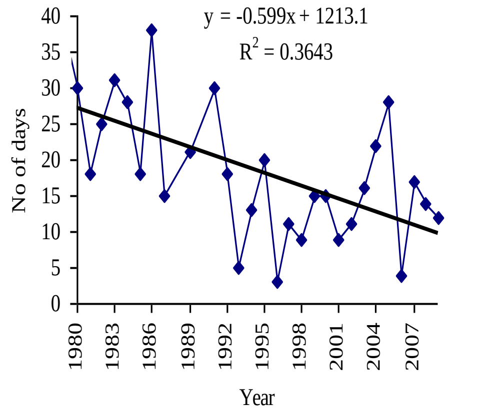
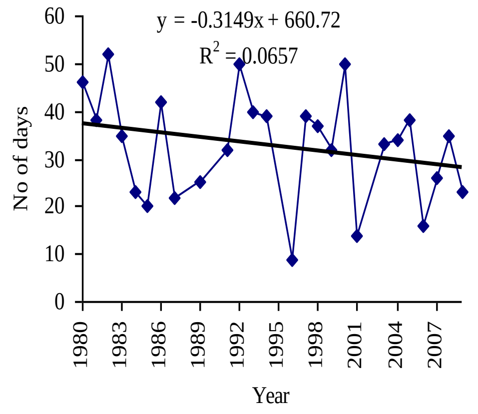
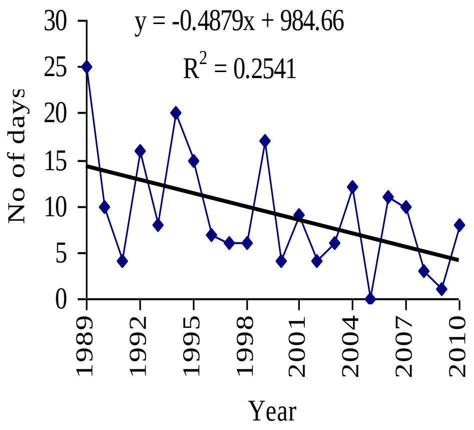


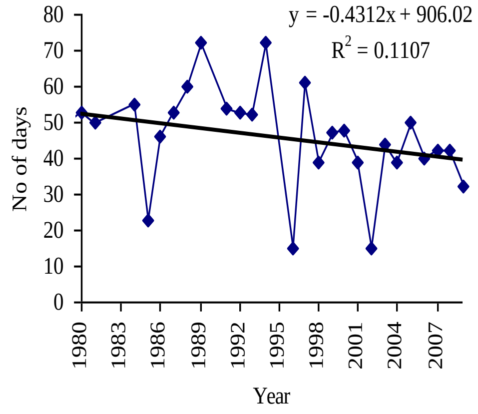
Koukernag



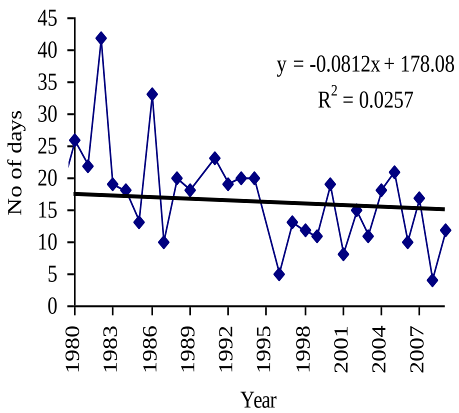
Phalgam



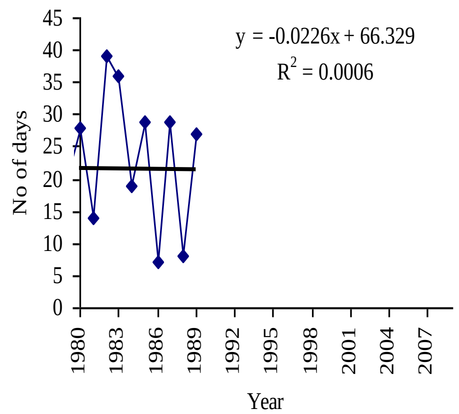
Shimla



Gulmarg



Srinagar



Leh

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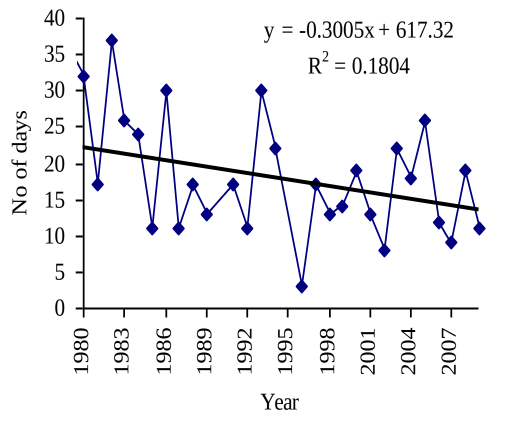
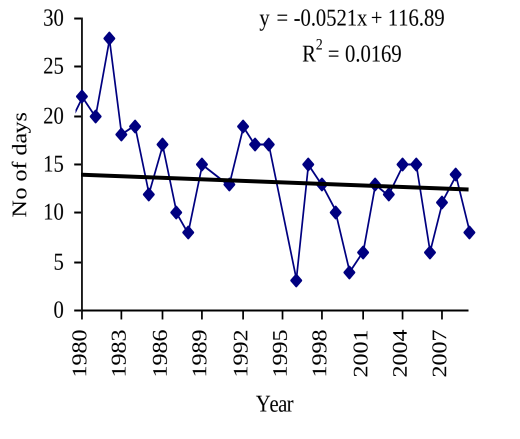


Quazikund



Banihal

Teleconnection

A permanent low-pressure system over Iceland (the Icelandic Low) and a permanent high-pressure system over the Azores (the Azores High) which control the direction and strength of westerly winds which bring precipitation in Himalyan region influence the precipitation in Himalayan region. The relative strengths and positions of these systems vary from year to year and this variation is known as the NAO. Warm NAO leads to increased westerlies and, consequently, cool summers and mild and wet winters whereas in low (NAO), westerlies are suppressed, these areas suffer cold winters and storms track southerly toward the Mediterranean Sea. This brings increased storm activity and rainfall

In order to see teleconnection between Atlantic weather system and winter rainfall in western Himlayan region for the stations under study, total monthly rainfall amount for winter(Dec-Feb) was correlated with average value of normalized sea level pressure difference over Azore and Iceland for winter months (Dec-Feb) for the period 1990-2000 for seventeen stations. Correlation between average value of normalized sea level pressure difference over Azore and Iceland(NAO- DF) and monthly total rainfall for winter period(Dec-Feb) is shown in table 6 below. Preliminary analysis indicate a significant positive correlation between winter North Atlantic Oscillation Index and winter precipitation at stations in middle and great Himalyas..

Table.6. Correlation between December to February NAO pressure Index and Dec-Feb rainfall total for selected station during the period 1990-2000

Banihal	0.07
Katra	-0.08
Batote	-0.08
Phalgam	0.12
Bhadrwaha	-0.11
Quazikund	-0.26
Kukernag	+0.40
Srinagar	0.47
Leh	0.50
Jammu	0.20
Kathua	-0.03
Gulmarg	0.4
Shimla	-0.11
Bhuntar	0.06
Sundernagar	-0.37
Kalpa	0.56
Dharamshala	-0.40

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CONCLUSIONS

The study revealed that the spatial and temporal variability in temperature and precipitation trends are very prominent and the western Himalayan region is witnessing the impacts of climate change by showing the increasing trends in temperature which is more prominent at higher altitudes. The rainfall is also decreasing but the rainy season has recorded positive trends. The increasing temperature in upper Himalayas resulting in reduced snowfall days. . Preliminary analysis indicate a significant positive correlation between winter North Atlantic Oscillation Index and winter precipitation at stations in middle and great Himalayas. However these correlation are not exhaustive and are of limited practical value for water resource management and more comprehensive analysis of global climate variable is needed .

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REFRENCES

Archer, David R. and Fowler, Hayley J. 2004. Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. Hydrol. Earth Sys. Sci. 8(1): 47-61.

Barnston, A. G., R. E. Livezey, 1987: Classification, seasonality and persistence of low-frequency circulation patterns. Monthly Weather Review, 115: 1083–1126, DOI: 10.1175/1520-0493.

Borgaonkar, H.P., Pant, G.B. and Rupa Kumar, k. 1996. Ring-width variations in Cedrus deodora and its climatic response over the western Himalaya. Int. J. Climatol. 16: 1409-1422.

Divya and Mehrotra, R., 1995. Climate change and hydrology with emphasis on the Indian subcontinent. Hydrol. Sci. J. 40: 231–242.

Himalayan catchment. ERB and Northern European FRIEND Project 5 Cof., Slovakia.

Horel, J. D., 1981: A rotated principal component analysis of the interannual variability of the Northern Hemisphere 500mb height field. Monthly Weather Review, 109: 2080–2092, DOI: 10.1175/1520-0493.

IPCC. 2007. Fourth Assessment Report. Intergovernmental Panel on Climate Change Secretariat. Geneva, Switzerland. http://www.ipcc.ch/

Raicich, F., Pinardi, N. and Navarra, A. 2003. Teleconnections between Indian monsoon and Sahel rainfall and the Mediterranean. Int. J. Climatol. 23: 173-186.

Syed, F. S., F. Giorgi, J. S. Pal, M. P. King, 2006: Effect of remote forcings on the winter precipitation of central southwest Asia part 1: observations. Theor. Applied Climatology, 86: 147–160.

Pant, G. B., and K. Rupa Kumar, 1997: Climates of South Asia. (eds), J. Wiley and Sons: Chichester, 1997. Pp. xxiii + 320. ISBN 0-471-94948-5.

Shrestha, A.B., wake, C.P., Dibb, J.E. and Mayweski, P.A. 2000. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. Int. J. Climatol. 20: 317-327.

Singh, P. and Kumar, N. 1997. Impact assessment of climate change on the hydrological response of a snow and glacier melt runoff dominated Himalayan river. J. Hydrol. 193: 316-350.

Singh, R.B. and Sen Roy, S. 2002. Climate variability and hydrological extremes in a

UNFCCC. 2007. United Nations Framework Convention on Climate Change. Climate Change: Impacts, Vulnerabilities and Adaptation an Developing Countries. http://www.unfccc.int

Yang, S. 1996. Enso-Snow-Monsoon associations and seasonal-interannual predictions. Int. J. Climatol. 16: 125-134.

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Webster, P. J. and S. Yang, 1992: Monsoon and ENSO: Selectively Interactive Systems. Quart. J. Roy. Meteor. Soc., 118: 877-926

Webster, P.J., V. O. Magana., T. N. Palmer, J. Shukla, R. A. Tomas, M. Yanai, and T. Yasunari, 1998: Monsoons: Processes, predictability,and the prospects for prediction J. Geophys. Res., (TOGA special issue), June 29, 103: 14451-14510.

Wallace, J.M. and D.S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. Mon. Wea. Rev., 109: 784–812.