CLIMATE VARIABILITY OVER THE WESTERN HIMALAYA SINCE THE LITTLE ICE AGE: DENDROCLIMATIC IMPLICATIONS

G.B. PANT, H.P. BORGAONKAR and K. RUPA KUMAR
Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune

Abstract *Information on long-term climate variability of western Himalayan region based on instrumental records and dendroclimatic investigation have been discussed. Instrumental records of monthly temperature and precipitation of 10 stations for about 100 years have been analysed to look into the pattern of climate variability during the 20th century. Wide network of tree-ring data of Himalayan conifers have been used to deduce climatic information beyond the instrumental period. Pre-monsoon (March-April-May) climate of western Himalaya reconstructed from tree-rings since AD 1747 do not show any impact of Little Ice Age in the later phase of the phenomenon.*

INTRODUCTION

There are very few studies available (Pant and Borgaonkar, 1984a) on climate change during the instrumental record for the Himalayan region. Most of the studies of the region deal with the climate conditions over the specific locale (Dhar and Farooqui, 1973; Dhar et al., 1987). Information on long-term variability based on instrumental as well as proxy records is equally important to understand the nature of different climatic systems over the region. Such information is very useful in various aspects of environmental studies such as glacier fluctuations, water resource projects, and forest ecosystem management. This also provides some glimpses of anthropogenic activities causing changes in the regional environment.

Due to the characteristic geographical setting of the Himalaya from west to east, the differences in temperature and precipitation regime are not only well marked but distinctly reflected in many of the environmental responses such as composition of flora, vertical limits of tree-growth, snow-line, time of snow melt discharge in the river etc. In winter, the great Himalayan ranges serve as an effective barrier to the intensely cold continental air blowing southwards into the subcontinent. In the monsoon months, the Himalayas force the rainbearing winds up the mountains to deposit most of their moisture on the Indian side. One of the most important effects of Himalayas on the summer monsoon of India is in the location of the 'heat low' over Sind and adjoining areas and the monsoon 'trough' across northern India. The heat low is known to be one of the controlling factors of the monsoon circulation in the lower levels in the Indian subcontinent. It is an established fact that the position of the heat low over Sind and that of the monsoon trough over the northern plains are determined by the mountain and surrounding hill configuration (Rao, 1981).

The geological, palaeobotanical and archaeological studies from this region point towards its palaeoclimatic history of glacial and interglacial phases in a broader sense. However, corroborative signals of climatic significance need careful examination. In the recent past, with about a century of recorded data, the region shows the most varied climate throughout the year. Large variations in topography and location result in great contrasting climates within short distances. Besides these local and regional variations in climate, the entire Himalaya experiences a general weather and climate pattern dictated by the monsoon systems of Asia and the chain of mid latitude extra-tropical systems.

INSTRUMENTAL PERIOD CLIMATE CHANGE

For the Himalayan region, most of the climate studies so far have dealt with the mean precipitation conditions over specific locales like Mount Everest (Dhar and Narayanan, 1965), Cherrapunji (Dhar and Farooqui,1973), Garhwal Kumaon Himalaya (Dhar et al., 1984a), Uttar Pradesh Himalaya (Dhar et al., 1987) and Ladakh region (Dhar and Mulye, 1987); extreme rainfall events (Dhar et al., 1975) and break-monsoon rains over the foothills of north India (Dhar et al., 1984b); and variation of rainfall with elevation (Dhar and Bhattacharya, 1976). There are very few studies available on the climate change of the Himalayan region during the instrumental record of the past century. Pant and Borgaonkar (1984a) studied the climate of the hill regions of Uttar Pradesh on the basis of annual rainfall data of six stations and temperature data at one station, for a period of about a century. They found that the rainfall at the six stations is significantly correlated, indicating that the interannual variability has good spatial coherence. They did not find any long-term trend in the rainfall series. However, there was a long period of below-normal rainfall during 1925-1975. A marked increase in winter maximum and winter mean temperature was also observed after the year 1935.

Attempts have been made to look at the available climatic records on rainfall and temperature at some observations in and around the western Himalaya, for possible evidences of long-term changes. The data are taken from the Monthly Weather Reports of the India Meteorographical Department and other published reports. The rainfall includes snowfall also, converted to rainwater terms, wherever applicable. It may, however, be noted that the results can only be an indicator of the broad signal of climatic change over the western Himalaya. Of course, the complex terrain of the Himalaya make generalizations extremely difficult, if not impossible.

RAINFALL

The mean, standard deviation and linear trend during the available period for all the stations are presented in Table 1. The linear trends are expressed in cm/100 years. These statistics have been given for four seasonal totals as well as the annual total of rainfall. Srinagar, which is well beyond the reach of the monsoon, shows conspicuously different rainfall regime both in terms of mean and standard deviation. Pre-monsoon season experiences maximum amount (38%) of annual rainfall. In case of Shimla, all the seasons except post-monsoon season show significant negative trend, whereas post-monsoon rainfall shows significant positive trend over the period of a century.

Table 1 Mean, standard deviation and long-term trends of rainfall of the Western Himalayan stations

Station	Period	Parameters @	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Srinagar	1893-1990	Mean	17.1	26.0	19.7	4.6	66.4
		Std.dev.	7.9	9.2	6.8	4.1	14.2
		Trend	-3.6	·1.2	-1.7	2.9*	-2.2
Shimla	1863-1990	Mean	16.6	18.2	120.0	4.7	157.7
		Std.dev.	9.7	10.3	28.2	5.0	31.2
		Trend	-4.6*	-7.5*	-18.1*	1.0*	-29.8**
Mussoorie	1869-1987	Mean	15.3	14.7	201.0	5.2	230.8
		Std.dev.	8.2	7.4	42.8	7.4	46.7
		Trend	-4.1	-2.2	-25.4	3.6	-29.2
Dehradun	1861-1990	Mean	14.8	9.2	199.6	4.4	221.1
		Std.dev.	9.1	5.5	47.5	6.1	49.3
		Trend	3.5	0.4	22.1	4.3*	28.8*
Pauri	1871-1980	Mean	15.0	13.6	97.2	4.3	130.0
		Std.dev.	7.9	7.6	23.5	6.5	26.9
		Trend	-1.5	-1.9	5.2	2.2	3.8
Nainital	1849-1980	Mean	17.2	16.3	209.9	7.7	252.3
		Std.dev.	10.9	10.5	60.4	13.1	66.0
		Trend	-2.8	-1.6	11.1	3.8	16.2
Mukteswar	1901-1990	Mean	13.9	13.7	98.0	6.8	135.2
		Std.dev.	7.6	7.0	26.2	9.5	30.2
		Trend	-3.8	1.9	-7.8	1.1	-8.8
Almora	1856-1980	Mean	11.3	12.1	78.1	4.3	105.9
		Std.dev.	6.0	6.2	20.5	6.5	23.3
		Trend	-1.1	-2.0	5.2	2.8	5.4
Joshimath	1871-1987	Mean	20.0	19.0	61.1	4.4	101.3
		Std.dev.	11.2	10.0	22.5	5.0	31.4
		Trend	-1.0	-1.4	-12.4	1.9	-13.7
Pithoragarh	1864-1980	Mean	12.4	15.0	97.8	4.9	130.2
		Std.dev.	7.0	7.8	25.0	6.9	28.2
		Trend	-1.0	-0.6	13.0	3.4*	14.7
Western	1901-1980	Mean	6.4	6.2	9.5	4.4	7.9
Himalaya		Std.dev.	-1.0	3.0	3.8	0.8	1.0
(Anomalies)		Trend					

@ Mean and standard deviation in cm; Trend in cm/100 years
* Significant at 5% level; ** Significant 1% level

Annual and post-monsoon rainfall of Dehradun and post-monsoon rainfall of Pithoragarh show significant increasing trend. A noticeable feature for all the stations except Dehradun is that they show decreasing rainfall tendency in the winter season, whereas all stations experience increasing tendency for post-monsoon rainfall. The mean rainfall anomalies for the Western Himalaya have also been computed for the common period 1901-80 using the ten stations listed in the Table 1. These anomalies have been obtained by arithmetic average of rainfall anomalies at individual stations from their respective means. The linear trends do not show any significant increase or decrease in rainfall during 1901-1980 in any of the seasons. Figure 1(a) represents annual Western Himalayan rainfall anomalies. The smooth curve (dashed line) is the 8th degree polynomial curve indicating low frequency variability. The smooth curve does not show any marked trend in the annual rainfall. However, except for winter season all other seasons and annual rainfall show a slight long-term increase in rainfall.

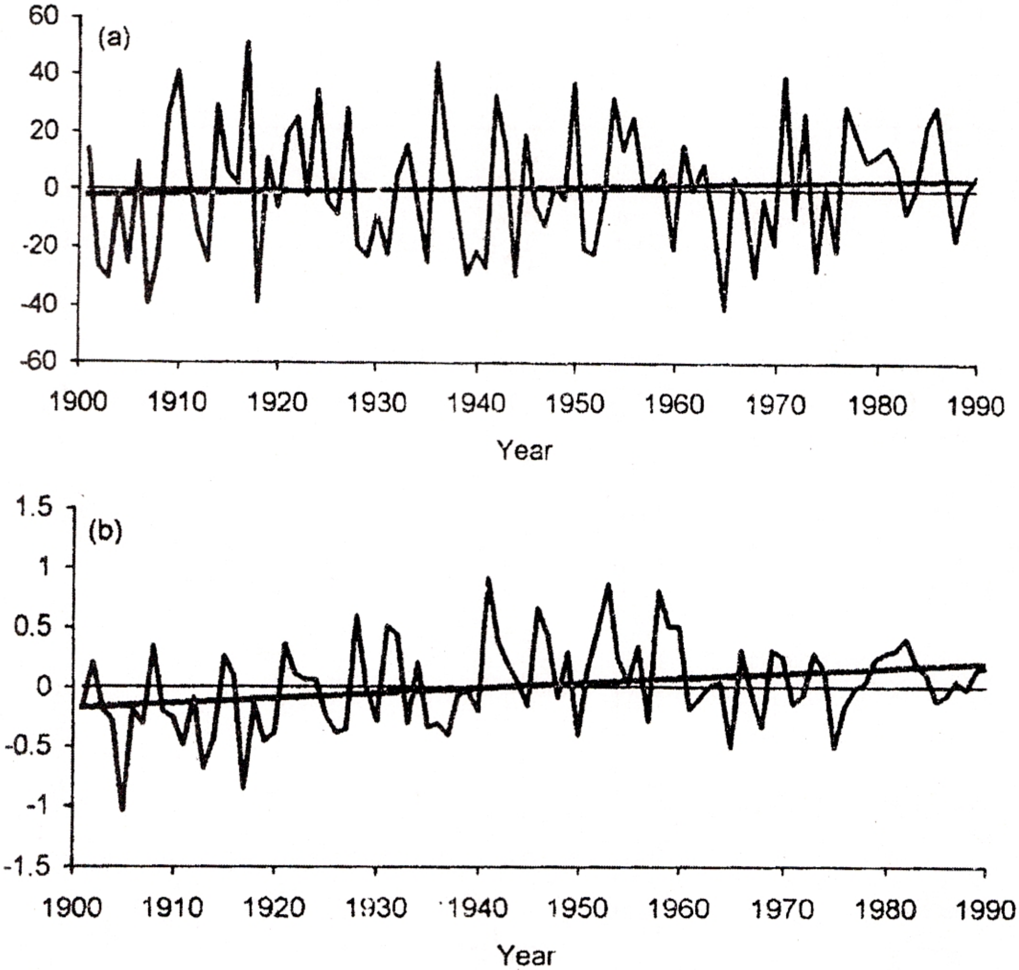

Fig. 1 Annual mean temperature and rainfall anomalies over western Himalaya based on instrument records.

TEMPERATURE

The mean, standard deviation and linear trend (^{o}C/100 years) for seasonal as well as annual mean temperature are presented in Table 2. During winter season all the six stations show increasing trend, of which Srinagar, Mussorie and Mukteswar experience significant increasing trend. During the pre-monsoon season, none of the stations shows any significant trend. During the monsoon season, Srinagar, which is beyond the monsoon regime, shows significant increasing trend, whereas the stations Mussoorie and Dehradun which are at the foothills of Himalaya show significant decreasing trend. In the post-monsoon season, all stations except Leh show increasing tendency of mean temperature, the increase being most conspicuous at Shimla and Mukteswar. The spatial mean temperature anomalies for four seasons as well as annual temperature have been computed for the common period 1901-90 using data of five stations namely Srinagar, Shimla, Mussoorie, Dehradun and Mukteswar. The station Leh has not been included in the common period analysis as data period is relatively short. A general increasing trend in mean temperature has been observed over the Western Himalaya during the period 1901-90 in all seasons. Temperature in monsoon season do not have any trend, whereas in other seasons conspicuous increase in mean temperature, particularly in pre-monsoon and post-monsoon temperature has been observed. Figure 1(b) indicates annual mean temperature anomalies of Western Himalaya.

Table 2 Mean, standard deviation and long-term trends of mean temperature of the Western Himalayan stations

Station	Period	Parameters @	Winter	Pre-monsoon	Monsoon	Post-monsoon	Annual
Lah	1901-1960	Mean	-4.9	5.3	15.3	3.8	5.8
		Std.dev.	0.8	1.1	0.8	1.1	0.6
		Trend	0.3	-0.6	0.4	-1.2	0.0
Srinagar	1893-1990	Mean	2.6	13.0	22.5	10.4	13.3
		Std.dev.	1.4	1.0	0.8	0.9	0.7
		Trend	1.4*	0.7	0.7*	0.3	0.8**
Shimla	1876-1990	Mean	6.5	14.9	18.4	12.6	13.5
		Std.dev.	1.2	1.2	0.5	1.0	0.7
		Trend	0.2	-0.3	-0.3	0.5*	-0.2
Mussoorie	1901-1990	Mean	6.7	16.4	18.1	13.0	14.4
		Std.dev.	0.9	1.1	0.3	0.7	0.7
		Trend	.4	0.3	-0.9*	0.8	0.4
Dehradun	1901-1990	Mean	13.8	24.5	25.9	19.8	21.7
		Std.dev.	0.8	1.0	1.2	0.8	0.7
		Trend	0.1	-0.3	-0.6	0.1	-0.2
Mukteswar	1901-1990	Mean	7.2	14.5	17.4	12.8	13.5
		Std.dev.	1.1	1.1	0.7	0.7	0.5
		Trend	1.3*	0.6	-0.2	0.8*	0.4
Western Himalaya (Anomalies)	1901-1990	Mean	0.6	1.0	0.2	0.8	0.4
		Std.dev.	0.5	0.7	0.0	0.8	0.5
		Trend					

@ Mean and standard deviation in °C; Trend in °C/100 years
* Significant at 5% level; ** Significant 1% level

DENDROCLIMATIC STUDIES

A very useful method of studying the climate of the recent past is based on the climatic inferences drawn from the annual growth rings of certain tree species. This area of study is known as dendroclimatology. There are several tree species which have distinct annual growth rings that can be precisely dated. Quite a few of them have a long life span, extending to several hundreds of years and occasionally reaching even a couple of thousands of years. These trees being substantially dependent on the climatic environment, provide the finest source of climatic information where instrumental records are not available. The climatic information recorded by the trees growing in stressful forest environment can be extracted from the size, structure and chemical composition of the annual growth rings. The precisely dated and continuous climatic information from tree rings is an important addition to other available data on seasonal to century scale climatic variations.

Over the Western Himalayan region a substantial work on tree-ring analysis has been carried out using Himalayan conifers such as Pinus, Picea, Cedrus, Abies (Pant, 1979, 1983; Pant and Borganokar, 1984b; Hughes and Davies, 1986; Borgaonkar et al., 1994, 1996). Tree-ring width index chronologies from different parts of the Western Himalaya show very significant relationship with pre-monsoon (March-April-May) climate (temperature and precipitation) of the region (Borgaonkar, 1996).

In the present analysis, total eight tree-ring index chronologies of Himalayan conifers (Borgaonkar, 1996) covering the period AD 1725-1988 have been subjected to principal component analysis. First three components of the data set explain more than 50% of the total variance, whereas first component itself explains about 35% of the total variance. Hence, first component has been used in further dendroclimatic analysis.

A stepwise multiple regression analysis is used to model tree growth-climate relationship. In this process when climatic parameters (monthly and seasonal temperature and precipitation) are predictors, it is called response function analysis (Fritts, 1996). It gives quantitative measure of relationship in terms of variance in tree growth due to particular climatic variable. In case of Himalayan conifers response function analysis revealed that the pre-monsoon (March-April-May) climate plays a very important role in tree growth-climate relationship (Borgaonkar et al., 1994, 1996; Borgaonkar, 1996). The strong association of pre-monsoon climate with tree growth is mainly due to severe moisture stress conditions occurring in these months. Figures 2(a) and 2(b) represent the response function analysis on monthly and seasonal scales, respectively. This analysis is based on first principal component of wide network of tree-ring data over entire Western Himalayan region and monthly as well as seasonal temperature and precipitation anomalies. In both cases, strong negative response of pre-monsoon temperature and positive response of precipitation during the same months on tree growth have been observed.

In climate reconstruction analysis tree growth parameters are used as predictions in multiple regression equation to estimate a most responsive climate. This is known as transfer function analysis. The calibration equation thus formed is verified width original climate data using various statistical test and then be used to reconstruct past climatic information by incorporating earlier part of tree-ring data in the equation. Figure 3 represents reconstructions of pre-monsoon temperature and precipitation anomalies of Western Himalaya from tree-ring data. The reconstructions go back to AD 1747, earlier to that the sample size is not sufficient to represent a signal to the significant level (Wigley et al., 1984). Smooth lines in the figure are low-frequency variations based on cubic spline smoothing at 50% VRF (Variance Reduction Frequency) of 10 year (Clock and Peters, 1981). Both temperature and precipitation series do not show any long-term trend. The reconstructions also reveal that the pre-monsoon climatic conditions during last 250 years were not significantly different that the present climatic conditions based on the instrumental records. Reconstructions cover later part of Little Ice Age. It is observed that this phenomenon was not significant in later phase over the Western Himalaya.

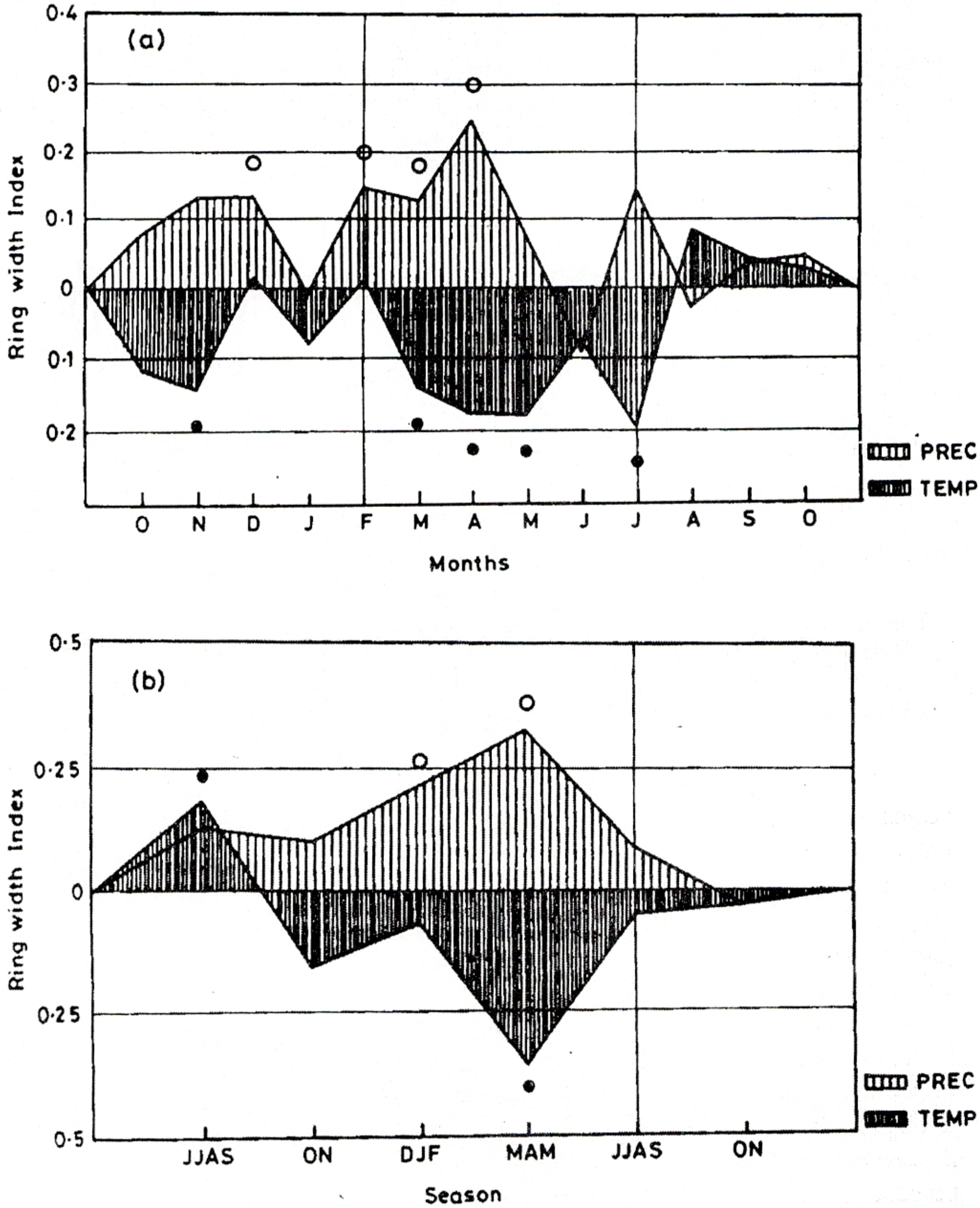

Fig. 2 Response function analysis (a) monthly, and (b) seasonal scale, using first component of western Himalaya tree-ring network and temperatute and precipation anomalies. Symbol • and o represent response of climate on tree growth significant level.

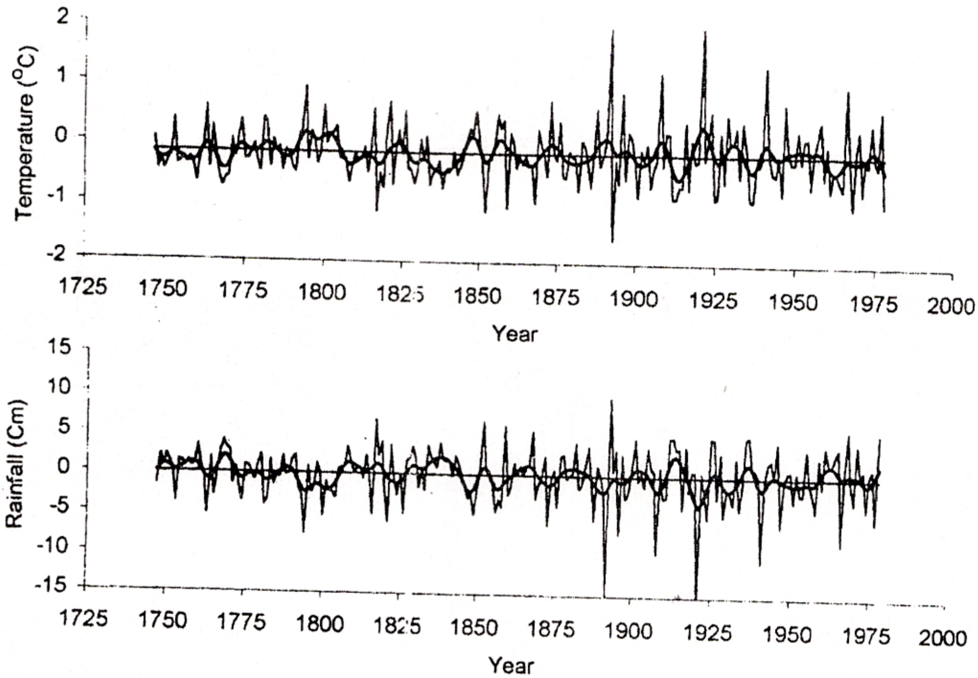

Fig. 3 Reconstructed pre monsoon (March-April-May), temperature and rainfall anomalies since AD 1747 over the western Himalaya using tree ring chronology network. Smooth lines indicate low frequency variations.

PALAEOCLIMATIC AND GLACIOLOGICAL STUDIES

The palaeoclimate of the Himalaya and north-west India on different time scales has been studied by various workers (e.g. Pilgrim, 1932, 1944; de Terra and Paterson, 1939; Moms, 1938; Zeuner, 1972; Agrawal, 1985; Agrawal et al. 1989; Bhattacharyya, 1989). On the whole, the climatic pattern of Kashmir and western part of the Himalaya follows a global trend: the warming up of the Pliocene, the glacial and interglacial oscillations of the Pleistocene, etc. However, the Pleistocene cooling was not abrupt but very gradual.

Information on past records of glacier fluctuations over the Himalayan region is also important to understand the cause and effect mechanism of climate variability. Very few studies (Mayewski and Jescke, 1979; Mayewski et al., 1980) are available which indicate glacier fluctuations since the beginning of 19th century in terms of absolute time scale. They reported the glacier fluctuations on the basis of percentage of advancement, retreating and stationary positions of several glaciers across the Himalaya on yearly scale since AD 1812. These records indicated the fluctuations in dominancy of advance and stationary positions of glaciers till AD 1870. During AD 1870 to 1940, random fluctuations in dominancy of retreat, advance and stationary regimes were observed followed by retreating phase in present decades. Mayewski et al. (1980) also discussed the relationship between glacial advances from 1890 to 1910 in the Trans-Himalaya and strengthened monsoon circulation pattern.

DISCUSSION AND CONCLUSIONS

Climatic information on Western Himalaya based on the instrumental records as well as dendroclimatic analysis do not indicate any long-term change in temperature and rainfall pattern since past 250 years. The role of Himalaya in controlling and maintaining Indian monsoon is so vital that it draws foremost attention of climatologists, geologists and other research workers to understand and the complex system of Himalaya in the context of regional as well as global climate change. Efforts are being made to extract palaeoclimatic information using various kind of proxy sources abundantly available in the Himalaya to look in to the past climate change and thereby model the cause and effect mechanism of monsoon and other related regional and global parameters such as snow cover, glacier fluctuations, El' Nino etc. Dendroclimatic reconstructions presented in this paper give pre-monsoon climatic variations for last 250 years. Reconstructed temperature and rainfall series do not show any long-term significant increasing or decreasing trend. Low-frequency variations indicate a warm and dry epoch from AD 1791-1805 and cool and wet epoch from AD 1827-1844. These reconstructions cover later part of Little Ice Age (AD 1747-1850) do not show strong influence of this phenomenon over this part of Himalaya.

Tree-ring data of the region have tremendous potential of past climatic information. Bhattacharyya and Yadav (1996) tried to analyse the relationship between tree-ring variations and glacier behaviour of few Western Himalayan glaciers. They showed the usefulness of tree-ring data to reconstruct the past information on the patterns of glacier movements. However, for a comprehensive and conclusive evidence of the climate change a better network of observations in remote areas is required. In the absence of long-period data over a dense network, proxy climatic records like tree-rings provide a very useful tool in understanding the contemporary climatic change patterns over the Himalaya.

Acknowledgement Authors are thankful to India Meteorological Department, Pune, for providing the basic meteorological data. Thanks are due to the Officials of the Forest Department of Uttar Pradesh and Himachal Pradesh for their co-operation during the field collection of samples. This study was supported by Department of Science and Technology, Govt. of India, under Research Grant No. ES/63/023/86.

REFERENCES

Agrawal, D.P. (1985) Cenzoic Climatic Changes in Kashmir: The Multi-disciplinary Data. In: Climate and Geology of Kashmir, Current Trends in Geology, Vol. VI (Eds. D.P. Agrawal, S. Kusumgar and R.V. Krishnamurthy) New Delhi, 1-12.

Agrawal, D.P., Dodia, R., Kotlia, B.S., Razdan, H. and Sahni, A. (1989) The Plio-Plestocene Geologic and Climatic Record of the Kashmir Valley, India: A Review and New Data. Paleogeogr. Palaeoclimatol, Palaeoecol., 73, 267-286.

Bhattacharya, A. (1989) Vegetation and Climate During the Last 30,000 Years in Ladakh. Palaeogeogr. Palaeoclimatol. Palaeoecol., 73, 25-38.

Bhattacharyya, A. and Yadav R.R. (1996) Dendrochronological Reconnaissance of Pinus Wallichiana to Study Glacial Behaviour in the Western Himalaya. Current Science, 70(8), 739-743.

Borgaonkar, H.P. (1996) Tree-Growth Climate Relationship and Long-Term Climate Change Over the Western Himalaya: A Dendroclimatic Approach. Ph.D. Thesis, Univ. of Pune, Pune.

Borgaonkar, H.P., Pant, G.B., Rupa Kumar, K. (1994) Dendroclimatic Reconstruction of Summer Precipitation at Srinagar, Kashmir, India since the late 18th Century. The Holocene 4, 3, 299-306.

Borgaonkar, H.P., Pant, G.B., Rupa Kumar, K. (1996) Ring-width Variations in Cedrus Deodara and its Climatic Response Over the Western Himalaya. Int. J. Climatology, 16, 1409-1422.

Cook, E.R. and Peters, K. (1981) The Smoothing Spline: A New Approach to Standardizing Forest Interior Tree-ring Width Series for Dendroclimatic Studies. Tree Ring Bull., 41, 45-53.

Dhar, O.N. and Battacharya, B.K. (1976) Variation of rainfall with elevation in the Himalayas-A pilot study. Ind. J. Power & Riv. Valley Dev., 26, 191-195.

Dhar, O.N. and Farooque, S.M.T. (1973) A study of rainfall recorded at the Cherrapunji observatory. Hydrol. Sci. Bull., 18.

Dhar, O.N. Kulkarni, A.K. and Snagam, R. B. (1975) A study of extreme point rainfall over flash flood prone regions of the Himalayan foothills of north India. Hydrol. Sci. Bull., 20, 61-67.

Dhar, O.N. Kulkarni, A.K. and Snagam, R. B., (1984a) Some aspects of winter and monsoon rainfall distribution over the Garhwal-Kumaon Himalayas- A brief appraisal. Himalayan Research & Development, 2, 10-19.

Dhar, O.N., Mandal, B. N. and Kulkarni, A.K. (1987) Some facts about precipitation distribution over the Himalayan region of Uttar Pradesh. In: Western Himalaya: Environment, Problems and Development, Vol. I (Eds. Y.P.S. Pangtey and S.C. Joshi), Gyanodaya Prakashan, Nainital, 72-86.

Dhar, O.N. and Mulye, S.S. (1987) Brief appraisal of precipitation climatology of the Ladakh region. In: Western Himalaya: Environment, Problems and Development, Vol. I (Eds. Y.P.S. Pangtey and S.C. Joshi), Gyanodaya Prakashan, Nainital, 87-98.

Dhar, O.N., and Narayanan, J. (1965) A study of Precipitation distribution in the neighoorhood of Mount Everest. Ind. J. Meteorol. Geophys., 16, 230-240.

Dhar, O.N., Soman, M.K. and Mulye, S.S. (1984b) Rainfall over the southern slopes of the Himalayas and the adjoining plains during breaks in monsoon. J. Climatol, 4, 671-676.

De Terra, H. and Paterson, T.T. (1939) Studies on the ice age in India and associated Human Cultures - Carnegic Inst. Washington, 493.

Fritts, H.C. (1976) Tree-Rings and Climate Academic Press Inc., New York.

Hughes, M.K., and Davies, A.C. (1986) Dendroclimatology in Kashmir using tree ring widths and densities in sub-alpine conifers, In: Methods in Dendrochronology-I: East-West Approaches (Eds. L. Kairiukstis, Z. Bednarz and E. Feliksik), Int. Inst. for Applied System Analysis, Polish Academy of Sciences, 163-175.

Mayewski, P.A. and Jescjke, P.A. (1979) Himalaya and Trans-Himalayan glacier fluctuations since AD 1812. Arctic and Alpine Res., 11, 267-287.

Mayewski, P.A., Pregent, G.P. and Jescjke, P. A. and Ahmad, N. (1980: Himalaya and Trans-Himalayan Glacier Fluctuations and South Asian Monsoon Records. Arctic and Alpine Res., 12, 171-182.

Morris T.O., (1938) The Bain Boulder Bed, A Glacial Episode in the Siwalik Series of the Marwet Kundi Range and Sheik Budin, North-west Frontier Province. Ind. J. Geol. Soc. London, 94, 385-421.

Pant, G.B. (1979) Role of Tree-Ring analysis and related studies in Palaeo-climatology: Preliminary survey and scope for Indian Region. Mausam, 30.

Pant, G.B. (1983) Climatological Signals from the Annual Growth Rings of Selected Tree Species of India. Mausam, 34.

Pant, G.B. and Borgaonkar, H.P. (1984a) Climate of the Hill regions of Uttar Pradesh. Himalayan Res. Dev., 3(1), 13-20.

Pant, G.B. and Borgaonkar, H.P. (1984b) Growth rate of Chir pines (Pinus roxburghii) trees in Kumaon Area in Relation to regional Climatology. Himalayan Res. Dev., 3(ll), 1-5.

Pilgrim, G.E. (1932) The fossil Comivora of India- Palaeol. India, Calcutta (n.s.), 18, 232.

Pligrim, G.E. (1944) The lower limit of the Pleistocene in Europe and Asia – Ged. Mag. London, 81, 28-38.

Rao, Y.P. (1981) The climate of the Indian subcontinent. In: Climates of Southern and Western Asia, World Survey of Climatology, Vol. 9 (Eds. K. Takahashi and H. Arakawa), Elsevier Scientific Publishing Company, Amsterdam, 67-182.

Wigley, T.M.L., Briffa, K.R. and Jones, P.D. (1984) On the average value of correlated time series with applications in dendroclimatology and hydrometeorology. J. Clim. Appl. Met., 23, 201-213.

Zeuner, F.E. (1972) Dating the Past. Harmer Publishing Co., New York.

JALVIGYAN SAMEEKSHA
(HYDROLOGY REVIEW)

Volume 18, Number 1-2, 2003

THEME : SNOW HYDROLOGY

Published by the Indian National Committee on Hydrology, Naational Institute of Hydrology. Roorkee. Printed at Gupta Printing Press, 22 Civil Lines, Roorkee-247667 Ph. 01332-271422.