EVALUATION OF TEMPORAL AND SPATIAL CLIMATIC VARIABILITY OVER INDIAN HIMALAYA

A THESIS

Submitted in partial fulfilment of the
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by

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **EVALUATION OF TEMPORAL AND SPATIAL CLIMATIC VARIABILITY OVER INDIAN HIMALAYA** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from July, 2002 to January, 2011 under the supervision of Dr. Ranvir Singh, Professor and Dr. N.K. Goel, Professor, Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee and Dr. Pratap Singh, Country Manager, Tahal Consulting Engineers Limited, New Delhi (Formerly Scientist, National Institute of Hydrology Roorkee).

The suggestions have been incorporated in compliance with the examiner's remarks.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

S.K. Shrivastava
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This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

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The Ph.D. Viva-Voce examination of **Mr. Salil Kumar Shrivastava,** Research Scholar, has been held on ...July 7, 2011........................

Signature of Supervisors

7/7/11
Signature of External Examiner

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ABSTRACT

The Indian Himalayas, the originating point of many important rivers, plays a vital role in controlling the weather of India. Despite this fact, the climate of Indian Himalayas is less studied because of its inaccessibility and hilly terrain that makes the data on meteorological and hydrological variables scarce. Mountains provide freshwater to half of the world's population and are home to half of all global biodiversity hotspots. Some of the questions which require a scientifically derived answer are as follows:

(i) What will be the impact of climate change in mountains and their adjacent lowlands?

(ii) Where will the change take place and who will be most affected?

To find the answer of the above questions, the Indian Himalayas where very limited studies have been undertaken was selected as the study area.

The present study has been taken up with the following objectives:

1. To analyze short-term and long-term dependence in the climate parameters
2. To study spatial and temporal trends in the climatic variables
3. To search for the evidences of short-range and long-range periodicity/hidden periodicity
4. To study the effect of climate change on the river discharge of a typical Himalayan river basin

Monthly meteorological data viz., maximum and minimum temperature, rainfall, number of rainy days and wind speed of varying length (22-59 years) for the period from 1933 to 2003 were procured from India Meteorological Department (IMD), Pune, for 23 selected stations (16 for wind speed) representatives of Indian Himalayas. For Satluj River basin daily maximum, minimum temperatures for six stations, rainfall data for eight stations, snowfall data for four stations and; discharge data for Bhakra gauging station were collected for the period 1985-2002 from the Bhakra Beas Management Board (BBMB), Nangal Township (Punjab), India.

Altogether 14 (13 for short-term and Hurst's H for long-term) tests, were used to determine the existence of statistically significant dependence structure in the annual series of climatological variables. Majority of the series indicated presence of short-term dependence where as conditional probabilities of existence of only long-term dependence were found to be negligible. The dependence was more pronounced in high altitude stations and stations with long records. Spatially, the eastern Himalayas show more dependence as compared to other regions of the Indian Himalayas.

The Mann-Kendall's test with boot strapping technique (1000 runs) and Linear regression test were applied using HYDROSPECT software to detect significant trends and magnitudes in the climatological variables. The trend test results were spatially analysed using Inverse Distance Weighted (IDW) interpolation technique in ArcGIS 9.2 software package. Significant falling trends in mean minimum, mean temperatures and mean wind speed while significant rising trends in the diurnal temperature range were found over various regions of Indian Himalayas and in the entire Indian Himalayas. The monsoon season was found to be badly affected season for all the climatological variables. Significant decrease in annual and monsoon rainfall and significant increase in winter rainfall were revealed. A sharp declining trend throughout the Indian Himalayas was observed in mean wind speed. Spatial trend analysis also indicate significant decrease in the mean temperature, rainfall, number of rainy days and mean wind speed over the western and central Himalayas.

The Blackman & Tukey power spectrum method was used to determine short-range and long-range periodicities in the climatological variables. In the entire Indian Himalayas very few periodicities were observed in the quasi-biennial oscillation (QBO) region (period 2-3 years). Most of the periodicities were observed at 3.3, 5, 6.7 years i.e. outside the QBO region in all the climatological variables. However, in eastern Himalayas for mean minimum temperature and mean wind speed and; in central Himalayas for mean temperature range the significant periodicities were also observed at some other periodicities near the sunspot cycle (11 years ± 1 years) and few near the Hale solar magnetic cycle (22 ± 1 years) in eastern Himalayas for annual rainfall. Since its effect is almost the same as that of a random component, no meaningful predictions can be made even though some significant larger periodicities exist.

Study of impact of climate change on water resources indicate a significant increase in annual mean temperature, mean maximum and mean minimum temperatures, unexpected

warming of pre-monsoon season, decrease in rainfall, snowfall and discharge at Satluj River basin of western Himalayas. The warming was more pronounced in high altitude stations receiving winter precipitation in the form of snowfall. Decrease in discharge from 1986-2002 in the Satluj River basin, may be due to diminishing contributions of the glaciers. The study also shows that there is decrease in the extreme flows. However, a detailed analysis of estimating impact of climate change in extreme flows is very important for designing of water resources, irrigation and hydropower projects.

LIST OF FIGURES

LIST OF TABLES

warming of pre-monsoon season, decrease in rainfall, snowfall and discharge at Satluj River basin of western Himalayas. The warming was more pronounced in high altitude stations receiving winter precipitation in the form of snowfall. Decrease in discharge from 1986-2002 in the Satluj River basin, may be due to diminishing contributions of the glaciers. The study also shows that there is decrease in the extreme flows. However, a detailed analysis of estimating impact of climate change in extreme flows is very important for designing of water resources, irrigation and hydropower projects.

CONTENTS

CHAPTERS

CHAPTER 1

INTRODUCTION

1.1 General

The 'global warming' is an undeniable fact of our lives today and its impacts are being felt all over the world by way of rising air temperature, changes in precipitation and faster melting of glaciers (Bhutiyani et al., 2010). According to the Fourth Assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007) the updated 100 years (1906-2005) series of global average surface temperature indicated an increase of 0.74°C ± 0.18°C as compared to the earlier estimated trends of 1901-2000 (0.6°C ± 0.2°C) series. The rate of warming over the last 50 years is almost double that over the last 100 years (0.13°C ± 0.03°C vs. 0.07°C ± 0.02°C per decade). Recent studies confirm that effects of urbanization and land use change on the global temperature record are negligible. The global average Diurnal Temperature Range (DTR) has stopped decreasing as no change has been observed from 1979 to 2004 due to equal rising of maximum and minimum temperature. The trends are highly variable from one region to another (IPCC, 2007). Global annual land mean precipitation showed a small, uncertain, upward trend of approximately 1.1 mm per decade (uncertainty ± 1.5 mm) over 1901-2005. During the 20th century, precipitation generally increased from 30°S to 85°N over land; but notable decreases have occurred between 10°S and 30°N in the last 30-40 years (IPCC, 2007).

The hydrologic system, which consists of the circulation of water from oceans to air and back to the oceans, is an integral part of the global climate system (Critchfield, 2002). It is widely accepted that changes in the climate system is influencing the components of hydrologic cycle. Glaciers are very sensitive to climate changes; therefore, they can be considered as good indicators of past climate changes (Nesje and Dahl, 2000). Widespread retreat of the world's glaciers was observed during the 20th century. The snow covered area of the world has decreased by 10% since the 1960s (IPCC, 2001a). The global mean sea level has increased at a rate of 1 to 2 mm per year during the 20th century due to thermal expansion of sea water and the melting of glaciers and ice sheets. For example, a local warming of 3°C, if sustained for thousands of years, would lead to a virtually complete melting of the Greenland ice sheet with a resulting sea-level rise of about 7 m (IPCC, 2001a). Such a projected sea-level rise may threaten the existence of coastal zones and their ecosystems.

Natural and human systems are expected to be exposed to direct effects of climatic variations such as changes in temperature and precipitation variability, as well as frequency and magnitude of extreme weather events. Similarly, there are indirect effects of climate change such as sea level rise, soil moisture changes, changes in land and water conditions, changes in the frequency of fire and changes in the distribution of vector-borne diseases.

Climate change may result in more intense precipitation events causing increased flood, landslide, avalanche and mudslide damages that will cause increased risks to human lives and properties (IPCC, 2001a). Likewise, warmer temperatures increase the water-holding capacity of the air and thus increase the potential evapotranspiration, reduce soil moisture and decrease ground water reserves (IPCC, 2001b), which ultimately affects the river flows and water availability.

Studies on the hydrological characteristics of watersheds in the Himalayan region have undergone reported changes due to land use leading to more frequent hydrological disasters, enhanced variability in rainfall and run-off events. The effect of climate change on hydrology of the region may be multifaceted: ranging from regional variations in precipitation characteristics, glacial shifts, mean run-off frequency etc. Increased temperatures and enhanced seasonal variability in precipitation are expected to result in glacier recession and increasing danger from glacier lake outburst floods. If the rainfall pattern in the Himalayas changes due to climate change, the impact could be felt in downstream countries like Bangladesh.

Studies show that developing countries like India are more vulnerable to climate change and are expected to suffer more from the adverse impacts than the developed countries (IPCC, 2001a). In a humid climate, there will be changes in the spatial and temporal distribution of temperature and precipitation due to climate change, which in turn will increase both the intensity and frequency of extreme events like droughts and floods (Mahtab, 1992). A warming climate would increase water demand on the one hand and would decrease river flows on the other. Reduced river flows may affect the hydro power generation, inland water transport and aquatic ecosystem. Results from regional studies indicated that the largest influence of climate change can be expected at high latitudes during winter time. The major river systems of the Indian subcontinent, Brahmaputra, Ganga and Indus, which originate in the Himalayas are expected to be extremely vulnerable to climate change because of the substantial contribution from snow and glaciers into these river systems (Singh and Bengtsson, 2004).

Due to limited knowledge of regional and local impacts of climate change, there are substantial uncertainties on quantifying the global impacts of climate change (IPCC, 1996a). Research efforts in these areas are "priorities for advancing understanding of potential consequences of climate change for human society and the natural world, as well as to support analyses of possible responses" (IPCC, 2001b).

It is very difficult to identify an accurate change in the Himalayan climate because of its large size, inaccessibility and unavailability of systematic climatological data (Chalise, 1994). The data on actual measurements of the changes in microclimate in most of the areas of the Himalaya remain empty and the limited climate observations are available only at the hill-stations in the foot-hills that have to be used to build up a broader picture of the climatology of the Himalaya (Mani, 1981).

Historic and pre-historic evidences show that mountain areas undergo major changes in glacio-hydrological and ecological conditions in response to changes in climate. Global models necessarily represent the orography of mountain areas in a highly simplified manner and the outputs give a generalized nature of the results (Barry, 1990). The evidence for changes in the climate has been mainly studied in a regional context and from a hemispheric or global perspective. The vertical spatial dimension has been largely neglected (Barry, 1990). In order to assess the possible future climatic trends and their effects, it is important to know whether these changes will be felt equally in mountain areas, or whether they will be reduced or amplified compared with the adjoining lowlands.

1.2 Objectives of the Study

The Indian Himalaya, which is the originating point of major river system viz., Brahmaputra, Ganga and Indus, plays a vital role in controlling the weather of India. Despite this fact, the climate of Indian Himalaya is less studied because of its inaccessibility and hilly terrain that makes the data on meteorological and hydrological variables scarce. Since, past studies were confined to few individual stations located in the Indian Himalaya; a group of stations forming a part of Indian Himalaya or by the neighbouring countries, the present study has been taken up with the objective to explore the possibility of making a base line information on climate change by analysing rainfall, number of rainy days, mean maximum temperature, mean minimum temperature, mean temperatures, temperature range (maximum – minimum) and mean wind speed over Indian Himalaya.

According to World Meteorological Organization (WMO, 1988) climate is defined as "the synthesis of weather over the whole of a period essentially long enough to establish its statistical ensemble properties (mean values, variances, probabilities of extreme events, etc.) and is largely independent of any instantaneous state". Thus, climatic change is defined as the differences in the mean values of climatic statistics between successive climatic periods. Changes in the statistics within a climatic period may be termed as climatic variation or climate change. There are various possible ways to study climate change. If climate is changing in a region or location it may be reflected in the dependence structure, trends or even in the periodicity of the climate variables.

The variation in the climatic statistics leads to describing climatic time series as non-stationary or dependent or short-term memory or long-term memory. Dependence is the tendency for successive values of climatological series to "remember" their previous values and to be influenced by them. For this purpose firstly the short-term and long-term dependence structure in the climate variables has to be investigated.

There is growing consensus that the temperature is increasing at a faster rate than the precipitation at global scale as well as at the regional scale. This increase (decrease) is nothing but the change in the mean value over a period of time which we call it trend. Detection of trend in the data series is another approach of studying climate change over an area or location. Therefore, there is a need to search for the temporal and spatial trends in the available climatic variables in the regions of Indian Himalayas.

Periodicities in natural time series are usually due to astronomical cycles such as the earth's rotation around the sun. The effect of changing climate may alter the cyclic pattern of the climate variables. Hence, presence of periodicity requires investigation as a final step to recognized link with the climate change.

Since, the impact of climatic change may have significant effect on the water resources of mountainous rivers, a typical Satluj River basin located in the western Himalayan region is chosen as the study basin. The physical impacts of climate change on water resources are investigated using the available temperature, rainfall, snowfall and discharge data with a hypothesis that any change in the climate will change the discharge of the river basin.

The main goal of this study is to address the "Evaluation of spatial and temporal climatic variability over Indian Himalaya". This overall goal is broken down in to following objectives:

1. To analyse short-term and long-term dependence in the climate parameters
2. To study spatial and temporal trends in the climatic variables
3. To search for the evidences of short-range and long-range periodicity/hidden periodicity
4. To study the effect of climate change on the river discharge of a typical river basin

1.3 Organization of Chapters

Chapter 1 covers the introductory and background information including significance of the study and its objectives. Chapter 2 deals with the state-of-the-art review and explore the research gap for the present study. At the end of chapter 2, a brief discussion is presented to justify the purpose of study. Chapter 3 describes the study area and data used for dependence, trend and periodicity analysis in Indian Himalaya. Chapter 4 discusses the presence of short-term and long-term dependence in the climatic parameters. Presence of short-term dependence is discussed on the basis of various statistical tests, whereas Hurst's phenomenon has been discussed for long-term dependence. Statistical significance of the trend and the rate of change in the climatic variables are presented and discussed in Chapter 5. This chapter also highlights the spatial interpolation of the trend test results over the Indian Himalayas. In Chapter 6 the short-range and long-range periodicities or the hidden periodicities are analysed. Chapter 7 addresses the fourth objective of the study. In this chapter the effect of climate change on the river discharge of a snowfed Himalayan river basin with special emphasis on the timings and volume of discharge and trends thereof are assessed. The conclusions drawn from the study of limited data are presented in the final chapter, Chapter 8, following which future directions of research are discussed.

CHAPTER 2
REVIEW OF LITERATURE

This chapter aims to briefly summarize the information on the state-of-the-art review on climate change and its impacts on the India, Indian Himalaya and neighboring countries. Based on the literature survey, the knowledge gaps in this field in case of Indian Himalayas are pointed out.

2.1 Short-term and Long-term Dependence

Dependence in rainfall or streamflow observations can be attributed to atmospheric, basin or sub-surface storage and has major implications for the design and management of water supply infrastructure.

Persistence (dependence) in the meteorological time series arises due to long life times of synoptic scale systems and other low frequency variations (Dahale et al., 1994). Many types of hydrologic time series exhibit serial correlation. That is the value of the random variable under consideration at one time period is correlated with the values of the random variable at earlier time period. However, annual series are assumed to be serially independent events in most analysis.

A number of statistical tests are available to estimate the occurrence and extent of persistence (dependence) in hydro-meteorological records. Some of these tests are designed to investigate the nature of wet and dry periods, which is generally termed runs analysis, while other tests consider the temporal dependence of persistent series through techniques such as autocorrelation.

The various alternatives to randomness which are of concern in the problem of climatic fluctuations have the common property of low frequency variation, which introduces positive serial correlation at small lags. The most common index of short-term dependence (persistence) is the lag-k correlation coefficient ρ_k. It is a measure of short-term dependence because beyond a few lags H, the coefficient usually decays to noise. The most common index of short-term dependence, ρ_1, only quantifies the correlation between successive values of random variables, as opposed to long-term measures of dependence such as Hurst coefficient (Vogel et al., 1998). Many scientists have tested hydrological time series for persistent behavior using lag-1 autocorrelation.

Yevjevich (1964) performed serial correlation analysis on sequences of annual river flow and detected positive serial correlation on many rivers.

Carrigan and Huzzen (1967) investigated the serial correlation of annual peak flows in the USA. In their analysis of records for 45 streamflow stations, the number of autocorrelation coefficients significantly different from zero for time lags of 1 and 2 years was greater than the expected number obtained by chance. Six of the 45 stations were judged to show signs of dependence (cf. Lye and Lin, 1994).

Jagannathan and Parthasarthy (1973) investigated persistence in the rainfall at 48 Indian stations using lag-1 autocorrelation coefficient. The results of their investigation revealed that the rainfall over India is not entirely random as some significant part is time controlled.

Mooley and Parthasarthy (1984) examined 108 years (1871-1978) of monsoon rainfall of 306 stations spread all over India for presence of persistence by checking the autocorrelation up to three lags and found that four stations have shown Markov type persistence at 5% significant level, but this number was less than the number of significant correlations expected by chance at 5% significance level and hence, the persistence was observed to be absent.

Domroes and Ranatunge (1993) examined the spatial distribution of rainfall persistence for twelve months and seasons over Sri Lanka. They showed that topography has a strong influence on persistence.

The analysis by Lal (1993) revealed that the Markov linear-type of persistence was observed in pre and post monsoon temperature series of Delhi.

Mirza et al. (1998) analysed annual rainfall of 16 meteorological subdivisions covering the Ganga, Brahmaputra and Meghna river basins for persistence on the basis of lag-1 autocorrelation and observed that the Markovian persistence was not present in the precipitation series in the Ganga basin but it was present in two common subdivisions in the Brahmaputra and Meghna basin.

The regional persistence of annual streamflow in the United States was studied by Vogel et al. (1998) using autocorrelation approach.

In the above approaches the judgment about dependence was made on the basis of single test i.e. autocorrelation.

Later, Srikanthan et al. (1983) analyzed dependence structure of annual streamflow records of Australia by using six tests of randomness and adopted a criteria that a series is said to be non-random if non-randomness is indicated by at least two of the six i.e. one third (five non-parametric and one parametric) tests of short-term dependence. On the basis of this criterion, 44 out of 156 streams showed short-term dependence.

In a similar approach with five independence tests, Wall and Englot (1985) observed that annual peak flows were independent for 57 streams in Pennsylvania. To arrive at this conclusion they have assumed that at least two of the five tests applied should indicate non-randomness.

By adding more number of tests for randomness, Lye and Lin (1994) analyzed short-term dependence structure of the peak flow series from 90 Canadian rivers by applying 11 short-term dependence (8 non-parametric and 3 parametric) tests. They have used the criteria that for a series to be dependent at least four out of eleven tests i.e. about one third should indicate short-term dependence. It was revealed from their analysis that 1 series out of 90 showed dependence. The conditional probabilities were also found to be high in the tested series.

Jigajinni (2001) applied the same approach as that of Lye and Lin (1994) to analyze the annual series of floods, rainfall and daily maximum rainfall in an around Zone-3 of India. The analysis showed that conditional probabilities of long-term dependence are high i.e. 18.84% for annual flood series, 12.64% for annual daily maximum series and 28.82% for annual total rainfall series.

Other than short-term dependence, there is another kind of dependence observed at larger timescales, known as long-term dependence, persistence, or memory. Ever since Hurst (1951) introduced a methodology for exploring the long-term persistence of geophysical records, numerous researches have used his approach to study the stochastic structure of streamflow, climate and other geophysical records (Lye and Lin, 1994).

Lye and Lin (1994) also applied Hurst's *H* and studied the long-term dependence of annual peak series of 90 Canadian rivers and observed that 17.8% (at 5%) and 28.9% (at 10%) of the testes series showed short-term dependence. A comparison of results of long-term and short-term dependence test revealed that the values of long-term dependence were much higher than the number of short-term dependence values.

2.2 Trends in the Climatological Variables

2.2.1 Global Trends

2.2.1.1 Global Temperature Trends

Measured temperature records of the earth have only been available since 1861 (IPCC, 2001c). The earth's temperature before the instrumental period has been reconstructed using different indirect tools and methods like tree rings, corals, ice sheets, ice cores, borehole measurements, glaciers, ancient sediments and sea level changes etc (IPCC, 2001c; Oliver and Hidore, 2003). The long term temperature record derived from paleoclimatic record shows clear evidence of fluctuations in temperature resulting in glaciation and deglaciation periods in the history of the earth since its formation some 4 billion years ago (WMO, 1991; Graedel and Crutzen,1993).

Reconstructed temperature records of the Earth during its entire history of development showed that there was a cooling trend up to 150,000 years before the present (yr BP) and a rapid warming trend thereafter till 120,000 yr BP (Graedel and Crutzen, 1993; Oliver and Hidore, 2003). Again, there was a cooling trend from 120,000 yr BP to 18,000 yr BP. The period from 18,000 to 5,500 yr BP corresponds to the deglaciation of the earth, i.e. a warming period (Oliver and Hidore, 2003). The warming peaked about 5,500 yr BP when the mean atmospheric temperature of mid-latitudes of the northern hemisphere was about 2.5°C above that of the present. Then, there was a cooling trend up to some 2500 yr BP and again warming after that (WMO, 1991).

The warming trend continued up to about 1200 AD, when the average temperature was higher than today (Oliver and Hidore, 2003). Then, there was a cooling trend up to about 1800 AD. During the time from 1450 AD to 1880 AD, which is also known as the Little Ice Age, glaciers enlarged to their maximum extent in the present era, "very cold winters led to the freezing of rivers and lakes that are seldom deeply frozen today, the ice was so thick that ice fairs were held on the frozen water" (Oliver and Hidore, 2003).

Karl et al. (1993) examined asymmetric trends in daily maximum and minimum temperature series of 37% of the global land mass using monthly average maximum and minimum temperatures. Both the temperatures were increased but rise in the minimum temperature was observed to be three times as compared to maximum temperature (0.84°C versus 0.28°C) during the period 1951-1990. The observed decrease in DTR was approximately equal to rise in the mean temperature.

Easterling et al. (1997) analyzed monthly average maximum and minimum temperatures and diurnal temperature range (DTR) at 5400 observing stations around the world for 1950-1993. The results of their analysis indicated that the maximum temperature was increased by 0.88°C per decade while minimum temperature was increased by 1.86°C per decade over the global land during the period of analysis. This differential changes in maximum and minimum temperature resulted in increased global mean temperature with narrowing of DTR in most parts of the world. They have further examined the data to find out the effect of urbanization on the observed trend by excluding the urban stations and found slight lower values of trend in the temperature variables.

Jones et al. (1999) from the analysis of surface temperature data for two 20 years period (1925-1944 and 1978-1997) revealed that the warming over the earlier period was slightly greater (0.37°C compared with 0.32°C) on a global basis. The recent warming has been accompanied by increases in areas affected by significantly warm temperatures and reductions in the areas affected by significantly cool temperatures. They further observed that the recent increase in mean temperature is the result of stronger warming in nighttime compared with daytime. Over the 1950–1993 period, nighttime (minimum) temperatures have warmed by 0.18°C per decade and daytime (maximum) temperatures have warmed by 0.08°C per decade and the diurnal temperature range has decreased by 0.08°C per decade.

According to IPCC (2001a) the observed temperature record from 1861 to 2000 shows that the earth's temperature is increasing and most of the warming occurred during the second half of the twentieth century. The equivalent linear rate of global temperature trend for the period of 1861 to 2000 was 0.044°C/decade, but that for the period of 1901 to 2000 was 0.058°C/decade. The warming rate over the period 1976-2000 was nearly twice that of the years 1910-1945. During three sub-periods (1910–1945, 1946–1975 and 1976–2000) the first and third sub-periods had rising temperatures, while the second sub-period had relatively stable global mean temperatures. The 1976 divide is the date of a widely acknowledged 'climate shift' and seems to mark a time when global mean temperatures began a discernible upward trend that has been at least partly attributed to increases in greenhouse gas concentrations in the atmosphere (IPCC, 2007).

Vose et al. (2005) with extended data set examined global trends in maximum, minimum temperatures and the diurnal temperature range (DTR) for the period 1950-2004. An increase in the minimum temperature was also reported by them. The minimum temperature was increased more rapidly than maximum temperature (0.204 versus 0.141°C per decade) from 1950–2004, resulting in a significant DTR decrease (−0.066°C per decade). In contrast, there were comparable increases in minimum and maximum temperature (0.295 versus 0.287°C per decade) from 1979–2004, muting recent DTR trends (−0.001°C per decade). Minimum and maximum temperature increased was found in almost all parts of the globe during both periods, whereas a widespread decrease in the DTR was only evident from 1950–1980.

2.2.1.2 Global Precipitation Trends

Global land precipitation has increased by 2% since the beginning of the 20th century, but largely varied in space and time. Despite the irregularity in the trends of precipitation in the last century, the annual average precipitation in mid- and high latitudes was increasing while that in tropics and sub-tropics was decreasing (IPCC, 2001c).

Narisma et al. (2007) analyzed high resolution gridded global historical rainfall (0.5 x 0.5 degrees) from the Climate Research Unit covering the years 1901–2000, to detect regions that have undergone large, sudden decreases in rainfall. The results of the analysis showed that in the 20th century about 30 regions in the world have experienced such changes that were statistically significant at the 99% level, persistent for at least ten years, and most have magnitudes of change that are 10% lower than the climatological normal (1901–2000 rainfall average).

2.2.2 Climate Change Studies in India

2.2.2.1 Temperature Trends

India has diversified climate. The north-eastern region receives very high rainfall whereas the western part receives less rainfall. Similarly, there is a great variation in the temperature over different parts of the India. This aspect of variability was studied by the Indian investigators in light of the climate change.

Pramanik & Jagannathan (1954) studied secular trends in the annual mean maximum and minimum temperatures over India and observed no trends in the variables. However, at few stations some oscillatory tendency has been observed by them.

Jagannathan (1963) analysed trends in the arid and semi-arid regions of the globe including 8 Indian stations of about 55 to 100 years data and reported no trend in the mean annual temperature of the Indian stations considered.

The time series of the mean annual temperature over another set of 8 Indian stations using about 90 years data was analysed by Jagannathan & Parthasarathy (1972). They, however, reported increasing trend in the mean annual temperature of Calcutta, Bombay, Bangalore and Allahabad and decreasing trend at Fort Cochin.

Hingane et al. (1985) evaluated the long-term variation of surface air temperature for India as a whole and for different regions of the country considering 73 fairly wide spread stations for the period 1901-1982. The findings of their study indicated a slight but definite warming trend in the mean annual Indian temperatures. Similar findings have been reported by Sarker & Thapliyal (1988) and Thapliyal & Kulshrestha (1991). The warming of Calcutta, Bombay and Bangalore was confirmed by RupaKumar & Hingane (1988). Further, it was also reported that Delhi showed a significant cooling trend while no significant trends were observed at Madras and Pune.

Rao (1993) analysed long-term seasonal and annual surface temperature changes of Mahanadi river basin in India and reported highly significant warming trend in the temperatures during the 80 years (1901-80). The rate of increase in the annual average surface temperature was observed to be 1.1 °C per hundred years.

RupaKumar et al. (1994) carried out linear trend analyses of maximum and minimum temperature data at 121 stations in India during the period 1901–87. The mean temperature trends over India were similar to the global and hemispheric trends, and the mean temperatures warming over India is because of the contribution of the maximum temperatures, since the minimum temperatures were practically trendless. Rising of maximum temperatures causes an increase in the diurnal temperature range. These trends do not show any significant urban or altitude bias. The increase of maximum temperature was predominant over a major part of India, particularly in winter and post-monsoon seasons.

In an analysis over Ganga basin in India indicated a warming trend in the temperature which began in second half of the 1960's (Kothyari & Singh, 1996 and Kothyari et al. 1997).

The 117 years long series of temperature data for the India was analysed by Pant & Kumar (1997). They have also observed a warming of 0.57 °C per hundred years. But, it is quite interesting to note that the magnitude of warming was found to be higher in the post monsoon and winter season.

Sinha Ray & De (2003) summarized existing information on climate change and trends in the occurrence of extreme events in various climatic variables over India. They have reported an increasing trend of 0.35 °C over the last year in temperature records.

Guhathakurta & Srivastava (2004) analysed temperature data of 50 stations widely spread over the India for searching of jump and reported absence of any significant climate jump and linked discontinuities in climate with the sudden changes in ecosystem caused by natural and human activities.

In order to give a detailed scenario of the prevailing temperature trends over India, the temperature records of 125 stations spread throughout the India were evaluated for trends by Arora et al. (2005). From their analysis of temperature variables on annual basis the warming of 0.42 °C/years, 0.92 °C/years and 0.09 °C/years was observed in mean, mean maximum and mean minimum temperatures, respectively. On seasonal basis, the post monsoon and winter seasons showed warming (increasing) trends of 0.94 °C/years and 1.1 °C/years, respectively.

Kothawale and RupaKumar (2005) analysed 103 (1901 – 2003) year's all-India mean annual temperature data and observed a rise of 0.05 °C per decade. Both maximum and minimum temperatures were reported to be increased but the rise in the maximum temperature was found to be 0.05° C per decade more than the rise in the minimum temperature. This increase in the maximum temperature increased the annual mean temperature as well as the diurnal temperature range.

A state-of-art regional climate modelling system, known as PRECIS (Providing Regional Climates for Impacts Studies) developed by the Hadley Centre for Climate Prediction and Research, was applied by RupaKumar et al., (2006) for India to develop high-resolution climate change scenarios. Model simulations under scenarios of increasing greenhouse gas concentrations and sulphate aerosols indicated marked increase in both rainfall and temperature towards the end of the 21st century. Extremes in maximum and minimum temperatures are also expected to increase into the future, but the night temperatures are increasing faster than the day temperatures. Extreme precipitation shows substantial increases over a large area, particularly over the west coast of India and west central India.

The warming is monotonously widespread over the country, but there are substantial spatial differences in the projected rainfall changes. West central India shows maximum expected increase in rainfall.

Dash et al. (2007) made a detailed study of temperature variations over Indian regions and observed that the annual mean temperature and the annual maximum temperature was increased by 0.7 °C and 0.8 °C respectively without any significant increase in the annual minimum temperature.

Singh et al. (2008) reported that the mean annual temperature was increased in the range of 0.40-0.64 °C/100 years over seven river basins while it was decreased in between -0.15 to -0.44 °C/100 years over two basins out of total of nine river basins studied. The maximum warming of Narmada basin and maximum cooling of Sabarmati basin was revealed from their study. It was also noted that majority of the basin show increasing trend in the temperature range, highest maximum temperature and lowest minimum temperature. Their seasonal analysis revealed that the greatest rising was observed in both, the maximum and mean temperature in the post-monsoon season whereas the variation of minimum temperature was largest during monsoon season.

The study of Bandyopadhyay et al. (2009) revealed that maximum and minimum temperatures were rising over the Agro-Ecological Regions of India with greater rising of minimum temperature than the maximum temperature.

Jhajharia and Singh (2010) investigated trends in maximum, minimum, mean and temperature range over northeast India. The decreasing trends in DTR were observed at three sites out of eight. Decreasing (increasing) trends in DTR were associated with the sites either increasing trends in minimum temperature (maximum temperature) or decreasing trends in maximum temperature (minimum temperature), with maximum temperature (minimum temperature) showing either no trend or increasing at a smaller rate than minimum temperature (maximum temperature).

2.2.2.2 Rainfall Trends

Rainfall is another important factor of climate reported to change during the last century over the Globe with varying magnitude. In India also good amount of work was reported by several researchers on the variability of seasonal and annual rainfall over India.

Pramanik & Jagannathan (1953) analysed 40-100 years of rainfall data from different Indian stations and revealed no major climate change in the rainfall series.

Parthasarathy and Dhar (1975) reported a significant increase of 5% in the mean values of annual rainfalls for the 30 years period from 1931 to 1960 over 1901 to 1930.

Sarker and Thapliyal (1988) studied 115 years of (1875-1989) annual rainfall of India and observed insignificant trends. Later, Thapliyal & Kulshrestha (1991) also confirmed that the all India rainfall is trendless. However, Study of RupaKumar et al. (1992) revealed that areas of north-east peninsula, north-east India and north-west peninsula showed increasing trend over the west coast, central peninsula and north-west India. Srivastava et al. (1998) also reported the existence of a trend in rainfall on spatial scale.

The analysis of Mirza et al. (1998) indicated that precipitation of the meteorological sub-divisions located in the Ganges basin is steady. But the results of Kothyari and Singh (1996) revealed that trend in annual rainfall as well as annual number of rainy days was decreasing over the Ganga basin and India as a whole from the second half of 1960's.

Naidu et al. (1999), on the basis of monthly data from 1871 to 1994, observed a negative trend in annual rainfall over west-central India, central north India and north-eastern parts of India, and a positive trend was present over north-west India and an area in north-east, i.e. Gangetic West Bengal, and the peninsular India.

Rao et al. (2004) analysed various climatological variables of different cities to see the effect of urbanization on them. They have revealed decrease in bright sunshine hours, wind speed and total cloud amounts, percentage number of days of maximum/minimum temperatures with a threshold value of > 35 °C / < 10 °C, respectively and increase in relative humidity and rainfall amounts. The role of orography, the density of population, the distance between the tail buildings, vehicular pollution and the industrial development in controlling the urban climate was highlighted by them. Further, they have suggested a study of this is needed for its generalization.

Dash and Hunt (2007) investigated the temperature and precipitation trends over north and south India for different phases of the monsoon. They have observed large differences in trends in minimum temperature and cloud cover between north and south India and asymmetry in increasing temperature trends between different seasons.

Singh et al. (2007) indicated an increasing trend of annual rainfall and relative humidity in north Indian river basins. The minimum variation was observed in monsoon rainfall.

Study of Basistha et al. (2007) indicated that the sub-divisional rainfall decreased over north India with the exception of Punjab, Haryana, West Rajasthan and Sourashtra; and increased over south India excluding Kerala and Madhya Maharashtra.

Pal and Al-Tabbaa (2010) assessed seasonal precipitation trends in the Indian regions and observed that the trends in seasonal precipitations have considerable regional variations. No significant trends were found in annual or seasonal precipitation amount in the period of 1871–2005 in various regions in India; however, significant changes were observed for the period of 1954–2003. The maximum decrease of 31.4 mm per season per decade in annual precipitation was found in West Coast India (WCIN) whereas maximum increase of 26 mm per season per decade was observed in Northeast India (NEIN). In all cases, all the regions were showing positive and negative trends. Precipitation showed an increasing tendency in the winter and autumn seasons whereas a decreasing tendency in spring and monsoon seasons in Kerala. These seasonal changes of rainfall in India, as they, described are due to either or the cumulative effect of multiple factors, namely the changes in the sea surface temperature changes, convective phenomena and ENSO.

2.2.3 Climate Change Studies in Himalayan Region

2.2.3.1 Climate Change studies in Indian Himalayas

Information on long-term climate variability based on instrumental as well as proxy records is equally important to understand the nature of different climatic systems over the region for various purposes. The main reason for limited number of studies on the Himalayan region has been the lack of information on precipitation at high elevations (Singh et al., 1995). This is unfortunate, particularly due to the fact that the River Ganga and all her perennial tributaries, the lifeline of entire North Indian plains, originate from this region.

For the Indian Himalayan region, so far reported studies mainly analysed rainfall over a specific locations. Very few studies on climate change have been reported for the stations located in the Indian Himalayas.

Pant & Borgaonkar (1984) analysed about 100 years data of annual rainfall of six stations and temperature data of one station located in the Uttar Pradesh hill regions and revealed no long-term trends in the rainfall and; increase in winter maximum and mean temperatures.

Study of Pant et al. (1999) revealed no significant increase or decrease in rainfall in any of the seasons however, a general increasing trend in mean temperature over the stations of western Himalaya during the 90 years of period (1901-90) was observed in all the seasons. In monsoon season the trend was negligible, whereas in other seasons evident increase in mean temperature, particularly in pre-monsoon and post-monsoon temperature was observed.

Singh and Sontakke (2002) carried out a detailed study of climatic fluctuations in Indo-Gangetic Plains region (IGPR) of India and revealed an increase of 0.53 °C/100 years during 1875-1958 and a decrease of 0.93 °C/100 years during 1958-1997 in the annual surface temperature. They have attributed that this decrease in temperature after 1958 may be due to expansion and intensification of agricultural activities and spreading of irrigation network in the region. For rainfall analysis an increasing trend in the summer monsoon rainfall over western Indo-Gangetic Plains region (IGPR), decreasing trend over central IGPR and eastern IGPR were observed. They have suggested that these changes in rainfall are due to global warming and associated changes in the Indian summer monsoon circulation and the general atmospheric circulation.

Yadav et al. (2004) using observations and reconstructions from tree rings studied pre-monsoon (March-May) temperature variables over the western Himalaya. Their analysis revealed that pre-monsoon minimum temperature is decreasing during the 20th century and this decrease was three times that of the rate of decrease of maximum temperature. They suggested that the greater decrease in the minimum temperature is the main reason for cooling trend in the pre-monsoon mean temperature.

Kumar et al. (2005) indicated an increasing trend in annual rainfall but decreasing trend in monsoon rainfall over Himachal Pradesh. The results depict a decrease in monsoon rainfall in three elevation zones of <1000m, 2000-3000m and >3000m.

The analysis of Arora et al. (2006) revealed that elevation and distance are equally important in explaining the variability in annual rainfall distribution in Chenab mountainous basin of Himalayan region.

Bhutiyani et al. (2007) analysed temperature variables of northwestern Himalaya and observed a significant rise of 1.6 °C in air temperature on century scale with winters warming at a faster rate across the northwestern Himalaya during the twentieth century. On decadal basis it was found that the real warming started in the decade of 1961-1970 with a modest rate and with an exception of the decade 1981-1990. The highest rate of warming was observed during 1991-2002. The results further revealed a gross rise of 2.2 °C in mean air temperature. The maximum temperature increased about four times (3.2 °C) than the minimum temperature (0.8 °C). The significantly increasing trend was also revealed in the winter, monsoon and annual diurnal temperature range (DTR).

Dash et al. (2007) observed that the maximum temperature was increased by 0.9 °C over western Himalayas India during the last century, accompanied by a small decrease in monsoon rainfall. The monthly rainfall data for various Indian sub divisions from 1871 to 2003 was also examined by Dash et al. (2007). They found that monsoon rainfall decreased 1.6 cm during study period with maximum decrease observed in central north-east and north-eastern regions (Eastern Himalaya region). They stated that the changes in monsoon precipitation pattern were mainly affected due to changes in monsoon cyclonic disturbances and monsoon depressions in the north Indian Ocean, which is more pronounced since the 1970s.

Immerzeel (2007) studied the monthly high-resolution temperature and precipitation data from 1900-2002 for three physiographic zones viz., the Tibetan Plateau (TP), the Himalayan belt (HB) and the floodplains (FP). Throughout the basin a warming trend at an average rate of 0.6 °C per 100 year was revealed. All zones showed largest warming trend in spring (TP = 1.1 °C per 100 year, HB = 1.0 °C per 100 year, FP = 0.9 °C per 100 year) and smallest warming trend in summer (TP = 0.2 °C per 100 year, HB = 0.4 °C per 100 year, FP = 0.5 °C per 100 year). However, he did not reveal any trend in the precipitation and suggested that the annual precipitation is primarily controlled by monsoon dynamics.

Ramanathan et al. (2007) observed that the combined simulated warming of greenhouse gases and atmospheric brown cloud (mainly soot) at higher levels (3-5 km above sea level) over the Himalayan-Hindukush region is about 0.25 °C/decade during 1950 to present, with peak warming during March to September.

Basistha et al. (2008) attempted to explore changes in rainfall pattern in the Uttarakhand Indian Himalayas and indicated that the most probable year of change in annual as well as monsoon rainfall in the region is 1964. There was an increasing trend up to 1964 (corroborating with all India and nearby plains), followed by a decreasing trend in 1965–1980 (exclusive to this region). In the entire region, changes are most conspicuous over the Shivaliks and the southern part of the Lesser Himalayas was reported by them.

Dimri and Kumar (2008) examined the changing trends of temperature and precipitation over the western Himalaya by calculating the number of warm and cold events during winter (December–February) for 32 years (1975–2006). They observed a trend of increasing temperature and decreasing precipitation at some specific locations.

Study of Bandyopadhyay et al. (2009) indicated that higher positive slope of 0.06 °C per year over western Himalaya and the highest negative slope of 0.10 °C per year in eastern Himalaya were observed in the maximum temperature.

Jhajharia et al. (2009) reported that in yearly and seasonal rainfall of north east India, no significant trends at eight sites, increasing trend at two sites while decreasing trend at one site were observed in winter rainfall out of total of eleven sites.

Bhutiyani et al. (2010) studied the variability of precipitation from 1866-2006 and temperature from 1876-2006 of Shimla, Srinagar and Leh located in the northwestern Himalaya (NWH). The trend analysis showed increasing but insignificant trend in winter precipitation. In contrast to winter precipitation significant decreasing trends were observed in the monsoon at Shimla and overall annual precipitation of the NWH during the period of study. The trends analysis of temperature over the same stations revealed significant increasing trends in winter, monsoon and annual temperature at Shimla and Leh. The monsoon temperature of Srinagar was also found to be increasing but was not statistically significant. The rate of increase was found to be 0.06 °C per decade, 0.14 °C per decade and 0.11 °C per decade in monsoon, winter and annual air temperature.

Kumara and Jain (2010) analysed seasonal and annual rainfall and rainy days at five stations namely Srinagar, Kulgam, Handwara, Qazigund and Kukarnag to examine rainfall trends over the Kashmir Valley for two common periods: 1903–1982 (80 years) at three stations and 1962–2002 (41 years) at three stations. The 102 years of data at Srinagar was also analysed to examine the trends for last century. During the period 1903–1982, Srinagar, Kulgam and Handwara stations experienced a decreasing trend in annual rainfall; the maximum decrease was found for Kulgam (−20.16% of mean/100 years) and minimum for Srinagar (−2.45% of mean/100 years). All three stations showed a decreasing trend in monsoon and winter rainfall and an increasing trend in pre-monsoon and post-monsoon seasonal rainfall. Significant decreasing trend in winter rainfall was found at Kulgam and Handwara. The insignificant increasing trends were found in pre-monsoon and post-monsoon season. Srinagar and Handwara witnessed a decreasing (non-significant) trend in annual rainy days, whereas Kulgam experienced the opposite trend. All the stations experienced a decreasing trend in monsoon and winter rainy days.

Qazigund and Kukarnag experienced decreasing annual rainfall, and Srinagar showed increasing annual rainfall during the period 1962–2002. Pre-monsoon and post-monsoon rainfall decreased at all three stations. None of the increasing/decreasing trends were found to be significant. Annual, pre-monsoon, post-monsoon and winter rainfall increased (non-significant) whereas monsoon rainfall decreased (non-significant), at Srinagar during the last century.

Shekhar et al. (2010) analysed long term observed wintertime data (November–April) of maximum, minimum and mean temperature, snowfall, cloud percentage, number of occurrences of western disturbances and number of snowfall days recorded at 18 SASE station locations, situated in different ranges of the western Himalaya and indicated that seasonal mean, maximum and minimum temperatures have increased by (approximately) 2, 2.8 and 1°C, respectively during the period from 1984/85 to 2007/2008. The Greater Himalaya showed an increase in maximum and minimum temperatures of 1 and 3.4 °C, respectively. On the other hand, over the Karakoram range decreases of 1.6 °C and 3 °C were observed in maximum and minimum temperatures, respectively. Their study further revealed that the cloud cover which controls the temperature and amount of precipitation across the region also found to decrease at all the stations except Haddan-Taj where no change was noticed.

2.2.3.2 Climate Change studies in Neighboring Himalayan Countries

Aizen et al. (1997) analysed climate and hydrologic data from 110 sites of Tien Shan and revealed no significant trend of decreasing air temperature in any of the season. However, an average rate of 0.10 °C per year increase in mean annual air temperature was observed by them. The rate of increase in annual temperature was greater at stations of northern (0.008) and western (0.013) regions above 2000 m, whereas in central region equal rate of change was noticed for stations of both smaller than 2000 m and greater than 2000 m. During the same period significant increase in the mean precipitation was observed. The statistically significant increase of 2.44 mm per year and 2.46 mm per year for northern and western regions, respectively was observed at altitude below 2000 m. A total increase of 1.2 mm per year was observed in annual mean precipitation at Tien Shan.

Shrestha et al. (1999) found that in Nepal the maximum temperature changes showed warming trends (0.6 °C to 0.12 °C/year) after 1977 in Middle Mountain and Himalayan region. High mean annual temperature increases (>0.06 °C/year) occur in most of the northern belt (the Trans-Himalayan and Himalayan regions and central and western parts of the Middle Mountains). Within the Middle mountain region there are two pockets of anomalously high warming rate (≥0.12°C/year): the western Middle Mountain region and the Kathmandu Valley. Most of the Siwalik and the Terai regions show considerably low increasing trends (<0.03°C/year).

All-Nepal precipitation record (1948-1994) indicates an absence of any trend (Shrestha et al., 2000). The increase in atmospheric aerosol might have begun to affect monsoon in the Himalayas, offsetting the increasing trend in monsoon precipitation that would have been caused by the increase in atmospheric greenhouse gases alone.

Archer (2004) investigated altitudinal variations in temperature. The analysis revealed positive relationship between all stations and the relationship show improvement at closer distance in mean annual temperature. In case of seasonal six months relationship the correlation between spring and summer months was much higher than during winter months. Upon investigating the lapse rate, high correlation coefficient > 0.90 was revealed between station temperature and elevation for annual and seasonal temperature. The correlation coefficient value exceeds 0.98 on inclusion of high altitude stations.

In another study in the same basin Archer & Fowler (2004) investigated spatial variation of precipitation records by regression and correlation analysis for Upper Indus Basin stations and found weak spatial relationship in seasonal precipitation during summer. He further revealed that long precipitation records exhibited no trends. But when the analysis was carried out for 1961-1990 period, significant increase in winter, summer and annual precipitation was observed. In order to find linkage between precipitation and global teleconnections, a significant positive and a negative correlation was found between winter precipitation and North Atlantic Oscillation (NAO) and monthly NAO and summer rainfall, respectively.

Xiong & Guo (2004) after analyzing discharge series of the annual maximum, annual minimum and annual mean of the Yangtze River at the Yichang hydrological station during the period 1882–2001 revealed that the annual maximum flood series did not have any statistically significant trend, but the annual minimum flow series and the annual mean discharge series exhibited a sign of decreasing trend. Further, the results of the Bayesian model show that, during the past 120 years, the mean levels of both the annual minimum discharge series and the annual mean discharge series have decreased by 8% and 6% respectively.

Fowler and Archer (2005) reviewed the existing information on contrasting hydrological regimes of the Upper Indus Basin, Pakistan. In a preliminary analysis of teleconnections, they have indicated links both to El Nino southern Oscillation and the North Atlantic Oscillation and suggested that the Upper Indus occupies a pivotal position between tropical and temperate weather system.

Monthly precipitation and temperature trends from 1950-2002 in the Yangtze basin were analyzed by Zhang et al. (2005). Results of the analysis for upper, middle and lower parts of the basin indicated that precipitation during summer season and in individual months of the summer season were increasing.

Fowler and Archer (2006) analyzed temperature data of six trans-Himalaya stations located in the Upper Indus Basin, Pakistan. The results of their analysis revealed decrease in summer mean and minimum temperature; decrease in fall minimum and increase in fall maximum temperature; increase in winter mean and maximum temperature; decrease and increase in annual minimum and maximum temperature and large increase in diurnal temperature range.

The data of annual runoff volume of the Toutun River of TianShan for the past 50 years (1956-2003) was tested for trends by Weihong et al. (2007). The result showed that the annual runoff volume of the river was decreased during the past 50 years. The temperature trends revealed that the annual temperature in the river basin in the 1990s was increased by 1.12 °C, 0.46 °C and 0.44 °C as compared with 1950s, 1960s and 1970s respectively however, precipitation was found trendless. Their analysis suggested that the reduction of streamflow in the Toutun River basin is possibly caused by the seasonal change of precipitation, especially the precipitation reduction in summer, and temperature increases.

Xu et al. (2007) in an analysis of monthly average air temperature and precipitation data of 80 stations located in the Yellow river basin China, revealed that temperature is increasing whereas precipitation is decreasing. On comparing the results of temperature and precipitation they observed that in the Yellow river basin several decades were the warmest and driest in the last century.

2.3 Periodicity in Climatological Variables

Considerable efforts and resources have been devoted to discover climatic parameter cycles by climatologist of various countries over the years mainly stressing on the rainfall and temperature (Goldreich, 1995).

Landsberg et al. (1963) found evidence of QBO (quasi-biennial oscillation) in the surface temperature in many parts of the world. Angell et al. (1966) observed QBO in tropospheric zonal winds of the Tropics and sub-tropics.

In India, few studies have been made to determine the periodicity mainly in the rainfall. Very limited work has been reported on the periodicity of all the climatic parameters.

Koteswaram and Alvi (1969) and Bhargava and Bansal (1969) reported a QBO in the southwest monsoon/annual rainfall over some stations on the west coast of south India.

Bhalme (1972) revealed presence of QBO in annual frequencies of cyclonic disturbances (storms/depressions) of Bay of Bengal. The QBO is also seen by Rao et al. (1973) in Palmer drought indices of various subdivisions of India.

Jagannathan and Bhalme (1973) showed that rainfall in India during the monsoon season (June to September) has oscillations corresponding to the sunspot cycle. Further, they have found that the QBO is significantly present in some of the parameters. Their study, however, was restricted to the monsoon season only and was based on pentad rainfall.

Jagannathan and Parthasarathy (1973) studied annual rainfall of 48 stations of India for periodicity. They have observed periodicity of more than 40 years wherever there is a significant trends. They have also reported that Quasi-Biennial oscillation

(QBO) is exhibited at several stations in the areas of increasing or decreasing trend. Similarly, the 11-yearr cycle (solar cycle) is also exhibited in both areas. However, the QBO and the solar cycle are both present at only Madras, Jagdalpur and Silcher.

Parthasarathy and Dhar (1976) applied power spectrum to the mean annual sub-divisional rainfall of east and west Madhya Pradesh of India and observed an eleven year cycle and highly significant Quasi-Biennial Oscillation (QBO) in the sub-divisions.

Basak and Sengupta (1998) analysed area-weighted southwest monsoon (SWM) rainfall series of All India and all region to test the periodicity through power spectral analysis and reveal that the All India and the series of northwest peninsula region contain a marginal periodicity of about 3 years.

Bhutiyani et al. (2007 & 2010) found presence of statistically significant periodicities in the range of 2.2 to 6.6 for standardized temperature index, 2.8 to 4.4 and 34 to 68 for standardized temperature range and 2.6 to 4.3 and 9.7 to 34 for standardized precipitation index, respectively over the stations of northwestern Himalaya.

2.4 Remarks

Literature review suggests that very limited studies have been conducted in the Indian Himalayas. Most the studies have dealt with the temperature and precipitation trends of few stations located in the western Himalaya. The information pertaining to climatic variability for other regions of the Indian Himalaya is lacking e.g. central Himalaya and eastern Himalaya. Moreover, dependence and periodicity in the climatic variables have not been analyzed in this important region of India. Most of the reported studies have used linear regression to analyze trends. Nonetheless, more powerful technique like Bootstrap (resampling) technique of Hydrospect Software is available. The literature survey also indicate that so far no concentrated efforts have been made over Indian Himalaya as a whole to corroborate the much debated issue of climate change.

It is therefore, this study has been undertaken to evaluate the Temporal and Spatial climatic variability in the entire Indian Himalaya using limited data to make baseline information.

CHAPTER 3

STUDY AREA AND DATA USED

This chapter deals with the description of whole Indian Himalayan region selected for the present study. Every analysis requires certain input parameters. This chapter also describes various input data used and their source of collection, period or length and pre-processing.

3.1 Study Area

3.1.1 Description of Indian Himalayas

The Himalaya, lying in the Indian Territory, is spread over a length of about 2,500 km and a width of 220 to 300 km. It has a total geographical area of approximately 591 thousand km^2. Physiographically the Indian Himalayan region is divided into three regions (a) Western Himalaya (Jammu & Kashmir and Himachal Pradesh); (b) Central Himalaya (Uttarakhand) and (c) Eastern Himalaya (West Bengal-Sikkim and Arunachal). Latitude, altitude and continentality are the most influencive factors regulating the climatic attributes over large areas in the mountains. Himalayan mountain system, instead of running parallel to east-west directions, runs from north-west to south east direction. The western ranges of Kashmir are located around 36 ^{o}N while the eastern ranges of Arunachal Pradesh are located around 27 ^{o}N.

3.1.1.1 Climate of Indian Himalayas

Basic patterns of the climate in the Himalayan region are governed by the summer and winter monsoon systems of Asia (Mani, 1981). The central and eastern Himalaya receives most precipitation during summer and the western Himalayan region receives most of its precipitation in winter. A substantial part of the summer monsoon rain occurs largely because of the orographic influence of the Himalaya on the monsoon winds (Mani, 1981). For every 1000 m of altitude, there is generally about a 6 °C temperature drop. However, the temperature may vary from place to place. The Himalaya itself acts as a climatic divide between the Indian subcontinent to the south and the central Asian highland to the north. The snow and ice over the Himalaya play an important role on the radiation balance of the region and on the strength of Indian monsoon (Meehl, 1994; Khandekar, 1991). The western region have stronger temperate influences compared to eastern sector. The Himalaya is characterized by intense rainfall in the east and heavy snowfall in the western reaches. It contain over half the permanent snow and ice-fields outside the Polar Regions and it is estimated that roughly 50,000 km^2 of glaciers feed in to the world's largest water drainage system of the Indus, Ganga and Brahmaputra Rivers.

3.1.1.2 Water Resources in Indian Himalayas

The water resources of the Himalayan region are a crucial part of the lives of millions of people living in the hills and the plains. There is no detailed scientific evaluation available for Himalayan water resources. This is partly due to insufficient network of observations for both precipitation and stream discharge measurements. Varying estimates of water resources in the Himalayan region have been made. Murthy (1978) estimated Himalayan water resources around 245 km^3 per year whereas Gupta (1983) estimated the total amount of water flowing from the Himalayas to the plains to be around 8643 km^3 per year. Bahadur and Dutta (1989) reported that a very conservative estimate gives at least 500 km^3 per year from snow and ice melt water contribution to Himalayan streams. Despite these widely differing estimates of the water resource of the Himalayan region, the water output could be the highest from any single mountain range in the world (Stone, 1992). Water availability, in terms of temporal as well as spatial distribution, is expected to be highly vulnerable to anticipated climate change (IPCC, 2001b).

3.1.1.3 Hydropower Potential in Indian Himalayas

The hydropower potential of Indian Himalayan River systems is about 78 per cent of the total Indian hydropower resources. In north east India, Arunachal Pradesh has the largest hydro-electricity potential followed by Meghalaya. The northeastern region accounts for a total of 31,857 MW assessed potential at 60 per cent load factor (LF), which is almost one third of the total potential of the country.

3.2 Data Used

To study dependence, trend and periodicity in the climatic variables over meteorological stations two different sets of data have been collected. The details of each of the data set are as given below:

(i) The monthly surface data of maximum and minimum temperature, rainfall, number of rainy days and mean wind speed for twenty three (seventeen in case of wind speed) stations spread over the Indian Himalayan region were collected from the India Meteorological Department (IMD), Pune. The length of data varies from station to station and ranges from 20 – 59 years covering a period from 1933 – 2003. The locations of the meteorological stations are shown in Figure 3.1 and the details about the stations i.e. name, state, latitude, longitude, period length and available meteorological variables are given in Table 3.1. The study area had a great altitudinal variation. The altitude of the meteorological stations used in this study varied from 157 m at Pasighat to 2311 m at Mukteswar. Majority of the stations are located above 1500 m.

(ii) This data set consists of more recent high-resolution (1^{o}x1^{o} lat/long) daily gridded rainfall data available from 1803 well distributed stations over India, prepared by the India Meteorological Department and set for the Indian region for 1951-2003 were collected from IMD, Pune. Forty five rain grid points that fall under the Indian Himalayan region (27.5^{o} N Latitude and 88.5^{o} E longitude to 36.5^{o} N Latitude and 75.5^{o} E Longitude) with 1^{o} buffer were transformed in to monthly time series and used in the present study.

3.3 Processing of Data

3.3.1 Filling of Missing Values

In the collected data there were missing values. Estimation of missing climatological data is an important task for meteorologists, hydrologists and environment protection workers. It is particularly important in mountain and forest regions where meteorological stations are scarce, and the observed climatological data are strongly influenced by topography and the forest microclimate (Xia et al., 1999). Several methods are available for filling the missing values e.g. arithmetic mean method, normal ratio method, inverse distance method and interpolation techniques. In the present study missing values are estimated using normal ratio method (Subramanya, 2007). While filling the gaps it was decided that the station should not have more than six monthly missing values in a year.

Fig. 3.1 Map of the Indian Himalayas showing locations of meteorological stations.

Table 3.1 Details of meteorological stations of the Indian Himalaya used in the present study. Rainfall (P), Temperature (T), Wind Speed (W)

Station	**Station I.D**	**State**	**Latitude (^{O}N)**	**Longitude (^{O}E)**	**Altitude (m a.s.l.)**	**Period of record**	**Climatic variables**
Srinagar	42027	J & K	34.08	74.83	1587	1958-1990	P,T
Quazigund	42044	J & K	33.58	75.08	1739	1968-1990	P,T
Banihal	42045	J & K	33.50	75.17	1630	1968-1990	P,T
Jammu	42056	J & K	32.67	74.83	367	1956-1990	P,T
Dalhousie	42059	HP	32.53	75.97	1959	1951-1988	P,T,W
Dharamshala	42062	HP	32.27	76.38	1211	1951-1998	P,T,W
Manali	42065	HP	32.27	77.17	2039	1968-2001	P,T
Bhuntar (A)	42081	HP	31.83	77.17	1096	1960-2000	P,T,W
Mandi	42078	HP	31.72	76.97	761	1954-2001	P,T,W
Bilaspur	42080	HP	31.25	76.67	589	1956-1992	P,T
Simla	42083	HP	31.10	77.17	2202	1933-1990	P,T,W
Mukhim	5211	UA	30.58	78.48	1981	1957-1990	P,T
Joshimath	42116	UA	30.55	79.57	1875	1958-1990	P,T,W
Mussoorie	42112	UA	30.45	78.05	2042	1933-1990	P,T,W
Tehri	42114	UA	30.40	78.48	770	1957-1983	P,T,W
Dehra Dun	42111	UA	30.32	78.03	682	1933-1991	P,T,W
Mukteswar	42147	UA	29.47	79.65	2311	1933-1991	P,T,W
Nainital	42146	UA	29.40	79.47	1953	1953-1979	P,T,W
Pasighat	42220	AR	28.10	95.38	157	1957-1992	P,T,W
Ziro	42312	AR	27.63	93.70	1476	1933-1961	P,T,W
Gangtok	42299	SIK	27.33	88.62	1812	1971-2001	P,T,W
Kalimpong	42296	WB	27.07	88.47	1209	1933-1991	P,T,W
Darjeeling	42295	WB	27.05	88.25	2127	1933-1991	P,T,W

3.3.1.1 Normal ratio method

If P1, P2, P3…Pm are the monthly precipitation at neighbouring M stations 1,2,3…..M respectively, then the missing monthly precipitation Px at a station X not included in the above M stations is filled out using the known values of normal monthly rainfall N1, N2, N3….Ni…. at each of the above (M+1) stations including station X. The missing rainfall Px is estimated by weighing the precipitation at the various stations by the ratios of normal monthly precipitation as (Subramanya, 2007)

$$Px = \frac{Nx}{M}\left[\frac{P1}{N1} + \frac{P2}{N2} + \frac{P3}{N3} + \cdots \frac{Pm}{Nm}\right] \qquad (3.1)$$

3.3.2 Data homogeneity

Reliability and interpretation of data depend on their accuracy and consistency: it is particularly important to distinguish trend and step changes in rainfall arising from changes in station location or practice from those resulting from climate change (Archer and Fowler, 2004). A time series is said to be homogeneous if all its fluctuations are caused by natural variability. In this sense, when an inhomogeneous time series is adjusted we are reducing the uncertainties of the results, and improving our understanding of the climate accordingly. The necessity of a precise scientific knowledge in this topic has recently increased its importance within the context of the study of climate change. Therefore, in applying the process of homogenisation to the data, utilising different techniques, we are searching for factors other than climate and weather.

Wide variety of factors such as relocation, replacement of the instrument, exposure modifications, and changes in the recording procedures are responsible for causing inconsistency in the data. Greater or lesser, all of them have a direct impact on the parameter values of the station. That is why a complete history of the station relates actual changes in the station with (gradual or sudden) observed changing patterns in the time series. It is well documented that small spatial and temporal variations or observational practices such as a slight change in the elevation of the station or the type of instrument could affect the consistency of records of a meteorological variable (Easterling et al., 1999). These changes could be reflected in the short or long term variation of the time series, and consequently influence the analysis of climate variability, and their influence on the results can be significant. For this reason, it is desirable to test the homogeneity of the stations selected before applying any analysis.

For the analysis of homogeneity a detailed documentation of the history of the station is desired. For meteorological purposes the information about the data is called metadata. The reliability of the results is increased when the documentation for the stations is available. In the absence of such information it is always better to check the consistency of the record by applying double mass curve technique. From the Tables of Climatic Normal's (1961 – 1990) published by IMD, Pune it was found that none of the considered stations had a history of relocation, change in instrument, so the question of change in the location and modification in the exposure is ruled out. Then, double mass curves were prepared as a quality control process for every single time series for all those stations having common data period to spot sudden changes in the climatic patterns.

3.3.2.1 Double Mass Curve Technique

The Double-Mass plot is a technique utilised to find inconsistencies in a climatogical time-series. Double-mass plots can be used to identify one or more in-homogeneities, and to correct them if the errors are clear enough. In this technique the accumulated quantity of the parameter of station whose record is to be tested is taken on the y-axis and the average accumulated quantity of surrounding stations is taken on the abscissa. The underlying assumption is that during the same period the plot will produce a straight line (45° slope). Thus, when a break is found that means a change in the constant of proportionality, or that the constant of proportionality is not the same at all rates of accumulation. These changes are then corrected by multiplying a correction factor to the values. Normally plotting is done from the latest to the oldest so that the oldest record may be corrected for the changed environment. Double mass analysis indicates that the available data can be considered as homogeneous for the purpose of climatic analyses.

The rapid urban growth is another possible factor for the increasing trend in temperatures across the globe. Several procedures have been suggested by Karl et al. (1988) to correct this urbanisation temperature bias. But when compared with the global average rise in mean temperatures, heat urban biases are relatively small (Karl et al., 1991). However, with the geographically widespread and accumulating evidence towards warming in temperatures, it is unlikely that urbanisation plays a key role in the upward trend (Karl et al., 1993). Principally because the SST average of the world is warming at a similar rate to the land average (IPCC, 2007). Urbanisation influences cannot be ignored at local scales, and care will be taken when evaluating the results on climate extreme indices for stations within urban areas. However, due to lack of detailed information on the population growth in the Indian Himalayas, this aspect was not considered in the present study.

Heterogeneity in climatic variables may also be arises due Atmospheric Brown Clouds (ABC) which is reported to be increasing in the atmosphere (Ramanathan, 2005). This has not been considered in the present study because of non-availability of ABC data.

3.4 Time-series Anomaly

For trend analysis it is always preferred to have a uniform data length for better comparison between the stations. Since, for the present study the length of data was not the same and even if trend exist the comparison of trend is meaningless. Therefore, in order to bring uniformity and facilitate comparison between stations the anomalies of variables is computed by subtracting the mean from the individual station values. The anomaly series is used for individual station trend analysis.

3.5 Regional Averages

While preparing regional climatic series it is a common practice to take the average of original data. But such a procedure will bias the regional estimates in favour of those with high numerical values especially rainfall and discharges. When calculating regional averages our interest lies with the dominant time-series features of the sites to remain. In the present study the regional averages for the common period from 1958 to 1990 were calculated arithmetically by averaging the standardized data (Bhutiyani et al., 2010) of stations having the common data length. The standardized series (zero mean and unit variance) is determined as

$$X_{ik} = \frac{Xi - \overline{Xi}}{\sigma i}$$

(3.2)

Where, X_{ik} is the standardized series, Xi is the parameter value in the i^{th} year, $\overline{Xi}$ is the long-term mean of the of the parameter at station *K* and σi is the standard deviation of the original series.

The stations having common period from 1958 to 1990 are as follows:

Western Himalaya - Srinagar, Jammu, Simla, Bhuntar, Mandi, Dharamsala and Bilaspur

Central Himalaya - Dehra Dun, Mussoorie, Joshimath, Mukteshwar and Mukhim
Eastern Himalaya - Darjeeling, Kalimpong, Gangtok and Pasighat

3.6 Preparation of Seasonal Time-series

For the present study a water year is considered as the starting of 1st October and thus the values of October, November and December months were carried over to the next year. The year was divided in to four principal seasons viz., post-monsoon (October-November), winter (December-January-February), pre-monsoon (March-April-May) and monsoon (June-July-August-September).

The monthly and annual averages for all the climatological variables of all the stations were calculated and presented in Table 3.2 through 3.8. The average annual mean temperature (Table 3.5) of the Indian Himalayas varies from 12.6 °C (Darjeeling) to 25.5 °C (Jammu). It is surprising to note that Jammu which is considered as the station of colder region recorded the highest temperature (39.6 °C) in mean maximum temperature (Table 3.3). From Table 3.7 it is seen that the eastern most station of Arunachal Pradesh (Pasighat) receive the highest normal monsoon and annual rainfall while in the westnorth Jammu & Kashmir (Srinagar) the monsoon and annual rainfall are on the lower side. The normal annual rainfall of the stations of the Indian Himalayas varies from 678.4 mm (Srinagar) to 4520.3 mm (Pasighat) and monsoon rainfall varies from 23.6% (Banihal) to 85.9% (Dehra Dun) of the normal annual rainfall.

Table 3.2 Monthly and annual averages of mean maximum temperature for the stations of Indian Himalayas

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Srinagar	4.9	7.3	12.9	18.6	22.9	28.2	29.2	28.9	27.0	21.2	14.1	7.2	18.5
Quazigund	6.1	8.0	13.7	19.7	23.3	27.6	27.9	27.8	26.4	21.8	15.6	8.4	18.9
Banihal	10.0	10.6	15.6	21.8	25.2	28.5	28.1	27.7	26.7	23.7	18.4	12.8	20.7
Jammu	18.7	21.1	26.0	33.0	37.7	39.6	34.7	33.2	33.3	31.6	26.6	20.9	29.7
Dalhousie	11.4	13.1	17.3	21.8	25.3	27.1	23.7	22.8	23.0	21.9	18.0	14.6	20.0
Dharamsala	14.8	16.6	20.9	26.2	30.2	31.4	27.3	26.5	26.4	24.9	20.8	16.9	23.6
Manali	10.6	11.6	16.1	21.7	25.1	26.9	25.7	25.4	25.0	22.5	18.4	13.9	20.2
Bhuntar (A)	15.2	17.4	21.7	27.0	30.9	33.1	31.3	30.6	30.2	27.7	22.8	17.5	25.5
Mandi	18.9	21.7	25.6	30.6	34.7	35.9	31.9	31.3	30.8	28.9	25.0	20.6	28.0
Bilaspur	19.4	21.8	26.4	32.4	36.2	37.1	32.8	31.4	31.3	30.2	25.9	21.4	28.9
Simla	8.9	10.4	14.4	19.3	23.1	24.1	21.1	20.2	20.2	18.6	15.1	11.6	17.3
Mukhim	12.8	13.7	17.8	22.5	25.0	25.8	23.9	23.6	23.5	21.8	18.2	14.9	20.3
Joshimath	11.7	12.5	17.3	22.0	24.6	26.0	24.2	23.7	23.0	20.9	16.8	13.6	19.7
Mussoorie	10.5	11.9	16.1	21.0	24.2	23.7	20.8	20.3	20.0	18.8	15.7	12.8	18.0
Tehri	19.8	22.2	27.1	32.9	36.0	36.7	33.4	32.6	32.5	30.2	25.9	21.7	29.2
Dehradun	19.3	21.6	26.5	32.1	35.7	34.8	30.5	29.6	29.7	28.5	25.0	21.2	27.9
Mukteswar	10.6	12.1	16.3	20.9	23.7	23.4	20.9	20.3	20.2	19.1	16.3	13.1	18.1
Nainital	10.8	12.2	16.2	20.8	23.5	23.5	21.6	21.0	20.7	18.7	15.4	12.9	18.1
Pasighat	22.8	23.1	26.1	27.8	29.4	30.7	30.4	31.5	30.5	29.5	27.1	24.1	27.7
Ziro	22.6	23.7	26.4	28.2	29.2	30.6	30.9	31.0	30.4	29.5	27.0	24.0	27.8
Gangtok	12.3	13.9	18.1	20.9	21.5	22.1	21.7	22.2	21.5	20.6	17.7	14.2	18.9
Kalimpong	17.2	18.4	21.3	23.7	24.8	25.2	25.3	25.3	25.2	24.2	21.5	18.7	22.6
Darjeeling	9.8	10.8	14.6	17.4	18.5	19.4	19.4	19.7	19.5	18.6	15.6	12.3	16.3
Mean	**13.9**	**15.5**	**19.8**	**24.4**	**27.4**	**28.8**	**26.8**	**26.4**	**26.0**	**24.1**	**20.1**	**16.1**	**22.4**
Max	**22.8**	**23.7**	**27.1**	**33.0**	**37.7**	**39.6**	**34.7**	**33.2**	**33.3**	**31.6**	**27.1**	**24.1**	**29.7**
Min	**4.9**	**7.3**	**12.9**	**17.4**	**18.5**	**19.4**	**19.4**	**19.7**	**19.5**	**18.6**	**14.1**	**7.2**	**16.3**

Table 3.3 Monthly and annual averages of mean minimum temperature for the stations of Indian Himalayas

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Srinagar	-2.9	-1.6	2.6	6.8	9.9	14.1	17.7	17.2	12.2	5.9	0.8	-2.3	6.7
Quazigund	-3.1	-2.0	2.7	7.0	9.9	13.7	16.9	16.2	11.0	5.7	0.9	-2.1	6.4
Banihal	-0.3	0.7	4.1	8.5	11.3	14.7	17.4	16.9	12.2	6.8	2.8	0.6	8.0
Jammu	7.0	8.8	13.5	18.7	23.2	26.2	25.3	24.7	22.9	17.9	11.9	7.7	17.3
Dalhousie	2.2	3.1	6.8	10.9	14.3	16.7	15.9	15.7	14.2	11.1	7.2	4.5	10.2
Dharamsala	5.8	7.5	11.5	15.9	19.8	21.7	20.6	20.2	18.6	15.0	10.8	7.3	14.6
Manali	-1.8	-0.8	2.5	5.8	8.7	12.4	15.1	14.9	11.0	5.3	1.5	-0.4	6.2
Bhuntar (A)	1.5	3.4	6.6	9.7	12.6	17.0	19.8	19.8	16.5	9.9	4.4	1.7	10.2
Mandi	2.9	3.9	8.5	13.1	17.3	20.0	21.1	20.5	18.6	12.2	7.3	3.5	12.4
Bilaspur	5.0	6.4	10.4	15.7	19.4	23.0	22.7	22.4	20.3	14.5	9.3	5.8	14.6
Simla	1.7	2.9	6.5	10.9	14.3	15.7	15.1	14.8	13.5	10.6	7.0	4.1	9.8
Mukhim	3.4	4.3	7.5	11.6	14.4	16.5	16.9	16.7	15.1	11.6	8.0	5.3	10.9
Joshimath	2.1	3.1	6.2	10.6	13.5	16.3	16.7	16.6	14.6	10.3	6.2	3.8	10.0
Mussoorie	2.5	3.6	7.1	11.6	14.7	16.0	15.4	15.2	14.0	11.0	7.3	4.4	10.2
Tehri	4.6	6.9	10.4	15.4	18.7	22.8	23.4	23.1	20.9	15.3	9.3	4.8	14.6
Dehradun	5.9	7.7	11.8	16.6	20.5	22.8	22.5	21.7	20.6	15.6	10.1	6.5	15.2
Mukteswar	1.4	2.6	5.9	10.1	12.9	14.1	13.9	13.9	12.2	9.4	5.9	3.3	8.8
Nainital	1.8	3.5	7.3	11.8	14.6	16.3	16.5	16.0	14.1	9.7	5.6	3.1	10.0
Pasighat	12.3	14.0	16.7	18.9	21.3	23.2	23.5	23.8	23.0	20.6	16.6	13.4	18.9
Ziro	10.2	13.0	16.2	19.2	21.7	23.7	24.4	24.7	23.8	20.9	15.5	11.1	18.7
Gangtok	4.2	5.5	8.8	11.5	13.6	16.0	16.6	16.5	15.5	12.5	8.8	5.5	11.2
Kalimpong	8.0	9.5	11.8	14.2	15.8	17.0	17.6	18.0	17.6	15.6	12.0	9.1	13.9
Darjeeling	1.8	3.2	6.6	9.6	11.6	13.5	14.1	14.0	13.1	10.2	6.3	3.4	9.0
Mean	**3.3**	**4.7**	8.3	12.3	**15.4**	**18.0**	**18.7**	18.4	**16.3**	**12.1**	7.6	**4.5**	**11.6**
Max	**12.3**	**14.0**	16.7	19.2	**23.2**	26.2	25.3	24.7	**23.8**	20.9	**16.6**	**13.4**	**18.9**
Min	**-3.1**	**-2.0**	2.5	5.8	8.7	**12.4**	**13.9**	**13.9**	**11.0**	5.3	**0.8**	**-2.3**	**6.2**

Table 3.4 Monthly and annual averages of mean temperature for the stations of Indian Himalayas

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Srinagar	1.0	2.9	7.7	12.7	16.4	21.2	23.5	23.0	19.6	13.6	7.4	2.5	12.6
Quazigund	1.5	3.0	8.2	13.4	16.6	20.7	22.4	22.0	18.7	13.7	8.2	3.2	12.6
Banihal	4.8	5.6	9.8	15.1	18.2	21.6	22.7	22.3	19.5	15.2	10.6	6.7	14.4
Jammu	12.8	14.9	19.8	25.8	30.4	32.9	29.6	29.0	28.1	24.7	19.3	14.3	23.5
Dalhousie	6.8	8.1	12.0	16.4	19.8	21.9	19.8	19.3	18.6	16.5	12.6	9.6	15.1
Dharamsala	10.3	12.0	16.2	21.0	25.0	26.5	23.9	23.3	22.5	20.0	15.8	12.1	19.1
Manali	4.4	5.4	9.3	13.8	16.9	19.7	20.4	20.1	18.0	13.9	9.9	6.8	13.2
Bhuntar (A)	8.3	10.4	14.2	18.4	21.7	25.1	25.6	25.2	23.3	18.8	13.6	9.6	17.8
Mandi	10.9	12.8	17.0	21.8	26.0	27.9	26.5	25.9	24.7	20.6	16.1	12.1	20.2
Bilaspur	12.2	14.1	18.4	24.0	27.8	30.1	27.7	26.9	25.8	22.3	17.6	13.6	21.7
Simla	5.3	6.6	10.5	14.9	18.7	19.9	18.1	17.5	16.8	14.6	11.0	7.8	13.5
Mukhim	8.1	9.0	12.6	17.1	19.7	21.1	20.4	20.1	19.3	16.7	13.1	10.1	15.6
Joshimath	6.9	7.8	11.8	16.3	19.0	21.1	20.4	20.2	18.8	15.6	11.5	8.7	14.8
Mussoorie	6.5	7.7	11.6	16.3	19.4	19.9	18.1	17.7	17.0	14.9	11.5	8.6	14.1
Tehri	12.2	14.5	18.8	24.1	27.3	29.7	28.4	27.9	26.7	22.8	17.6	13.3	21.9
Dehradun	12.6	14.7	19.1	24.3	28.1	28.8	26.5	25.6	25.2	22.0	17.5	13.9	21.5
Mukteswar	6.0	7.3	11.1	15.5	18.3	18.8	17.4	17.1	16.2	14.3	11.1	8.2	13.4
Nainital	6.3	7.8	11.8	16.3	19.0	19.9	19.1	18.5	17.4	14.2	10.5	8.0	14.1
Pasighat	17.5	18.5	21.4	23.3	25.3	27.0	26.9	27.6	26.7	25.0	21.8	18.7	23.3
Gangtok	8.3	9.7	13.4	16.2	17.6	19.1	19.1	19.3	18.5	16.6	13.2	9.8	15.1
Ziro	16.4	18.3	21.3	23.7	25.4	27.1	27.7	27.8	27.1	25.2	21.3	17.5	23.2
Kalimpong	12.6	13.9	16.5	18.9	20.3	21.1	21.5	21.6	21.4	19.9	16.7	13.9	18.2
Darjeeling	5.8	7.0	10.6	13.5	15.1	16.4	16.8	16.9	16.3	14.4	10.9	7.8	12.6
Mean	**8.6**	**10.1**	**14.0**	**18.4**	**21.4**	**23.4**	**22.7**	**22.4**	**21.1**	**18.1**	**13.9**	**10.3**	**17.0**
Max	**17.5**	**18.5**	**21.4**	**25.8**	**30.4**	**32.9**	**29.6**	**29.0**	**28.1**	**25.2**	**21.8**	**18.7**	**23.5**
Min	**1.0**	**2.9**	**7.7**	**12.7**	**15.1**	**16.4**	**16.8**	**16.9**	**16.2**	**13.6**	**7.4**	**2.5**	**12.6**

Table 3.5 Monthly and annual averages of mean diurnal temperature range for the stations of Indian Himalayas

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Srinagar	7.8	8.9	10.4	11.8	13.0	14.1	11.6	11.8	14.7	15.3	13.3	9.5	11.8
Quazigund	9.2	10.0	11.1	12.8	13.4	13.8	11.0	11.6	15.4	16.1	14.6	10.5	12.5
Banihal	10.3	9.9	11.5	13.2	14.0	13.8	10.7	10.7	14.5	16.9	15.6	12.2	12.8
Jammu	11.7	12.3	12.5	14.2	14.5	13.5	10.1	8.5	10.4	13.8	14.7	13.3	12.4
Dalhousie	9.2	9.9	10.5	11.0	11.0	10.4	7.7	7.1	8.8	10.8	10.8	10.0	9.8
Dharamsala	9.0	9.1	9.5	10.3	10.4	9.7	6.7	6.3	7.8	9.8	10.1	9.6	9.0
Manali	12.4	12.4	13.5	15.9	16.4	14.5	10.6	10.5	13.9	17.2	16.9	14.3	14.0
Bhuntar (A)	13.8	14.0	15.1	17.3	18.3	16.1	11.5	10.7	13.7	17.8	18.4	15.8	15.2
Mandi	16.0	17.8	17.1	17.5	17.4	15.9	10.8	10.8	12.2	16.7	17.7	17.1	15.6
Bilaspur	14.4	15.3	16.1	16.7	16.9	14.0	10.1	9.0	11.0	15.7	16.6	15.6	14.3
Simla	7.1	7.6	7.9	8.1	8.8	8.5	6.0	5.4	6.7	8.0	8.0	7.6	7.5
Mukhim	9.4	9.4	10.3	10.9	10.5	9.3	7.0	6.9	8.4	10.2	10.3	9.6	9.3
Joshimath	9.6	9.4	11.2	11.4	11.1	9.7	7.5	7.1	8.4	10.6	10.7	9.9	9.7
Mussoorie	8.0	8.3	9.0	9.4	9.5	7.7	5.3	5.1	6.0	7.8	8.4	8.4	7.8
Tehri	15.2	15.2	16.7	17.5	17.3	13.9	10.0	9.5	11.6	14.9	16.6	16.9	14.6
Dehradun	13.4	13.9	14.7	15.6	15.2	12.0	8.0	7.9	9.1	12.9	14.9	14.6	12.7
Mukteswar	9.2	9.5	10.4	10.8	10.8	9.3	7.0	6.4	8.0	9.7	10.4	9.8	9.3
Nainital	9.0	8.7	8.8	9.0	8.9	7.2	5.1	5.0	6.6	9.0	9.8	9.9	8.1
Pasighat	10.4	9.1	9.4	8.9	8.1	7.6	6.9	7.7	7.5	8.9	10.6	10.7	8.8
Ziro	12.4	10.7	10.3	9.0	7.6	6.9	6.5	6.4	6.6	8.5	11.5	13.0	9.1
Gangtok	8.1	8.4	9.3	9.4	7.8	6.1	5.1	5.7	6.1	8.2	8.9	8.7	7.6
Kalimpong	9.3	8.8	9.5	9.6	9.0	8.2	7.7	7.4	7.6	8.6	9.4	9.6	8.7
Darjeeling	7.9	7.6	8.0	7.8	6.9	5.9	5.3	5.7	6.5	8.4	9.3	8.9	7.3
Mean	**10.6**	**10.7**	**11.4**	**12.1**	**12.0**	**10.8**	**8.2**	**8.0**	**9.6**	**12.0**	**12.5**	**11.5**	**10.8**
Max	**16.0**	**17.8**	**17.1**	**17.5**	**18.3**	**16.1**	**11.6**	**11.8**	**15.4**	**17.8**	**18.4**	**17.1**	**15.6**
Min	**7.1**	**7.6**	**7.9**	**7.8**	**6.9**	**5.9**	**5.1**	**5.0**	**6.0**	**7.8**	**8.0**	**7.6**	**7.3**

Table 3.6 Monthly and annual averages of rainfall for the stations of Indian Himalayas

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Monsoon rainfall	% of annual rainfall
Srinagar	67.5	68.7	106.4	89.3	63.2	33.0	59.1	46.8	29.1	30.7	27.9	56.9	678.4	168.0	24.8
Quazigund	140.0	186.8	207.2	133.2	101.6	65.1	112.7	83.8	42.8	38.7	59.8	97.8	1269.5	304.4	24.0
Banihal	134.3	231.9	233.1	127.7	96.4	48.6	106.8	107.4	50.1	32.6	57.5	97.7	1324.1	312.9	23.6
Jammu	62.5	67.5	68.9	34.8	31.5	62.9	351.5	330.0	119.6	25.0	19.1	37.4	1210.7	863.9	71.4
Dalhousie	137.2	137.2	141.3	92.5	68.2	140.2	582.9	591.7	271.0	82.5	43.5	66.6	2355.0	1585.8	67.3
Dharamsala	122.2	109.1	115.4	57.3	62.7	225.6	883.0	862.2	388.3	64.5	22.4	58.7	2971.3	2359.1	79.4
Manali	131.4	131.8	193.5	107.8	79.4	78.3	218.4	203.8	110.1	39.1	43.0	59.9	1396.7	610.7	43.7
Bhuntar (A)	99.8	108.7	142.6	85.7	72.3	56.1	134.7	128.0	59.9	27.3	26.1	41.5	982.8	378.7	38.5
Mandi	64.9	59.3	81.3	51.6	60.2	139.6	443.2	355.8	161.2	52.9	16.4	31.0	1516.5	1099.9	72.5
Bilaspur	71.0	60.8	62.9	28.6	59.6	130.1	365.2	294.7	149.8	29.8	16.5	38.1	1307.0	939.8	71.9
Simla	54.2	48.5	58.1	44.1	61.3	167.4	399.9	332.7	182.6	41.3	15.4	22.3	1427.7	1082.5	75.8
Mukhim	54.7	73.3	91.1	61.3	85.6	173.0	398.3	368.5	197.2	43.7	15.2	36.7	1598.6	1137.0	71.1
Joshimath	61.5	99.6	118.0	58.9	59.9	103.3	254.5	220.0	111.1	38.0	15.3	25.9	1166.0	688.9	59.1
Mussoorie	55.6	61.4	62.1	36.1	57.3	183.8	646.6	674.7	286.4	52.4	11.3	23.6	2151.3	1791.4	83.3
Tehri	55.3	53.6	63.4	30.6	46.5	94.2	237.7	224.6	119.4	24.2	12.4	32.5	994.5	675.9	68.0
Dehradun	55.0	57.3	55.3	21.8	41.9	212.6	695.0	723.9	314.2	55.6	8.5	23.6	2264.7	1945.8	85.9
Mukteswar	53.4	53.8	50.6	34.5	55.5	142.5	316.8	295.1	187.9	71.3	6.3	24.1	1292.0	942.4	72.9
Nainital	78.0	62.3	57.6	33.6	75.5	317.4	715.4	564.6	384.1	142.2	6.7	26.8	2464.3	1981.5	80.4
Pasighat	51.9	97.4	130.6	258.9	389.3	824.7	1079.7	777.6	593.2	250.9	35.1	30.8	4520.3	3275.2	72.5
Ziro	34.9	57.2	107.1	197.4	355.4	490.1	503.4	402.8	340.3	167.2	27.5	19.8	2703.1	1736.6	64.2
Gangtok	28.7	86.3	110.4	288.3	533.2	599.0	606.5	562.1	459.5	179.8	44.7	21.4	3520.0	2227.1	63.3
Kalimpong	17.6	19.1	40.3	74.8	138.6	381.3	652.9	476.5	353.9	108.1	10.5	7.3	2280.9	1864.6	81.8
Darjeeling	22.3	23.3	53.3	95.1	184.9	496.8	729.5	539.1	432.4	123.2	15.3	9.1	2724.4	2197.8	80.7
Mean	**71.9**	**85.0**	**102.2**	**88.9**	**120.9**	**224.6**	**456.3**	**398.5**	**232.4**	**74.8**	**24.2**	**38.7**	**1918.2**	**1311.7**	**64.2**
Max	**140.0**	**231.9**	**233.1**	**288.3**	**533.2**	**824.7**	**1079.7**	**862.2**	**593.2**	**250.9**	**59.8**	**97.8**	**4520.3**	**3275.2**	**85.9**
Min	**17.6**	**19.1**	**40.3**	**21.8**	**31.5**	**33.0**	**59.1**	**46.8**	**29.1**	**24.2**	**6.3**	**7.3**	**678.4**	**168.0**	**23.6**

Table 3.7 Monthly and annual averages of number of rainy days for the stations of Indian Himalayas

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Srinagar	5	5	7	7	6	3	5	4	3	3	2	3	54
Quazigund	8	9	9	8	9	4	7	6	4	3	3	5	75
Banihal	7	9	10	8	7	4	8	6	4	3	3	5	73
Jammu	4	4	5	3	2	4	12	12	5	1	1	2	55
Dalhousie	6	6	6	5	5	7	18	19	9	3	3	3	91
Dharamsala	6	6	7	5	5	10	21	22	13	4	2	4	102
Manali	7	8	9	6	6	7	14	14	8	3	3	4	89
Bhuntar (A)	6	7	8	6	7	5	9	9	5	2	2	3	69
Mandi	5	4	5	4	5	8	17	15	9	3	2	2	79
Bilaspur	4	4	4	2	3	5	15	14	7	2	1	2	63
Simla	5	5	5	4	5	10	18	18	9	3	2	2	85
Mukhim	4	5	6	5	6	10	18	17	10	3	1	2	86
Joshimath	4	6	7	5	6	8	16	16	9	3	1	2	84
Mussoorie	4	4	5	3	4	9	21	22	12	3	1	2	90
Tehri	4	4	5	3	4	6	13	12	6	2	1	2	62
Dehradun	4	3	3	2	3	9	21	22	12	3	1	2	85
Mukteswar	4	4	4	3	4	9	17	17	10	3	0	2	77
Nainital	4	4	4	3	4	13	22	20	12	4	0	1	91
Pasighat	4	7	10	13	14	18	22	17	15	8	3	2	131
Ziro	4	6	8	12	16	20	20	18	15	8	3	2	131
Gangtok	3	5	9	15	21	23	25	25	21	9	3	2	159
Kalimpong	1	2	3	6	10	16	22	19	12	4	1	1	95
Darjeeling	2	2	5	8	14	20	25	23	17	6	2	1	124
Mean	**4.5**	**5.2**	**6.3**	**5.8**	**7.2**	**9.9**	**16.9**	**15.9**	**9.8**	**3.6**	**1.8**	**2.4**	**89.2**
Max	**7.9**	**9.3**	**9.7**	**14.7**	**20.7**	**23.2**	**25.4**	**24.6**	**20.9**	**8.5**	**3.3**	**5.0**	**159.4**
Min	**1.2**	**1.7**	**3.2**	**2.0**	**2.5**	**3.3**	**5.0**	**4.5**	**2.8**	**1.5**	**0.5**	**0.7**	**54.1**

Table 3.8 Monthly and annual averages of mean wind speed for the stations of Indian Himalayas

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Dalhousie	3.5	3.9	4.8	4.9	5.4	3.7	1.9	1.4	1.9	2.6	2.6	2.8	3.3
Dharamsala	4.0	4.6	4.8	5.0	5.2	4.0	2.9	2.5	2.9	3.2	3.0	3.3	3.8
Bhuntar (A)	2.9	3.7	4.4	4.8	4.8	5.5	6.4	6.0	5.4	4.3	3.4	2.5	4.5
Manadi	1.6	2.1	2.5	2.5	2.8	2.5	1.9	1.6	1.4	1.7	1.3	1.2	1.9
Simla	3.8	4.2	4.5	4.1	4.0	3.2	2.3	1.8	2.1	2.8	3.0	3.3	3.3
Joshimath	5.6	6.4	7.6	6.4	5.8	4.2	3.2	2.9	3.1	4.0	4.6	5.4	4.9
Mussoorie	7.2	8.0	8.6	8.3	8.6	7.0	5.8	5.2	5.6	6.4	6.7	7.0	7.0
Tehri	1.1	1.5	2.2	2.7	3.4	3.9	2.9	2.3	2.0	1.8	1.1	0.8	2.2
Dehradun	2.6	3.0	3.4	3.8	3.9	3.4	2.7	2.4	2.7	3.1	2.8	2.5	3.0
Mukteswar	10.1	11.9	12.3	13.7	15.3	14.7	12.1	10.6	10.0	9.4	9.4	9.8	11.6
Nainital	7.0	7.5	7.5	7.2	7.4	6.6	7.6	7.7	6.4	6.3	6.3	6.4	7.0
Pasighat	12.4	12.7	13.5	9.6	6.8	4.3	2.5	3.0	3.8	7.6	11.8	13.0	8.4
Ziro	1.6	2.1	2.8	3.3	2.8	2.5	2.5	2.2	2.1	1.8	1.5	1.5	2.2
Gangtok	1.3	1.8	2.7	3.1	2.4	1.3	1.0	0.9	1.0	1.3	1.3	1.1	1.6
Kalimpong	6.9	6.6	7.9	8.1	7.3	6.6	6.0	6.3	6.1	6.7	6.6	7.1	6.9
Darjeeling	3.0	4.1	5.3	6.0	5.3	4.7	4.3	4.2	3.7	3.2	2.8	2.8	4.1
Mean	**5.2**	**5.8**	**6.5**	**6.4**	**6.1**	**5.2**	**4.4**	**4.1**	**4.1**	**4.5**	**4.8**	**5.1**	**5.2**
Max	**12.4**	**12.7**	**13.5**	**13.7**	**15.3**	**14.7**	**12.1**	**10.6**	**10.0**	9.4	**11.8**	**13.0**	**11.6**
Min	**1.1**	**1.5**	2.2	2.7	2.4	1.3	1.0	0.9	1.0	1.3	**1.1**	**0.8**	**1.6**

CHAPTER 4

INVESTIGATION OF SHORT-TERM AND LONG-TERM DEPENDENCE

4.1 INTRODUCTION

As demands upon the existing global water resources increase, the accurate measurement of water supplies will demand a clear understanding of many interactions within the hydrological cycle, in particular the impact of climate variability upon the spatial and temporal distribution of climate variables. Interactions between various global climate phenomena produce extended hot and cold, wet and dry cycles. The supposition of the broader climate having a tendency to fluctuate between a discrete number of stable regimes has a long history in meteorological studies.

Many hydrological and other geophysical time series have some structure, that is, consecutive values of hydrological time series are dependent to each other. If a time series is not random then either it will be short-term dependent or long-term dependent. Occurrence of dependence (short-term or long-term) in a time series may give an indication of the change in the climate.

This chapter deals with the investigation of presence of short-term and long-term dependence in the annual time series of temperature (mean, maximum, minimum and temperature range), rainfall, number of rainy days and; wind speed for the Indian Himalaya. The results obtained from the analysis have been discussed in length to arrive at some conclusions.

4.2 REVIEW OF LITERATURE

The review of literature has been presented in Chapter 2 under section 2.1 from page no. 7 – 10.

4.3 STUDY AREA AND DATA USED

The study area and data used for the present analysis has been described in Chapter 3 under section 3.1 to 3.2.

4.4 METHODOLOGY

4.4.1Tests of Short-term Dependence

Most of the statistical tests of independence are designed to show up only short-term serial correlation. They are insensitive to the long-term serial correlation structure of the series. The following tests were applied to each time series. The first eleven tests are non-parametric, and the last three tests are parametric. The non-parametric tests are free from any assumptions, however, parametric tests requires that the data should be normal and free from outliers. A null hypothesis of independent series has been tested at 5% and 10% significance levels in this study.

4.4.1.1 Non-parametric tests

(i) Median-Crossing test (Fisz, 1963; Lye and Lin, 1994)

X is replaced by zero if $x_i < x_{median}$, and X is replaced by one if $x_i > x_{median}$. If the original sequence of X_x has been generated by a purely random process, then u, the number of times zero is followed by one or one is followed by zero, is approximately normally distributed. The above statement can be simply understood as follows.

$$\begin{array}{ll} x_i < x_{median} & then\ X = 0 \\ x_i > x_{median} & then\ X = 1 \end{array} \qquad (4.1)$$

$$u = 0$$

If $x_i > x_{median}\ and\ x_{i+1} < x_{median}\ or\ x_i < x_{median}\ and\ x_{i+1} > x_{median}$ then $u = u + 1$. The expected value of u is defined as follows.

$$E(u) = \frac{n-1}{2} \qquad (4.2)$$

$$Var(u) = \frac{n-1}{4} \qquad (4.3)$$

The Z statistic can be computed as follows.

$$Z = \frac{u - E(u)}{[Var(u)]^{1/2}} \qquad (4.4)$$

If $Z < Z_a$ then the null hypothesis is true otherwise false (i.e., the series is assumed to non-random).

(ii) Turning point test (Kendall's test, 1976; Lye and Lin, 1994)

Kendall's test (Kendall and Stuart, 1976; Lye and Lin, 1994) is also based on the binary series. $If\ x_{i-1} < x_i > x_{i+1}\ or\ x_{i-1} > x_i < x_{i+1}\ then\ x_i = 1;\ otherwise\ x_i = 0$. The total number of ones u i.e., $initial\ value\ of\ u = 0\ and\ if\ the\ above\ condition\ satisfies\ then\ u = u + 1$), is approximately normally distributed. The expected value of u is defined as follows.

$$E(u) = \frac{2(n-2)}{3} \tag{4.5}$$

$$Var(u) = \frac{16n-29}{90} \tag{4.6}$$

The Z statistic can be computed as follows.

$$Z = \frac{u - E(u)}{[Var(u)]^{1/2}} \tag{4.7}$$

If $Z_\alpha < Z$ then the null hypothesis is failed and the series is assumed to be non-random.

(iii) Rank difference test (Meacham, 1968; Lye and Lin, 1994)

Variable values are replaced by their relative ranks R_i with the lowest being denoted by Rank 1 (R1). The statistic u is calculated by

$$u = \sum_{i=2}^{n} |R_i - R_{i-1}| \tag{4.8}$$

The expected value of u is estimated by using the following relationship.

$$E(u) = \frac{(n+1)\cdot(n-1)}{3} \tag{4.9}$$

The variance of u is given by

$$Var(u) = \frac{(n-2)\cdot(n+1)\cdot(4n-7)}{90} \tag{4.10}$$

The Z statistic is estimated as follows:

$$Z = \frac{u - E(u)}{[Var(u)]^{1/2}} \tag{4.11}$$

If $Z_\alpha < Z$ then the null hypothesis is failed and the series is assumed to be non-random.

(iv) Kendall's rank correlation test (Kendall's test 1973)

If the series is thought to have a random component, Kendall's rank correlation test can be used to test the significance. This measures the 'disarray' in the data; it is particularly effective if the underlying trend is of a linear type. This test is also referred as τ – test and is based on the proportionate number of subsequent observations which exceeds a particular value. Kendall's rank correlation test is performed by using the following steps;

```
Initially $u = 0$
    if $(x_{i+1} > x_i)$ then $u = u + 1$
```

The Z statistic is computed as follows.

$$Z = \frac{T}{[Var(T)]^{1/2}} \tag{4.12}$$

where, $$T = \frac{4u}{n(n-1)} - 1 \tag{4.13}$$

$$Var(T) = \frac{2(2n+5)}{9n(n-1)} \tag{4.14}$$

If $Z_\alpha < Z$ then the null hypothesis is failed and the series is assumed to be non-random.

(v) Run test (WMO, 1966a)

X is replaced by zero if $x_i < x_{median}$, and X is replaced by one if $x_i > x_{median}$. If the original sequence of X_s has been generated by a purely random process, then u, the number of times zero is followed by one or one is followed by zero, is approximately normally distributed. The test is worked out using the following steps.

```
Initially $u = 0$
    if $(x_i > x_{median} > x_{i+1}$ or $x_i < x_{median} < x_{i+1})$
        then $u = u + 1$
```

The expected value of u is defined as follows.

$$E(u) = m + 1 \tag{4.15}$$

where, m is the rank corresponding to the median value. The variance of u is estimated as follows.

$$Var(u) = \frac{m(m-1)}{2m-1} \tag{4.16}$$

The Z statistic can be computed as follows.

$$Z = \frac{u - E(u)}{[Var(u)]^{1/2}} \tag{4.17}$$

If $Z < Z_\alpha$ then the null hypothesis is true otherwise false (i.e., the series is assumed to non-random).

(vi) Wald-Wolfowitz test (Wald and Wolfowitz, 1943; Lye and Lin, 1994)

For a sample of size n

$$R = \sum_{i=1}^{n-1} x_i x_{i-1} + x_1 x_n \tag{4.18}$$

If the elements of the sample are independent then expectation is computed by

$$E(R) = \frac{{s_1}^2 - s_2}{n-1} \tag{4.19}$$

$$Var(R) = \frac{s_2{}^2 - s_4}{n-1} - \left(\frac{s_1{}^2 - s_2}{n-1}\right)^2 + \frac{s_1{}^4 - 4s_1{}^2 s_2 + 4s_1 s_3 + s_2{}^2 - 2s_4}{(n-1)\cdot(n-2)} \qquad (4.20)$$

where,

$$s_r = x_1{}^r + x_2{}^r + \cdots\cdots + x_n{}^r \qquad (4.21)$$

If the mean is subtracted first, $s_1 = 0$, then

$$R \approx \left\{ \frac{-s_2}{n-1}, \left[\frac{s_2{}^2 - s_4}{n-1} - \left(\frac{-s_2}{n-1}\right)^2 + \frac{s_2{}^2 - 2s_4}{(n-1)\cdot(n-2)} \right]^{1/2} \right\} \qquad (4.22)$$

(vii) Rank Von Neumann ratio test (Madansky, 1988; Lye and Lin, 1994)

Let $r_1, r_2, \cdots, r_n$ denote the ranks associated with the x_i values. The rank Von Nuemann ratio is given by

$$\upsilon = \frac{\sum_{i=2}^{n} (r_i - r_{i-1})^2}{n(n^2-1)/12} \qquad (4.23)$$

Critical value of $C = [n^2(n^2-1)/12]\upsilon$ and approximate critical value of υ were given by Madansky (1988). For large *n*, υ is approximately distributed as *N* (2, 4/*n*), although Bartels recommended $20/(5n+7)$ as a better approximation to the variance of υ (Madansky, 1988).

(viii) Mann-Kendall test (Mann, 1945 –Kendall, 1975)

The Mann-Kendall test is described by Yue et al. (2002). It is based on the test statistics S, which is defined as follows.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \qquad (4.24)$$

where, x_j are the sequential data values, n is the length of the data set and

$$\operatorname{sgn}(t) = \begin{cases} 1, & for\, t > 0 \\ 0, & for\, t = 0 \\ -1, & for\, t < 0 \end{cases} \qquad (4.25)$$

Mann-Kendall have documented that when $n \ge 8$, the test statistics S is approximately normally distributed with mean and variance as follows.

$$E(S) = 0 \qquad (4.26)$$

$$Var\,(S) = \frac{n\,(n-1)\,(2n+5) - \sum_{i=1}^{m} t_i\,(t_i-1)(2t_i+5)}{18} \tag{4.27}$$

where, m is the number of tie groups and t_i is the size of the i^{th} tie group. The standardized test statistics Z is computed as follows.

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{Var\,(S)}}, & for\, S>0 \\ 0 \quad , & for\, S=0 \\ \dfrac{S+1}{\sqrt{Var\,(S)}}, & for\, S<0 \end{cases} \tag{4.28}$$

The standardized Mann-Kendall statistics Z follows the standard normal distribution with zero mean and unit variance.

(ix) Spearman's rho test (Lehmann, 1975; Sneyers, 1990)

For a sample data set of $\{x_i, i = 1,2,......,n\}$, the null hypothesis H_o of S-R test is that all the x_i are independent and identically distributed. The alternative hypothesis is that x_i increases or decrease with i, then randomness exists. The Z statistics of S-R test is given as follows:

$$D = 1 - \frac{6\sum_{i=1}^{n}\{R(x_i)-i\}^2}{n(n^2-1)} \tag{4.29}$$

$$Var(D) = 1/(n-1) \tag{4.30}$$

$$Z = \frac{D}{[Var(D)]^{0.5}} \tag{4.31}$$

Where, $R(x_i)$ is the rank of i^{th} observation x_i in the sample of size n. The standardized statistics Z follow the standard normal distribution $Z \approx N(0,1)$.

(x) Cumulative Periodogram test (Box and Jenkins, 1970; Srikanthan et al., 1983)

The periodogram of a time series is defined as

$$I\left(f_j\right) = \frac{2}{n}\left[\left(\sum_{i=1}^{n} x_i \cos 2\pi i f_j\right)^2 + \left(\sum_{i=1}^{n} x_i \sin 2\pi f_j\right)^2\right] \tag{4.32}$$

Where $f_j = j/n$ is the frequency, and;

$J = 1,2,\ldots\ldots, (n-2)/2$ for n even, and $j = 1,2,\ldots\ldots, (n-1)$ for n odd.

The normalised cumulative periodogram is obtained from

$$C(f_j)=\sum_{i=1}^{j} I(f_i)/ns^2 \tag{4.33}$$

where s^2 is the variance of x_i. For a white-noise series the plot of $C(f_i)$ against f_i would be scattered about a straight line joining points (0, 0) and (0.5, 1). The approximate confidence limit lines for a truly random series are drawn at distances:

$$\pm k_\alpha/\left[(n-2)/2\right]^{1/2} \tag{4.34}$$

Where n is even and $K\alpha$ is 1.63 (99%), 1.36 (95%), 1.22 (90%) or 1.02 (75%)

4.4.1.2 Parametric tests

(i) Von Neumann ratio test (Madansky, 1988; Lye and Lin, 1994)

It is one of parametric test used to detect the randomness of the time series. Parametric test is more robust than the non-parametric test. It can be considered as more sharp and efficient which is based on the values associated with the series not only on the relative signs. Parametric test must follow a normality assumption of the population. If $x_i, i=1,2,.....$ is a time series of hydrologic variable then the V-statistics need to be computed based on the assumption that the series is normally distributed with N (0, 1) and is computed as follows:

Let

$$V=\frac{\sum_{i=2}^{n}(x_i-x_{i-1})^2}{\sum_{i=1}^{n}(x_i-\overline{x})^2} \tag{4.35}$$

If data are independent, V is approximately normally distributed with

$$E(V)=2 \tag{4.36}$$

and $$Var(V)=\frac{4(n-2)}{(n^2-1)} \tag{4.37}$$

$$Z(V)=\frac{V-E(V)}{[Var(V)]^{0.5}} \tag{4.38}$$

For independent time series, $Abs[Z(V)]<Z_{1-\alpha/2}$.

(ii) Autocorrelation test (Yevjevich, 1971; Srikanthan et al., 1983)

Short-term dependence is usually measured by the magnitude of the low-order autocorrelation coefficients. In this paper the autocorrelation function, r_H, is estimated as

$$r_k = \left[\sum_{i=1}^{n-k}\left(x_i - \bar{x}\right)\left(x_{i+k} - \bar{x}\right)\right] \Big/ \left[\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2\right] \tag{4.39}$$

where H is lag; x_i is annual data at time I; n is sample size; and

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{4.40}$$

The lag-one autocorrelation, r_1 is calculated from eq. (42) and checked whether or not is significantly different from the expected value as

$$E\left(r_1\right) = -1/n \tag{4.41}$$

and,

$$Var\left(r_1\right) = \left(n^3 - 2n^2 + 2\right) \Big/ \left[n^2\left(n^2 - 1\right)\right] \tag{4.42}$$

and,

$$Z = E\left(r_1\right) - E\left(r_0\right) \Big/ \left[Var\left(r_1\right)\right]^{0.5} \tag{4.43}$$

where, Z is the normally distributed Z-statistic at α significance level.

(iii) Linear Regression test

The regression test is a parametric test for detecting the randomness in time series. It assumes the normality of data. Following steps are involved in regression test. Consider that the data follow the following linear form of equation:

$$x_t = x_0 + \beta t + \xi_t \tag{4.44}$$

For $\beta = 0$

$$\beta = \frac{\sum (t - \bar{t}) \cdot (x_t - \bar{x})}{\sum (t - \bar{t})^2} \tag{4.45}$$

$$\hat{x}_0 = \bar{x} - \beta \bar{t} \tag{4.46}$$

The estimated sum of squared errors is computed as follows:

$$\sum \xi_t^2 = \sum (x_t - \bar{x})^2 - \beta^2 \sum (t - \bar{t})^2 \tag{4.47}$$

The standard error of regression is computed using eq. (51):

$$S = \left\{\sum \xi_t^2 / (n-2)\right\}^{0.5} \tag{4.48}$$

The estimate of variance of $\hat{\alpha}$ is:

$$S_\beta^2 = S^2 / \{\sum (t - \bar{t})^2\} \tag{4.49}$$

The Student's t-statistics is computed as follows.

$$t-\text{statistics} = \frac{\beta}{S_\beta} \tag{4.50}$$

It is assumed here that the residual ξ_i are stationary, sequentially independent and normally distributed. If $|t| < t_{1-\alpha/2,n-2}$ implies the true hypothesis at $\alpha\,\%$ of significance level.

4.4.2. Test for Long-term Dependence (Lye and Lin, 1994)

The only measurement available for long-term dependence is the Hurst coefficient. Long term dependence is measured by the magnitude of the Hurst coefficient *H* and it is given by

$$h = \frac{\log(R_n / \sigma_n)}{\log(n/2)} \tag{4.51}$$

Where R_n = range of cumulative departure from mean, σ_n = standard deviation of the sample, n = sample length. The Hurst coefficient *H*, always lies between 0 and 1, and equals to 0.5 for series that have independent increments, while $H > 0.5$ indicates relatively long-term dependence.

4.4.2.1 Range analysis: Computation of R_n (Lye and Lin, 1994)

Range of the cumulative departure from mean R_n can be expressed as follows.

$$R_n = d_n^+ - d_n^- \tag{4.52}$$

where, d_n^+ is the maximum value of the cumulative departure from mean, and d_n^- is the minimum value of cumulative departure from mean.

If z_i $(z_1, z_2, z_3, ...)$ is the flow series with mean of $\bar{z}$, then

$$d_n^+ = \max_{1 \le i \le n} \sum_{i=1}^{n} (z_i - \bar{z}) \tag{4.53}$$

and
$$d_n^- = \min_{1 \le i \le n} \sum_{i=1}^{n} (z_i - \bar{z}) \tag{4.54}$$

4.4.2.2 Parametric method for testing the significance of Hurst's H (Lye and Lin, 1994)

To test the significance of the calculated Hurst's *H* of a given time series, percentage points of Hurst's *H* for serially independent data at different probability levels are required. Lye and Lin (1994) have obtained the empirical percentage points for Hurst's *H* by Monte Carlo simulation for normally distributed independent data with zero mean and standard deviation of one. The empirical percentage points are given in Table 4.1 and 4.2 for sample sizes ranging from 20 to 200. The test for long-term dependence was based on comparing the observed H value with that which could arise by chance alone from a series of normally distributed independent data. Hence, if the value of H of a given time series is greater than the H value given in the tables at a given significance level for a given sample size, it is concluded that this series is having long-term dependent at this probability level. Otherwise it has no long-term dependence. The 5% and 10% significance levels are used in the present study.

4.4.2.3 Non-parametric Bootstrap method for testing the significance of Hurst's K (Lye and Lin, 1994)

To check the assumption of using normally distributed data for testing Hurst's H, the non-parametric bootstrap approach was used. The following steps are involved:
The bootstrap samples are generated from the data of the original sample as follows:

(i) Supposing that the annual flow series $x_1, x_2, ...x_n$ are independent observations. Each x_i has the same probability of occurrence and is equal to $1/n$, where n is the number of observations in the series.

(ii) Generated a uniform random data i between 1 and n, then chooses x_i as one point in the bootstrap sample.

(iii) Repeated these step n times to generate a bootstrap sample of the same size n as the original sample size.

(iv) Calculated the Hurst's H for the bootstrap samples.

(v) Repeated steps (ii) to (iv) for a large number of times (10 000 in this study).

(vi) Counted the number of times the observed H value of sample is exceeded by 10 000 bootstrap H values.

(vii) Computed the P value as follows:

$$P_{\text{value}} = \frac{\text{Number of } k > k_{\text{observed}}}{\text{Number of Bootstrap samples (i.e. 10000)}} \tag{4.55}$$

Therefore, if the P_{value} is less than the specified significance level, it is concluded that the sample being tested has long term dependent at the specified level. Otherwise, series does not have long term dependence.

Table 4.1 Empirical percentage points for Hurst's *H* for normally distributed independent data (n= 20 – 50) (After Lye and Lin, 1994)

Sample Size	**Significant Levels**				
	1%	**5%**	**10%**	**20%**	**50%**
20	0.837	0.796	0.767	0.728	0.645
21	0.833	0.793	0.765	0.726	0.644
22	0.830	0.790	0.762	0.724	0.644
23	0.827	0.787	0.760	0.722	0.643
24	0.824	0.784	0.758	0.720	0.642
25	0.821	0.782	0.756	0.719	0.642
26	0.818	0.779	0.754	0.717	0.641
27	0.815	0.777	0.752	0.715	0.640
28	0.813	0.774	0.750	0.714	0.640
29	0.810	0.772	0.748	0.712	0.639
30	0.808	0.770	0.746	0.711	0.639
31	0.805	0.768	0.744	0.710	0.638
32	0.803	0.766	0.743	0.708	0.637
33	0.801	0.764	0.741	0.707	0.637
34	0.799	0.762	0.739	0.706	0.636
35	0.797	0.760	0.738	0.705	0.636
36	0.795	0.759	0.736	0.704	0.635
37	0.794	0.757	0.735	0.703	0.635
38	0.792	0.755	0.734	0.702	0.634
39	0.790	0.754	0.732	0.701	0.634
40	0.789	0.752	0.730	0.700	0.633
41	0.787	0.751	0.729	0.699	0.633
42	0.786	0.750	0.728	0.698	0.632
43	0.785	0.748	0.727	0.697	0.632
44	0.783	0.747	0.726	0.696	0.631
45	0.782	0.746	0.725	0.695	0.631
46	0.781	0.745	0.724	0.694	0.630
47	0.780	0.743	0.723	0.693	0.630
48	0.779	0.742	0.722	0.692	0.630
49	0.778	0.741	0.721	0.691	0.629
50	0.777	0.739	0.720	0.691	0.629

Table 4.2 Empirical percentage points for Hurst's *H* for normally distributed independent data (n= 55 – 200) (After Lye and Lin, 1994).

Sample Size	**Significant Levels**				
	1%	**5%**	**10%**	**20%**	**50%**
55	0.772	0.735	0.715	0.687	0.627
60	0.768	0.731	0.711	0.683	0.625
65	0.765	0.727	0.708	0.680	0.623
70	0.762	0.724	0.704	0.678	0.622
75	0.759	0.721	0.702	0.675	0.621
80	0.757	0.718	0.699	0.673	0.619
85	0.754	0.716	0.696	0.671	0.618
90	0.752	0.714	0.694	0.669	0.617
95	0.749	0.711	0.692	0.667	0.616
100	0.747	0.709	0.690	0.666	0.616
110	0.742	0.706	0.687	0.663	0.614
120	0.738	0.703	0.684	0.660	0.613
130	0.734	0.700	0.681	0.658	0.611
140	0.730	0.698	0.679	0.656	0.610
150	0.727	0.695	0.676	0.654	0.609
160	0.725	0.693	0.675	0.653	0.608
170	0.722	0.690	0.673	0.651	0.607
180	0.720	0.688	0.671	0.649	0.606
190	0.718	0.686	0.670	0.648	0.605
200	0.715	0.685	0.668	0.647	0.604

4.4.3 Conditional Probabilities (Lye and Lin, 1994)

On the basis of parametric Hurst's *H*, the conditional probabilities, *P*, of the existence of long-term dependence when the series has passed the short-term dependence tests are calculated for all the climate variables for 5% and 10% significance levels as:

P (long-term dependence/short-term independence) x 100 (4.56)

4.5 RESULTS AND DISCUSSION

4.5.1 Results

14 tests for dependence as described in section 4.4, 13 for short-term dependence and one for long-term dependence, are applied to annual time series of temperature (mean, maximum, minimum and, diurnal temperature range), rainfall, number of rainy days and; wind speed. For all the tests significance levels of 5% and 10% is used.

The various tests employed do not have equal power in discriminating between time series which are truly random. The power of the tests depends somewhat on the nature of the dependence present, and not on the length of the record. Hence, sometimes for the same series various tests employed give different results. This means that a time series may fail one test of independence but pass the other tests (Lye and Lin, 1994).

As a result, it is difficult to judge on the basis of result of one test whether a time series is independent or not. It is therefore a good practice to do various tests first before making any conclusions. As such no general guidelines are available to fix the number of failed tests needed to decide for a short-term dependence (Lye and Lin, 1994). Therefore, it was found appropriate to assume in this analysis that, for short-term dependence, at least four tests (~one-third) out of the 13 short-term dependence tests applied to each data series should indicate dependence. However, the judgment for long-term dependence of series has been made on the basis of the results of Hurst's *H* test. The results are discussed in the subsequent sections.

The length of record, Hurst's *H*, and r(1) for each station is given in Table 4.3 to 4.9. It could be seen from these Tables that for all climatological variables, the values of Hurst's *H* are greater than 0.5 for all stations and it varies from 0.9787 to 0.5513 with a mean value of 0.7603. The lag-1 autocorrelation, r (1), values are also fairly high and ranges from -0.394 to 0.444.

Table 4.3 Meteorological stations with their Husrt's *H* and r (1) values for annual mean maximum temperature.

Station	**State**	**n (years)**	**Hurst's *H***	**r(1)**
Srinagar	J & K	32	0.7800	0.430
Quazigund	J & K	22	0.7969	0.224
Banihal	J & K	22	0.5554	0.201
Jammu	J & K	34	0.5969	0.064
Dalhousie	HP	37	0.8133	0.488
Dharamsala	HP	47	0.7763	0.546
Manali	HP	33	0.5917	0.200
Bhuntar (A)	HP	40	0.6221	0.167
Mandi	HP	47	0.6625	0.355
Bilaspur	HP	36	0.7282	0.065
Simla	HP	59	0.6877	0.240
Mukhim	UA	33	0.6255	0.229
Joshimath	UA	32	0.8192	0.630
Mussoorie	UA	57	0.7686	0.277
Tehri	UA	26	0.7418	0.546
Dehradun	UA	58	0.6586	0.137
Mukteshwar	UA	58	0.8872	0.623
Nainital	UA	26	0.6117	0.172
Pasighat	AR	33	0.7547	-0.017
Ziro	AR	28	0.7557	0.066
Gangtok	SIK	30	0.8916	0.551
Kalimpong	WB	58	0.8499	0.528
Darjeeling	WB	58	0.8789	0.747

Table 4.4 Meteorological stations with their Husrt's *H* and r (1) values for annual mean minimum temperature.

Station	**State**	**n (years)**	**Hurst's *H***	**r(1)**
Srinagar	J & K	32	0.8493	0.115
Quazigund	J & K	22	0.7024	0.146
Banihal	J & K	22	0.8111	0.417
Jammu	J & K	34	0.8650	0.351
Dalhousie	HP	37	0.8803	0.580
Dharamsala	HP	47	0.8516	0.637
Manali	HP	33	0.7446	0.218
Bhuntar (A)	HP	40	0.6130	0.130
Mandi	HP	47	0.8080	0.409
Bilaspur	HP	36	0.8145	0.542
Simla	HP	59	0.8573	0.476
Mukhim	UA	33	0.7533	0.268
Joshimath	UA	32	0.8305	0.390
Mussorie	UA	57	0.7981	0.429
Tehri	UA	26	0.6540	0.349
Dehradun	UA	58	0.8357	0.483
Mukteshwar	UA	58	0.8977	0.680
Nainital	UA	26	0.7633	0.217
Pasighat	AR	33	0.7650	0.478
Ziro	AR	28	0.9417	0.678
Gangtok	SIK	30	0.872	0.799
Kalimpong	WB	58	0.8438	0.547
Darjeeling	WB	58	0.8601	0.736

Table 4.5 Meteorological stations with their Husrt's *H* and r (1) values for annual mean temperature.

Station	**State**	**n (years)**	**Hurst's *H***	**r(1)**
Srinagar	J & K	32	0.5831	0.182
Quazigund	J & K	22	0.7784	0.331
Banihal	J & K	22	0.7326	0.455
Jammu	J & K	34	0.6987	0.077
Dalhousie	HP	37	0.8295	0.503
Dharamsala	HP	47	0.8052	0.546
Manali	HP	33	0.6528	0.247
Bhuntar (A)	HP	40	0.6083	0.206
Mandi	HP	47	0.7110	0.280
Bilaspur	HP	36	0.6389	0.169
Simla	HP	59	0.6631	0.221
Mukhim	UA	33	0.6632	0.179
Joshimath	UA	32	0.8517	0.672
Mussoorie	UA	57	0.8077	0.310
Tehri	UA	26	0.7094	0.550
Dehradun	UA	58	0.7279	0.284
Mukteshwar	UA	58	0.7783	0.372
Nainital	UA	26	0.6633	0.146
Pasighat	AR	33	0.7676	0.316
Ziro	AR	28	0.7910	0.392
Gangtok	SIK	30	0.8288	0.631
Kalimpong	WB	58	0.6871	0.527
Darjeeling	WB	58	0.7652	0.684

Table 4.6 Meteorological stations with their Husrt's *H* and r (1) values for annual mean diurnal temperature range.

Station	**State**	**n (years)**	**Hurst's *H***	**r(1)**
Srinagar	J & K	32	0.8659	0.469
Quazigund	J & K	22	0.6075	-0.230
Banihal	J & K	22	0.6282	-0.056
Jammu	J & K	34	0.8054	0.299
Dalhousie	HP	37	0.8605	0.603
Dharamsala	HP	47	0.8364	0.714
Manali	HP	33	0.7317	0.205
Bhuntar (A)	HP	40	0.5657	0.025
Mandi	HP	47	0.8033	0.527
Bilaspur	HP	36	0.8728	0.547
Simla	HP	59	0.9610	0.827
Mukhim	UA	33	0.7573	0.503
Joshimath	UA	32	0.7314	0.490
Mussoorie	UA	57	0.7156	0.617
Tehri	UA	26	0.6970	-0.043
Dehradun	UA	58	0.8917	0.594
Mukteshwar	UA	58	0.9624	0.884
Nainital	UA	26	0.7557	0.279
Pasighat	AR	33	0.6041	0.200
Ziro	AR	28	0.8491	0.110
Gangtok	SIK	30	0.9468	0.871
Kalimpong	WB	58	0.8912	0.542
Darjeeling	WB	58	0.9563	0.798

Table 4.7 Meteorological stations with their Husrt's *H* and r (1) values for annual rainfall.

Station	**State**	**n (years)**	**Hurst's *H***	**r(1)**
Srinagar	J & K	32	0.6796	0.032
Quazigund	J & K	22	0.6689	-0.018
Banihal	J & K	22	0.6947	0.249
Jammu	J & K	34	0.6410	-0.255
Dalhousie	HP	37	0.8748	0.475
Dharamsala	HP	47	0.6879	0.021
Manali	HP	33	0.6514	0.204
Bhuntar (A)	HP	40	0.6147	-0.138
Mandi	HP	47	0.7303	0.102
Bilaspur	HP	36	0.7554	0.074
Simla	HP	59	0.7146	0.012
Mukhim	UA	33	0.6211	0.212
Joshimath	UA	32	0.8211	0.434
Mussorie	UA	57	0.7866	0.170
Tehri	UA	26	0.5272	-0.150
Dehradun	UA	58	0.6640	-0.146
Mukteshwar	UA	58	0.5133	0.107
Nainital	UA	26	0.6727	0.079
Pasighat	AR	33	0.6625	0.153
Ziro	AR	28	0.6907	-0.053
Gangotk	SIK	30	0.6206	-0.363
Kalimpong	WB	58	0.6437	0.127
Darjeeling	WB	58	0.7181	0.061

Table 4.8 Meteorological stations with their Husrt's *H* and r (1) values for annual number of rainy days

Station	**State**	**n (years)**	**Hurst's *H***	**r(1)**
Srinagar	J & K	32	0.7397	-0.150
Quazigund	J & K	22	0.6898	0.108
Banihal	J & K	22	0.7406	0.185
Jammu	J & K	34	0.7085	-0.032
Dalhousie	HP	37	0.8150	0.468
Dharamsala	HP	47	0.5719	-0.207
Manali	HP	33	0.7728	0.238
Bhuntar (A)	HP	40	0.6392	-0.084
Mandi	HP	47	0.8434	0.382
Bilaspur	HP	36	0.6776	-0.085
Simla	HP	59	0.7212	0.215
Mukhim	UA	33	0.7633	0.222
Joshimath	UA	32	0.8183	0.325
Mussoorie	UA	57	0.7199	0.099
Tehri	UA	26	0.6187	0.026
Dehradun	UA	58	0.5809	-0.046
Mukteshwar	UA	58	0.7176	0.019
Nainital	UA	26	0.7030	0.175
Pasighat	AR	33	0.7002	-0.173
Ziro	AR	28	0.7801	0.005
Gangtok	SIK	30	0.5376	-0.394
Kalimpong	WB	58	0.8760	0.608
Darjeeling	WB	58	0.7540	0.120

Table 4.9 Meteorological stations with their Husrt's *H* and r (1) values for annual mean wind speed.

Station	**State**	**n (years)**	**Hurst's *H***	**r(1)**
Dalhousie	HP	37	0.8781	0.745
Dharamsala	HP	47	0.7916	0.450
Bhuntar (A)	HP	40	0.9564	0.856
Mandi	HP	47	0.8320	0.662
Simla	HP	59	0.7518	0.688
Joshimath	UA	32	0.8925	0.662
Mussorie	UA	57	0.7456	0.444
Tehri	UA	26	0.8325	0.622
Dehradun	UA	58	0.8611	0.452
Mukteshwar	UA	58	0.8646	0.505
Nainital	UA	26	0.7623	0.460
Pasighat	AR	33	0.9058	0.563
Ziro	AR	28	0.8771	0.774
Gangtok	SIK	30	0.9249	0.868
Kalimpong	WB	58	0.9147	0.835
Darjeeling	WB	58	0.9787	0.939

4.5.1.1 Annual Mean Temperature

The success and failure of each test is presented in Table 4.10 and the percentage and no. of series indicating dependence for annual mean temperature at 5% and 10% significance levels are summarized in Table 4.11. A comparison of short-term and long-term dependence tests is shown in Table 4.12. From the table it could be seen that Autocorrelation test has failed maximum number of series i.e. 60.87% and 73.91% at 5% and 10% levels of significance. About 56.50% (at 5% level) and 73.90% (at 10% level) of the series show short-term dependence. The values are higher than the results of parametric Hurst's *H* that indicated about 37.9% and 48.3% of the series are long-term dependent at 5% and 10% significance levels, respectively. Results from the non-parametric test of Hurst's *H* are similar to those from the parametric test, and show that about 31.0% (at 5% level) and 44.8% (at 10% level) of the tested series show long-term dependence. The 9 out of 13 (at 5% level) and 11 out of 17 (at 10% level) series show both short-term and long-term dependence. None of the series exhibited only long-term dependence. However, 4 and 6 series have indicated only short-term dependence at 5% and 10% significance levels, respectively.

Table 4.10 Success and failure of dependence tests and no. of series indicating dependence as a function of tests for annual mean temperature (√-success of the test; X -failure of the test)

S. No.	Station	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	Srinagar	32	√	X*	√	√	√	√	√	√	√	√	√	√	√	1*	√	√
2.	Quazigund	22	X**	√	X**	X*	X**	X*	X*	X*	X*	X**	X*	√	X*	11*,4**	√	√
3.	Banihal	22	√	√	X**	X**	X**	X**	X**	X**	X**	X*	X**	√	X**	10*,9**	X*	√
4.	Jammu	34	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
5.	Dalhousie	37	√	X**	X**	X**	√	X**	X**	X**	X**	X**	X**	X*	X**	11*10**	X**	X**
6.	Dharamsala	47	√	X**	X**	X*	√	X**	X**	X**	X**	√	√	X**	√	8*,7**	X**	X**
7.	Manali	33	√	√	√	√	√	√	√	√	X*	√	√	√	√	1*	√	√
8.	Mandi	47	√	X**	X*	√	√	√	X*	X**	X**	√	√	√	√	5*,03**	√	√
9.	Bilaspur	36	√	√	√	√	√	√	√	√	√	√	√	X*	√	1*	√	√
10.	Bhuntar (A)	40	√	X**	X**	√	X*	√	√	√	√	√	√	√	X*	4*,2**	√	√
11.	Simla	59	√	X**	√	√	√	X*	√	X*	X*	√	√	√	√	4*,1**	√	√
12.	Dehradun	58	√	X*	X*	X*	√	X**	X**	X**	X**	√	X*	X*	X**	10*,5**	X*	X*
13.	Mussorie	57	√	X**	X**		√	X**	X**	X**	X**	√	√	X**	√	7**	X**	X**
14.	Tehri	26	√	X**	X**	X*	√	X*	X**	X**	X**	√	X*	X*	X**	10*,6**	√	√
15.	Joshimath	32	X**	X*	X**	X**	X**	X**	X**	X**	X**	X*	X**	X**	X**	13*,11**	X**	X**
16.	Nainital	26	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
17.	Mukteshwar	58	√	X*	X**	√	√	X**	X**	X**	X**	√	√	X**	√	7*,6**	X**	X**
18.	Mukhim	33	√	√	√	X*	√	√	√	√	√	√	√	√	√	1*	√	√
19.	Pasighat	33	√	√	√	√	√	X**	√	X*	X**	√	√	X**	√	4*,3**	X**	X*
20.	Darjeeling	58	X**	√	X**	X**	X**	X**	X**	X**	X**	√	X**	X**	X**	11**	X**	X**
21.	Kalimpong	58	X**	X*	X**	√	X**	X**	X**	X**	X**	√	√	X**	X*	10*,8**	√	√
22.	Gangtok	30	X*	√	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	8*,7**	X**	X**
23.	Ziro	28	X*	√	X**	X*	X**		X**	X**	X**	√	X**	√	X**	9*,7**	X**	X*
No. of series failed by the test			6* 4**	12* 7**	15* 13**	10* 4**	8* 7**	14* 11**	14* 12**	16* 13**	17* 14**	4* 2**	8* 5**	12* 8**	10* 7**		11* 9**	10* 7**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.11 Percentage and no. of series indicating dependence for annual mean temperature at 5% and 10% significance levels. **No. of stations = 23**

No. of tests indicating dependence	**Annual mean temperature**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
13	00	00.00	01	04.35
12	00	00.00	00	00.00
11	02	08.70	03	13.04
10	01	04.35	04	17.39
9	02	08.70	01	04.35
8	00	00.00	02	08.70
7	06	26.10	02	08.70
6	00	00.00	00	00.00
5	01	04.35	01	04.35
4	01	04.35	03	13.04
3	02	08.70	00	00.00
2	01	04.35	00	00.00
1	01	04.35	04	17.39
0	06	26.10	02	08.70

Table 4.12 Comparison of short-term and long-term dependence for annual mean temperature at 5% and 10% significance levels.

Description	**Annual mean temperature**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Short-term dependence	13	56.52	17	73.91
Long-term dependence				
(a) Parametric test	09	39.13	11	47.83
(b) Bootstrap method	07	30.43	10	43.48
Only short-term dependence	04	17.39	06	26.10
Only long-term dependence				
(a) Parametric test	00	00.00	00	00.00
(b) Bootstrap method	00	00.00	00	00.00
Both short-and long-term dependence	09	39.13	11	47.83

4.5.2 Annual Mean Maximum Temperature

The results of the short-term and long-term dependence analysis for annual mean maximum temperature are summarized in Table 4.13 and Table 4.14 and comparison of the results is shown in Table 4.15. From Table 4.13, it is clear that maximum number of series i.e. 52.2% has failed in Length of run and Autocorrelation tests at 5% significance level and; 60.9% failed in Length of run test at 10% significance level, respectively. For the parametric test of Hurst's *H*, 43.5% (at 5% level) and 52.2% (at 10% level) of the tested series show long-term dependence whereas, for non-parametric Bootstrap Hurst's *H*, 34.8% (at 5%) and 47.8% (at 10%) of the series show long-term dependence. In Table 4.14, number of series indicating short-term dependence is presented. The 47.80% (at 5% level) of the series were found to be short-term independent. Comparison of results (Table 4.15) clearly show that on the basis of parametric test, about 52.17% (at 5% level) and 56.52% (at 10% level) of the tested series show short-term dependence. About 39% of the series have both short-term and long-term dependence at 5% and 10% significance level. The percentage of only long-term dependence was 4.35% while the percentage of only short-term dependence was 13.04% , higher than the percentage of only long-term dependence.

4.5.3 Annual Mean Minimum Temperature

The results of dependence as a success and failure of tests for annual mean minimum temperature are given in Table 4.16. The maximum number of series i.e. 18 (78.26%) has failed to pass the von-neumann ratio tests at 5% and von-neumann ratio test and Linear regression test at 10% significance level. Table 4.17 shows percentage and no. of series indicating dependence, while Table 4.18 compares the results of both short-term and long-term dependence analysis. It was observed that about 73.91% (at 5% level) and 86.96% (at 10% level) of the tested series in case of parametric Hurst's *H* test, and 65.22% (at 5% level) and 73.91% (at 10% level) of the tested series for non-parametric bootstrap Hurst's *H* show long-term dependence. These values are found to be similar to short-term dependence tests values, 78.26% (at 5% level) and 73.91% (a 10% level). It can also be seen from the Table, that 73.91% and 78.26% of the series showed both, the short-term and long- term dependence at 5% and 10% significance levels, respectively. Only 13.04% of the tested series were found to be independent.

Table 4.13 Success and failure of dependence tests and no. of series indicating dependence as a function of tests for annual mean maximum temperature (√-success of the test; X -failure of the test)

S. No.	Station	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	Srinagar	32	√	√	X**	X*	X**	X**	X**	X**	X**	X**	X**	√	X**	10*,9**	X**	X*
2.	Quazigund	22	√	√	X**	X*	X*	√	√	√	√	√	√	√	√	03*,1**	X**	X*
3.	Banihal	22	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
4.	Jammu	34	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
5.	Dalhousie	37	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X*	X**	13*,12**	X**	X**
6.	Dharamsala	47	X**	X**	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	09**	X**	X**
7.	Manali	33	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
8.	Mandi	47	X*	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	√	X**	12*,11**	√	√
9.	Bilaspur	36	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
10.	Bhuntar (A)	40	√	√	X*	√	√	√	√	√	√	X*	X**	√	X*	04*,1**	√	√
11.	Simla	59	√	X*	√	X**	X*	X*	√	X*	X**	X**	X**	√	X**	09*,5**	√	√
12.	Dehradun	58	√	X**	√	√	√	√	√	√	√	X*	X*	√	√	03*,1**	√	√
13.	Mussorie	57	X*	X**	X*	√	X**	X**	X**	X**	X**	√	√	X**	√	09*,7**	X**	X**
14.	Tehri	26	√	X*	X**	X*		X**	X**	X**	X**	√	X*	X**	X*	10*,6**	√	√
15.	Joshimath	32	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12**	X**	X**
16.	Nainital	26	√	√	√	√	X**	√	√	√	√	√	√	√	√	01**	√	√
17.	Mukteshwar	58	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
18.	Mukhim	33	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
19.	Pasighat	33	√	√	√	√	√	√	√	√	√	X*	√	√	X*	02*	X*	X*
20.	Darjeeling	58	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
21.	Kalimpong	58	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
22.	Gangtok	30	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12**	X**	X**
23.	Ziro	28	X**	√	√	√	X**	√	√	√	√	√	√	√	√	02**	X*	√
No. of series failed by the test			10* 08**	10* 08**	13* 11**	11* 08**	14* 12**	12* 11**	11**	12* 11**	12**	12* 09**	12* 10**	09* 08**	12* 09**		12* 10**	11* 08**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.14 Percentage and no. of series indicating dependence for annual mean maximum temperature at 5% and 10% significance levels. **No. of stations = 23**

No. of tests indicating dependence	**Annual mean maximum temperature**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
13	03	13.04	04	17.40
12	03	13.04	03	13.04
11	01	04.35	00	00.00
10	00	00.00	02	10.34
9	02	10.34	03	13.04
8	00	00.00	00	00.00
7	01	04.35	00	00.00
6	01	04.35	00	00.00
5	01	04.35	00	00.00
4	00	00.00	01	04.35
3	00	00.00	02	06.90
2	01	04.35	02	06.90
1	04	17.40	01	04.35
0	06	26.10	05	21.74

Table 4.15 Comparison of short-term and long-term dependence for annual maximum temperature at 5% and 10% significance levels.

Description	**Annual mean maximum temperature**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Short-term dependence	12	52.17	13	56.52
Long-term dependence				
(a) Parametric test	10	43.48	12	52.17
(b) Bootstrap method	08	34.78	11	47.83
Only short-term dependence	03	13.04	04	17.39
Only long-term dependence				
(a) Parametric test	01	04.35	03	13.04
(b) Bootstrap method	00	00.00	00	00.00
Both short-and long-term dependence	09	39.13	09	39.13

Table 4.16 Success and failure of dependence tests and no. of series indicating dependence for annual mean minimum temperature (√-success of the test; X -failure of the test)

S. No.	Station	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	Srinagar	32	X**	√	√	X**	X**	√	√	√	√	X**	X**	√	X**	06**	X**	X**
2.	Quazigund	22	√	√	√	X*	√	√	√	√	√	X*	X*	√	X**	04*,1**	√	√
3.	Banihal	22	√	√	√	X**	√	X**	√	X**	X**	X*	X**	√	X**	07*,6**	X**	X*
4.	Jammu	34	√	√	X**	X**	√	X**	X**	X**	X**	X**	X**	√	X**	09**	X**	X**
5.	Dalhousie	37	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
6.	Dharamsala	47	X*	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13*,12**	X**	X**
7.	Manali	33	X*	X**	√	√	X**	√	√	√	√	√	√	√	√	03*,1**	X*	√
8.	Mandi	47	√	X*	X**	√	√	X**	X**	X**	X**	√	√	X**	√	07*,6**	X**	X**
9.	Bilaspur	36	X**	X**	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	09**	X**	X**
10.	Bhuntar (A)	40	X*	√	√	√	X**	√	√	√	√	√	√	√	√	02*,1**	√	√
11.	Simla	59	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
12.	Dehradun	58	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12**	X**	X**
13.	Mussorie	57	√	X**	X**	√	X*	X**	X**	X**	X**	√	√	X**	X*	09*,7**	X**	X**
14.	Tehri	26	√	√	√	√	√	√	√	X**	X*	√	X*	√	X*	04*,1**	√	√
15.	Joshimath	32	X**	√	X**	X**	X**	√	X**	X**	X**	X**	X**	√	X**	10**	X**	X**
16.	Nainital	26	√	√	√	X*	√	√	√	√	√	X*	√	√	X**	03*,1**	X*	√
17.	Mukteshwar	58	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
18.	Mukhim	33	√	√	√	X**	√	√	√	X**	√	X**	X**		X**	05**	X*	√
19.	Pasighat	33	√	√	√	√	√	X**	√	X**	X**	√	√	X**	√	04**	X**	X*
20.	Darjeeling	58	X**	√	X**	X**	X**	X**	X**	X**	X**	√	X**	X**	X**	11**	X**	X**
21.	Kalimpong	58	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
22.	Gangtok	30	X**	√	X**	X**	X**		X**	X**	X**	X**	X**	X**	X**	11**	X**	X**
23.	Ziro	28	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12**	X**	X**
No. of series failed by the test			14* 11**	09* 08**	14**	16* 14**	15* 14**	14**	14**	18**	17* 16**	15* 12**	16* 14**	13**	18* 16**		20* 17**	17* 15**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.17 Percentage and no. of series indicating dependence for annual mean minimum temperature at 5% and 10% significance levels. **No. of stations = 23**

No. of tests indicating dependence	**Annual mean minimum temperature**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
13	04	17.39	05	21.74
12	03	13.04	02	08.70
11	02	08.70	02	08.70
10	01	04.35	01	04.35
9	02	08.70	03	13.04
8	00	00.00	00	00.00
7	01	04.35	02	08.70
6	03	13.04	01	04.35
5	01	04.35	01	04.35
4	01	04.35	03	13.04
3	00	00.00	02	08.70
2	01	04.35	01	04.35
1	04	17.39	00	00.00
0	00	00.00	00	00.00

Table 4.18 Comparison of short-term and long-term dependence for annual minimum temperature at 5% and 10% significance levels.

Description	**Annual mean minimum temperature**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Short-term dependence	18	78.26	20	86.96
Long-term dependence				
(a) Parametric test	17	73.91	20	86.96
(b) Bootstrap method	15	65.22	17	73.91
Only short-term dependence	01	04.35	02	08.70
Only long-term dependence				
(a) Parametric test	00	00.00	02	08.70
(b) Bootstrap method	00	00.00	00	00.00
Both short-and long-term dependence	17	73.91	18	78.26

4.5.4 Annual Mean Temperature Range

It can be seen from Table 4.19, that the maximum number of series i.e. 65.22% is failed by Wald-wolfowitz and Autocorrelation tests at 5%, and 69.57% by Aucorrelation test at 10% significance levels, respectively and indicating the presence of short-term independence. On the basis of success and failure of tests for independence (Table 4.19) a table for percentage and no. of series indicating dependence has been prepared and presented in Table 4.20. The short-term and long-term dependence test results are compared and presented in Table 4.21. About 21.74% and 17.39% of the tested series show short-term independence at 5% and 10% significance levels, respectively. At 5% significance level, both the parametric and non-parametric Hurst's *H*, gave the similar results and show that 56.52% of the tested series have long-term dependence but at 10% level the percentage of parametric test was little higher than the non-parametric test by about 8.7%. There are 52.17% of the series which indicated the presence of both short-term and long-term dependence, however, only 13.04% and 4.35% series were found indicating only short-term and only long-term dependence, respectively.

Table 4.19 Success and failure of dependence tests and no. of series indicating dependence for annual mean temperature range (√-success of the test; X -failure of the test)

S. No.	Station	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	Srinagar	32	√	√	X**	X**	X**	X**	X**	X**	X**	√	X**	X**	X**	10**	X**	X**
2.	Quazigund	22	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
3.	Banihal	22	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
4.	Jammu	34	√	√	√	X**	√	X**	√	X*	X*	√	X**	√	X**	6*,4**	X**	X**
5.	Dalhousie	37	X**	X**	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	9**	X**	X**
6.	Dharamsala	47	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
7.	Manali	33	√	√	√	√	X*	√	√	√	√	√	√	√	√	1*	√	√
8.	Mandi	47	X**	X**	X**	√	X**	X**	X**	X**	X**	X*	X**	X**	X*	12*,10**	X**	X**
9.	Bilaspur	36	X**		X**	√	X**	X**	X**	X**	X**	√	√	X**	√	8**	X**	X**
10.	Bhuntar (A)	40	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
11.	Simla	59	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
12.	Dehradun	58	X**	√	X**	X**	X**	X**	X**	X**	X**	X*	X**	X**	X**	12*,11**	X**	X**
13.	Mussorie	57	√	X**	X**	√	√	X**	X**	X**	X**	√	√	X**	√	7**	X*	√
14.	Tehri	26	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
15.	Joshimath	32	√	√	X**	√	√	X**	X**	X**	X**	√	√	X**	√	6**	√	√
16.	Nainital	26	√	√	√	√	X**	√	√	√	X**	√	√	√	√	2**	X*	√
17.	Mukteshwar	58	X**	√	X**	X**	X**	X**	X**	X**	X**	X*	X**	X**	X**	12*,11**	X**	X**
18.	Mukhim	33	√	√	X**	X**	X*	X**	X**	X**	X**	√	X**	X**	X**	10*,9**	X*	X*
19.	Pasighat	33	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
20.	Darjeeling	58	X**	√	X**	X**	X**	X**	X**	X**	X**	X*	X**	X**	X**	12*,11**	X**	X**
21.	Kalimpong	58	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
22.	Gangtok	30	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
23.	Ziro	28	√	√	X*	X*	X*	√	X*	√	√	√	X*	√	√	5*	X**	X**
No. of series failed by the test			10**	7**	15* 14**	11* 10**	15* 12**	15**	15* 14**	15* 14**	16* 15**	8* 4**	12* 11**	14**	11* 10**		16* 13**	14* 13**

*** - Significant at 10 percent only; ** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
15. NP-Non-parametric Hurst test

Table 4.20 Percentage and no. of series indicating dependence for annual mean temperature range at 5% and 10% significance levels. **No. of stations = 23**

No. of tests indicating dependence	**Annual mean temperature range**			
	5%		**10%**	
	No. of series	Percentage	No. of series	Percentage
13	04	17.39	04	17.39
12	02	08.70	04	17.39
11	01	04.35	00	00.00
10	02	08.70	02	08.70
9	01	04.35	01	04.35
8	02	08.70	01	04.35
7	01	04.35	01	04.35
6	01	04.35	02	08.70
5	00	00.00	01	04.35
4	01	04.35	00	00.00
3	00	00.00	00	00.00
2	00	00.00	01	04.35
1	01	04.35	01	04.35
0	07	30.43	05	21.73

Table 4.21 Comparison of short-term and long-term dependence for annual mean temperature range at 5% and 10% significance levels.

Description	**Annual mean temperature range**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Short-term dependence	15	65.22	16	69.57
Long-term dependence				
(a) Parametric test	13	56.52	16	69.57
(b) Bootstrap method	13	56.52	14	60.87
Only short-term dependence	03	13.04	01	04.35
Only long-term dependence				
(a) Parametric test	01	04.35	02	08.70
(b) Bootstrap method	01	04.35	00	00.00
Both short-and long-term dependence	12	52.17	15	65.22

4.5.5 Annual Rainfall

The results of short-term dependence as a function of test along with the no. of series indicating dependence are shown in Table 4.22 whereas Table 4.23 presents percentage and no. of series indicating dependence. The Spearman rho at 5% and Spearman rho, Linear regression and Kendall's rank correlation tests showed equal power by rejecting the null hypothesis of independence of the series and failed 34.78% of the tested series at 10% significance levels, respectively. Comparison of the methods of Hurst *H* indicates that at 5% significance level the results were identical but at 10% Non-parametric Hurst *H* under-estimated the long-term dependence (Table 4.24). From Table 5.24 it is evident that 26% and 43.48% of the series exhibited dependence at 5% and 10% significance levels and out of which 13.04% and 21.74% contained presence of both kinds of dependence.

4.5.6 Gridded Annual Rainfall

No. of series indicating dependence of tests in response to the success and failure of tests is given in Table 4.25. At 5% significance level about 93.3% of the series were passed by the Mann-Kendall's and Kendall's rank correlation tests. While ~ 64.4% of the series were failed by Rank von-Neumann ratio and Rank difference tests. The percentage and no. of tests indicating dependence is shown in Table 4.46 and comparison of the dependence tests is shown in Table 4.27. The parametric and non parametric *Hurst H* indicated dependence in 26.64% and 17.78% of the series, respectively at 5% significance level. The values observed at 10% significance level by both the tests were almost same. It is interesting to note that 37.78% series were found short-term dependent while the percentage of long-term dependence was only 4.44%. When we look at the percentage of series indicated both short-term and long-term dependence it comes out to be 22.22%.

Table 4.22 Success and failure of dependence tests and no. of series indicating dependence for annual rainfall (√-success of the test; X -failure of the test)

S. No.	Station	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	Srinagar	32	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
2.	Quazigund	22	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
3.	Banihal	22	√	√	√	√	√	√	√	√	√	√	√	√	X*	1*	√	√
4.	Jammu	34	X**	X**	X**	√	X**	√	X**	√	√	√	√	√	√	5**	√	√
5.	Dalhousie	37	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12**	X**	X**
6.	Dharamsala	47	√	X**	√	X*	√	√	√	√	√	X*	X**	√	X**	5*,3**	√	√
7.	Manali	33	√	√	X*	√	√	√	√	√	√	√	√	√		1*	√	√
8.	Mandi	47	X*	√	√	X**	X**	√	√	√	√	X**	X**	√	X**	6*,5**	X*	√
9.	Bilaspur	36	√	√	√	√	√	√	√	√	√	√	√	√	√	00	X*	X*
10.	Bhuntar (A)	40	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
11.	Simla	59	√	√	√	X**	X*	√	√	√	√	X**	X**	√	√	4*,3**	X*	√
12.	Dehradun	58	√	√	√	X**	√	√	√	√	√	X**	X**	√	X**	4**	√	√
13.	Mussorie	57	√	√	X*	X**	√	√	√	√	√	X**	X**	√	X**	5*,4**	X**	X**
14.	Tehri	26	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
15.	Joshimath	32	X**	√	X**	X**	X**	X**	X**	X**	X**	√	X**	X**	X**	11**	X**	X**
16.	Nainital	26	√	√	√	X**	√	√	√	√	√	X*	X**	√	X**	4*,3**	√	√
17.	Mukteshwar	58	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
18.	Mukhim	33	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
19.	Pasighat	33	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
20.	Darjeeling	58	√	√	√	√	√	√	√	√	√	√	√	√	√	00	X*	√
21.	Kalimpong	58	√	√	X*	√	X*	√	√	√	√	√	√	√	√	2*	√	√
22.	Gangtok	30	√	√	√	√	√	X*	X*	X*	X*	√	√	√	√	4*	√	√
23.	Ziro	28	√	√	√	√	√		√	√	√	√	√	√	√	00	√	√
No. of series failed by the test			4* 3**	2**	6* 3**	8* 7**	6* 4**	3* 2**	4* 3**	3* 2**	3* 2**	7* 5**	8**	2**	8* 7**		7* 3**	4* 3**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.23 Percentage and no. of series indicating dependence for annual rainfall at 5% and 10% significance levels. **No. of stations = 23**

No. of tests indicating dependence	**Annual rainfall**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
13	00	00.00	00	00.00
12	01	04.35	01	04.35
11	01	04.35	01	04.35
10	00	00.00	00	00.00
9	00	00.00	00	00.00
8	00	00.00	00	00.00
7	00	00.00	00	00.00
6	00	00.00	01	04.35
5	01	04.35	03	13.04
4	03	13.04	04	17.39
3	02	08.70	00	00.00
2	01	04.35	01	04.35
1	00	00.00	02	08.70
0	14	60.87	10	43.48

Table 4.24 Comparison of short-term and long-term dependence for annual rainfall at 5% and 10% significance levels.

Description	**Annual rainfall**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Short-term dependence	06	26.10	10	43.48
Long-term dependence				
(a) Parametric test	03	13.04	07	30.43
(b) Bootstrap method	03	13.04	04	17.39
Only short-term dependence	03	13.04	05	21.74
Only long-term dependence				
(a) Parametric test	00	00.00	02	08.70
(b) Bootstrap method	00	00.00	00	00.00
Both short-and long-term dependence	03	13.04	05	21.74

Table 4.25 Success and failure of dependence tests and no. of series indicating dependence as a function of tests for gridded annual rainfall (√-success of the test; X -failure of the test)

S. No.	Rain Grid Location	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	27.5N-88.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
2.	27.5N-89.5E	52	X*	X*	√	√	√	√	√	√	√	√	√	√	√	00	√	√
3.	27.5N-90.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	X*	01*	√	√
4.	27.5N-91.5E	52	√	X**	X*	√	√	√	X*	√	√	√	√	√	√	03*	√	√
5.	27.5N-92.5E	52	√	X**	√	√	√	√	√	√	√	√	√	√	X**	02**	√	√
6.	27.5N-93.5E	52	√	X**	√	√	X**	√	√	√	√	√	√	√	X**	03**	√	√
7.	28.5N-93.5E	52	√	X*	√	√	√	√	√	√	√	√	√	√		01*	√	√
8.	28.5N-94.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	X**	01**	√	√
9.	28.5N-95.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
10.	28.5N-96.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
11.	29.5N-78.5E	52	√	√	√	X*	X*	√	√	√	√	X*	X*	√	√	04*	√	√
12.	29.5N-79.5E	52	√	√	√	√	√	X*	X*	X*	X*	√	√	√	X**	05*,1**	√	√
13.	29.5N-80.5E	52	√	√	X**	√	X*	X**	X**	X**	X**	√	√	X**	X**	08*,7**	√	√
14.	29.5N-95.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
15.	30.5N-77.5E	52	X**	√	X**	X*	X**	X**	X**	X**	X**	X*	X**	X**	X**	12*,10**	X**	X**
16.	30.5N-78.5E	52	X**	√	X**	X*	X**	X**	X**	X**	X**	X*	√	√	X**	10*,08**	√	√
17.	30.5N-79.5E	52	√	√	X**	X**	X**	√	X*	√	√	X**	X**	√	√	06*,05**	X**	X*
18.	31.5N-76.5E	52	√	√	X**	√	X*	X**	X**	X**	X**	√	√	X*	√	07*,05**	X*	X*
19.	31.5N-77.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
20.	31.5N-78.5E	52	X**	X*	X**	√	X**	X**	X**	X**	X**	√	√	X*	√	09*,07**	√	√
21.	32.5N-75.5E	52	√	√	√	X**	X*	√	√	√	√	X**	X**	√	√	04*,03**	X**	X**
22.	32.5N-76.5E	52	√	√	X**	X**	√	X**	X**	X**	X**	X**	X**	X**	√	09**	√	√
23.	32.5N-77.5E	52	X**	√	X**	X*	X**	X**	X**	X**	X**	X*	X*	X**	√	11*,08**	X**	X**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.25 (continued)

S. No.	Rain Grid Location	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
24.	32.5N-78.5E	52	X**	X**	X**	X*	X**	X**	X**	X**	X**	X*	√	√	√	10*, 08**	X**	X**
25.	32.5N-79.5E	52	X**	X*	X**	√	X**	X**	X**	X**	X**	√	√	X*	√	09*,07**	X*	X*
26.	33.5N-74.5E	52	√	√	X**	√	√	X*	X**	X**	X**	√	√	X**	X*	07*,05**	√	√
27.	33.5N-75.5E	52	X*	√	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	08*,07**	√	√
28.	33.5N-76.5E	52		√	X*	X*	√	X**	√	X**	X**	X*	X*	X**	X**	09*,05**	√	√
29.	33.5N-77.5E	52	X*	√	X**	X*	X**	X**	X**	X**	X**	X*	X*	X**	X**	12*,08**	X*	X*
30.	33.5N-78.5E	52	X**	√	X**	√	X**	X**	X**	X**	X**	√	√	X**		08**	X**	X**
31.	34.5N-74.5E	52	X*	X**	X**	√	X**	X**	X**	X**	X**	√	√	X*	X**	10*,08**	X**	X*
32.	34.5N-75.5E	52	√	X*	X**	√	X*	X**	X**	X**	X**	√	√	X**	√	08*,06**	X*	√
33.	34.5N-76.5E	52	√	√	X**	√	X*	X**	X**	X**	X**	√	√	X**	√	07*,06**	√	√
34.	34.5N-77.5E	52	√	√	X**	√	√	X**	X**	X**	X**	√	√	X**	√	06**	√	√
35.	34.5N-78.5E	52	X**	√	X**	X*	X**	X**	X**	X**	X**	√	X*	X**	X**	11*,09**	X**	X*
36.	34.5N-79.5E	52	X*	√	X**	√	X**	X**	X**	X**	X**	X*	√	X**	X**	10*,07**	X**	X**
37.	35.5N-74.5E	52	√	√	X**	√	√	X**	X**	X**	X**	√	√	X*	√	06*,05**	X**	X**
38.	35.5N-75.5E	52	X*	√	X**	√	X**	X**	X**	X**	X**	√	√	X**	X**	09*,08**	X**	X**
39.	35.5N-76.5E	52	√	X*	X*	√	√	X**	X*	X**	X**	√	√	X*	X**	08*,04**	√	√
40.	35.5N-77.5E	52	√	√	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	07**	√	√
41.	35.5N-78.5E	52	X**	√	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	08**	√	√
42.	35.5N-79.5E	52	X**	√	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	08**	X*	X*
43.	36.5N-73.5E	52	√	√	√	√	√	X*	√	√	√	√	√	√	√	01*	√	√
44.	36.5N-74.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
45.	36.5N-75.5E	52	√	√	X**	√	√	√	X*	X*	X*	√	√	X*	√	05*,01**	X**	X*
No. of series failed by the test			16* 10**	11* 05**	29* 26**	11* 03**	24* 18**	28* 25**	29* 24**	28* 26**	28* 26**	11* 03**	09* 04**	25* 18**	16* 14**		17* 12**	16* 08**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.26 Percentage and no. of series indicating dependence for gridded annual rainfall at 5% and 10% significance levels. **No. of grids = 45**

No. of tests indicating dependence	**Gridded annual rainfall**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
13	00	00.00	00	00.00
12	00	00.00	01	02.22
11	00	00.00	02	04.44
10	01	02.22	04	08.88
9	02	04.44	05	11.10
8	09	17.76	08	15.56
7	06	13.32	04	08.88
6	03	06.66	03	06.66
5	05	11.11	02	04.44
4	01	02.22	02	04.44
3	02	04.44	02	04.44
2	01	02.22	02	04.44
1	03	06.66	04	08.88
0	06	13.32	07	15.56

Table 4.27 Comparison of short-term and long-term dependence for gridded annual rainfall at 5% and 10% significance levels.

Description	**Gridded annual rainfall**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Short-term dependence	27	60.00	31	68.88
Long-term dependence				
(a) Parametric test	12	26.64	17	37.78
(b) Bootstrap method	08	17.78	16	35.56
Only short-term dependence	17	37.78	14	31.12
Only long-term dependence				
(a) Parametric test	02	04.44	00	00.00
(b) Bootstrap method	02	04.44	00	00.00
Both short-and long-term dependence	10	22.22	17	37.78

4.5.7 Annual Number of Rainy Days

From Table 4.28, it can be observed that 47.83% annual number of rainy days series were found to be sensitive against Spearman rho and Linear regression tests and did not pass the tests at 5% level of significance and 69.7% fail in Kendall's rank correlation test at 10% significance level. From the results obtained in Table 4.28 the test results for short-term and long-term dependence are summarized in Table 4.29 and the comparison is made in Table 4.30. From Table 4.30, it can be noted that for the parametric Hurst's *H*, 30.43% (at 5% level) and 47.83% (at 10% level) of the tested series show long-term dependence. These values are lower than the values obtained from the short-term dependence tests, 39.13% at 5% and 65.22% at 10% levels of significance, respectively. The results obtained for the non-parametric test of Hurst's *H* are comparable with the results of parametric test, and show that 21.74% (at 5% level) and 43.48% (at 10% level) of the tested series show long-term dependence. Out of 9 series indicated short-term dependence, 4 series were actually found to be short-term dependent while 5 series showed long-term and short-term both at 5% significance level. At 10% significance level, out of 15 series, 10 indicated presence of both the short-term and long-term dependence and remaining were only short-term dependent.

4.5.8 Gridded Annual Number of Rainy Days

Table 4.31 presented success and failure of dependence test and no. of series indicating dependence as a function of test. The Autocorrelation test has failed 57.78% series at 5% significance level. The percentage failure of series at 10% was 62.22% and Wald-wolfowitz, Rank von-neumann ratio and Autocorrelation showed equal power in rejecting the series. Table 4.32 depicts percentage and no. of series indicating dependence. The comparison of short-term and long-term dependence tests may be seen from Table 4.33. From the table it may be reveal that about 56.78% and 66.67% series were short-term dependent at 5% and 10% significance levels. The non-parametric *Hurst H* indicated little lower percentage of values of long-term dependence as compared to parametric test. The existence of only short-term dependence was found in 40% of the series at 5% and 44.44% at 10% significance level, respectively. The long-term dependence was present in a very small percentage.

Table 4.28 Success and failure of dependence tests and no. of series indicating dependence for annual number of rainy days (√-success of the test; X -failure of the test)

S. No.	Station	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	Srinagar	32	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
2.	Quazigund	22	√	√	√	X*	√	√	√	√	√	X*	X*	√	X**	4*,1**	√	√
3.	Banihal	22	√	√	√	X*	√	√	√	√	√	X**	X**	√	X**	4*,3**	√	√
4.	Jammu	34	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
5.	Dalhousie	37	√	√	X**	X**	√	X**	X**	X**	X**	X**	X**	X*	X**	10*,9**	X**	X**
6.	Dharamsala	47	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
7.	Manali	33	√	X**	√	X*	√	X*	√	√	√	X*	X*	X*	X*	7*,1**	X**	X*
8.	Mandi	47	√	√	X**	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	10**	X**	X**
9.	Bilaspur	36	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
10.	Bhuntar (A)	40	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
11.	Simla	59	√	√	√	X**	√	X*	X*	X*	X*	X**	X**	√	X**	8*,4**	X*	X*
12.	Dehradun	58	√	√	√	X*	√	√	√	√	√	√	√	√	√	1*	√	√
13.	Mussorie	57	√	√	√	X**	√	√	√	√	√	X**	X**	√	X**	4**	X*	X*
14.	Tehri	26	√	√	√	X*	√	√	√	√	√	X*	X*	√	√	3*	√	√
15.	Joshimath	32	X**	√	X*	X**	X**	X**	X*	X*	X**	X**	X**	√	X**	11*,8**	X**	X**
16.	Nainital	26	√	√	√	X**	√	√	√	√	√	X*	X**	√	X*	4*,2**	√	√
17.	Mukteshwar	58	X*	√	√	X**	√	√	√	√	√	X**	X**	√	X**	5*,4**	X*	√
18.	Mukhim	33	X*	√	X*	X**	X**	√	√	√	√	X**	X**	√	X**	7*,5**	X*	X*
19.	Pasighat	33	√	√	√	X*	√	√	√	√	√	X*	X*	√	X*	4*	√	√
20.	Darjeeling	58	X**	√	X*	X**	X**	√	√	√	√	X**	X**	√	X**	7*,6**	X**	X**
21.	Kalimpong	58	X**	√	X**	X**	X**	X**	X**	X**	X**	X*	X**	X*	X**	12*,10* *	X**	X**
22.	Gangtok	30	√	√	√	√	√	X**	X*	X**	X**	√	√	X*	√	5*,3**	√	√
23.	Ziro	28	√	√	√	√	√	√	√	√	√	√	√	√	√	00	X**	X*
No. of series failed by the test			5* 3**	1**	6* 3**	16* 10**	4**	7* 5**	6* 3**	6* 4**	6* 5**	15* 9**	15* 11**	5* 1**	14* 11**		11* 7**	10* 5**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.29 Percentage and no. of series indicating dependence for annual number of rainy days at 5% and 10% significance levels. **No. of stations = 23**

No. of tests indicating dependence	**Annual number of rainy days**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
13	00	00.00	00	00.00
12	00	00.00	01	04.35
11	00	00.00	01	04.35
10	02	08.70	01	13.04
9	01	04.35	00	00.00
8	01	04.35	01	04.35
7	00	00.00	03	13.04
6	01	04.35	00	00.00
5	01	04.35	02	08.70
4	03	13.04	04	21.74
3	02	08.70	01	04.35
2	01	04.35	00	00.00
1	02	08.70	01	04.35
0	09	39.13	08	34.78

Table 4.30 Comparison of short-term and long-term dependence for annual number of rainy days at 5% and 10% significance levels.

Description	**Annual number of rainy days**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Description	5%		10%	
Short-term dependence	09	39.13	15	65.22
Long-term dependence				
(a) Parametric test	07	30.43	11	47.83
(b) Bootstrap method	05	21.74	10	43.48
Only short-term dependence	04	17.39	05	21.74
Only long-term dependence				
(a) Parametric test	02	08.70	02	08.70
(b) Bootstrap method	00	00.00	01	04.35
Both short-and long-term dependence	05	21.74	10	43.48

Table 4.31 Success and failure of dependence tests and no. of series indicating dependence for gridded annual number of rainy days (√-success of the test; X -failure of the test)

S. No.	Rain Grid Location	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	27.5N-88.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
2.	27.5N-89.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
3.	27.5N-90.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	X*	01*	√	√
4.	27.5N-91.5E	52	√	X**	√	√	√	√	√	√	√	√	√	√	√	01**	√	√
5.	27.5N-92.5E	52	√	X*	√	√	√	√	√	√	√	√	X*	√	X**	03*,01**	X*	√
6.	27.5N-93.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	X**	01**	√	√
7.	28.5N-93.5E	52	√	√	√	√	√	√	√	√	√	√	√	√		00	√	√
8.	28.5N-94.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	X**	01**	√	√
9.	28.5N-95.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
10.	28.5N-96.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
11.	29.5N-78.5E	52	√	√	X*	√	√	X**	X*	X**	X**	√	√	X**	√	06*,04**	X**	X*
12.	29.5N-79.5E	52	√	√	√	X**	X*	√	√	√	√	X*	X*	√	X**	05*,02**	X**	X*
13.	29.5N-80.5E	52	√	√	X**	X*	√	X**	X**	X**	X**	X*	X*	X**	X**	10*,07**	√	√
14.	29.5N-95.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
15.	30.5N-77.5E	52	√	√	X**	√	X*	X*	X**	X*	X*	√	√	√	X**	07*,03**	√	√
16.	30.5N-78.5E	52	√	√	√	X**	√	√	√	√	√	X**	X**	√	X**	04**	X*	√
17.	30.5N-79.5E	52	X**	X**	X**	X**	X**	X**	X**	X**	X**	X*	X**	X**	√	12*,11**	X**	X**
18.	31.5N-76.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
19.	31.5N-77.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	√	√
20.	31.5N-78.5E	52	√	√	X**	X**	X*	X**	X**	X**	X**	X**	X**	X**	√	10*,09**	X**	X**
21.	32.5N-75.5E	52	√	√	√	√	√	√	√	√	√	√	√	√	√	00	X*	X*
22.	32.5N-76.5E	52	√	√	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	07**	√	√
23.	32.5N-77.5E	52	√	√	X**	X**	X*	X**	X**	X**	X**	X**	X**	X**	√	10*,08**	X**	X**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
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3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.31 (continued)

S. No.	Rain Grid Location	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
24.	32.5N-78.5E	52	√	√	√	X**	√	X**	X*	X**	X**	X**	X**	X*	√	08*,06**	X**	X**
25.	32.5N-79.5E	52	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	√	01**	X**	X**
26.	33.5N-74.5E	52	√	√	X**	X**	√	X**	X**	X**	X**	X**	X**	X**	X*	10*,09**	X**	X**
27.	33.5N-75.5E	52	√	√	X**	X*	√	X*	X**	√	X*	√	√	√	√	05*,02**	√	√
28.	33.5N-76.5E	52	√	√	√	X**	√	X**	√	X**	X**	X**	X**	X**	X**	08**	X**	X*
29.	33.5N-77.5E	52	X*	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12*,11**	X**	X*
30.	33.5N-78.5E	52	X*	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**		12*,11**	X**	X**
31.	34.5N-74.5E	52	√	√	X**	X*	X*	X**	X**	X**	X**	X**	X**	X**	X**	11*,09**	X**	X**
32.	34.5N-75.5E	52	√	√	X**	√	X*	X**	X**	X**	X**	X*	X*	X*	√	09*,05**	X**	X**
33.	34.5N-76.5E	52	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	√	11**	X**	X**
34.	34.5N-77.5E	52	X*	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	√	11*,10**	X**	X**
35.	34.5N-78.5E	52	X*	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12*,11**	X**	X**
36.	34.5N-79.5E	52	√	X**	X**	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	11**	X**	X**
37.	35.5N-74.5E	52	X**	√	X**	X*	X**	X**	X**	X**	X**	X*	X**	X**	√	11*,09**	X**	X**
38.	35.5N-75.5E	52	X**	√	X**	√	X**	X**	X**	X**	X**	√	√	X*	X**	09*,08**	X**	X**
39.	35.5N-76.5E	52	X**	√	X**	X**	X**	X*	X**	X*	X**	X**	X*	√	X**	11*,08**	√	√
40.	35.5N-77.5E	52	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	√	11**	X**	X**
41.	35.5N-78.5E	52	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	√	11**	X**	X**
42.	35.5N-79.5E	52	X*	X*	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	√	12*,10**	X**	X**
43.	36.5N-73.5E	52	X*	√	X*	√	X**	√	X*	√	√	X*	X*	√	√	06*,01**	X**	X**
44.	36.5N-74.5E	52	X*	√	X**	√	X**	X**	X**	X**	X**	√	X*	X**	√	09*,07**	X**	X**
45.	36.5N-75.5E	52	X*	√	X**	√	X**	X**	X**	X**	X**	√	X*	X**	√	09*,06**	X**	X**
No. of series failed by the test			16* 08**	06* 04**	27* 25**	23* 19**	23* 17**	28* 25**	28* 25**	27* 25**	28* 26**	24* 18**	27* 19**	25* 22*	16* 14**		28* 25**	26* 21**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.32 Percentage and no. of series indicating dependence for gridded annual number of rainy days at 5% and 10% significance levels. **No. of grids = 45**

No. of tests indicating dependence	**Gridded annual number of rainy days**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
13	00	00.00	00	00.00
12	00	00.00	05	11.10
11	08	17.76	08	17.76
10	02	04.44	04	08.88
9	04	08.88	04	08.88
8	04	08.88	02	04.44
7	03	06.66	02	04.44
6	02	04.44	02	04.44
5	01	02.22	02	04.44
4	02	04.44	01	02.22
3	01	02.22	01	02.22
2	02	04.44	00	00.00
1	05	11.10	05	11.10
0	09	19.98	09	19.98

Table 4.33 Comparison of short-term and long-term dependence for gridded annual number of rainy days at 5% and 10% significance levels.

Description	**Gridded annual number of rainy days**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Description	**5%**		**10%**	
Short-term dependence	26	57.78	30	66.67
Long-term dependence				
(a) Parametric test	25	55.56	28	62.22
(b) Bootstrap method	21	46.67	26	57.78
Only short-term dependence	18	40.00	20	44.44
Only long-term dependence				
(a) Parametric test	01	02.22	01	02.22
(b) Bootstrap method	01	02.22	00	00.00
Both short-and long-term dependence	08	17.76	10	22.22

4.5.9 Annual Mean Wind Speed

The dependence as a function of tests with success and failure of dependence test is given in Table 4.34, which revealed that 6 tests viz; Rank difference, Lengths of run, Wald-wolfowitz, Rank von-neumann ratio, Autocorrelation and von neumann ratio, failed maximum number i.e. 69.57% of the tested series of annual wind speed at both the significance levels. The percentage and no. of series indicating dependence has been worked out and is given in Table 4.35. It is visible from Table 4.36, that the results of both, the parametric and non-parametric Hurst's *H*, are similar and indicated long-term dependence in 93.75% of the series tested for dependence analysis at 5% significance level and 100% for parametric and 93.75% for non-parametric test at 10% significance level, respectively. Although, tested series are short-term dependent but are long-term dependent at the same time.

4.5.10 Conditional Probabilities

The conditional probabilities of the existence of long-term dependence when the series has passed the short-term dependence are determined for all the climate variables and tabulated in Table 4.37. The probabilities for all the climate variables at both 5% and 10% significance level are very low. The highest probability of 14.44% and 66.67% were observed in annual number of rainy days and annual mean minimum temperature at 5% and 10% significance levels, respectively. The results clearly indicate that long-term dependence is absent in the series and series are short-term dependent.

Table 4.34 Success and failure of dependence tests and no. of series indicating dependence for annual mean wind speed (√-success of the test; X -failure of the test)

S. No.	Station	N	MCT	TPT	RDT	KRCT	RT	WWT	RVNRT	VNRT	ACT	MKT	SRT	CPT	LRT	No. of tests failed the series	HURST	
																	P	NP
1.	Dalhousie	37	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
2.	Dharamsala	47	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
3.	Mandi	47	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
4.	Bhuntar (A)	40	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
5.	Simla	59	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	13**	X**	X**
6.	Dehradun	58	X**	√	X**	X**	X**	X**	X**	X**	X**	X*	X**	X**	X**	12*,11**	X**	X**
7.	Mussorie	57	X**	X**	X**	√	X**	X**	X**	X**	X**	√	√	X**	√	9**	X**	X**
8.	Tehri	26	X*	√	X**	X**	X**	X**	X**	X**	X**	√	X**	X**	X**	11*,10**	X**	X**
9.	Joshimath	32	√	√	X**	X**	X**	X**	X**	X**	X**	√	X**	X**	X**	10**	X**	X**
10.	Nainital	26	X*	X**	X**	√	X**	X**	X**	X**	X**	√	X*	√	X**	10*,8**	X*	√
11.	Mukteshwar	58	X*	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X*	X**	12*,10**	X**	X**
12.	Pasighat	33	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12**	X**	X**
13.	Darjeeling	58	X**	X*	X**	X**	X**	X**	X**	X**	X**	X*	X**	X**	X**	13*,11**	X**	X**
14.	Kalimpong	58	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12**	X**	X**
15.	Gangtok	30	X**	√	X**	√	X**	X**	X**	X**	X**	√	√	X**	X*	9*,8**	X**	X**
16.	Ziro	28	X**	√	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	X**	12**	X**	X**
No. of series failed by the test			15* 12**	8* 7**	16**	13**	16**	16**	16**	16**	16**	11* 9**	14* 13**	15* 14**	15* 14**		16* 15**	15**

*** - Significant at 10 percent only;** **** - Significant at 5 and 10 percent both**

1. MCT-Median crossing test
2. TPT-Turning point test
3. RDT- Rank difference test
4. KRCT-Kendall rank correlation test
5. RT-Run test
6. WWT-Wold-wolfowidz Test
7. RVNRT-Rank von neumen ratio test
8. VNRT- von-neuman ratio test
9. ACT- Autocorrelation test
10. MKT-Mann-Kendalls test
11. SRT-Spearman rho test
12. CPT- Cummulative periodogram test
13. LRT-Linear regression test
14. P-Parametric Hurst test
14. NP-Non-parametric Hurst test

Table 4.35 Percentage and no. of series indicating dependence for annual wind speed at 5% and 10% significance levels. **No. of stations = 16**

No. of tests indicating dependence	**Annual mean wind speed**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
13	05	31.25	06	37.50
12	03	18.75	05	31.25
11	02	18.75	01	06.25
10	03	18.75	02	12.50
9	01	06.25	02	12.50
8	02	12.50	00	00.00
7	00	00.00	00	00.00
6	00	00.00	00	00.00
5	00	00.00	00	00.00
4	00	00.00	00	00.00
3	00	00.00	00	00.00
2	00	00.00	00	00.00
1	00	00.00	00	00.00
0	00	00.00	00	00.00

Table 4.36 Comparison of short-term and long-term dependence for annual mean wind speed at 5% and 10% significance levels.

Description	**Annual mean wind speed**			
	5%		**10%**	
	No. of series	**Percentage**	**No. of series**	**Percentage**
Description	**5%**		**10%**	
Short-term dependence	16	100.00	16	100.00
Long-term dependence				
(a) Parametric test	15	93.75	16	100.00
(b) Bootstrap method	15	93.75	15	93.75
Only short-term dependence	01	06.25	00	00.00
Only long-term dependence				
(a) Parametric test	00	00.00	00	00.00
(b) Bootstrap method	00	00.00	00	00.00
Both short-and long-term dependence	15	93.75	16	93.75

Table 4.37 Conditional probabilities of existence of long-term dependence in climatological variables at 5% and 10% significance levels.

Climate variables	Conditional Probabilities at significance levels of	
	5%	10%
Annual mean temperature	00.00	00.00
Annual mean maximum temperature	09.10	10.00
Annual mean minimum temperature	00.00	66.67
Annual mean temperature range	12.50	28.58
Annual rainfall	00.00	15.38
Gridded annual rainfall	11.11	00.00
Annual number of rainy days	14.44	25.00
Gridded annual number of rainy days	05.26	06.66
Annual mean wind speed	00.00	00.00

4.5.2 Discussion

As such no specific study has been conducted in India and in neighboring Himalayan territories to make comparison of results. From the analysis of limited data it was observed that majority of climatological series have revealed short-term and long-term dependence, however, presence of only long-term dependence was not found in most of the series. The spatial variation indicate that dependence is more pronounced in the eastern Himalayas followed by the central Himalayas. The effect of altitude and length of data on the dependency structure was also investigated and it was revealed that high altitude (above 1500 m) stations and long records exhibited more dependence as compared to low altitude and short records (Table 4.38 and 4.39). The plausible reason for dependence structure in the series could be the contribution of Atmospheric Brown Cloud (ABC) which was reported to be increasing in the atmosphere (Ramanathan et al, 2005). The faster rate of urbanization of cities (Rao et al., 2004) and increase of irrigation network (Singh and Sontakke, 2003) may also be responsible to cause dependence in climatological variables. The results clearly indicate that trend like phenomenon is present in most of the series and this is not purely by chance The effect of external forcings on the climatological variables could not be ruled out; however, a detailed study using other methods with teleconnections is warranted to confirm the results..

Table 4.38 Elevational Dependency of Meteorological stations for different climatological variables (√ - dependent; X - independent)

Station	Elevation m. a.s.l.	Tmax	Tmin	Tmean	DTR	Rainfall	Rainy days	Wind Speed
Pasighat	157	X	√	√	x	X	√	√
Jammu	367	X	√	X	√	√	X	-
Bilaspur	589	X	√	X	√	X	X	-
Dehradun	682	X	√	√	√	√	X	√
Mandi	761	X	X	X	X	X	√	√
Tehri	770	√	√	√	X	X	X	√
Bhuntar (A)	1096	√	X	√	X	X	X	√
Kalimpong	1209	√	√	√	√	X	√	√
Dharamsala	1271	√	√	√	√	√	√	√
Ziro	1476	X	√	√	√	X	X	√
Srinagar	1587	√	√	√	√	X	X	-
Banihal	1630	X	√	√	X	X	√	-
Quazigund	1739	X	√	√	X	X	√	-
Gangtok	1832	√	√	√	√	√	√	√
Joshimath	1875	√	√	√	√	√	√	√
Nainital	1953	X	X	X	X	√	√	√
Dalhousie	1959	√	√	√	√	√	√	√
Mukhim	1981	X	√	X	√	X	√	-
Manali	2039	√	√	√	√	√	√	√
Mussorie	2042	√	√	√	√	√	√	√
Darjeeling	2127	√	√	√	√	X	√	√
Simla	2202	√	√	√	√	√	√	√
Mukteswar	2311	√	√	√	√	X	√	√
Elevation class (m)		**No. of series indicated dependence**						
0 – 500		-	2	1	1	1	1	1
500 – 1000		1	3	2	2	1	1	3
1000 – 1500		3	3	4	3	1	2	4
1500 – 2000		4	7	6	5	4	7	4
2000 – 2500		5	5	5	5	3	5	5

Table 4.39 Effect of length of record of meteorological station on dependence in climatological variables (√ - dependent; X - independent)

Station	Length of data	Tmax	Tmin	Tmean	DTR	Rainfall	Rainy days	Wind Speed
Quazigund	22	X	√	√	X	X	√	-
Banihal	22	X	√	√	X	X	√	-
Tehri	26	√	√	√	X	X	X	√
Nainital	26	X	X	X	X	√	√	X
Ziro	28	X	√	√	√	X	X	√
Gangtok	30	√	√	√	√	√	√	√
Srinagar	32	√	√	X	√	X	X	-
Joshimath	32	√	√	√	√	√	√	√
Mukhim	33	X	√	X	√	X	√	-
Pasighat	33	X	√	√	X	X	√	√
Manali	33	X	X	X	X	X	√	-
Jammu	34	X	√	X	√	√	X	-
Bilaspur	36	X	√	X	√	X	X	-
Dalhousie	37	√	√	√	√	√	√	√
Bhuntar (A)	40	√	X	√	X	X	X	√
Dharamsala	47	√	√	√	√	√	X	√
Mandi	47	√	√	√	√	√	√	√
Mussorie	57	√	√	√	√	√	√	√
Dehradun	58	X	√	√	√	√	X	√
Mukteswar	58	√	√	√	√	X	√	√
Darjeeling	58	√	√	√	√	X	√	√
Kalimpong	58	√	√	√	√	X	√	√
Simla	59	√	√	√	√	√	√	√
Record interval		**No. of series indicated dependence**						
< 29		1	4	4	1	1	3	2
30 – 39		4	8	4	7	4	6	4
40 – 49		3	2	3	2	2	1	3
50 – 59		5	6	6	6	3	5	6

CHAPTER 5

ANALYSIS OF TEMPORAL AND SPATIAL TRENDS

5.1 INTRODUCTION

From the analysis of Chapter 4, it is seen that the short-term dependence is present in the series of climate variables. This tendency needed to be investigated for the presence of trends.

Studies of large scale changes in atmospheric phenomena over wide areas especially for temperature and rainfall are pre-requisites for the planning and development of a Country's natural resources (Parthasarathy & Dhar, 1975). Study of past climate condition is particularly important to know more recent and future changes taking place in the climate. The first climate change was recognized as a serious problem in the First World Climate Conference held in February 1979 (IUCC – Fact sheet 201). Since then researchers have been studying the undergoing changes in the climate. The levels of CO_2 and other Greenhouse gases are rising in the atmosphere (Ramanathan, 1988) along with the global mean temperatures (Hansen and Labedeff, 1987, and Strong, 1989). From the ongoing research, now it is well documented that the climate is changing and this change is observed in various climate indicators. Therefore, in this chapter, annual and seasonal temporal trends and their spatial interpolation has been studied and discussed in detail for the climate variables of Indian Himalayas.

5.2 REVIEW OF LITERATURE

The existing information on trends in the climatological variables has been reviewed and discussed in Chapter 2 of section 2.2.

5.3 STUDY AREA AND DATA USED

This has been presented and described under section 3.2 of Chapter 3.

5.4 METHODOLOGY

Trend is a systematic increase or decrease in the time-series. Several methods are available for detection of trends in the hydro-climatic time series. These trend detection methods can be divided in to two groups (1) Parametric methods and; (2) Non-parametric methods. Parametric trend detection tests are more powerful than non-parametric tests (Chen et al., 2007). The parametric methods assume that the data should be normally distributed without any outliers. While, non-parametric methods are free from such assumptions. The Mann-Kendall (MK) test (Mann,1945; Kendall,1955) is a non-parametric trend detection test and most commonly used for identifying trend in the hydro-climatic time series. However, it requires that the data should be serially independent. Although, Mann-Kendall's test is a widely used (Zhang et al., 2005; Aziz & Burn, 2006; Chen et al., 2007; Jhajharia et al., 2009 and Bandyopadhyay et al., 2009) and useful method for trend detection but a resampling (like one which is being practiced to analyse long-term dependence structure of the time-series) may be a more useful basis for analysis.

5.4.1. Resampling Technique (Radziejewski and Kundzewicz (2000)

Resampling offers an alternative way to compute the significance levels of tests results. It may allow us to use a test even if its assumptions are not satisfied by the series like uncorrelated series. Resampling works by generating many random time series with distribution identical to that of the time series. The test results obtained for the original time series are compared with to those obtained for the random series and significance is evaluated based on this comparison. Random series are generated either by permuting the series (sampling its value without replacement) or by sampling its values with replacement (bootstrapping). Radziejewski and Kundzewicz (2000) have developed HYDROSPECT software package for detection of trends in a climatolgical time-series by incorporating several test and suggested that results obtained from resampling are probably more valid than without resampling. The method is now the preferred method for detecting trend in climatological series (Kundzewicz and Robson, 2000). Therefore, in this study, the climatological variables at annual and seasonal time scales were subjected to MK trend detection test with resampling (bootstrapping) techniques and the magnitude of trend was estimated with linear regression using HYDROSPECT software (Radziejewski and Kundzewicz, 2000).

5.4.2 Mann-Kendall Test

In HYDROSPECT software Mann-Kendall test can only be applied to a series of ranks or ranked deviations from the median. So the raw data were pre-processed and ranks were calculated using the inbuilt option in the software. The test statistic displayed is

Kendall's sum (commonly denoted as S) divided by the square root of its variance under the hypothesis of independent and identically distributed observations. The test statistic equals

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\operatorname{sgn}(x_j-x_i) \qquad (5.1)$$

where, x_j are the sequential data values, n is the length of the data set and

$$\operatorname{sgn}(t)=\begin{cases}1, & for\, t>0\\ 0, & for\, t=0\\ -1, & for\, t<0\end{cases} \qquad (5.2)$$

The value of S indicates the direction of trend. A negative (positive) value indicate falling (rising) trend. Mann-Kendall documented that when $n \geq 8$, the test statistics S is approximately normally distributed with mean and variance as follows:

$$E(S)=0 \qquad (5.3)$$

$$Var(S)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{m}t_i(t_i-1)(2t_i+5)}{18} \qquad (5.4)$$

where, m is the number of tied groups and t_i is the size of the i^{th} tie group. The standardized test statistics Z is computed as follows.

$$Z_{MK}=\begin{cases}\dfrac{S-1}{\sqrt{Var(S)}}, & for\, S>0\\ 0\quad, & for\, S=0\\ \dfrac{S+1}{\sqrt{Var(S)}}, & for\, S<0\end{cases} \qquad (5.5)$$

The HYDROSPECT software displays the Z score and associated significance level for the chosen bootstrap sampling (1000 in this case) and; as an option it also displays Kendall's *tau*. The significance level is valid under the null hypothesis of independent and identically distributed observations. For linear regression test it gives correlation coefficient, significance level and the change in slope value.

5.4.3 Interpretation of Hydrospect Results (Radziejewski and Kundzewicz (2000)

Hydrospect returns the values of the test statistic and of the significance level actually achieved. High value of the actual significance level means that the hypothesis of a lack of change is rejected in the light of evidence. If the significance level returned by Hydrospect is 99% (tantamount to 1% in another convention), there is a high chance that a change exists in the hydrological time series subject to analysis. A value of significance equal to 99.3% means that a change is detected at the 95% (or 5%) significance level and at the 99% significance level, but not at the 99.9% (or 0.1%) level. For the present trend analysis the interpretations were made at 90% significance level.

5.2 Spatial Interpolation of Trend Results

Any observed trends could be spatially interpolated by calculating values between known pixels (Su et al., 2005). Several interpolation techniques namely, IDW, Krigging, CoKrigging, Radiall Basis Function etc are in use. Therefore, to spatially interpolate the results of Mann-Kendall test, the simple Inverse Distance Weighted (IDW) Interpolation Technique is used using the ArcGIS 9.2 software package. It is a commonly used interpolation technique creates a raster surface. The interpolated raster surface is based on a weighted average of the station values. The value of each cell is influenced mostly by nearby points and less by more distant stations. The IDW method works on the power parameter and a search radius. The power parameter controls the significance of calculated station values on the interpolated values. A high power value means more emphasis is placed on the nearest points, and the resulting surface will have more detail. In the present analysis a power of six is fixed with quadrant search radius and the results are discussed for each variable.

5.5 RESULTS AND DISCUSSION

5.5.1 Temporal Trends

Fig. 5.1 to 5.7 depict annual variation in the normalized series of climatological variables, namely, mean temperature, mean maximum and mean minimum temperatures, temperature range, rainfall, number of rainy days and mean wind speed along with linear trends in the different regions of the Indian Himalayas and entire Indian Himalayas. The magnitude of change is described by the slope of the regression line. The significant results of the MK trend test and linear regression test applied on the available climatological variables are given in Table 5.1 to 5.9.

5.5.1.1 Temperature Trend Results

5.5.1.1.1 Mean Temperature

Mean temperature data for all the selected stations were analyzed. Annual and seasonal temperature trends were calculated separately for each station and for each season. Statistical tests of the mean temperature data showed the existence of trends in the records. The results from the analysis are presented in Table 5.1 and the variation in normalized mean temperature over different regions of the Indian Himalayas is shown in Fig. 5.1. The results of the MK test analysis showed that the mean temperature has significantly decreased in six stations and increased in four stations. The linear slopes of the trends clearly indicate that in majority of the stations mean temperature is decreasing and the maximum significant cooling was recorded at Banihal station. Since, the data length is not uniform the results are discussed on regional basis. It is evident from Table 5.1 and Fig. 5.1 that western, central regions and entire Indian Himalayas had negative trends in annual mean temperature and it is significant in central Himalayas with a cooling rate of -0.50 °C/decade during the period 1959-1990.

The analysis of seasonal mean temperature indicated decreasing trends in monsoon season. About 50% of the stations showed significant cooling trends and their magnitude range from -0.10 to -0.57 °C/decade. The regional analysis also indicates cooling of monsoon season with significant larger cooling of central and entire Indian Himalayas. Similarly, a significant cooling of pre-monsoon (summer) season is evident at nine stations (11 by MK test). The observed rate of cooling of -0.95 °C/decade was found to be uppermost and it was recorded at Banihal station. At the regional scale also, the results for entire Indian Himalayas show significant cooling trend. These cooling trends in entire Indian Himalayas are evident because of the higher cooling rates in central Himalayas. In contrast to above, the winter season experienced warming trends. The MK test and linear regression indicated that seven stations had warming trends. However, on regional basis, only eastern Himalayas revealed a significant warming. In post-monsoon season insignificant increases and decreases were observed.

5.5.1.1.2 Mean Maximum Temperature

The results of MK test and linear regression are depicted in Table 5.2. It may be seen that significant positive trends indicated by both the tests are almost similar for annual mean maximum temperature. The significant positive linear slopes had a variation from

+0.14 °C/decade to +0.71 °C/decade. The warming of stations was reflected in regional analysis and indicated increase in annual maximum temperature in western, eastern and entire Indian Himalayas. Most significant warming rate of +0.52 °C/decade is found in eastern Himalayas (Fig. 5.2).

The warming of post-monsoon and winter season was revealed by both the tests and it is comparable with annual warming trends. However, rates of warming in post-monsoon were larger than that of annual maximum temperature. The largest warming of +0.83 °C/decade was found in Kalimpong station in post monsoon season. On annual scale also, the Kalimpong station showed highest warming rates of +0.71 °C/decade compared to other stations. It is surprising to note that the pre-monsoon season, which includes high temperature months, experienced significant cooling trends at six stations. As far as trends of monsoon season are concerned, the analysis showed mixed results of significant warming at four stations and significant cooling at three stations.

5.5.1.1.3 Mean Minimum Temperature

The results of the mean minimum temperature are most striking. The linear regression analysis indicated that the annual minimum temperature had significant cooling trends at fifteen stations i.e. 65% percent of the total stations considered for the analysis (Table 5.3). Also, the results from the MK test revealed significant cooling trends at fourteen stations. Similarly, minimum temperature in monsoon and pre-monsoon season also showed significant cooling. The results reveal greatest cooling rates of -0.98 and -0.81 °C/decade in monsoon and pre-monsoon season, respectively. Trend in post-monsoon minimum temperature is comparable to that of winter. The regional linear trends are shown in Fig. 5.3. A sharp decline in the trend line may be seen in all the regions of Indian Himalayas with a significant declining rate of 0.57 °C/decade in the annual mean minimum temperature over the entire Indian Himalayas. The trend of mean minimum temperature in monsoon and pre-monsoon are found more alarming.

5.5.1.1.4 Mean Temperature Range

Although maximum temperature was observed to be increasing but due to large reduction in minimum temperature, there is an unexpected increase in temperature range in almost all the stations. The rate of annual temperature range was as high as 1.1.3 °C/decade (Table 5.4). In general all the seasons shows increase in temperature range but the largest change was found during monsoon with maximum increase of 1.54

°C/decade. On visual inspection of Fig. 5.4, the region wide increase was revealed. Referring the same figure it may also be seen that during 1959-1990 in entire Indian Himalayasn the minimum value of DTR was as low as -2.4 °C which has increased to +0.50 °C. Perhaps it is the result of the highest rise in DTR at the rate of +0.70 °C/decade observed in eastern Himalayas.

5.5.1.2 Discussion on Trends in Temperature

It emerged out from the results of temperature trends that annual mean temperature over Indian Himalayas is going down at the rate of -0.20 °C/decade. This may be attributed to the contrasting tendency shown by the two temperature maxima. Similar studies have been conducted in India or in different parts of India and warming trends have been reported (Hingane et al., 1985; Rupa Kumar et al., 1994; Pant and Kumar, 1997; Sinha Ray and De, 2003; Dash et al., 2007; Singh et al., 2008 and Bandyopadhyay et al., 2009). This clearly indicates that the trends of mean temperature in the Indian Himalayas behave differently as compared to the other parts of India. Using PRESIS model simulations, RupaKumar et al. (2006) projected increase in temperature towards 21st century in different parts of India. However, Singh and Sontakke (2002) reported a decrease in mean temperature of 0.93 °C/100 years during 1958-1997 in Indo-Gangetic Plains of India and linked this decrease with the increase in irrigation network. Also, a study carried out for Indian Himalayas by Bhutiyani et al. (2007) showed contradicting findings. They reported a significant rise of 1.6 °C in temperature in the northwestern Himalayas, whereas, the results of this study revealed cooling of western Himalayas with a linear rate of -0.17 °C/decade. The plausible reasons for such variations in the estimates of mean temperature trends may be attributed to use of different length of data, number of stations and physiographic condition of the stations etc.

The observed trends in the Indian Himalayas are comparable with the some studies in neighboring Himalayasn countries. For instance, Fowler and archer (2006) observed similar results of cooling of annual mean temperature in Upper Indus Basin of Pakistan Himalayas. On comparing the mean temperature records of Kathmandu and India a cooling during monsoon and pre-monsoon season for the period 1901-95 were observed by Cook et al. (2003) which also supports the present finding of cooling of mean temperature.

However, in contrast to present finding of cooling of Indian Himalayas, Aizen et al.(1997) reported average rate of 0.10 °C/year rise in annual air temperature in Tien

Shan. Increasing trend in the temperature was also reported by Xu et al. (2007) for China.

The rising of maximum temperature in western Himalayas was well supported by the findings of Bandyopadhyay et al. (2009) who reported a rise of 0.06 °C/year in maximum temperature. Similarly, warming of western Himalayas was also reported by Dash et al. (2007) with the same rate of rising. For Pakistan Himalayas, Fowler and Archer (2006) reported increase in maximum temperature. Similarly, for Nepal Himalayas, Shrestha et al. (1999) showed that maximum temperatures for the period of 1971-1994 were increasing at a rate of 0.06 °C/year and the estimates are much lower than the present finding of 0.20 °C/decade.

All the three regions and entire Indian Himalayas showed decrease in the minimum temperature in all the seasons. However, significant decreases were observed during annual, monsoon and pre-monsoon season with a variation in linear rates from -0.40 to 0.77 °C/decade. The results are well supported by the findings of Yadav (2004) who revealed similar trend of decrease in minimum temperature for western Himalayas. However, Dash et al. (2007) did not observed any trend in the minimum temperature during pre-monsoon in sub-divisions of India. The results of Bhutiyani et al. (2007) are not in agreement with the present finding of decreasing rate in minimum temperature; rather they have observed an increase of 0.8 °C in northwestern Himalayas. A decrease in annual and summer minimum temperature was also reported in Pakistan (Fowler and Archer, 2006) which reinforced the findings of this study. However, in Nepal Himalayas no trend in minimum temperature was found during 1968-1992 (Sharma, 2000). Similarly, studies in Alps (Beniston, 2003; Bhutiyani et al., 2007) and the Rocky Mountains in Colorado (Brown et al., 1992; Bhutiyani et al., 2007) have shown that minimum temperatures have increased much more rapidly than the maximum temperatures.

Primarily, greater decrease in minimum temperature resulted in cooling of mean temperature. Since, nighttime temperature is largely controlled by the greenhouse effect of lower atmospheric water vapor while the day time maximum temperature depends heavily on the surface heating, which is strongly affected by cloud cover (Dai, et al., 1999). However, the possibility of other reasons cannot be ignored. One reason could be the increasing contribution of aerosols over South Asia and the Indian sub-continent (Fowler and Archer, 2006). Ramanathan et al. (2005) have reported the effect of greenhouse gases and sulphates on the trends in temperature. They further reported that since 1930, the increasing contribution of Atmospheric Brown Clouds (ABC) due to South Asian emissions of fossil fuel SO_2 and black carbon reduced the receipt of solar radiation, and these aerosols are responsible for heating of the earth.

In recent years the issue of changes in diurnal temperature range has gained momentum. In the present study decreasing rates of minimum temperature was higher than the rising trends of maximum temperature. This has resulted in large increase in temperature range throughout the Indian Himalayas during all seasons. Rupakumar et al. (1994) found that the minimum temperature was trendless and rise in the temperature range was caused due to increase in maximum temperature over India. In a similar study, Kothwale and Rupakumar (2005) also reported increasing trend in temperature range due to higher rate of increase in the maximum temperature than the minimum temperature over India. However, Jhajharia and Singh (2010) for northeast India, and Karl, et al. (1993), Easterling et al. (1997) and Jones (1999) for globe demonstrated decreasing trends in temperature range with varying estimates. Significant increasing trends in temperature range for northwestern Himalayas was reported by Bhutiyani et al. (2007) which reconfirm the present finding of rising temperature range in Indian Himalayas. The results of increasing temperature range in Indian Himalayas are well supported by the results of significant increase of temperature range in Hindu-Kush Karakoram Himalayas (Fowler and Archer, 2006). These comparisons of temperature range results indicate that the Indian Himalayas shares the increasing temperature range as that of Indian sub-continent.

The probable explanations for increase in temperature range in the Indian Himalayas may be due to large diurnal variations of fogs and haze. Changes in land cover associated with deforestation (Dai et al., 1999), urbanization of the area (Rao et al., 2004), bringing more area into irrigation (Singh and Sontakke, 2002) could also affect the temperature range through variations in the temperature maxima.

Table 5.1 MK trend results with linear slope (^{o}C/decade) over the stations of Indian Himalayas for mean temperature (- for decreasing trend and + for increasing trend).

Station	**MK test result**					**Linear slope (^{o}C/decade)**				
	S1	S2	S3	S4	S5	**S1**	S2	S3	S4	S5
Srinagar	(+)	-	(-)	-	-	**+0.50**	-0.03	**-0.34**	-0.17	-0.03
Quazigund	-	(-)	-	-	(-)	-0.07	**-0.76**	**-0.53**	-0.17	**-0.41**
Banihal	-	(-)	(-)	(-)	(-)	+0.06	**-0.95**	**-0.51**	**-0.52**	**-0.48**
Jammu	-	-	(-)	+	-	+0.08	-0.10	**-0.19**	+0.02	-0.05
Dalhousie	(-)	(-)	(-)	(-)	(-)	**-0.35**	**-0.48**	**-0.32**	**-0.35**	**-0.37**
Dharamsala	-	(-)	-	+	-	-0.03	**-0.26**	-0.05	-0.01	-0.09
Manali	+	-	(+)	+	+	+0.10	-0.01	-0.23	+0.06	+0.11
Bhuntar (A)	(+)	-	+	(+)	(+)	**+0.15**	-0.03	+0.12	+0.14	**+0.09**
Mandi	(+)	-	+	(+)	+	**+0.28**	-0.02	+0.01	+0.11	+0.09
Bilaspur	-	+	-	+	+	-0.05	+0.01	-0.00	+0.16	+0.02
Simla	+	-	-	+	+	+0.09	-0.12	-0.02	+0.04	-0.01
Mukhim	-	-	(-)	+	-	+0.01	**-0.40**	**-0.18**	+0.13	-0.14
Joshimath	-	(-)	(-)	-	(-)	-0.14	**-0.76**	**-0.57**	-0.19	**-0.45**
Mussoorie	+	(-)	(-)	+	-	+0.11	**-0.20**	**-0.10**	+0.04	-0.05
Tehri	-	-	(-)	-	(-)	-0.06	**-0.74**	**-0.25**	-0.12	**-0.31**
Dehra Dun	-	(-)	(-)	+	(-)	+0.01	**-0.23**	**-0.11**	+0.03	**-0.09**
Mukteswar	(+)	-	(-)	+	-	**+0.16**	-0.07	-0.06	+0.05	+0.01
Nainital	-	-	(-)	+	-	-0.08	-0.25	**-0.29**	+0.20	-0.15
Pasighat	+	+	+	(+)	+	+0.12	-0.005	+0.14	**+0.23**	+0.12
Ziro	(+)	-	+	(+)	(+)	**+0.34**	-0.15	-0.11	**+0.20**	+0.05
Gangtok	+	-	+	-	+	+0.11	+0.006	+0.13	-0.02	+0.07
Kalimpong	(+)	-	-	(+)	(+)	**+0.69**	-0.11	**-0.21**	**+0.38**	**+0.14**
Darjeeling	(+)	+	+	(+)	(+)	**+0.28**	+0.08	+0.02	**+0.34**	**+0.15**
No. of significant trend										
-ve trend	01	07	11	02	06	01	09	12	02	05
+ve trend	07	00	01	06	04	07	00	00	04	03
Total No. of trend	08	07	12	08	10	08	09	12	06	08
Regional	**S1**	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Western Himalayas	+	-	(-)	-	-	+0.11	-0.18	-0.27	-0.05	-0.17
Central Himalayas	-	(-)	(-)	-	(-)	-0.09	**-0.45**	**-0.55**	-0.00	**-0.50**
Eastern Himalayas	(+)	(-)	-	+	-	**+0.41**	-0.27	-0.26	+0.24	+0.05
All India Himalayas	+	(-)	(-)	+	(-)	+0.15	**-0.29**	**-0.36**	+0.06	-0.20

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual; Bracketed term indicate significant trend at 10% confidence level

Bracketed signs and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

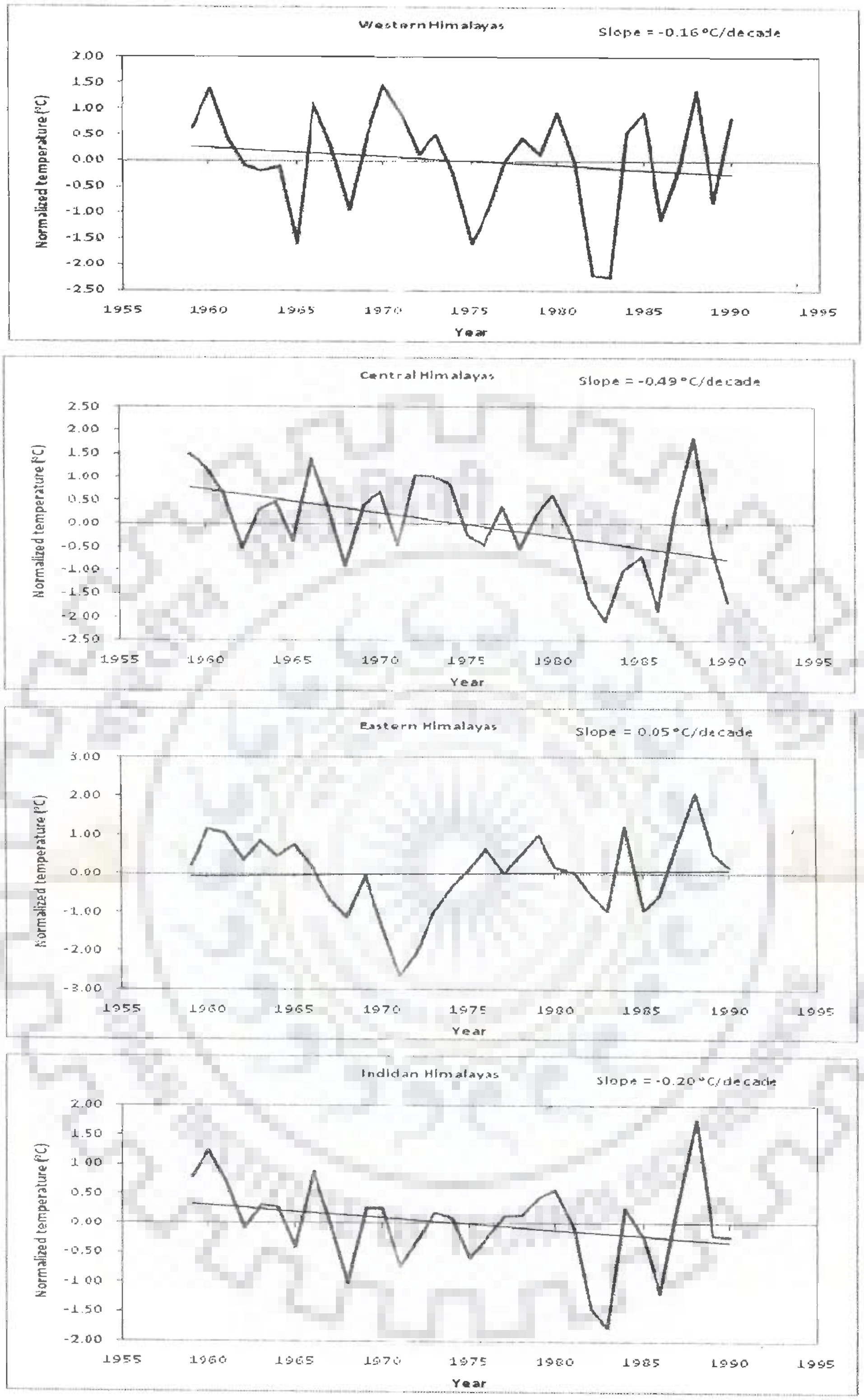

Fig. 5.1 Annual temporal variation of normalized mean temperature and fitted linear slope line in Indian Himalayas

Table 5.2 MK trend results with linear slope (°C/decade) over the stations of Indian Himalayas for mean maximum temperature (- for decreasing trend and + for increasing trend).

Station	**MK test result**					**Linear slope (°C/decade)**				
	S1	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Srinagar	(+)	+	+	+	(+)	**+0.94**	+0.28	+0.01	+0.29	**+0.36**
Quazigund	-	-	-	-	-	-0.10	-0.71	-0.46	-0.14	-0.38
Banihal	+	-	-	-	-	+0.31	**-0.79**	-0.30	-0.31	-0.27
Jammu	+	+	-	(+)	+	+0.32	+0.09	+0.04	**+0.33**	+0.17
Dalhousie	-	(-)	(-)	-	(-)	-0.30	**-0.46**	**-0.23**	**-0.39**	**-0.33**
Dharamsala	+	-	+	+	-	+0.15	-0.11	+0.04	**+0.18**	+0.05
Manali	+	+	+	+	+	+0.21	+0.03	+0.12	-0.06	+0.09
Bhuntar (A)	(+)	+	+	(+)	(+)	**+0.24**	+0.01	+0.15	+0.18	**+0.14**
Mandi	(+)	+	(+)	(+)	(+)	**+0.47**	+0.13	+0.08	+0.16	**+0.20**
Bilaspur	-	-	+	+	+	-0.10	+0.002	+0.09	+0.17	+0.03
Simla	(+)	+	(+)	(+)	(+)	**+0.20**	-0.003	**+0.10**	**+0.16**	**+0.11**
Mukhim	+	-	-	+	+	+0.14	-0.22	+0.07	+0.21	+0.04
Joshimath	-	(-)	(-)	-	(-)	-0.22	**-0.92**	**-0.68**	-0.25	**-0.54**
Mussoorie	+	-	-	+	-	+0.14	**-0.22**	-0.004	+0.03	-0.02
Tehri	-	(-)	-	+	-	+0.01	**-0.96**	-0.08	-0.14	**-0.28**
Dehra Dun	(+)	-	+	(+)	(+)	**+0.15**	-0.11	+0.03	**+0.17**	+0.05
Mukteswar	(+)	(+)	(+)	(+)	(+)	**+0.50**	**+0.27**	**+0.19**	**+0.38**	**+0.32**
Nainital	+	-	-	+	-	-0.07	-0.26	-0.08	+0.19	-0.09
Pasighat	+	+	+	(+)	(+)	+0.23	-0.01	+0.12	**+0.34**	**+0.15**
Ziro	+	-	+	-	+	+0.05	-0.46	-0.30	+0.03	-0.19
Gangtok	(-)	(-)	(-)	(-)	(-)	**-0.48**	**-0.54**	**-0.33**	**-0.60**	**-0.46**
Kalimpong	(+)	(+)	(+)	(+)	(+)	**+1.14**	**+0.37**	**+0.57**	**+0.83**	**+0.71**
Darjeeling	(+)	(+)	(+)	(+)	(+)	**+0.57**	**+0.36**	**+0.35**	**+0.79**	**+0.48**
No. of significant trend										
-ve trend	01	04	03	01	03	01	06	03	02	03
+ve trend	08	03	05	09	09	08	03	04	08	08
Total No. of trend	09	07	08	10	12	09	09	07	10	11
Regional	**S1**	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Western Himalayas	+	+	+	+	+	+0.24	+0.01	+0.29	**+0.33**	+0.29
Central Himalayas	-	-	-	+	-	+0.01	**-0.32**	-0.17	+0.19	-0.20
Eastern Himalayas	(+)	+	(+)	(+)	(+)	**+0.55**	+0.11	**+0.37**	**+0.58**	**+0.52**
All India Himalayas	+	-	+	(+)	(+)	**+0.27**	-0.06	+0.17	**+0.37**	+0.20

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual; Bracketed term indicate significant trend at 10% confidence level

Bracketed signs and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

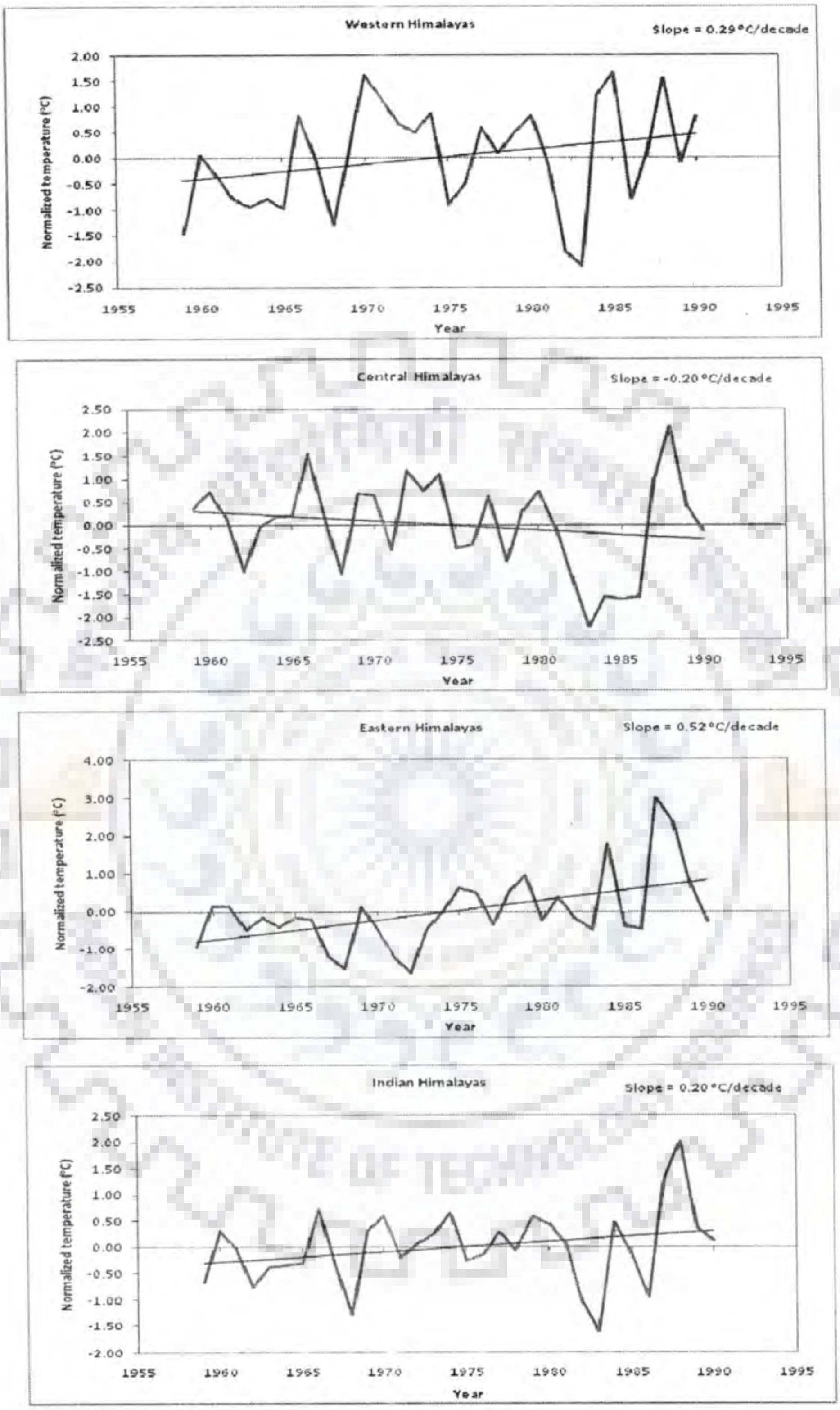

Fig. 5.2 Annual temporal variation of normalized mean maximum temperature and fitted linear slope line in Indian Himalayas

Table 5.3 MK trend results with linear slope (°C/decade) over the stations of Indian Himalayas for mean minimum temperature (- for decreasing trend and + for increasing trend).

Station	**MK test result**					**Linear slope (°C/decade)**				
	S1	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Srinagar	+	(-)	(-)	(-)	(-)	+0.05	**-0.35**	**-0.69**	**-0.63**	**-0.41**
Quazigund	+	(-)	(-)	-	(-)	-0.03	**-0.81**	**-0.60**	-0.20	**-0.44**
Banihal	-	(-)	(-)	(-)	(-)	-0.20	**-1.11**	**-0.71**	**-0.74**	**-0.69**
Jammu	-	-	(-)	(-)	(-)	-0.15	-0.29	**-0.42**	**-0.30**	**-0.27**
Dalhousie	(-)	(-)	(-)	(-)	(-)	**-0.39**	**-0.49**	**-0.41**	**-0.30**	**-0.41**
Dharamsala	(-)	(-)	(-)	-	(-)	**-0.21**	**-0.42**	**-0.15**	**-0.20**	**-0.24**
Manali	+	-	(-)	(-)	+	-0.00	-0.05	**-0.34**	+0.19	+0.13
Bhuntar (A)	+	-	+	+	+	+0.06	-0.06	+0.08	+0.09	+0.04
Mandi	-	-	-	+	-	+0.10	-0.16	-0.06	+0.07	-0.03
Bilaspur	+	-	(-)	+	-	-0.00	+0.02	-0.09	+0.14	-0.00
Simla	-	(-)	(-)	-	(-)	-0.01	**-0.24**	**-0.15**	-0.07	**-0.12**
Mukhim	-	(-)	(-)	-	(-)	-0.14	**-0.57**	**-0.42**	+0.05	**-0.31**
Joshimath	-	(-)	(-)	-	(-)	-0.06	**-0.60**	**-0.48**	-0.14	**-0.35**
Mussoorie	+	-	(-)	+	-	+0.09	**-0.18**	**-0.19**	+0.05	-0.08
Tehri	-	-	(-)	-	-	-0.13	-0.53	**-0.43**	-0.11	**-0.33**
Dehra Dun	(-)	(-)	(-)	-	(-)	**-0.14**	**-0.36**	**-0.25**	-0.12	**-0.23**
Mukteswar	(-)	(-)	(-)	(-)	(-)	**-0.17**	**-0.40**	**-0.31**	**-0.29**	**-0.30**
Nainital	-	-	(-)	+	(-)	-0.10	-0.25	**-0.49**	+0.22	**-0.21**
Pasighat	+	-	+	+	+	+0.03	-0.00	+0.16	+0.13	+0.08
Ziro	(+)	+	+	(+)	(+)	**+0.62**	+0.15	+0.06	**+0.38**	**+0.29**
Gangtok	(+)	(+)	(+)	(+)	(+)	**+0.70**	**+0.55**	**+0.59**	**+0.57**	**+0.61**
Kalimpong	(-)	(-)	(-)	-	(-)	**+0.23**	**-0.59**	**-0.98**	-0.07	**-0.43**
Darjeeling	+	(-)	(-)	-	(-)	-0.01	**-0.20**	**-0.32**	-0.11	**-0.17**
No. of significant trend										
-ve trend	05	12	18	06	14	04	13	17	06	15
+ve trend	02	01	01	02	02	03	01	01	02	02
Total No. of trend	07	13	19	08	16	07	14	18	08	17
Regional	**S1**	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Western Himalayas	-	(-)	(-)	(-)	(-)	-0.20	**-0.46**	**-0.58**	**-0.40**	**-0.57**
Central Himalayas	(-)	(-)	(-)	-	(-)	-0.21	**-0.53**	**-0.77**	-0.24	**-0.65**
Eastern Himalayas	+	(-)	(-)	-	(-)	+0.04	**-0.62**	**-0.51**	-0.25	**-0.47**
All India Himalayas	-	(-)	(-)	-	(-)	-0.12	**-0.54**	**-0.59**	-0.29	**-0.57**

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual; Bracketed term indicate significant trend at 10% confidence level

Bracketed signs and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

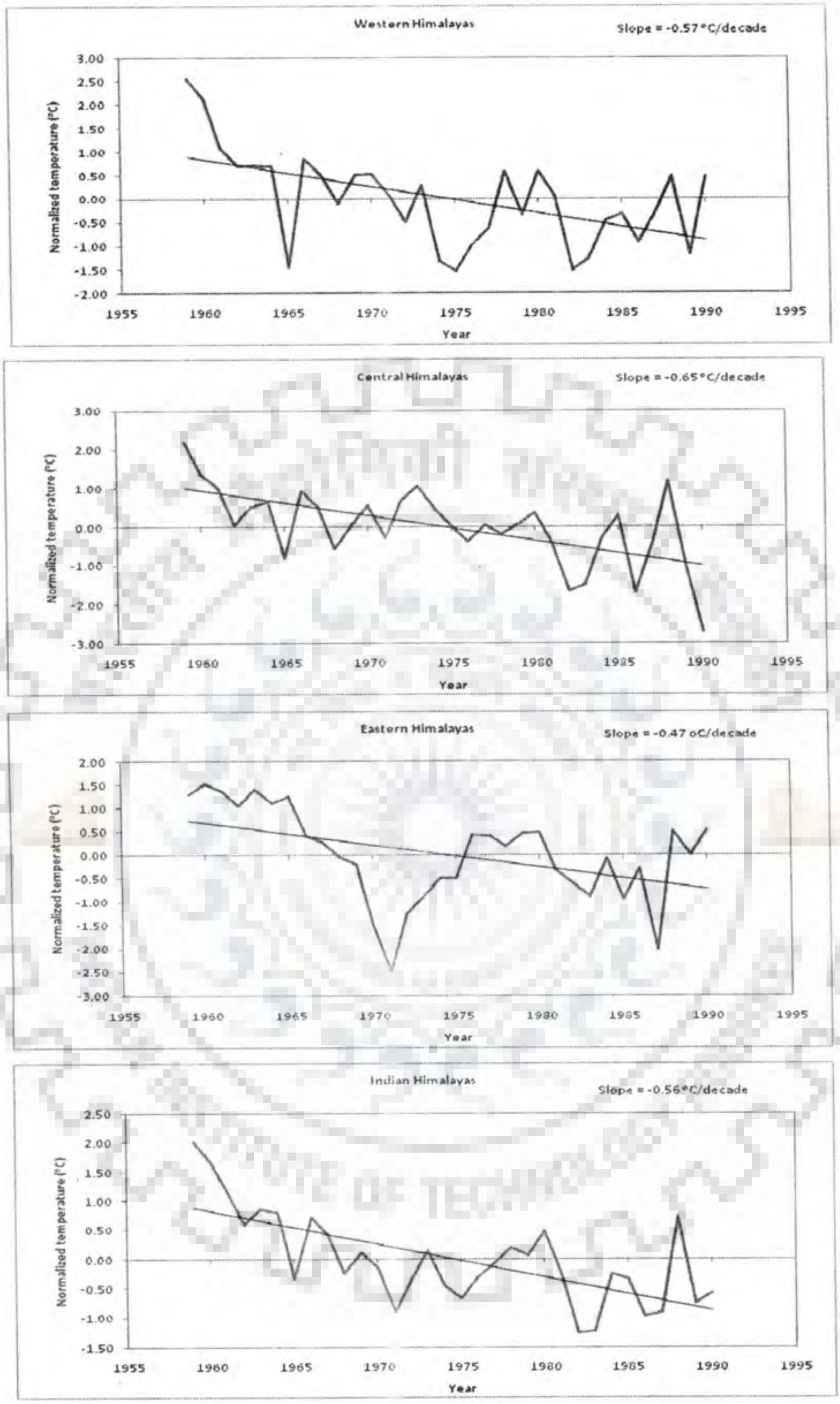

Fig. 5.3 Annual temporal variation of normalized mean minimum temperature and fitted linear slope line in Indian Himalayas

Table 5.4 MK trend results with linear slope (°C/decade) over the stations of Indian Himalayas for mean temperature range (- for decreasing trend and + for increasing trend).

Station	**MK test result**					**Linear slope (°C/decade)**				
	S1	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Srinagar	(+)	(+)	(+)	(+)	(+)	**+0.89**	**+0.62**	**+0.70**	**+0.92**	**+0.77**
Quazigund	-	-	+	-	-	-0.07	+0.09	+0.14	+0.06	+0.06
Banihal	+	+	+	+	+	+0.51	+0.33	**+0.41**	+0.43	+0.42
Jammu	+	(+)	(+)	(+)	(+)	+0.47	**+0.38**	**+0.46**	**+0.63**	**+0.44**
Dalhousie	+	+	+	+	+	+0.09	+0.03	+0.17	-0.08	+0.07
Dharamsala	(+)	(+)	(+)	(+)	(+)	**+0.36**	**+0.31**	**+0.19**	**+0.38**	**+0.29**
Manali	+	+	-	-	-	+0.21	+0.08	-0.22	-0.25	-0.04
Bhuntar (A)	+	+	+	+	+	+0.18	+0.07	+0.07	+0.09	+0.10
Mandi	(+)	(+)	+	+	(+)	**+0.37**	+0.30	+0.14	+0.09	**+0.23**
Bilaspur	-	+	+	+	+	-0.10	-0.02	+0.18	+0.03	+0.03
Simla	(+)	(+)	(+)	(+)	(+)	**+0.21**	**+0.23**	**+0.26**	**+0.23**	**+0.24**
Mukhim	(+)	(+)	(+)	(+)	(+)	**+0.29**	**+0.34**	**+0.49**	+0.16	**+0.35**
Joshimath	+	-	-	+	+	-0.16	-0.31	-0.19	-0.10	-0.20
Mussoorie	+	-	(+)	-	+	+0.04	-0.04	**+0.18**	-0.02	+0.06
Tehri	+	(-)	+	+	+	+0.13	**-0.44**	**+0.36**	-0.02	+0.04
Dehra Dun	(+)	(+)	(+)	(+)	(+)	**+0.29**	**+0.26**	**+0.29**	**+0.29**	**+0.28**
Mukteswar	(+)	(+)	(+)	(+)	(+)	**+0.67**	**+0.67**	**+0.50**	**+0.67**	**+0.61**
Nainital	+	+	(+)	-	+	+0.04	-0.004	**+0.39**	-0.03	+0.13
Pasighat	+	+	-	+	+	+0.20	-0.01	-0.04	+0.21	+0.07
Ziro	-	-	-	(-)	(-)	-0.35	-0.20	-0.24	-0.36	**-0.28**
Gangtok	(-)	(-)	(-)	(-)	(-)	**-1.18**	**-1.08**	**-0.93**	**-1.17**	**-1.07**
Kalimpong	(+)	(+)	(+)	(+)	(+)	**+0.91**	**+0.96**	**+1.54**	**+0.91**	**+1.13**
Darjeeling	(+)	(+)	(+)	(+)	(+)	**+0.58**	**+0.56**	+0.67	**+0.90**	**+0.66**
No. of significant trend										
-ve trend	1	2	1	2	2	01	02	01	01	02
+ve trend	9	10	11	9	10	09	09	13	08	10
Total No. of trend	10	12	12	11	12	10	11	14	09	12
Regional	**S1**	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Western Himalayas	+	(+)	(+)	(+)	(+)	**+0.34**	**+0.44**	**+0.61**	+0.50	**+0.65**
Central Himalayas	+	+	(+)	(+)	(+)	+0.25	**+0.35**	**+0.42**	+0.44	**+0.51**
Eastern Himalayas	(+)	(+)	(+)	(+)	(+)	**+0.59**	**+0.59**	**+0.64**	+0.65	**+0.70**
All India Himalayas	(+)	(+)	(+)	(+)	(+)	**+0.39**	**+0.46**	**+0.56**	**+0.53**	**+0.62**

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual; Bracketed term indicate significant trend at 10% confidence level

Bracketed signs and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

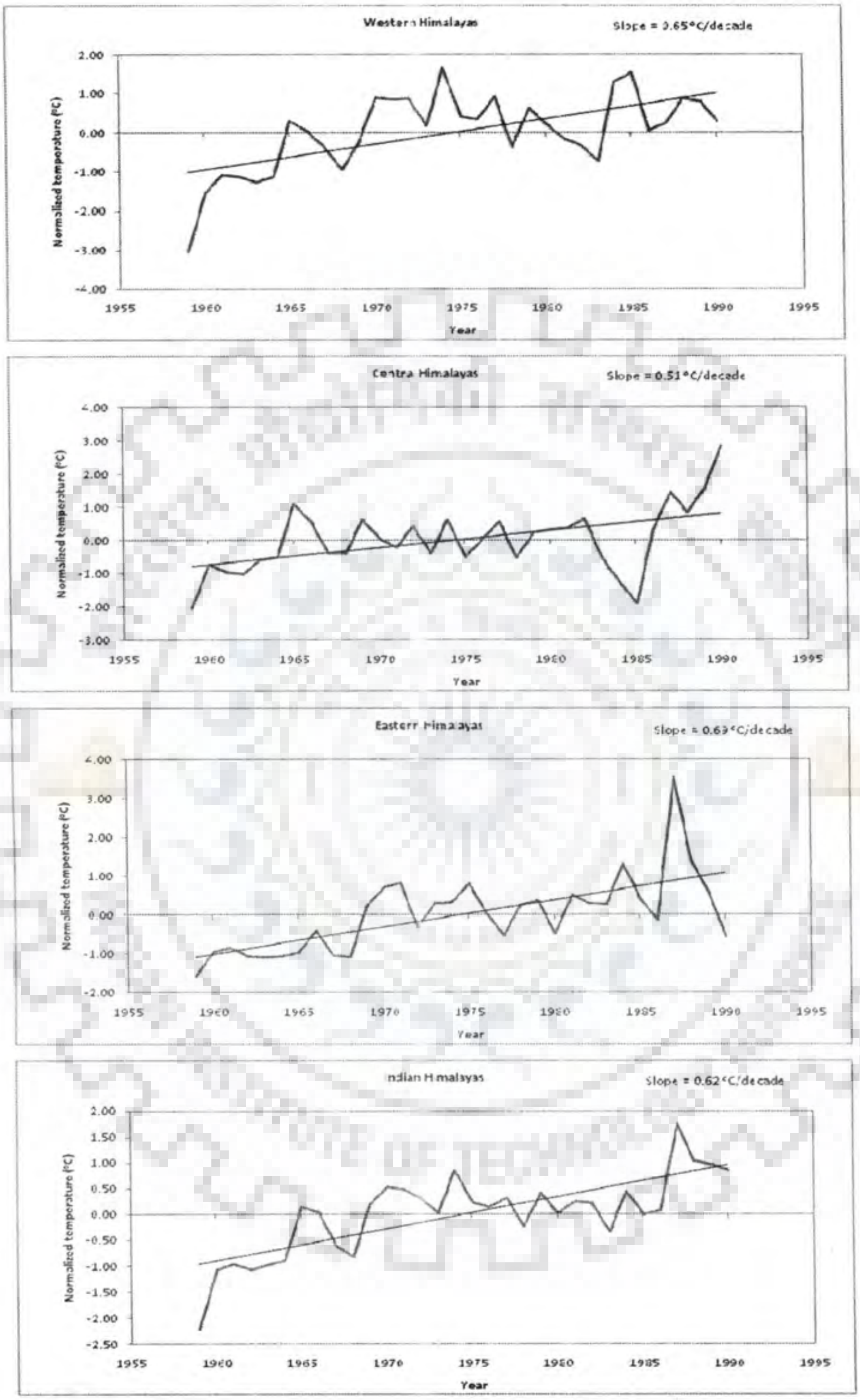

Fig. 5.4 Annual temporal variation of normalized mean temperature range and fitted linear slope line in Indian Himalayas

5.5.1.3 Rainfall Trend Results

The MK test results for rainfall and number of rainy days are given in Table 5.5. It may be seen (from Table 5.5) that 8 stations have shown significant decreasing trends in the annual rainfall. The rainfalls of stations located in the Jammu & Kashmir, West Bengal and Arunachal were observed to be stable and indicated no trends. Fig. 5.5 demonstrates linear trends in the normalized annual rainfall in different regions of Indian Himalayas. An increase of annual rainfall in the eastern Himalayas and; decrease in the western and central Himalayas can also be noted from Fig. 5.5. A decrease of 0.04 cm/decade and 0.02 cm/decade was found in the annual rainfall over central and western Himalayas, respectively. The eastern Himalayas which also receives maximum rainfall showed an increase of 0.02 cm/decade in the annual value. Although, eastern Himalayas was observed with increase in the annual rainfall, but due to high rate of decrease in the other two regions, the estimates for entire Indian Himalayas showed decrease in annual rainfall. This decrease in annual rainfall may affect the availability of surface water resources in the western and central Himalayas in general, and Indian Himalayas in particular. Seasonal analysis of rainfall show that the monsoon season is undergoing drastic changes and it was revealed from the MK test results (Table 5.5) that 11 stations indicated significant decreasing trends. It is obvious that the decrease in the annual rainfall was mainly caused by the decrease in the monsoon rainfall. Besides monsoon season, the significant decreasing trends at five stations were observed during pre-monsoon season. From Table 5.5, it can be revealed that the maximum decrease of 0.05 cm/decade was found in monsoon rainfall in the central Himalayas. A significant decrease in pre-monsoon seasonal rainfall was experienced over the western Himalayan region.

The trends for the gridded rainfall for the period from 1952-2003 are given in Table 5.6. The trend tests results also indicate that the annual rainfall is decreasing. The MK test and linear regression test have revealed significant decrease at 9 and 13 stations, respectively. The percentage of linear decrease was found to be 29%, slightly lower than the percentage trend of point rainfall observations (35%). In monsoon season 21 number of grids experienced significant linear decreasing trends i.e. about 50% of the total no. of grids. On the other hand, the winter rainfall showed increase in the value and found significant at 10 grids (12 by MK test). From the trend results, it emerged that the annual and monsoon rainfall is decreasing over the Indian Himalayas.

5.5.1.4 Number of Rainy Days Trend Results

Out of 23 stations, 10 were found with significant decreasing trends (Table 5.6). Thus, the trend results for number of rainy days confirmed the reason for the decrease in annual rainfall. From Fig. 5.6, it can also be seen that the annual number of rainy days was decreasing in the western, central and entire Indian Himalayas, while it was increasing in the eastern Himalayas. The maximum change of -0.50 rainy days/decade was observed in the normalized rainy days of central Himalayas. The decrease in number of rainy days further indicates towards the possible reduction in surface water availabilities in future.

The number of rainy days in monsoon season also found to decrease significantly in 11 stations. The decreasing trend in regional analysis was the result of the decreasing station rainy days. The western, central Himalayas and entire Indian Himalayas indicated significant decrease with variation from -34 to -50 rainy days/decade. In contradiction to significant increasing rainfall trends during winter, significant decreasing trends of rainy days were observed.

The analysis of gridded rainy days follows the same trend of significant decrease in number of rainy days in annual, monsoon and post-monsoon season while significant increase in pre-monsoon season.

5.5.1.5 Discussion on Trends in Rainfall and Number of Rainy Days

It is revealed from the trend analysis that the annual and monsoon rainfall, and number of rainy days were decreasing. There has been a conflicting result for the changes in rainfall since past e.g. Parthasarthy and Dhar (1975) reported significant rise of 5% in the mean values of rainfall values. Whereas, Sarker and Thapliyal (1988) and Thapliyal and Kulshreshtha (1991) observed no trends in Indian rainfall. Singh and Sontakke (2002) revealed increase in summer monsoon rainfall in the Indo-Gangetic Plains. On a river basin scale analysis, Singh et al. (2007) found an increasing trend in rainfall. For Uttarakhand Himalayas, an increase in rainfall up to 1964 and then decrease from 1965-1980 was found (Basistha, et al. 2008). The results of above reported studies support the findings of present study well. The findings of Bhutiyani (2010) and Kumara and Jain (2010) further confirm the results of the present study that the annual precipitation in the northwest Himalayas is decreasing. However, in Nepal Himalayas no trend was observed in precipitation (Shreshtha et al. 2000; Shanrma et al. 2000a). Similar are the observation from

China (Xu et al. 2007). Significant increase in winter rainfall during 1961-1990 in Karakoram ranges of Pakistan Himalayas (Fowler and Archer, 2006) is in good agreement with the results of present study. The possible cause of changing pattern of precipitation may be due to Global climate shift or weaking of global monsoon circulation, reduction in forest cover, change in land use including introduction of irrigated agriculture and increasing aerosols due to anthropogenic activities. The Asian Brown Cloud may reduce the precipitation by -5% (Ramanathan et al. 2005). An overall decreasing trend in both depressions and cyclonic systems after the middle of 20th century may have been partly responsible for such behavior (Bhaskar Rao et al., 2001, c.f. Bhutiyani et al., 2010).

Table 5.5 MK trend results with linear slope (cm/decade) over the stations of Indian Himalayas for rainfall (- for decreasing trend and + for increasing trend).

Station	**MK test result**					**Linear slope (cm/decade)**				
	S1	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Srinagar	-	+	+	+	+	-0.91	+3.47	+1.46	+0.63	+4.64
Quazigund	-	+	-	+	+	-0.72	+3.08	-2.33	+2.0.	+2.02
Banihal	+	(+)	+	+	+	+10.65	**+15.76**	-2.75	+3.50	**+27.15**
Jammu	+	(+)	(-)	-	-	+1.54	**+3.03**	-7.37	-0.22	-3.03
Dalhousie	(-)	+	(-)	-	(-)	**-6.70**	+1.34	**-17.78**	**-4.63**	-27.77
Dharamsala	-	+	(-)	-	(-)	-1.34	+1.69	**-14.71**	**-0.86**	**-15.21**
Manali	(-)	-	-	-	-	**-5.15**	-1.56	-0.68	-0.45	-7.84
Bhuntar (A)	-	+	-	+	-	-0.18	+2.13	-1.48	+0.28	+0.76
Mandi	-	+	(-)	-	(-)	-1.06	+0.59	**-8.38**	-0.40	**-9.26**
Bilaspur	+	+	(-)	-	-	+0.43	+2.77	-7.19	+0.35	-3.63
Simla	(-)	(+)	(-)	+	(-)	**-1.02**	+1.25	**-4.38**	+0.10	**-4.05**
Mukhim	+	(+)	(-)	+	-	+1.01	**+7.12**	**-13.90**	+0.11	-5.66
Joshimath	(-)	+	(-)	(-)	(-)	**-2.86**	+2.04	**-8.18**	**-1.48**	**-10.48**
Mussoorie	(-)	+	(-)	+	(-)	**-1.78**	**+1.58**	**-12.31**	+0.20	**-12.30**
Tehri	+	(+)	-	-	-	-1.08	**+5.60**	-5.62	+0.05	-1.10
Dehra Dun	-	+	(-)	+	(-)	-0.79	**+1.69**	**-7.29**	-0.10	**-6.49**
Mukteswar	-	+	(-)	+	-	-0.63	+0.63	**-3.44**	+0.78	-2.67
Nainital	-	+	-	-	(-)	-3.94	+1.37	-13.12	**-11.93**	**-27.62**
Pasighat	+	-	+	+	+	+1.56	+2.67	+13.78	+5.37	+23.38
Ziro	-	+	-	(+)	-	-0.92	+4.35	-9.54	**+5.28**	-0.83
Gangtok	-	-	+	-	-	-1.78	**-9.11**	+0.77	+0.12	-9.99
Kalimpong	+	-	-	-	-	+0.48	+0.25	-1.32	+0.42	-0.16
Darjeeling	+	(-)	-	+	-	+0.04	-1.15	-2.57	-0.51	-4.19
No. of significant trend										
-ve trend	05	01	11	01	08	05	01	09	03	08
+ve trend	00	05	00	01	00	00	06	00	01	01
Total No. of trend	05	06	11	02	00	05	07	09	04	09
Regional	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Western Himalayas	-	(+)	(-)	+	(-)	-0.02	**-0.04**	-0.04	+0.02	-0.02
Central Himalayas	+	+	(-)	-	(-)	-0.01	+0.03	**-0.05**	-0.01	**-0.04**
Eastern Himalayas	(+)	+	+	+	+	+0.03	+0.03	+0.01	+0.02	+0.02
All India Himalayas	+	(+)	(-)	+	-	-0.001	**+0.03**	**-0.03**	+0.01	-0.02

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual; Bracketed term indicate significant trend at 10% confidence level

Bracketed signs and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

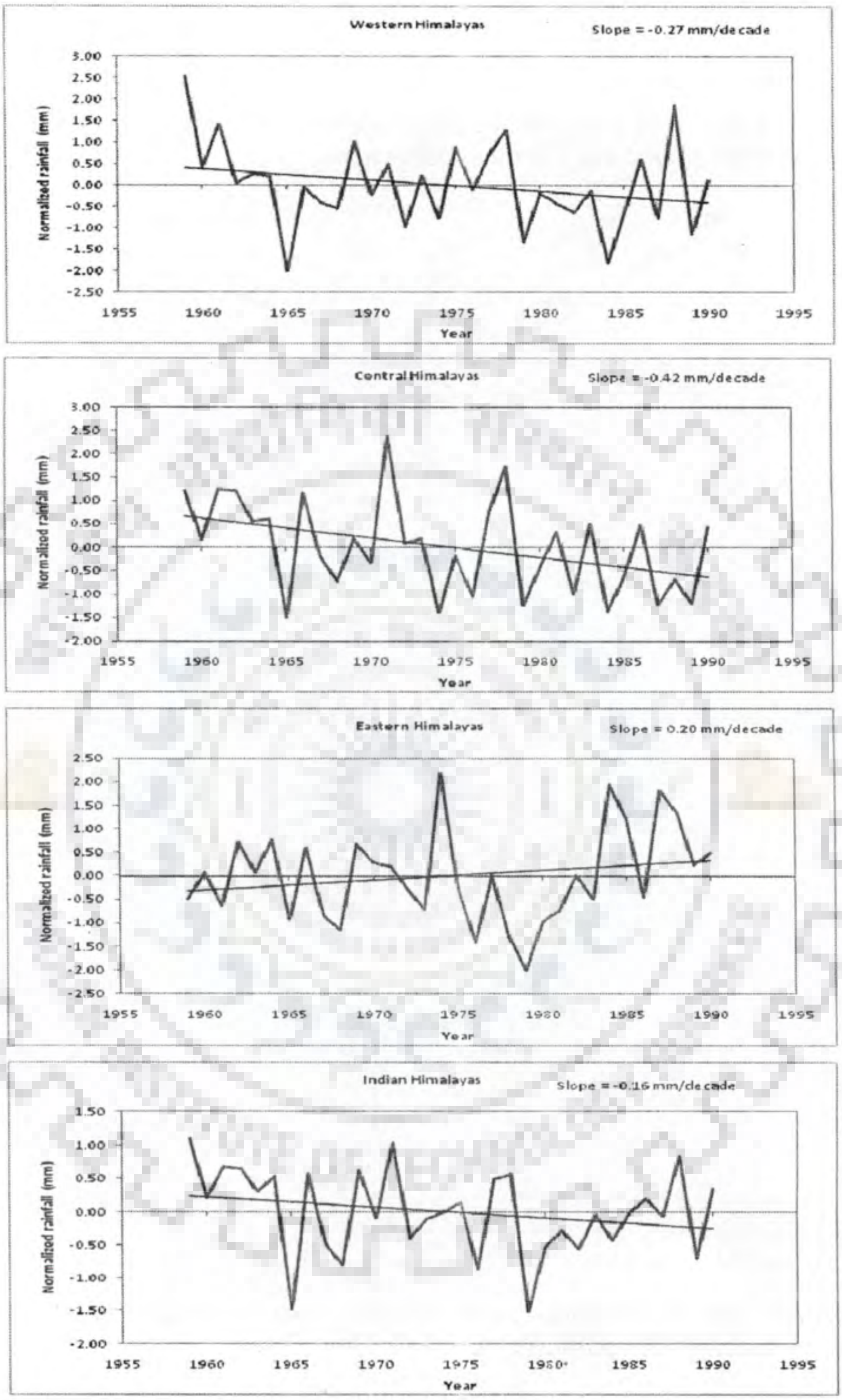

Fig. 5.5 Annual temporal variation of normalized rainfall and fitted linear slope line in Indian Himalayas

Table 5.6 MK trend results and linear slope (cm/decade) for gridded rainfall of Indian Himalayas (- for decreasing trend and + for increasing trend).

Series No.	Grid Location	MK test result					Linear slope (cm/decade)				
		S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
1.	27.5N-88.5E	+	+	-	+	+	+0.20	+1.77	+3.10	+0.06	+5.46
2.	27.5N-89.5E	(+)	+	+	+	+	+0.35	+2.01	+8.35	+0.05	**+7.70**
3.	27.5N-90.5E	+	-	-	+	-	+0.25	-1.26	+0.36	+0.31	-0.12
4.	27.5N-91.5E	+	-	-	+	-	+0.11	-0.99	-0.47	+0.45	-0.79
5.	27.5N-92.5E	+	-	+	+	+	+0.22	-1.0	+1.20	+0.50	+1.02
6.	27.5N-93.5E	+	(-)	+	-	-	+0.24	-2.49	+3.18	-0.56	+0.51
7.	28.5N-93.5E	-	-	+	-	+	-0.01	-2.54	+3.53	-1.03	+0.12
8.	28.5N-94.5E	-	-	+	-	+	-0.34	-1.61	+4.24	-1.24	+1.25
9.	28.5N-95.5E	-	-	+	-	+	-0.39	-0.75	+6.44	-1.23	+4.34
10	28.5N-96.5E	-	-	+	-	+	-0.40	-0.66	+6.12	-1.20	+4.13
11	29.5N-78.5E	-	-	-	(-)	(-)	-0.39	-0.01	**-6.24**	-1.69	**-8.21**
12	29.5N-79.5E	+	+	-	(-)	-	+0.65	+0.86	-1.09	-2.35	**-1.90**
13	29.5N-80.5E	+	(+)	+	(-)	+	+0.21	**+2.86**	+6.22	-2.60	**+6.80**
14	29.5N-95.5E	-	-	+	-	+	-0.39	-0.60	+6.48	-1.20	+4.56
15	30.5N-77.5E	-	+	-	(-)	(-)	-0.92	+0.22	**-10.67**	-1.64	**-13.1**
16	30.5N-78.5E	-	(+)	(-)	(-)	(-)	-0.30	+1.81	**-7.96**	-1.58	**-8.00**
17	30.5N-79.5E	-	(+)	(-)	(-)	(-)	-1.05	+1.24	**-5.50**	-2.20	**-7.90**
18	31.5N-76.5E	+	(+)	-	-	-	-0.03	**+1.13**	-3.22	-1.19	-3.38
19	31.5N-77.5E	-	+	-	-	-	-2.52	+0.90	-0.86	-0.74	-3.33
20	31.5N-78.5E	-	+	(+)	-	+	-3.38	+0.60	**+9.68**	-0.59	**+6.14**
21	32.5N-75.5E	-	+	(-)	-	(-)	-0.85	+0.13	**-6.56**	-1.61	**-8.75**
22	32.5N-76.5E	+	+	(-)	-	(-)	+0.03	+1.61	**-16.26**	-1.50	**-16.02**
23	32.5N-77.5E	-	(-)	-	(-)	(-)	-2.31	**-4.43**	+0.12	-2.52	**-9.37**
24	32.5N-78.5E	-	+	(+)	-	(+)	-1.56	+1.29	**+3.61**	-0.59	+2.58
25	32.5N-79.5E	-	+	(+)	-	+	-3.11	+0.97	**+5.26**	-0.38	+2.58
26	33.5N-74.5E	(+)	(+)	-	-	+	**+3.61**	**+5.16**	-7.16	-0.33	+1.29
27	33.5N-75.5E	(+)	(+)	(-)	-	-	**+3.06**	**+5.09**	**-11.80**	-0.67	-4.31
28	33.5N-76.5E	+	-	(-)	-	(-)	-0.11	-0.95	**-7.26**	-1.52	-9.65
29	33.5N-77.5E	-	(-)	-	(-)	(-)	-1.52	**-4.35**	+2.30	-2.38	-6.03
30	33.5N-78.5E	-	(-)	+	(-)	-	-2.01	**-4.87**	+1.65	-2.49	**-7.83**
31	34.5N-74.5E	(+)	(+)	(-)	+	+	**+4.21**	**+5.73**	**-8.10**	-0.16	+1.70
32	34.5N-75.5E	(+)	(+)	(-)	+	+	**+4.02**	**+5.71**	**-8.78**	-0.23	+0.76
33	34.5N-76.5E	(+)	(+)	(+)	-	-	+2.90	**+4.07**	**-10.82**	-0.72	-4.56
34	34.5N-77.5E	+	-	-	-	-	+0.69	-0.15	**-4.26**	-1.55	**-5.31**
35	34.5N-78.5E	-	(-)	-	(-)	-	-0.66	**-2.50**	-1.31	-2.02	**-6.57**
36	34.5N-79.5E	-	(-)	+	(-)	-	-1.61	**-2.23**	+1.07	-1.73	-4.60

Table 5.6 (continued)

37	35.5N-74.5E	(+)	(+)	(-)	+	+	**+3.64**	**+4.96**	**-6.05**	+0.14	+2.70
38	35.5N-75.5E	(+)	(+)	(-)	+	+	**+3.63**	**+5.27**	**-7.42**	-0.02	+1.45
39	35.5N-76.5E	(+)	(+)	(-)	-	-	**+3.26**	**+4.67**	**-9.12**	-0.37	-1.56
40	35.5N-77.5E	+	(+)	(-)	-	-	+1.97	+2.26	**-6.69**	-0.96	-3.43
41	35.5N-78.5E	+	-	-	-	-	+0.65	-0.12	**-4.00**	-1.49	**-5.00**
42	35.5N-79.5E	+	-	-	-	-	-0.47	-1.18	-1.46	-1.61	-4.80
43	36.5N-73.5E	(+)	(+)	-	+	+	**+1.53**	**+2.46**	**-3.36**	+0.36	+0.99
44	36.5N-74.5E	(+)	(+)	(-)	+	+	**+2.59**	**+3.71**	**-4.70**	+0.25	+1.85
45	36.5N-75.5E	(+)	(+)	(-)	+	+	**+3.11**	**+4.49**	**-6.06**	+0.11	+1.65
No. of significant trend											
-ve trend		00	06	14	11	09	00	05	21	00	13
+ve trend		12	16	04	00	01	10	13	03	00	02
Total No. of trend		12	22	18	11	10	10	18	24	00	15

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual; Bracketed term indicate significant trend at 10% confidence level

Bracketed signs and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

Table 5.7 MK trend results and linear slope (rainy days/decade) over the stations of Indian Himalayas for number of rainy days (- for decreasing trend and + for increasing trend).

Station	**MK test result**					**Linear slope (rainy days/decade)**				
	S1	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Srinagar	+	+	+	+	+	-0.20	+0.70	+0.60	+0.60	+1.80
Quazigund	+	(+)	-	+	(+)	+1.60	**+5.10**	-1.10	+1.80	**+7.50**
Banihal	(+)	(+)	-	+	(+)	+2.60	+6.40	-0.70	+2.10	**+10.50**
Jammu	+	(+)	-	-	+	+0.30	+1.40	+0.40	-0.01	+2.10
Dalhousie	(-)	-	(-)	-	(-)	**-2.10**	+0.20	**-3.10**	-0.30	**-5.30**
Dharamsala	-	+	-	-	+	-0.50	+0.80	-0.10	+0.02	+0.24
Manali	(-)	+	-	-	(-)	**-1.90**	+0.20	-2.80	-0.40	**-4.90**
Bhuntar (A)	-	+	-	(-)	-	-1.00	+0.13	-0.92	-0.32	-2.10
Mandi	(-)	+	(-)	-	(-)	**-1.20**	+0.01	**-4.24**	-0.42	**-5.81**
Bilaspur	+	(+)	-	-	-	+0.08	**+1.32**	-2.22	-0.06	-0.87
Simla	(-)	+	(-)	+	(-)	**-10.20**	**+12.5**	**-43.8**	+1.0	**-2.65**
Mukhim	-	+	(-)	-	(-)	-0.14	**+2.02**	**-6.50**	-0.66	**-5.25**
Joshimath	-	+	(-)	-	(-)	-0.96	+1.24	**-6.61**	-0.85	**-7.17**
Mussoorie	(-)	+	(-)	+	(-)	**-0.92**	+0.50	**-2.54**	+0.16	**+2.82**
Tehri	+	(+)	-	-	(-)	+0.76	**+3.80**	-1.20	-0.37	+3.00
Dehra Dun	-	+	(-)	+	-	-0.34	+0.56	**-1.50**	+0.15	-1.12
Mukteswar	-	+	(-)	+	(-)	-0.44	+0.23	**-2.36**	-0.00	**-2.58**
Nainital	-	+	(-)	-	(-)	-1.03	+1.36	**-4.31**	-1.11	**-5.10**
Pasighat	+	+	+	+	(+)	+0.75	+0.69	+1.74	+0.57	**+3.76**
Ziro	-	+	-	(+)	-	-0.64	+1.10	-2.41	**+1.73**	-0.22
Gangtok	+	+	+	-	+	+0.11	+0.11	+0.02	-0.73	-0.48
Kalimpong	-	-	(-)	-	(-)	**-0.31**	-0.74	**-2.83**	-0.14	**-4.02**
Darjeeling	-	(-)	(-)	(+)	(-)	-0.08	**-1.10**	**-1.90**	+0.32	**-2.75**
No. of significant trend										
-ve trend	05	01	11	01	12	06	01	11	00	10
+ve trend	01	05	00	02	03	00	05	00	01	04
Total No. of trend	06	06	11	03	15	06	06	11	01	14
Regional	**S1**	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	S5
Western Himalayas	-	+	(-)	-	-	-0.21	+0.28	**-0.37**	-0.06	-0.30
Central Himalayas	-	+	(-)	(-)	(-)	-0.09	+0.28	**-0.50**	-0.31	**-0.50**
Eastern Himalayas	(+)	+	-	+	+	**+0.53**	+0.31	-0.09	+0.25	+0.24
All India Himalayas	+	(+)	(-)	-	-	+0.08	**+0.29**	**-0.34**	-0.04	-0.19

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual; Bracketed term indicate significant trend at 10% confidence level

Bracketed signs and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

Table 5.8 MK trend results and linear slope (rainy days/decade) for gridded number of rainy days of Indian Himalayas (- for decreasing trend and + for increasing trend).

Series No.	**Grid Location**	**MK test result**					**Linear slope (rainy days/decade)**				
		S1	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
1.	27.5N-88.5E	+	+	(-)	-	-	+0.3	+0.7	**-1.60**	-0.20	-0.80
2.	27.5N-89.5E	(+)	(+)	-	-	+	**+0.30**	+1.20	+0.10	-0.00	+0.10
3.	27.5N-90.5E	+	-	+	-	+	+0.10	-0.10	+1.10	-0.10	+0.90
4.	27.5N-91.5E	+	-	(+)	-	+	+0.10	+0.10	**+1.50**	-0.30	+1.40
5.	27.5N-92.5E	+	+	(+)	+	+	+0.00	+0.20	**+1.60**	+0.00	+1.80
6.	27.5N-93.5E	-	-	(+)	-	+	-0.10	-0.30	**+1.10**	-0.50	+0.20
7.	28.5N-93.5E	+	-	+	(-)	+	-0.00	+0.00	**+1.00**	**-0.60**	+0.40
8.	28.5N-94.5E	-	+	(+)	(-)	+	-0.50	+0.50	**+1.40**	**-0.60**	+0.80
9.	28.5N-95.5E	-	+	+	(-)	+	-0.40	+0.20	+0.30	**-0.60**	-0.50
10	28.5N-96.5E	-	+	+	(-)	-	-0.50	+0.30	+0.50	**-0.50**	-0.10
11	29.5N-78.5E	-	+	-	(-)	-	-0.20	+0.40	-0.30	**-0.50**	-0.60
12	29.5N-79.5E	+	+	(-)	(-)	(-)	-0.10	+0.70	**-2.10**	**-0.50**	**-2.00**
13	29.5N-80.5E	+	(+)	-	-	(+)	+0.20	**+2.50**	+0.80	-0.50	+3.00
14	29.5N-95.5E	-	+	+	(-)	-	-0.40	+0.30	+0.40	**-0.50**	-0.20
15	30.5N-77.5E	+	+	-	(-)	-	+0.10	+0.70	-1.00	**-0.50**	-0.70
16	30.5N-78.5E	+	(+)	(-)	(-)	(-)	-0.10	**+1.20**	**-3.80**	**-0.50**	**-3.20**
17	30.5N-79.5E	-	+	(-)	(-)	(-)	-0.40	+0.70	**-2.60**	-0.50	**-2.70**
18	31.5N-76.5E	-	(+)	-	-	-	-0.10	**+1.20**	-0.40	-0.30	+0.40
19	31.5N-77.5E	-	+	-	-	-	-0.40	+0.60	-1.10	-0.40	-1.30
20	31.5N-78.5E	-	+	(+)	-	(+)	-0.80	+0.20	**+5.50**	-0.30	**+4.70**
21	32.5N-75.5E	+	(+)	-	-	-	-0.10	+0.80	-1.00	-0.30	-0.40
22	32.5N-76.5E	-	(+)	-	(-)	-	-0.30	**+1.10**	**-2.20**	-0.40	-1.80
23	32.5N-77.5E	(-)	(-)	(-)	(-)	(-)	**-2.00**	**-2.50**	**-2.80**	**-1.40**	**-8.80**
24	32.5N-78.5E	+	+	(+)	-	(+)	+0.20	+0.60	**+2.90**	-0..20	**+3.30**
25	32.5N-79.5E	-	+	(+)	-	(+)	-0.60	+0.50	**+4.20**	-0.20	**+4.00**
26	33.5N-74.5E	(+)	(+)	+	-	(+)	**+1.80**	**+2.90**	+0.20	+0.00	**+4.90**
27	33.5N-75.5E	+	(+)	(-)	-	-	+1.00	**+2.40**	**-4.60**	-0.20	-1.30
28	33.5N-76.5E	-	(-)	-	-	(-)	-0.80	**-1.30**	**-3.00**	-0.40	**-5.50**
29	33.5N-77.5E	(-)	(-)	(-)	(-)	(-)	**-1.80**	**-3.00**	**-2.70**	**-1.20**	**-8.80**
30	33.5N-78.5E	(-)	(-)	(-)	(-)	(-)	**-2.00**	**-3.10**	**-2.70**	**-1.40**	**-9.20**
31	34.5N-74.5E	(+)	(+)	-	+	(+)	**+2.00**	**+3.00**	**-1.70**	+0.00	**+3.40**
32	34.5N-75.5E	(+)	(+)	-	-	(+)	**+1.80**	**+3.10**	**-2.10**	-0.00	**+2.70**
33	34.5N-76.5E	+	(+)	(-)	-	(-)	+0.60	**+1.00**	**-6.00**	-0.30	**-4.60**
34	34.5N-77.5E	-	(-)	(-)	(-)	(-)	-0.80	-1.10	**-4.10**	**-0.70**	**-6.80**
35	34.5N-78.5E	-	(-)	(-)	(-)	(-)	-1.20	**-1.60**	**-4.10**	**-1.10**	**-7.90**
36	34.5N-79.5E	(-)	(-)	-	(-)	(-)	**-1.40**	**-1.40**	-2.00	**-1.10**	**-5.90**

Table 5.8 (continued)

37	35.5N-74.5E	(+)	(+)	(-)	+	(+)	**+1.90**	**+3.10**	**-2.30**	+0.10	**+2.80**
38	35.5N-75.5E	(+)	(+)	(-)	-	+	**+1.70**	**+2.80**	**-3.00**	-0.00	+1.50
39	35.5N-76.5E	+	(+)	(-)	-	(-)	+1.80	**+2.10**	**-5.20**	-0.20	**-2.10**
40	35.5N-77.5E	-	-	-	-	(-)	-0.00	-0.10	**-4.20**	-0.50	**-4.70**
41	35.5N-78.5E	-	(-)	(-)	(-)	(-)	-0.80	-1.00	**-3.90**	**-0.70**	**-6.40**
42	35.5N-79.5E	-	(-)	-	(-)	(-)	-1.00	-1.10	**-3.30**	**-0.80**	**-6.20**
43	36.5N-73.5E	(+)	(+)	(-)	+	(+)	**+1.30**	**+2.20**	**-1.90**	+0.20	**+1.80**
44	36.5N-74.5E	(+)	(+)	(-)	+	+	**+1.60**	**+2.70**	**-2.30**	+0.20	**+2.20**
45	36.5N-75.5E	(+)	(+)	(-)	+	+	**+1.70**	**+2.80**	**-2.60**	+0.10	**+2.10**
No. of significant trend											
-ve trend		04	09	18	19	15	04	07	24	17	14
+ve trend		09	15	07	00	09	09	15	08	00	10
Total No. of trend		13	24	25	19	24	13	22	32	17	24

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual

Bracketed term and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

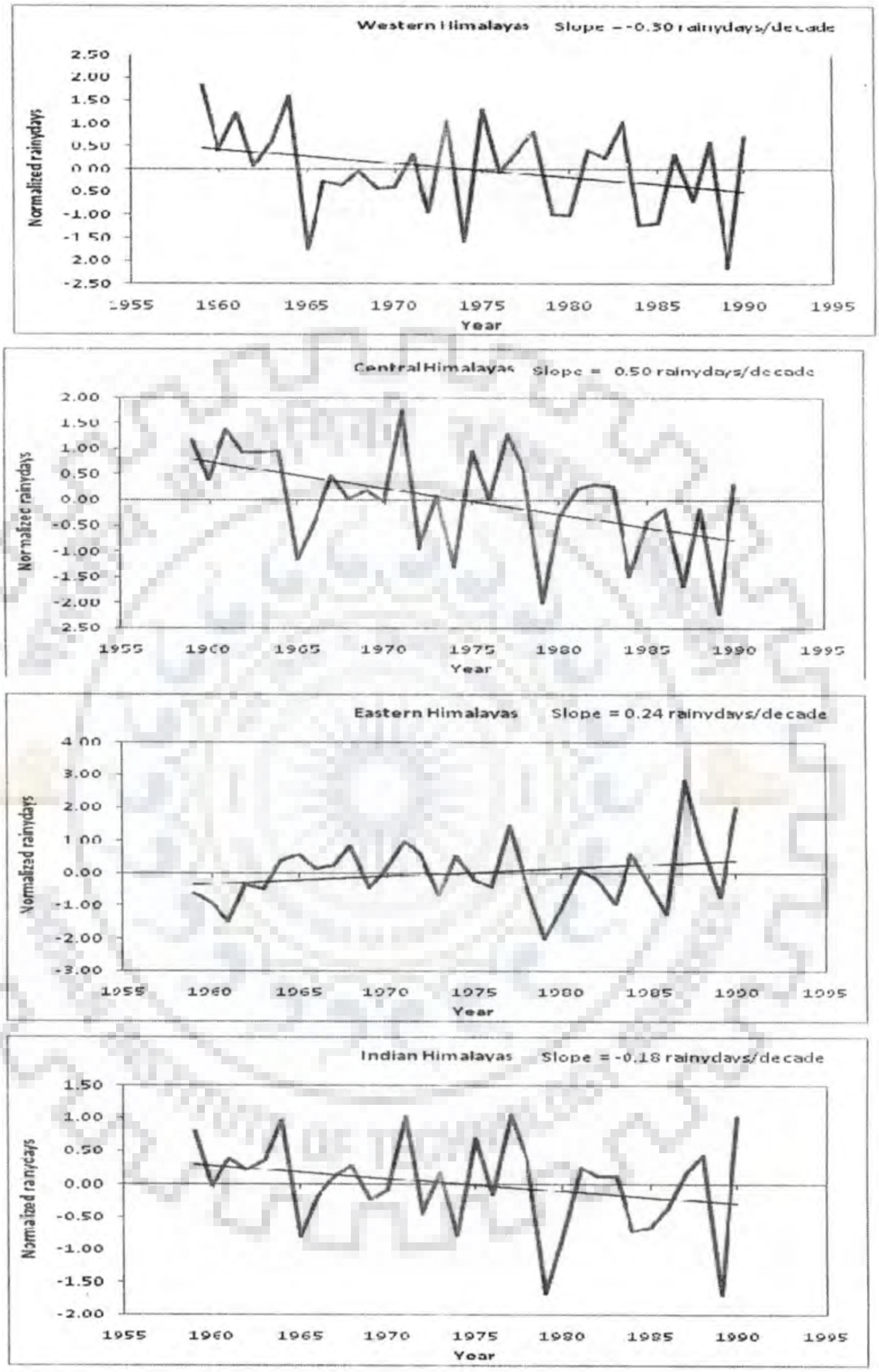

Fig. 5.6 Annual temporal variation of normalized number of rainy days and fitted linear slope line in Indian Himalayas

5.5.1.5 Mean Wind Speed Trend Results

The trends in the wind speed were very surprising. It could be seen from Table 5.9 that out of sixteen stations majority of the stations 15, 12, 15, 13 and 14 have experienced significant decreasing trends at annual, winter, pre-monsoon, monsoon and post-monsoon, respectively in linear regression test and almost equal number by the MK test. Mussorie was the only station which showed increasing trend in all the seasons and was significant in winter season. Fig. 5.7 depicts variation in the mean wind speed over the regions of Indian Himalayas. It can be seen from the figure that the mean wind speed was found to decrease sharply throughout the regions of Indian Himalayas. However, the magnitude was not the same everywhere. The significant trends were observed in all the seasons in central and eastern Himalayas. The maximum decrease of 0.89 m/s/decade was observed in the central Himalayas.

5.5.1.6 Discussion on Wind Speed Trends

The findings of the present study clearly revealed a decreasing trend in the mean wind speed throughout the Indian Himalayas. The annual mean wind speed has decreased by 0.43 km/h/decade over the whole of Indian Himalayas. Bandyopadhyay et al. (2009) also reported sharp decrease in the wind speed throughout the country. Roderick et al. (2007) demonstrated that wind speed across Australia has been declining over the past three decades, and this decline has been the main cause of the observed declines in pan evaporation. Similarly, Jiang et al. (2010) revealed a decrease in the annual mean wind speed since 1956 over China of −0.124 m/s/decade. A sudden increase occurred in 1969. Before and after this point, the mean wind speed decreased steadily by −0.08 and −0.18 m/s/decade, respectively. Seasonal values showed the similar results. The magnitude estimated in the present study was much higher than the estimates obtained by Jiang et al. (2010). The main reason for such a sharp decline may be attributed to global warming, the contrasts of the sea level pressure and near-surface temperature between the Asian continent and the Pacific Ocean have become significantly smaller, and the East Asian trough has shifted eastward and northward, and has weakened as well. Both East Asian winter and summer monsoons are decreasing.

Table 5.9 MK trend results and linear slope (m/s/decade) over the stations of Indian Himalayas for mean wind speed (- for decreasing trend and + for increasing trend).

Station	**MK test result**					**Linear slope (m/s/decade)**				
	S1	**S2**	**S3**	**S4**	**S5**	**S1**	**S2**	**S3**	**S4**	**S5**
Dalhousie	-	(-)	(-)	-	(-)	-0.14	**-0.75**	**-0.54**	**-0.30**	**-0.45**
Dharamsala	(-)	(-)	(-)	(-)	(-)	**-0.27**	**-0.54**	**-0.44**	-0.19	**-0.38**
Bhuntar (A)	(-)	(-)	(-)	(-)	(-)	**-0.70**	**-0.93**	**-1.13**	**-0.73**	**-0.90**
Mandi	(-)	(-)	(-)	(-)	(-)	**-0.20**	**-0.29**	**-0.23**	**-0.13**	**-0.22**
Simla	-	(-)	(-)	(-)	(-)	-0.04	**-0.15**	**-0.30**	**-0.12**	**-0.17**
Joshimath	(-)	(-)	(-)	(-)	(-)	**-0.58**	**-1.13**	**-0.51**	**-0.87**	**-0.75**
Mussoorie	(+)	+	+	+	+	**+0.18**	+0.12	+0.02	+0.08	+0.10
Tehri	(-)	(-)	(-)	(-)	(-)	**-0.18**	**-0.37**	-0.26	**-0.31**	**-0.27**
Dehra Dun	-	(-)	-	(-)	(-)	**-0.08**	**-0.15**	**-0.08**	**-0.17**	**-0.11**
Mukteswar	(-)	(-)	-	(-)	(-)	**-0.50**	**-0.90**	**-0.34**	**-0.65**	**-0.58**
Nainital	-	-	-	(-)	-	-0.20	**-0.49**	**-0.48**	**-0.93**	**-0.49**
Pasighat	(-)	(-)	(-)	(-)	(-)	**-0.91**	**-1.40**	**-0.93**	**-1.15**	**-1.10**
Ziro	(-)	(-)	(-)	(-)	(-)	**-0.30**	**-0.41**	**-0.15**	**-0.32**	**-0.28**
Gangtok	-	-	-	-	-	**-0.35**	**-0.59**	**-0.34**	**-0.40**	**-0.42**
Kalimpong	(-)	(-)	(-)	(-)	(-)	**-1.20**	**-1.28**	**-0.85**	**-1.25**	**-1.11**
Darjeeling	(-)	(-)	(-)	(-)	(-)	**-0.89**	**-1.51**	**-1.30**	**-0.91**	**-1.18**
No. of significant trend										
-ve trend	10	13	11	13	13	12	15	13	14	15
+ve trend	01	00	00	00	00	01	00	00	00	00
Total No. of trend	11	13	11	13	13	13	15	13	14	15
Regional	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Western Himalayas	-	-	(-)	-	(-)	-0.24	-0.30	**-0.57**	-0.31	**-0.43**
Central Himalayas	(-)	(-)	(-)	(-)	(-)	**-0.58**	**-0.57**	**-0.34**	**-0.62**	**-0.59**
Eastern Himalayas	(-)	(-)	(-)	(-)	(-)	**-0.45**	**-0.55**	**-0.34**	**-0.47**	**-0.53**
All India Himalayas	-	-	(-)	-	(-)	-0.24	-0.29	**-0.57**	-0.31	**-0.43**

S1: winter; S2: pre-monsoon; S3: monsoon; S4: post-monsoon; S5: annual; Bracketed term indicate significant trend at 10% confidence level

Bracketed term and Figures in bold face indicates statistically significant increasing (decreasing) trends at 90% significance level

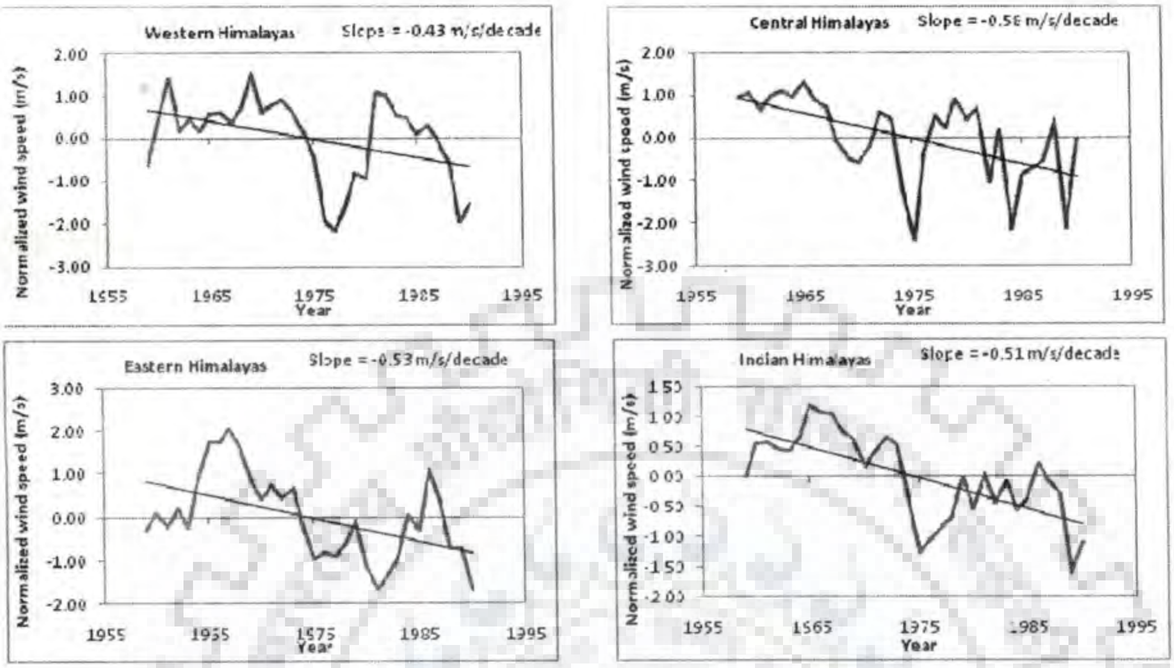

Fig. 5.7 Annual variation in normalized mean wind speed and fitted linear slope line in the Indian Himalayas.

5.5.1.7 Elevation Dependency

Fig. 5.8 shows the altitudinal variation of linear slopes for all the climatological variables. As can be seen at low altitude the mean temperature was maximum and it has decreased up to an altitude of 1800 m and thereafter a sharp increase in the mean temperature. A more pronounced warming of high altitude stations may be revealed for maximum temperature and temperature range. The rate of increase at high altitude was almost twice of the normalized rate observed at low altitude (0.15 versus 0.30 °C/decade) for maximum temperature and five times for temperature range (0.10 versus 0.5 °C/decade), respectively. Similar are the results indicated by Liu and Chen (2000) in the study of climate change in the Tibetan Plateau. In case of precipitation and rainy days the maximum value was found at 300 m and then it decreases up to 2100 m and thereafter again starts increasing with a small magnitude indicating effect of orography and atmospheric circulation pattern in the precipitation. In case of wind speed it was lowest at the low altitude and increases with respect to elevation indicating human induced activities such as construction of buildings or in more precise words urbanization at low altitudes.

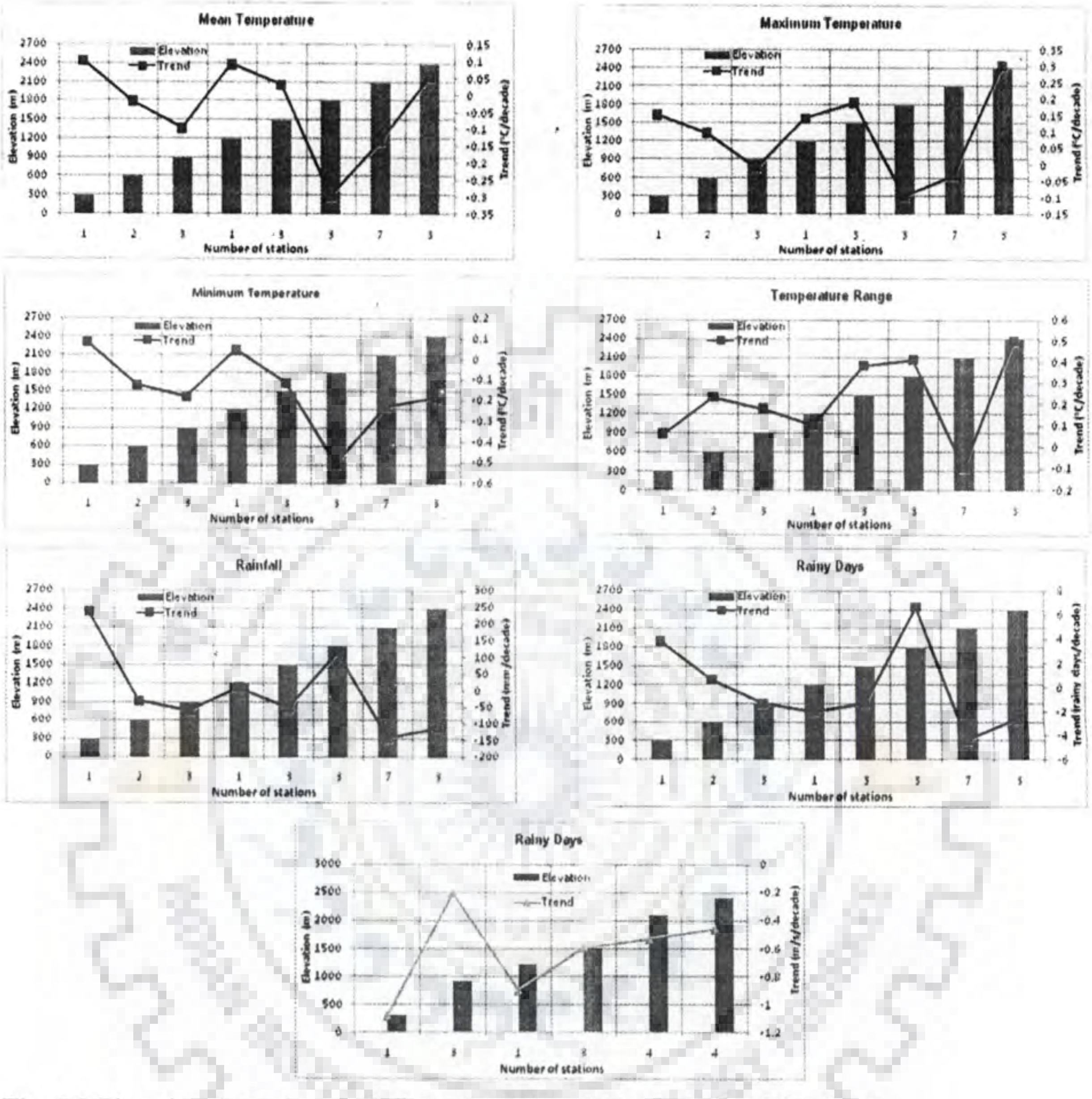

Fig. 5.8 Elevation dependence of climatological variables in Indian Himalayas

5.5.2 Spatial Interpolation of Trends

5.5.2.1 Mean Temperature Trends

Fig. 5.9a-e depicts the interpolated surfaces of mean temperature trends in Indian Himalayas. The annual temperature showed significant decreasing trends in the upper western and lower central Himalayas and; significant trends in eastern and in a small portion of middle of western Himalayas (Fig. 9a).

As can be seen from Fig. 5.9b a cluster of stations shows significant increasing trends in the winter temperature over western part, in a small patch of lower western and central Himalayas and in the entire eastern Himalayas. Whereas significant decreasing trends was noticed in the middle of western Himalayas.

In pre-monsoon temperature significant decreasing trends was observed in the western and central Himalayas, while no trend was found in the entire eastern Himalayas (Fig. 5.9c).

The upper western and entire central Himalayas were predominantly occupied by the significant decreasing trends in monsoon season (Fig. 5.9d). However, a small portion in the middle of western Himalayas depicted significant increasing trend. Interpretations of spatial trends show that the no significant trend exist in the entire eastern Himalayas.

Post-monsoon was the least affected season as indicated by the interpolated trend surfaces. In case of post-monsoon season (Fig. 5.9e) significant decreasing and increasing trends were observed in the upper and middle of western Himalayas while no trend was seen in the central Himalayas. The eastern Himalayas experienced significant warming during the post-monsoon season.

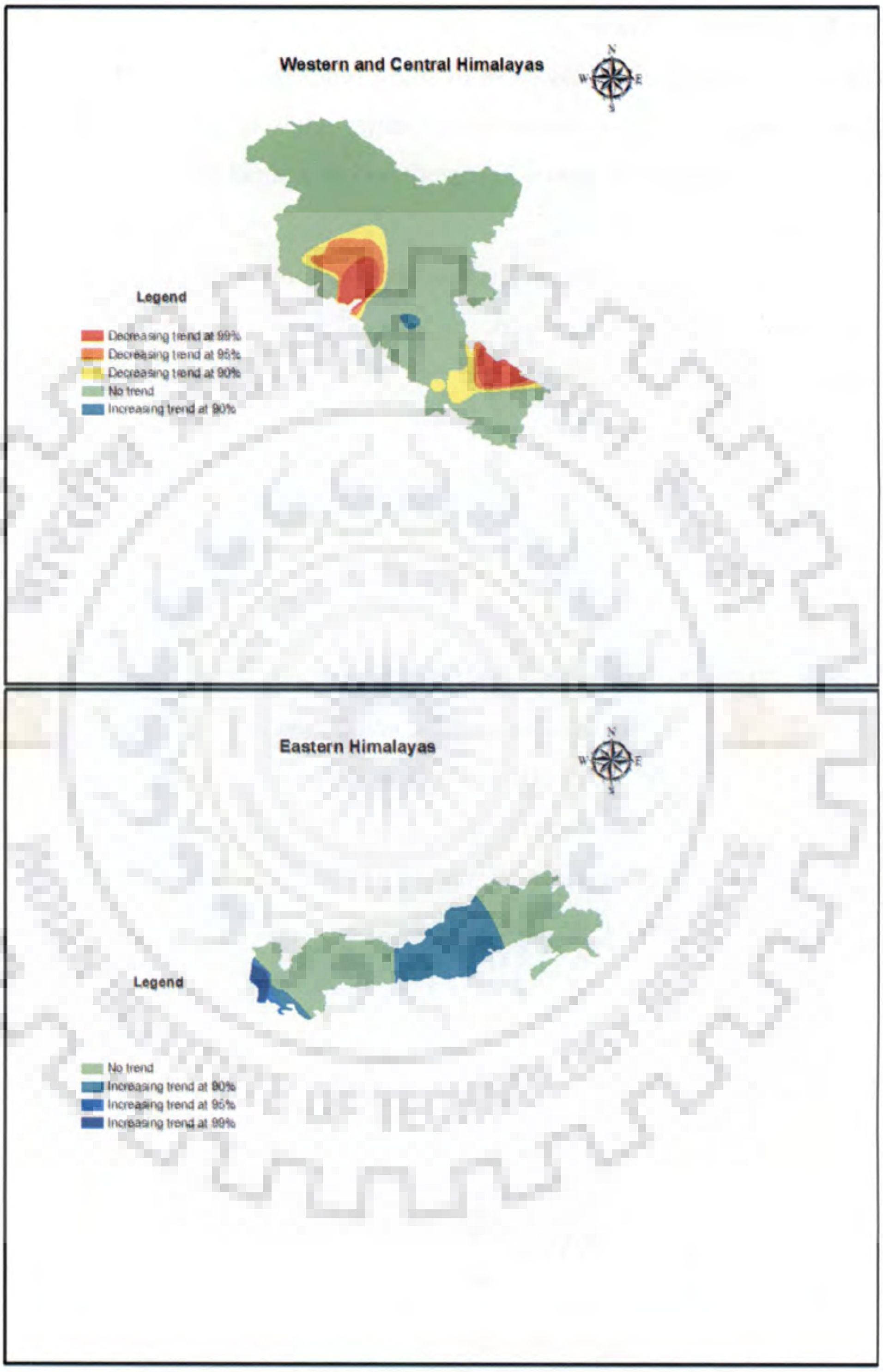

Fig. 5.9a Interpolated surface of MK trend test results for annual mean temperature in western and eastern Himalayas

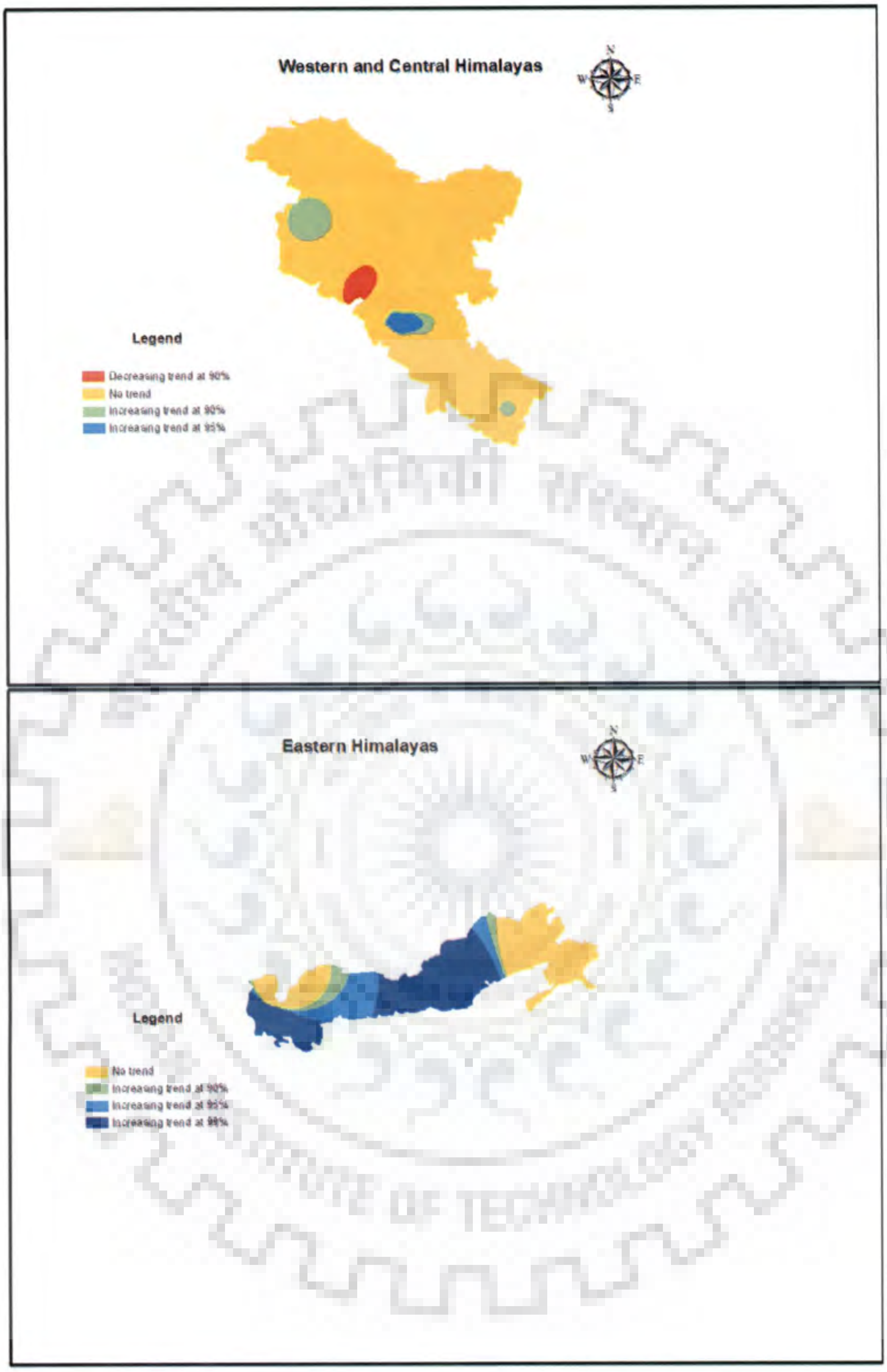

Fig. 5.9b Interpolated surface of MK trend test results for winter mean temperature in western and eastern Himalayas

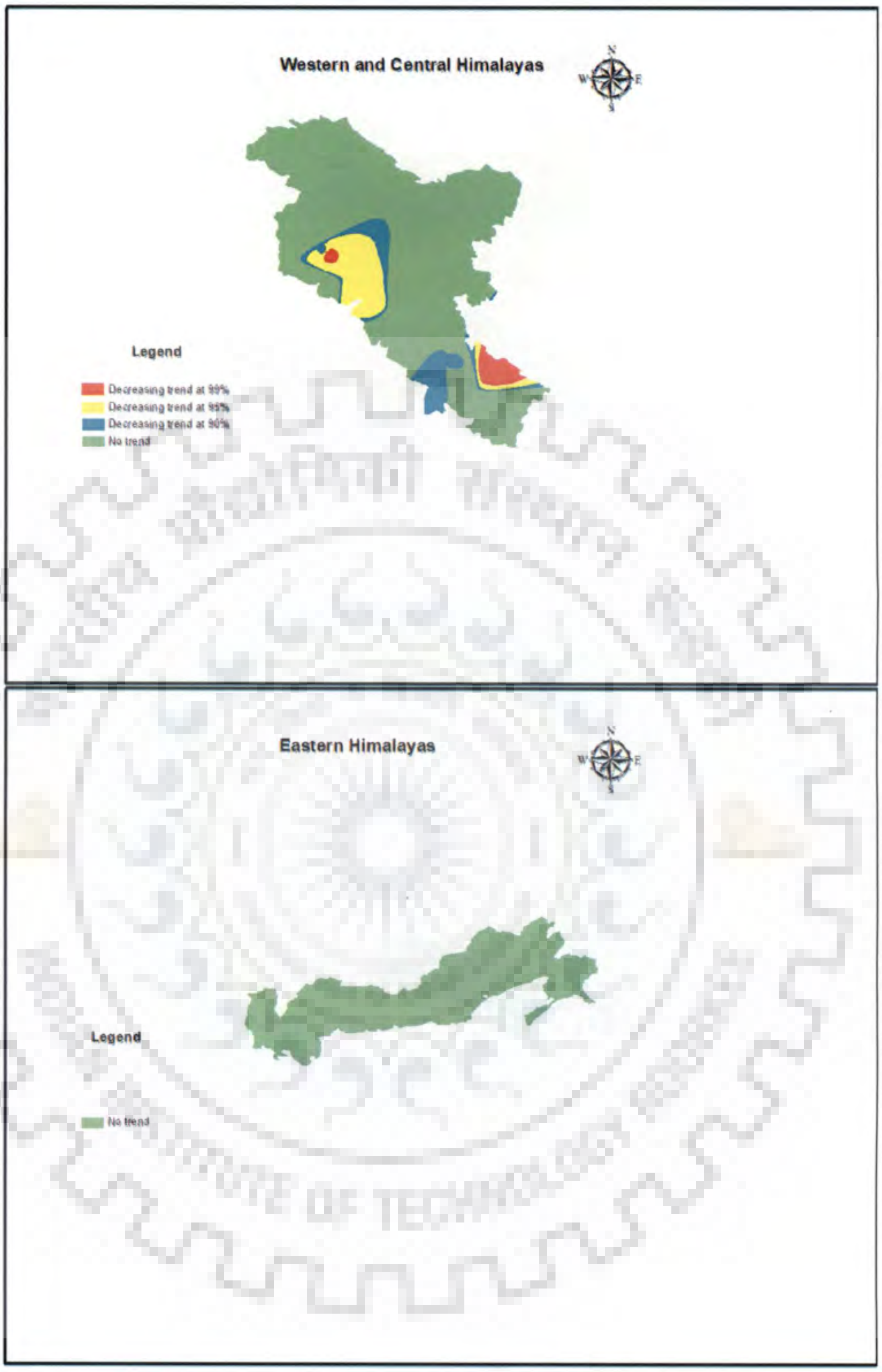

Fig. 5.9c Interpolated surface of MK trend test results for pre-monsoon mean temperature in western and eastern Himalayas

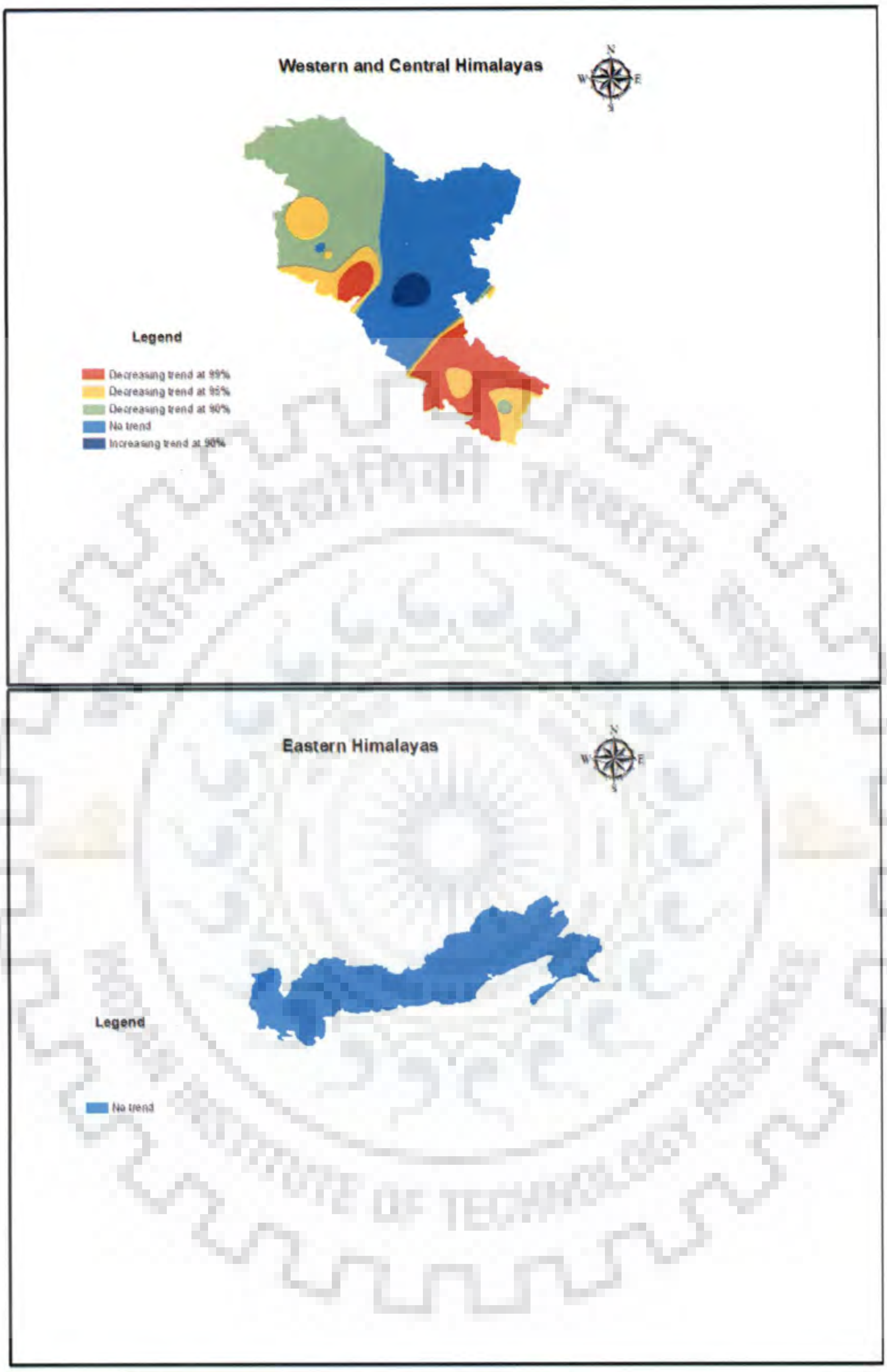

Fig. 5.9d Interpolated surface of MK trend test results for monsoon mean temperature in western and eastern Himalayas

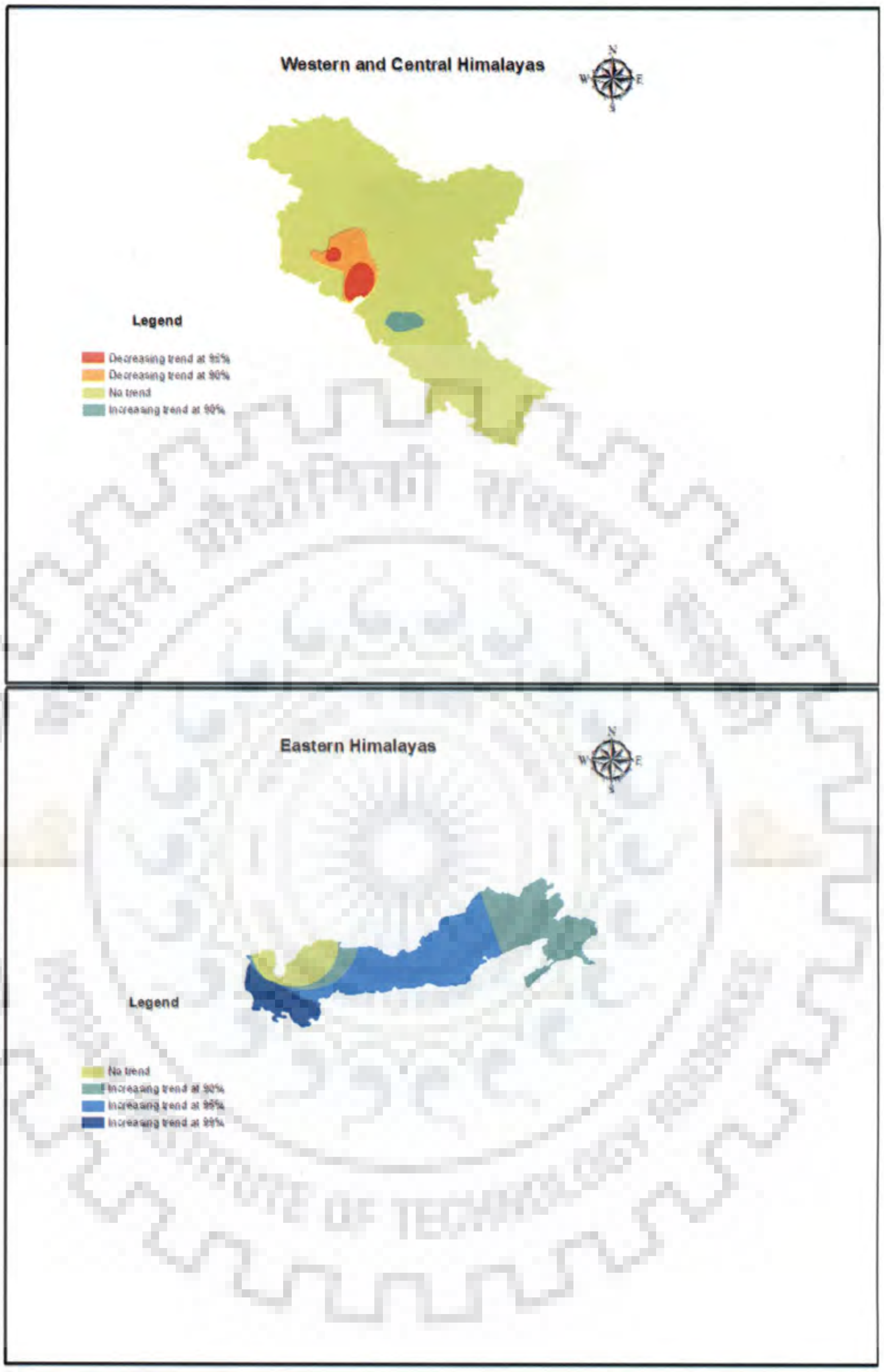

Fig. 5.9e Interpolated surface of MK trend test results for post-monsoon mean temperature in western and eastern Himalayas

5.5.2.2 Rainfall Trends

The spatial patterns of temporal trends in rainfall and number of rainy days are shown in Fig. 5.10a-e and Fig. 5.11a-e, respectively. It may be seen from Fig. 5.10a that the significant decreasing trends dominant the lower part of western Himalayas and central Himalayas while no trends are there in the eastern Himalayas. During winter, clusters of decreasing trends were observed in the middle and lower part of western Himalayas and; upper right of the central Himalayas. No significant trends were found in the eastern Himalayas (Fig. 5.10b). In pre-monsoon season significant increasing and decreasing trends exist. It is clear from Fig 5.10c that the upper part of western Himalayas and central Himalayas show significant increasing trends while lower portion of eastern Himalayas shows decreasing trends. The spatial patterns of monsoon rainfall (Fig. 5.10d) indicated presence of significant decreasing trend over major portion of the western Himalayas and in the entire central Himalayas. The eastern Himalayas exhibited no significant trends. In the post-monsoon (Fig. 5.10e) the upper part of eastern Himalayas shows increasing trends whereas the upper right part of central Himalayas indicates decreasing trends. In rest of the Indian Himalayas no trends were observed.

5.5.2.3 Number of Rainy Days Trends

Fig. 5.11a demonstrates the spatial patterns of annual number of rainy days and shows that the upper part of western and eastern Himalayas experienced increasing trends while significant decreasing trends prevails in the middle of western; middle and lower portion of central and in the lower part of eastern Himalayas. As per Fig. 5.11b during winter season significant decreasing trends were present in the lower western Himalayas and upper central Himalayas. However, no trends were observed in the eastern Himalayas. The spatial patterns of pre-monsoon (Fig. 5.11c) season indicated reverse trends as compared to the winter. The lower part of the eastern Himalayas show decreasing trends whereas increasing trends were observed in the upper and middle part of the western Himalayas and in small portion of middle of central Himalayas. In Fig. 5.11d significant decreasing trends in a small part of middle of western Himalayas and significant increasing trends in the middle of the eastern Himalayas were revealed. After the post monsoon hardly any possibility of occurrence of rainfall can be seen by inspecting Fig. 5.11e. Leaving a small patch of significant decreasing trends in the middle of western Himalayas and a significant increasing trends in the middle of eastern Himalayas no significant trends were found.

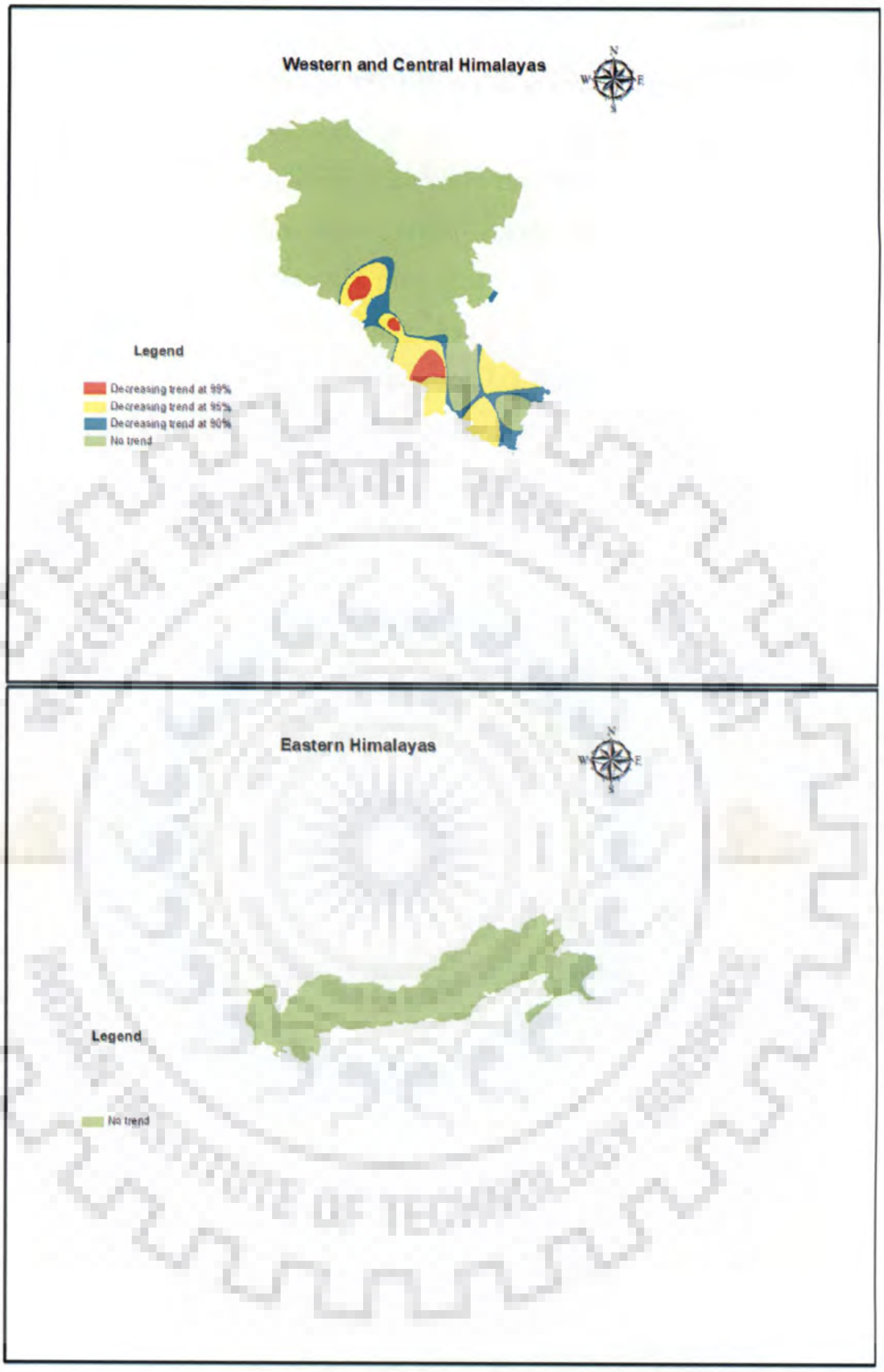

Fig. 5.10a Interpolated surface of MK trend test results for annual rainfall in western and eastern Himalayas

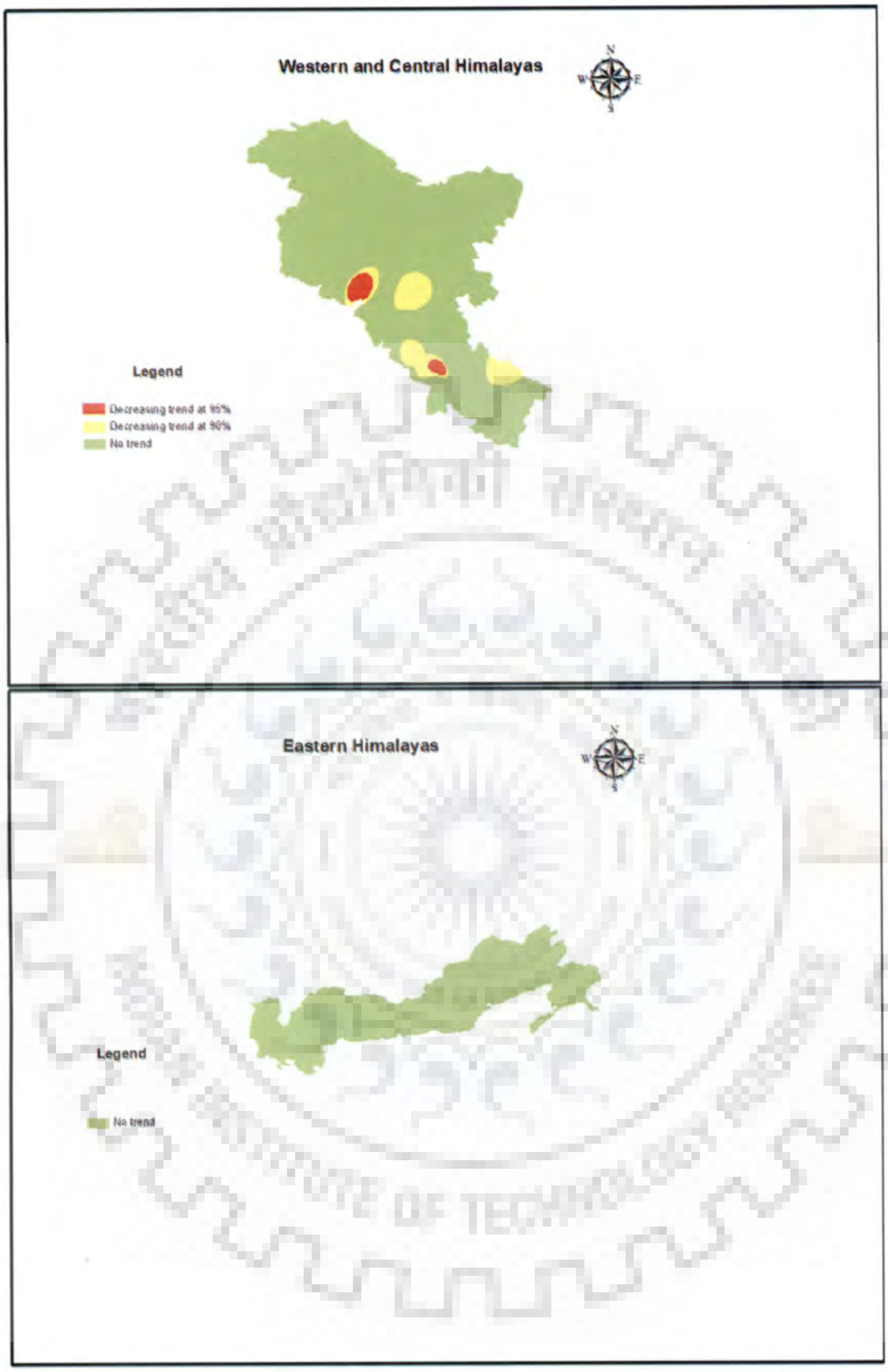

Fig. 5.10b Interpolated surface of MK trend test results for winter rainfall in western and eastern Himalayas

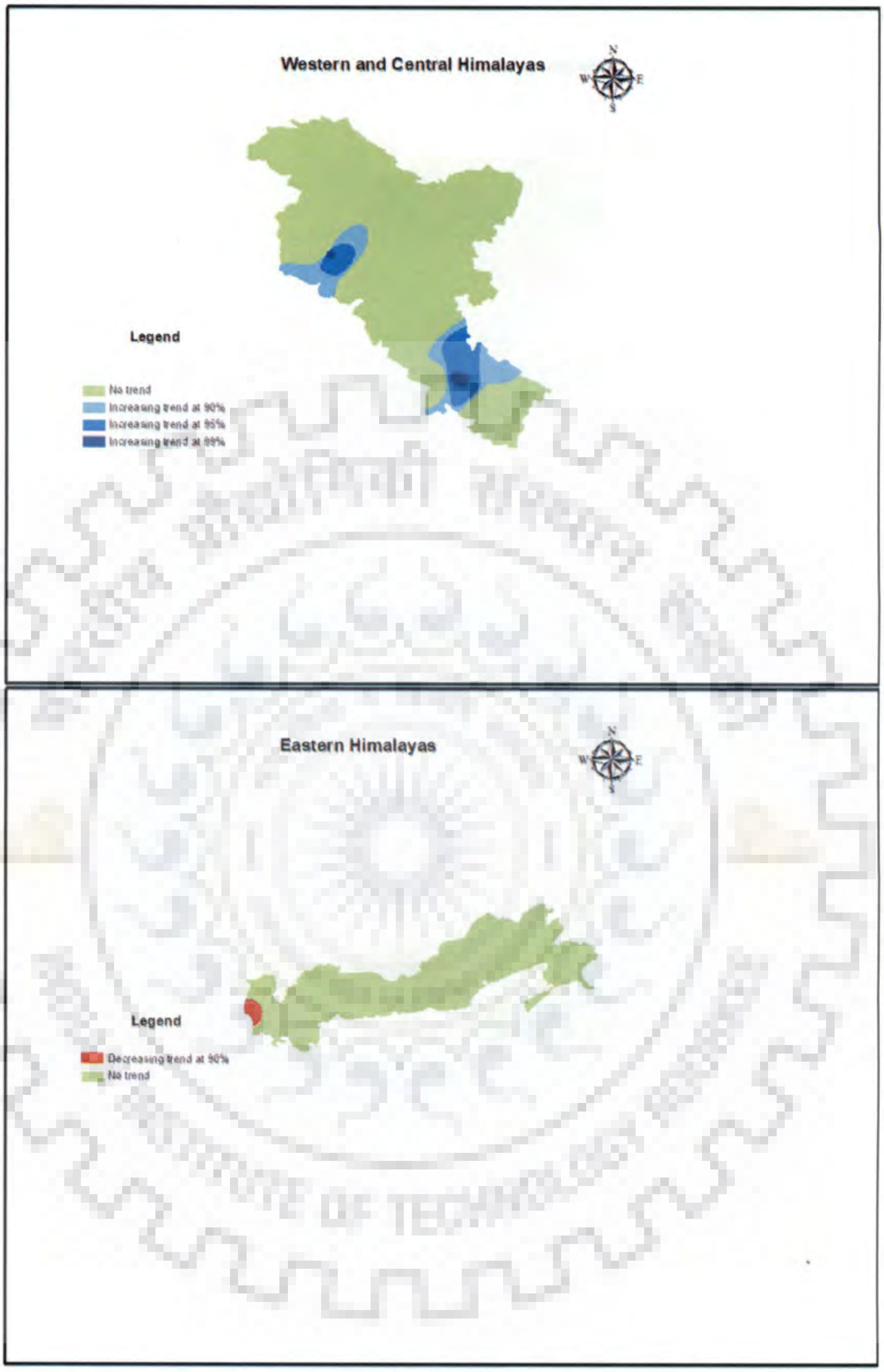

Fig. 5.10c Interpolated surface of MK trend test results for pre-monsoon rainfall in western and eastern Himalayas

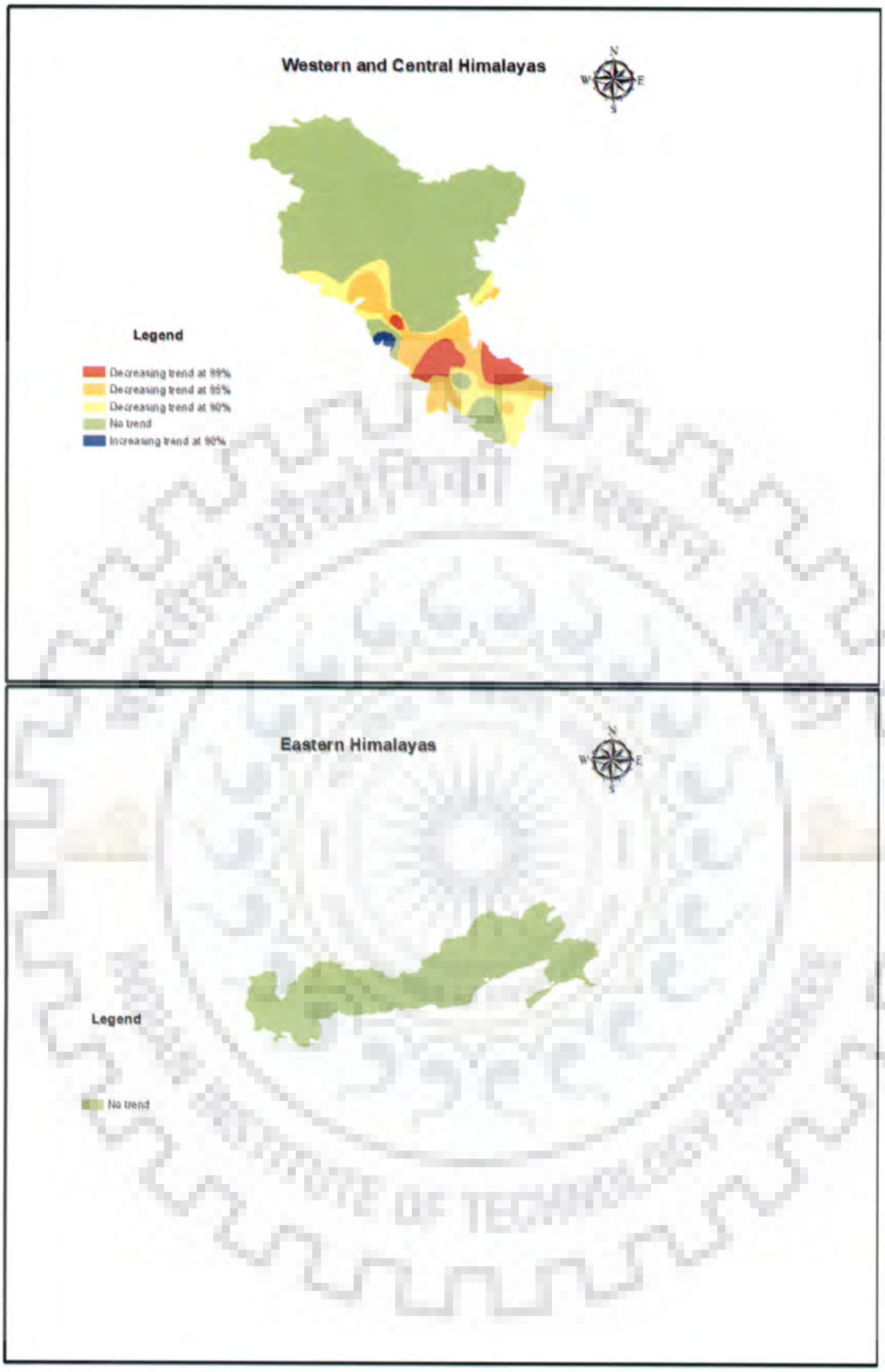

Fig. 5.10d Interpolated surface of MK trend test results for monsoon rainfall in western and eastern Himalayas

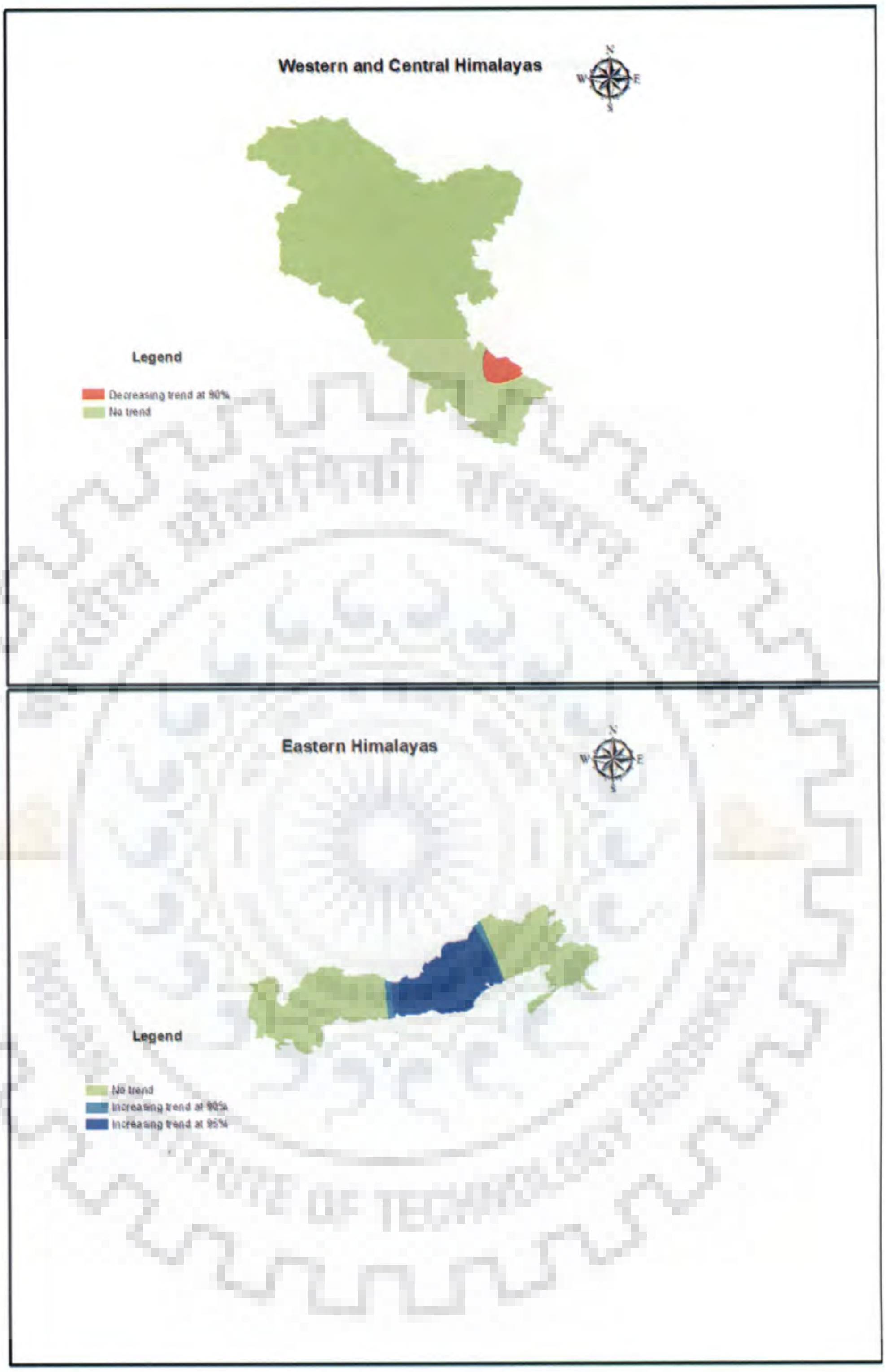

Fig. 5.10e Interpolated surface of MK trend test results for post-monsoon rainfall in western and eastern Himalayas

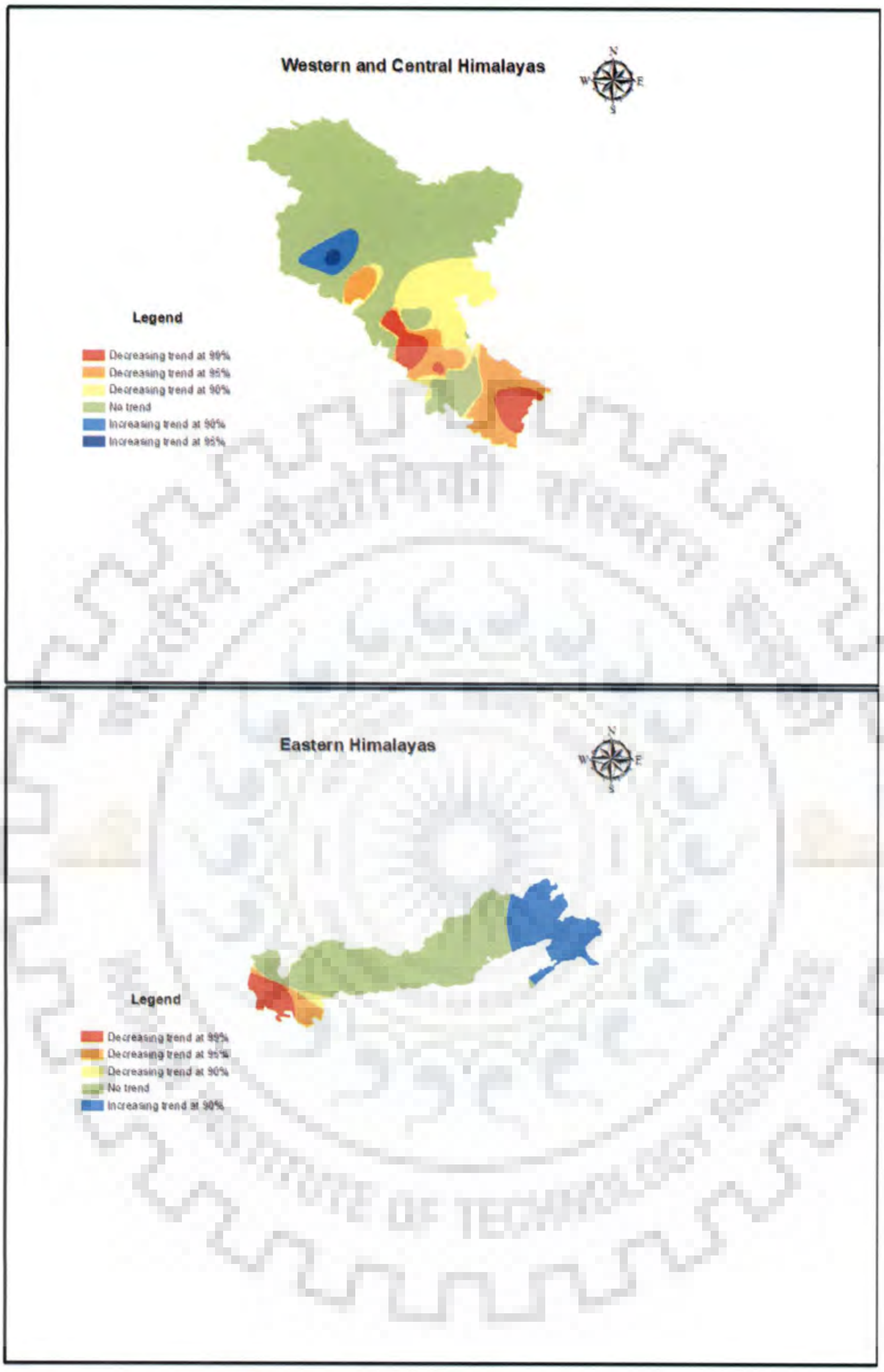

Fig. 5.11a Interpolated surface of MK trend test results for annual number of rainy days in western and eastern Himalayas

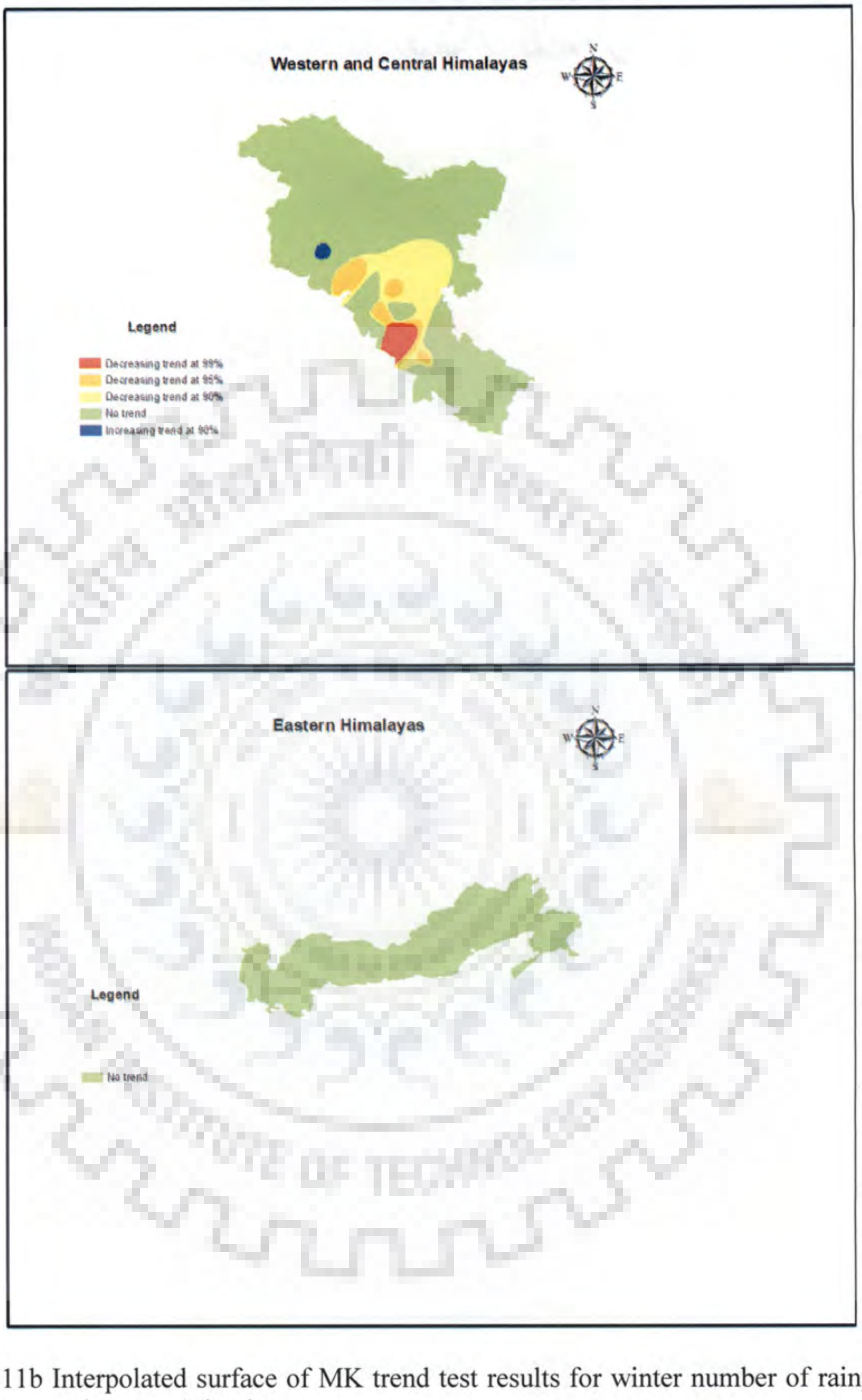

Fig. 5.11b Interpolated surface of MK trend test results for winter number of rainy days in western and eastern Himalayas

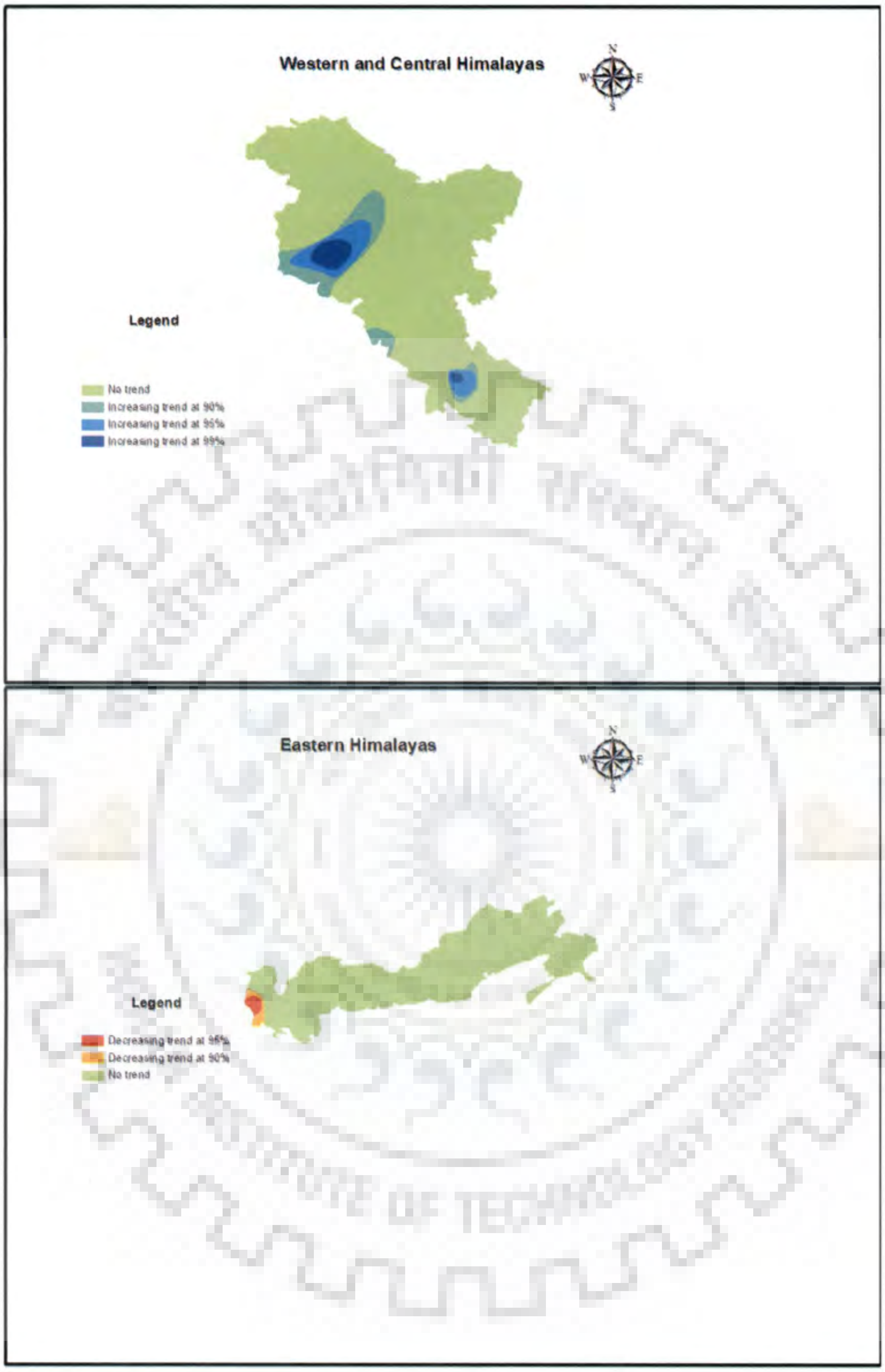

Fig. 5.11c Interpolated surface of MK trend test results for pre-monsoon number of rainy days in western and eastern Himalayas

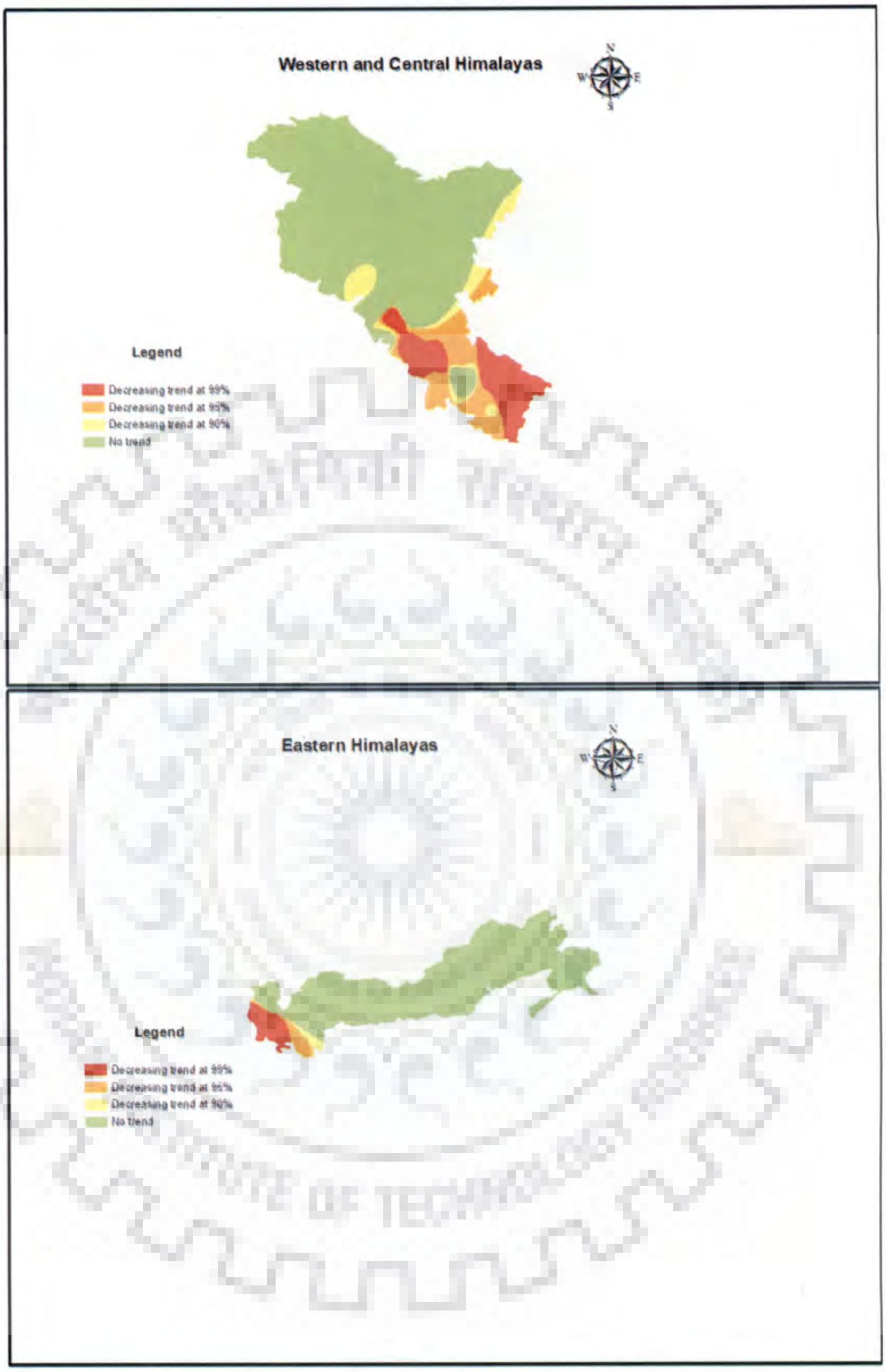

Fig. 5.11d Interpolated surface of MK trend test results for monsoon number of rainy days in western and eastern Himalayas

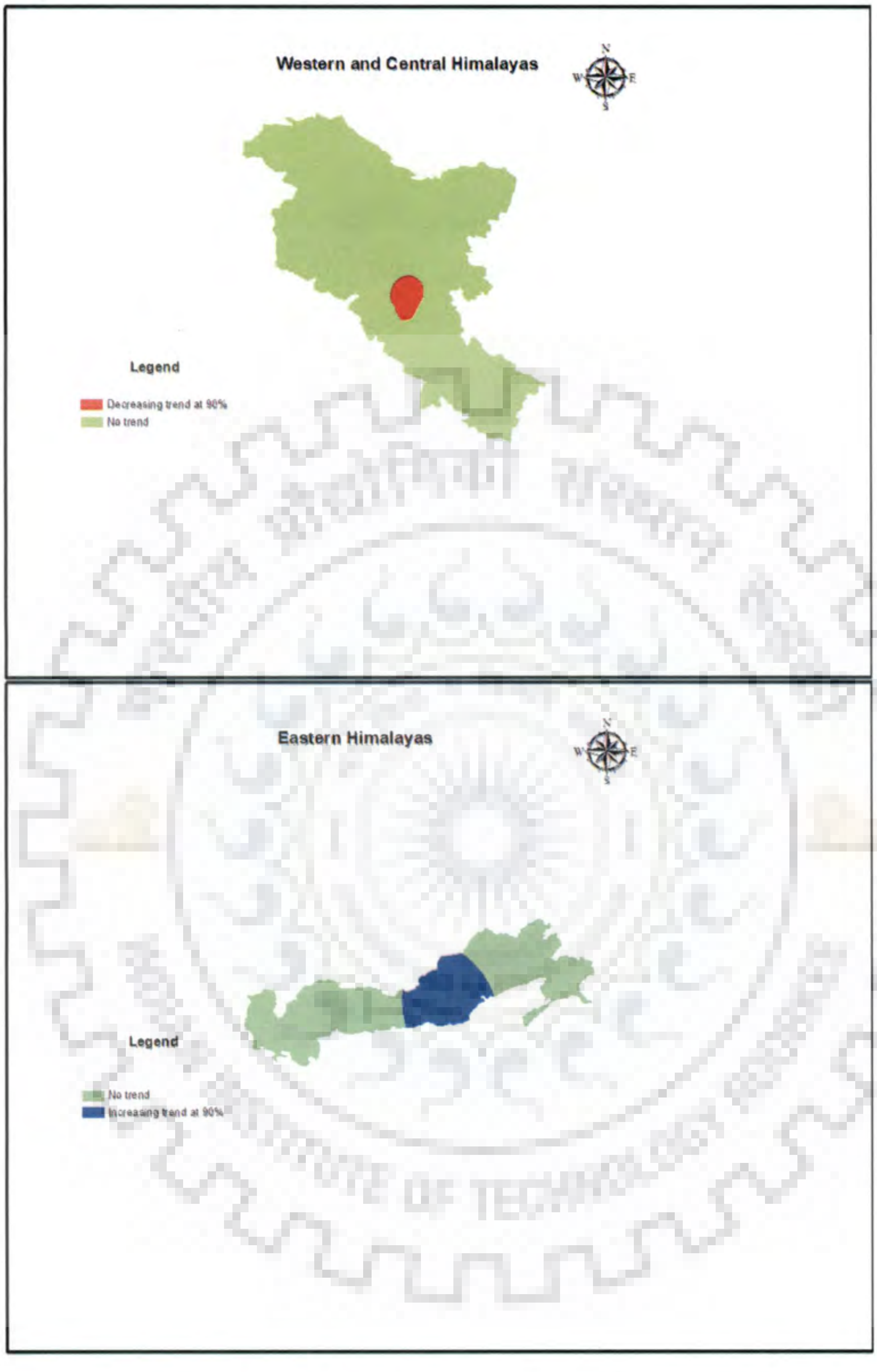

Fig. 5.11e Interpolated surface of MK trend test results for post-monsoon number of rainy days in western and eastern Himalayas.

5.5.2.4 Mean Wind speed

Fig. 5.12a-e shows the spatial interpolation of trend results. It is very clear from Fig. 5.12a that middle of western and lower central Himalayas and entire eastern Himalayas showed significant decreasing trends. In case of winter mean wind speed, the eastern Himalayas exhibited the same pattern of pronounced significant decreasing trends. However, the portion of significant decreasing trends in the western and central Himalayas had reduced (Fig. 5.12b). In Fig. 5.12c the spatial pattern of pre-monsoon mean wind speed trends is shown. It was observed from the figure that the pre-monsoon season depicted the same pattern of decreasing trend as that of annual mean wind speed. The trends during monsoon and post-monsoon experienced the similar significant decreasing trends in the entire eastern, middle of western and upper boundaries of central Himalayas.

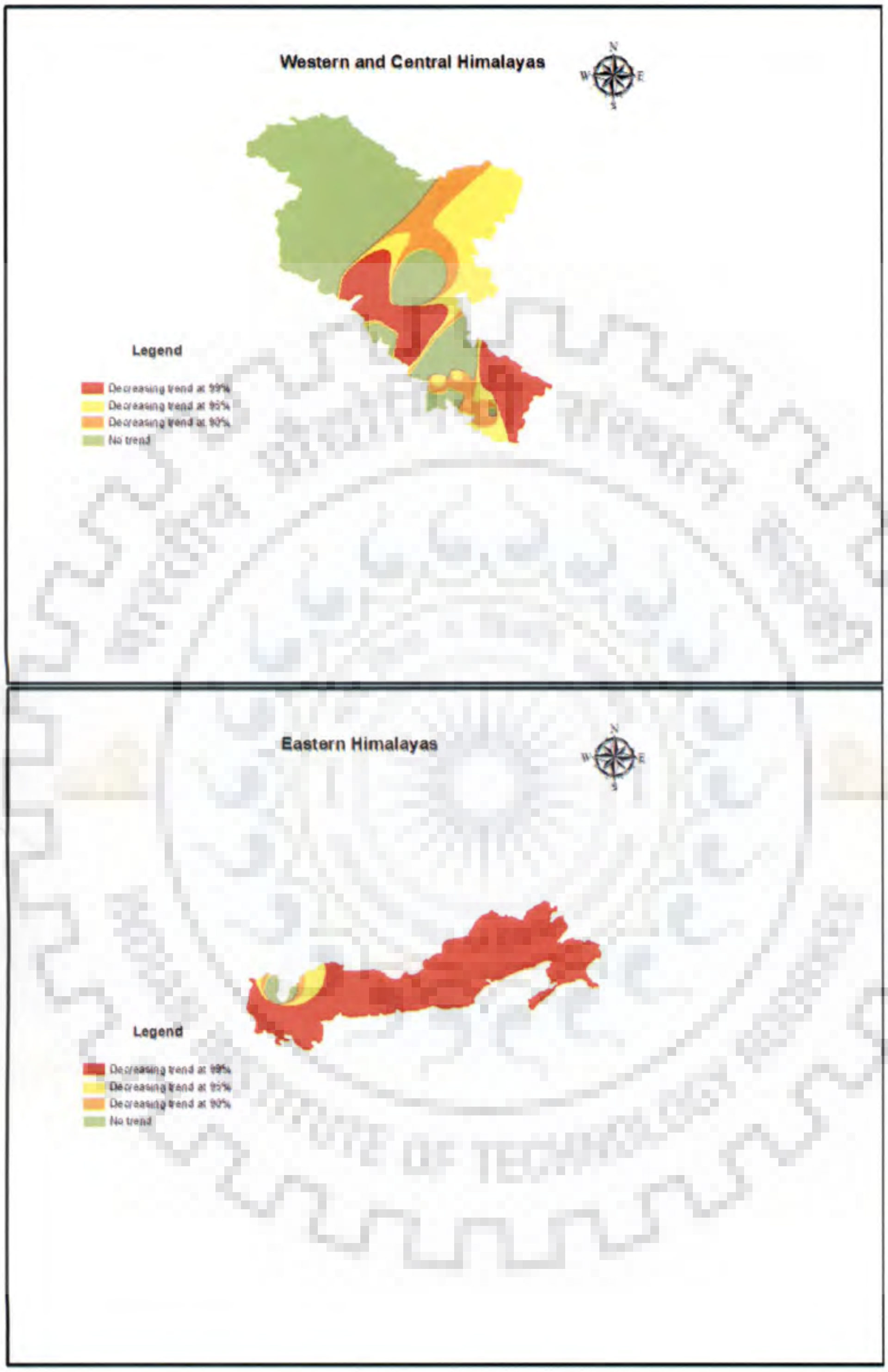

Fig. 5.12a Interpolated surface of MK trend test results for annual mean wind speed in western and eastern Himalayas

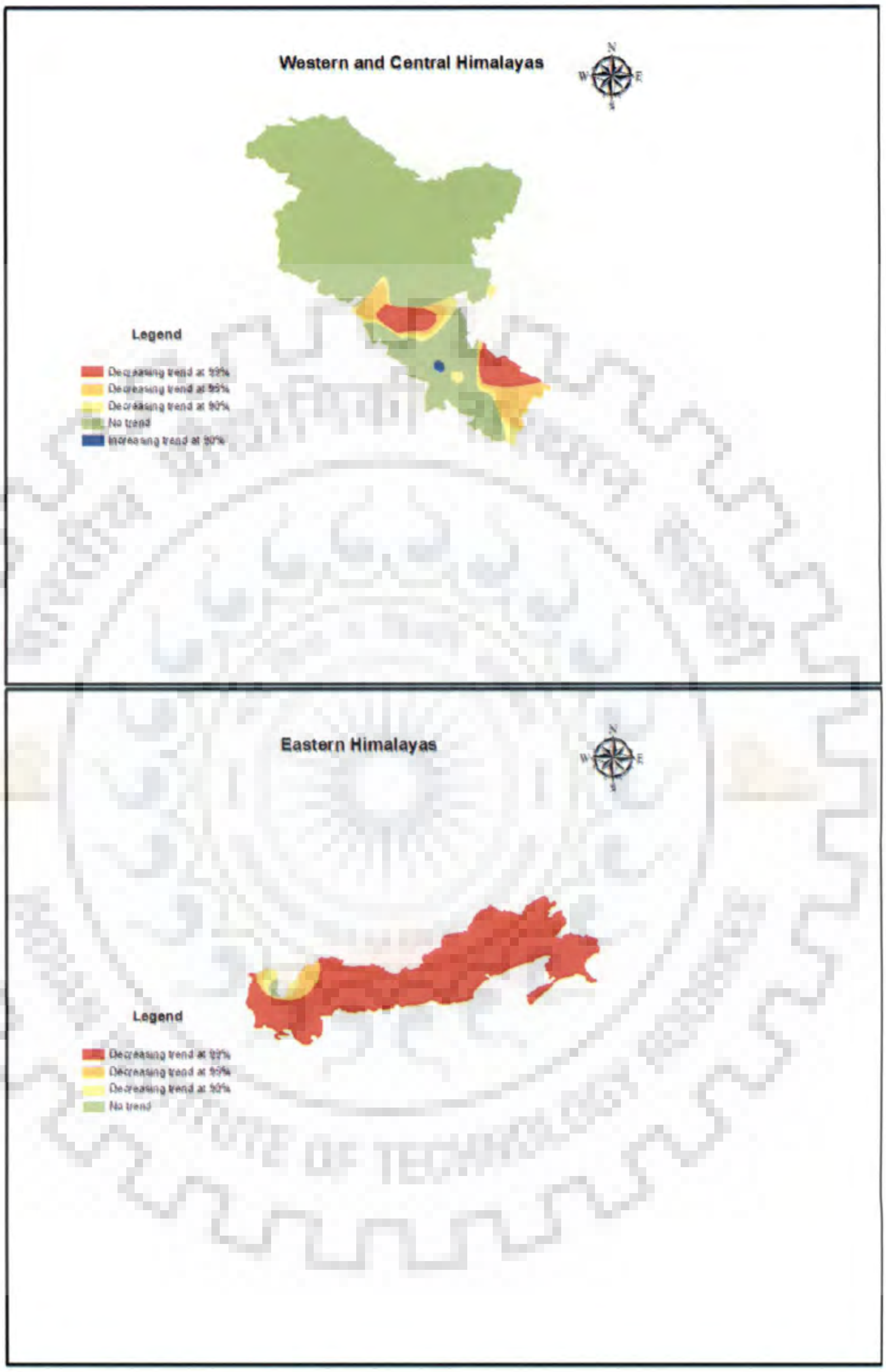

Fig. 5.12b Interpolated surface of MK trend test results for winter mean wind speed in western and eastern Himalayas

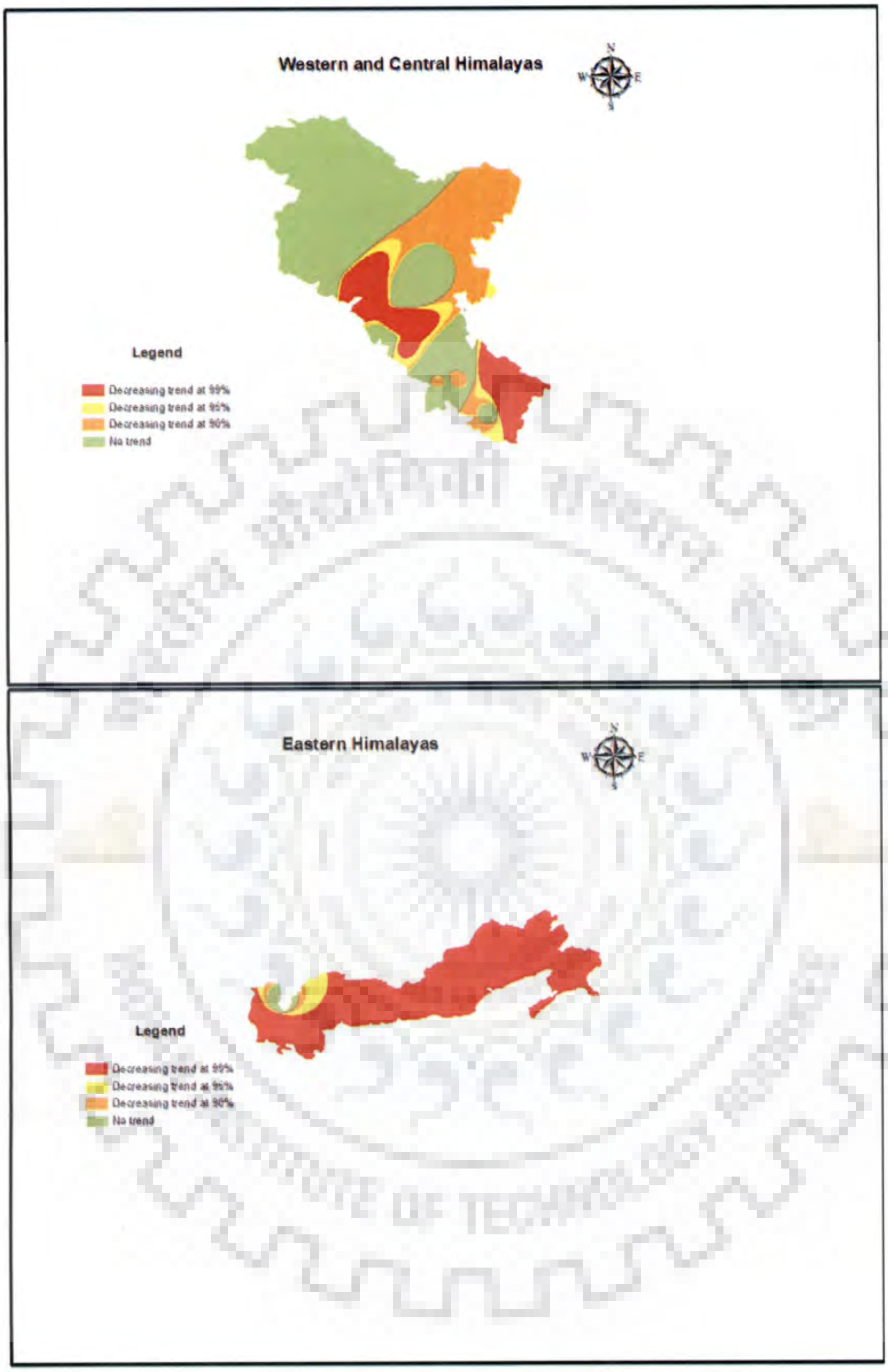

Fig. 5.12c Interpolated surface of MK trend test results for pre-monsoon mean wind speed in western and eastern Himalayas

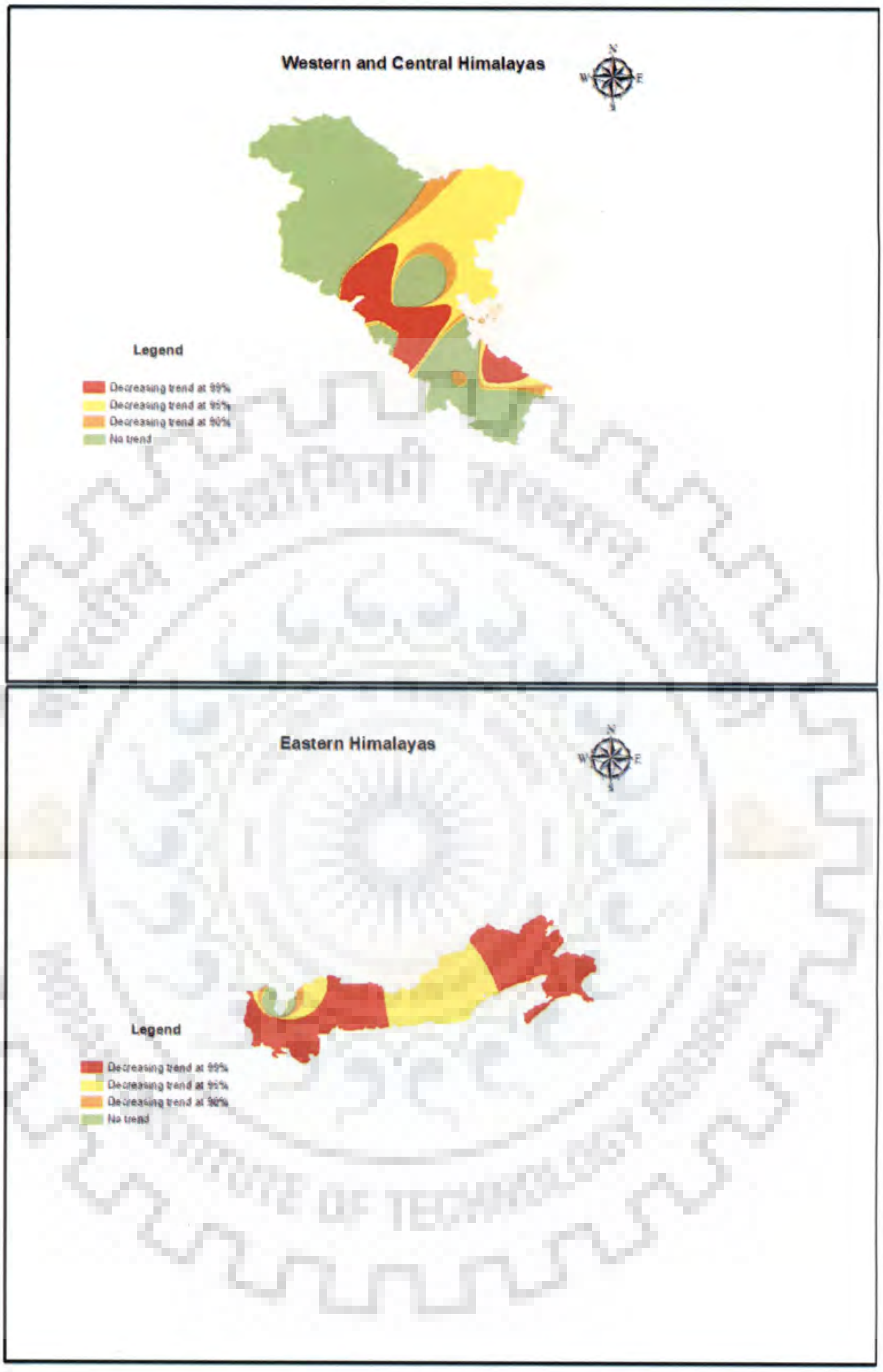

Fig. 5.12d Interpolated surface of MK trend test results for monsoon mean wind speed in western and eastern Himalayas

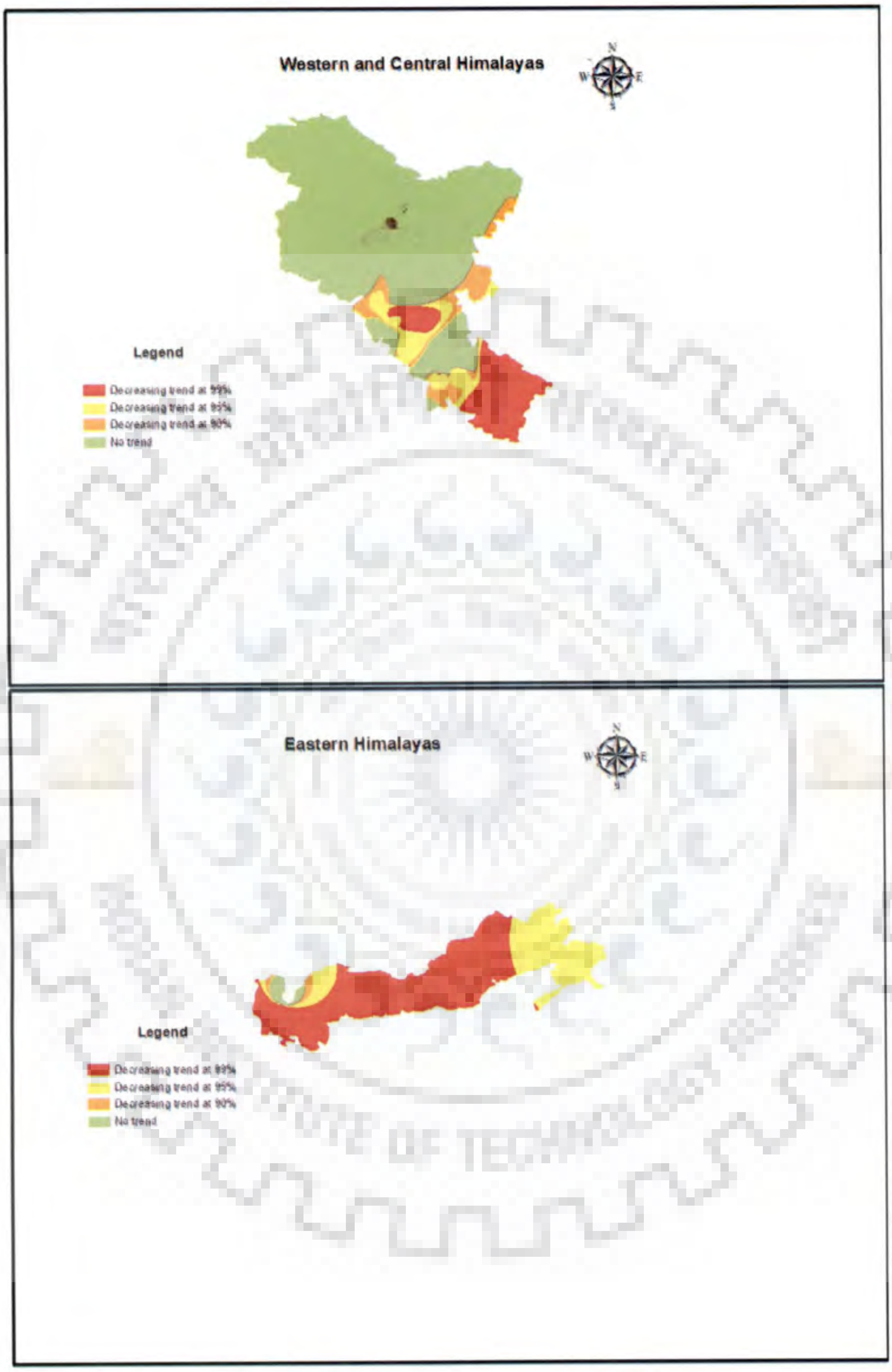

Fig. 5.12e Interpolated surface of MK trend test results for post-monsoon mean wind speed in western and eastern Himalayas

CHAPTER 6

SHORT-RANGE AND LONG-RANGE PERIODICITIES IN THE CLIMATIC PARAMETERS

6.1 INTRODUCTION

In Chapter 5 the trend analysis was performed for the climatic variables of Indian Himalayas and significant trends were observed. Based on both real observational records and statistical models, it is well known that trends in climatological series are rarely linear and cycles are rarely purely sinusoidal waves. Presence of trend indicates the existence of power in one or a few very narrow bands. For Indian continent, periodic component is very important and need to be examined to know the overall behavior of climatic variations. The power spectrum analysis was developed to examine the periodicity in variations of natural events observed in time, such as in climatological and hydrological time series.

In this chapter, the annual time series of climatological variables are subjected to power spectrum analysis to find out the nature of periodicity i.e. short-range or long-range. The results obtained from the analysis are discussed variable wise.

6.2 REVIEW OF LITERATURE

Literature survey pertaining to the chapter has been discussed in Chapter 2 under section 2.3.

6.3 STUDY AREA AND DATA USED

Details of the study area and data considered for this analysis has been presented in Chapter 3 under section 3.2.

6.4 METHODOLOGY

Periodicities in natural time series are usually due to astronomical cycles such as the earth's rotation around the sun. The effect of changing climate may alter the cyclic pattern of the climate variables. Several approaches viz., Maximum Entropy method (MEM), Multi-Taper method (MTM), Wavelet Transform and; Blackman & Tukey method are available to examine presence of periodicity in the time-series. However, in the present analysis the Blackman & Tukey Power spectrum method (WMO, 1966b) was used. The steps involved are described as follows:

6.4.1 Normalisation of Time-Series

The series of climatic variables is normalised and used in the present analysis. A normalized series is obtained as

$$X_{sN(i)} = (X_{s(i)} - \bar{X}_s)/\sigma_s \tag{6.1}$$

where, $X_{sN(i)}$ is the normalized anomaly of the series, X_s is the observed time series for station s during ith year, $\bar{X}_s$ and σ_s are the long-term mean and standard deviation of annual time series.

6.4.2 Computation of the power spectrum

For the computation of power spectrum the method developed by Tukey (1950) and described in WMO (1966) is used. The steps involved in the computation of power spectrum are given as follows:

(i) First, serial correlation (or autocorrelation) coefficients of normalized climatic series are computed for all lags from $L = 0$ to m, where m is the maximum lag equal to about 1/3 of the length of the series N, by using the following formula:

$$r_L = \frac{\sum_{t=1}^{n-L} (x_t - \bar{x}_t)\cdot(x_{t+L} - \bar{x}_{t+L})}{\left[\sum_{t=1}^{n-L} (x_t - \bar{x}_t)^2 \cdot \sum_{t=1}^{n-L} (x_{t+L} - \bar{x}_{t+L})^2\right]^{1/2}} \tag{6.2}$$

(ii) Then the 'raw' spectral estimates, s_k, are computed from r_L using the following relationships:

(a) For the zeroth spectral estimate,

$$\hat{s}_0 = \frac{1}{2m}(r_0 + r_m) + \frac{1}{m}\sum_{L=1}^{m-1} r_L \tag{6.3}$$

(b) For all the intervening $m-1$ spectral estimates, $k = 1, 2, \ldots\ldots, m-1$,

$$\hat{s}_k = \frac{r_0}{m} + \frac{2}{m}\sum_{L=1}^{m-1} r_L \, Cos(\frac{\pi k L}{m}) + \frac{1}{m} r_m (-1)^k \tag{6.4}$$

(c) For the last spectral estimate, this is the shortest wavelength in the spectrum,

$$\hat{s}_m = \frac{1}{2m}[r_0 + (-1)^m r_m] + \frac{1}{m}\sum_{L=1}^{m-1} (-1)^L r_L \tag{6.5}$$

(iii) Finally, the final spectral estimates s_k are then computed by smoothing the 'raw' estimates with a 3-term weighted average. In the smoothing procedure, smoothing equations of the Hanning method of WMO (1966b) are used.

$$s_0 = \frac{1}{2}(\hat{s}_0 + \hat{s}_1) \tag{6.6a}$$

$$s_k = \frac{1}{4}(\hat{s}_{k-1} + 2\,\hat{s}_k + \hat{s}_{k+1}) \tag{6.6b}$$

$$s_m = \frac{1}{4}(\hat{s}_{m-1} + \hat{s}_m) \tag{6.6c}$$

The averaging procedure is performed to derive a constant estimate of the final spectrum in terms of $m+1$ discrete estimates (WMO, 1966b).

6.4.3 Test for Statistical Significance

To test the statistical significance, first a 'null' hypothesis continuum is fitted to the computed spectrum in which the significance of the lag-1 serial correlation (L-1SC) coefficient r_1 of the climatic series is tested by the following equation.

$$(r_1)_t = \frac{-1 \pm t_g\sqrt{N-1}}{N-1} \tag{6.7}$$

where, $t_g = 1.645$ for the 0.10 level of significance (i.e. at 90 percent confidence level).

If L-1SC (i.e. r_1) $< (r_1)_t$ or ($r_1 < 0$) $> (r_1)_t$, it is assumed that series does not contain persistence. In this case, the appropriate null continuum is 'white noise'. In other words, a horizontal straight line, the value of which is everywhere equal to the average of the values of all the $m+1$ 'raw' spectral estimates in the computed spectrum, is taken as the most suitable theoretical approach.

On the other hand, if the computed r_1 is positive and statistically significant, serial correlation coefficients for higher lags i.e. lag-2 and lag-3 are checked to see whether they approximate the exponential relations $r_2 \cong r_1^2$ and $r_3 \cong r_1^3$ (WMO, 1966). If these relations are ensured with the computed serial correlation coefficients, the approximate 'null' continuum is assumed as the simple Markov red noise, whose shape depends on unknown value of the L-1SC coefficient for a population P. Then the continuum can be created by following approximate procedure. By assuming that the sample r_1 is an unbiased estimation of P, various choices of the Harmonic number of *k* between $k = 0$ to m are assessed:

$$S_{c,k} = \overline{s}\left(\frac{1-r_1^2}{1+r_1^2-2r_1 Cos(\frac{\pi k}{m})}\right) \tag{6.8}$$

where, $\overline{s}$ is the average of all $m+1$ 'raw' spectral estimates $\hat{s}_{c,k}$ in the computed spectrum. The resulting values of $s_{c,k}$ may then be plotted superposed on the sample spectrum, and a smoothed curve passed through these values to reach the required null continuum.

If r_1 is statistically significant but a few serial correlation coefficient for higher lags do not show the required exponential relations with r_1, then it is doubtful whether the simple Markov-type persistence is the dominant form of non-randomness in the series of climatic parameters. Under this situation the calculations are performed assuming this as the red noise continuum for r_1.

At this stage of the power spectrum analysis a first choice of the null continuum is made, and this selected continuum is superposed on the studied spectrum. In this case, it would be possible to make an assessment of the spectrum for its consistency with the chosen continuum. Then, the value of each spectral estimate s_k is compared with the local value of the null continuum.

6.4.4 Confidence Limits

The statistic associated with the each spectral estimate is the ratio of the magnitude of the spectral estimate to the local magnitude of the continuum (red noise continuum). Tukey (1950) found that the quantity of this ratio is distributed as Chi-square divided by the degree of freedom. The degree of freedom, v, of each estimate of a computed spectrum is given as follows.

$$v = \frac{2N - m/2}{m} \tag{6.9}$$

where, *N* is the length of series and *m* is the maximum lag.

The ratio of any sample spectral estimate s_k to its local value of the "null" continuum is then compared with critical percentage-point levels of χ^2/v distribution for the proper v value. This comparison produces the required statistical significance level. The χ^2values are obtained from standard statistical books. The confidence limits are derived by multiplying degrees of freedom ν with the value of spectral continuum for each spectral estimate. In the present analysis 90% and 95% confidence limits are used. Finally, periodicity is computed by following relationship:

$$P = \frac{2m}{L}; \quad \text{for } S_k > \nu * S_{c,k} \tag{6.10}$$

where, P is the periodicity (year).

6.5 RESULTS AND DISCUSSION

The power spectrum analysis was performed on annual series of temperature (maximum, minimum, mean and range), rainfall, number of rainy days and wind speed and the parameters wise results are presented and discussed. Since, varying length of the data was used; it was find difficult to prepare a table for the classification of periodicity. The power spectrum works on lag-1 serial correlation coefficient (r_1). The same has been determined and mention in the tables but not discussed as the main interest was determining periodicity in the climatic variables.

6.5.1 Annual Mean Maximum Temperature

The power spectrum results for maximum temperature are given in Table 6.1 and for visual inspection the power spectrum plots are shown in Fig. 6.1. It is evident from table and figures that 11 and 8 year periodicity is present in Mukhim and Manali and; Nainital. Significant medium range cycles vary from 2.8 to 6.7 years in the Himalayan region. Interestingly, in the long-range periodic stations the persistence is absent and they are "white noise". All stations have one or other class of periodicity but, this phenomenon was not present in Zero and Pasighat. In all Indian Himalaya significant periodicities of 3.3 to 4 years was observed

6.5.2 Annual Mean Minimum Temperature

Figure 6.2 depicts power spectrum plots and the determined values of periodicity are shown in Table 6.2. For minimum temperature, major peak values dominated over the spectral bands corresponding generally to cycles of 2 year (2.0, 2.1, 2.2, 2.7, 2.9) (QBO), 3 year (3.4, 3.5, 3.7, 3.8), 4 year (4.2, 4.8), 5.3, 6.0, 7 year (7.2, 7.5) 8 year (8.0, 8.7) and 11 year (Sun spot). It may also be seen from the table, that the minimum temperature series of Jammu & Kashmir and Arunachal Pradesh is non-periodic. In regional analysis significant periodicities in the range of 2.2 to 4 years are witnessed. The eastern Himalaya revealed a cycle of sunspot number.

Table 6.1 Serial correlation and power spectrum analyses for the annual mean maximum temperature. L: lag; m: maximum lag; WN: white noise; and RN: red noise

Station	r_1	L (m)	Cycle	Continuum
Srinagar	0.430*	5 (10)	4.0*	RN
Quazigund	0.224	2 (7)	7.0*	WN
Banihal	0.201	2 (7) 3 (7)	7.0* 4.7*	WN
Jammu	0.064	4 (11) 5 (11)	5.5* 4.4*	WN
Dalhousie	0.488*	6 (12) 7 (12)	4.0** 3.4*	RN
Dharamsala	0.546*	5 (15) 9 (15)	6.0* 3.3*	RN
Manali	0.200	2 (11) 3 (11)	11.0* 7.3**	WN
Bhuntar (A)	0.167	4 (13) 7 (13	6.5* 3.7**	WN
Mandi	0.355*	5 (15) 8 (15) 9 (15)	6.0* 3.8** 3.3*	RN
Bilaspur	0.065	-	-	WN
Simla	0.240*	6(19) 11 (19)	6.3** 3.5*	RN
Mukhim	0.229	2 (11)	11.0*	WN
Joshimath	0.630*	3(10) 4 (10)	6.7** 5.0**	RN
Mussoorie	0.277*	10 (19) 11 (19)	3.8** 3.5**	RN
Tehri	0.546*	6 (8)	2.7**	RN
Dehradun	0.137	6 (19) 7 (19) 10 (19)	6.3** 5.4* 3.8*	WN
Mukteshwar	0.623*	10 (19) 11 (19)	3.8* 3.5**	RN
Nainital	0.172	2 (8)	8.0**	WN
Pasighat	-0.017	-	-	WN
Ziro	0.066	-	-	WN
Gangtok	0.551*	7 (10) 8 (10)	2.9* 2.5*	RN
Kalimpong	0.528	8(19) 9 (19) 11 (19) 12 (19) 13 (19)	4.8* 4.2** 3.5* 3.2** 2.9**	RN
Darjeeling	0.747*	14 (19) 15 (19)	2.7* 2.5**	RN
Western Himalaya	0.245	5(10)	4*	WN
Central Himalaya	0.399*	3 (10) 6 (10)	6.7* 3.3*	RN
Eastern Himalaya	0.369*	5 (10) 7 (10	4* 2,8*	RN
All Indian Himalaya	0.209	5 (10) 6 (10)	4* 3.3*	WN

* Significant at 0.90 confidence level; ** Significant at 0.95 confidence level

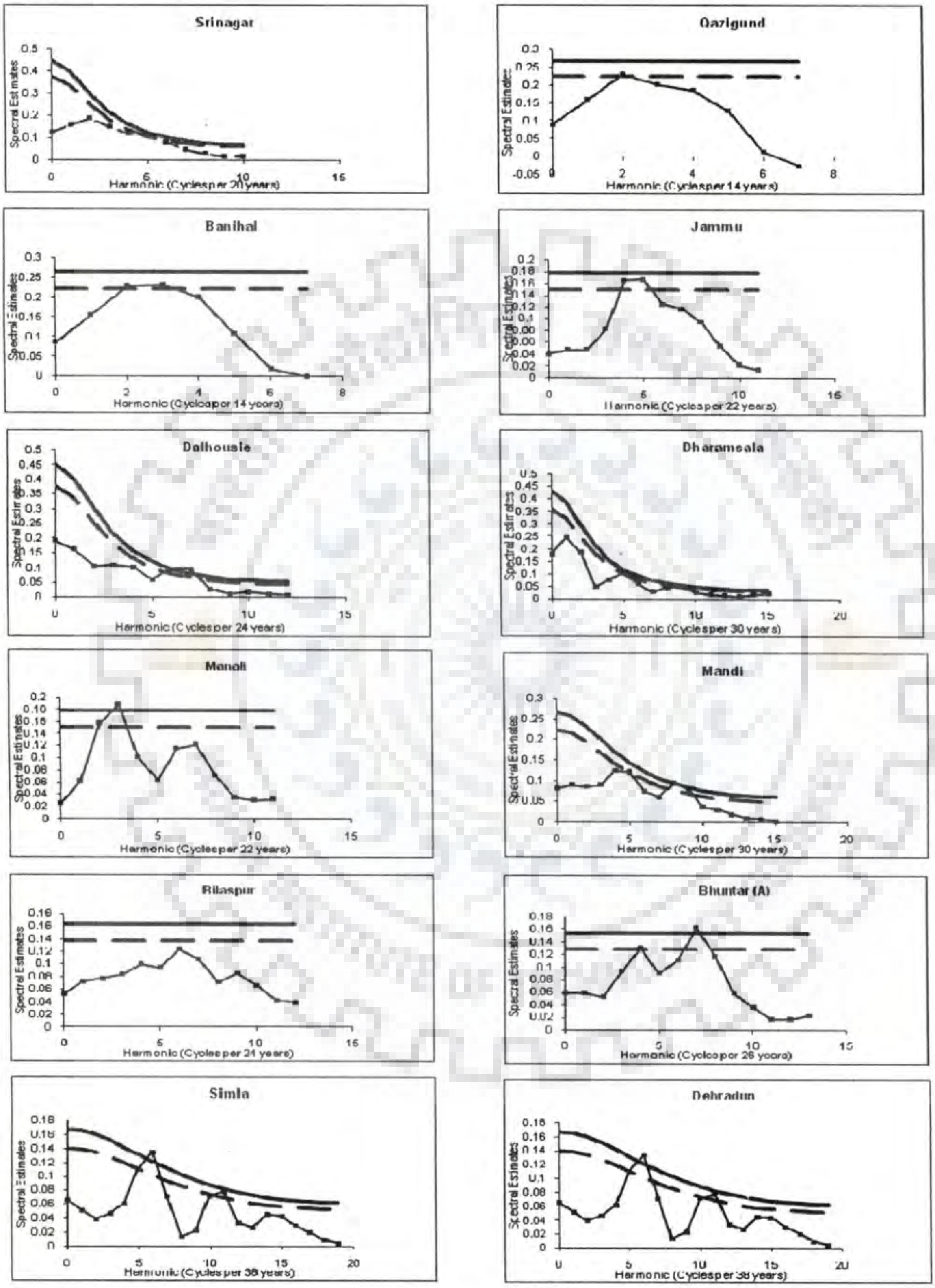

Fig. 6.1 Power spectrum plots of annual mean maximum temperature of Indian Himalayan stations. –'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum.

Table 6.2 Serial correlation and power spectrum analyses for the annual mean minimum temperature. L: lag; m: maximum lag; WN: white noise; and RN: red noise

Station	**r_1**	**L (m)**	**Cycle**	**Continuum**
Srinagar	0.115	-	-	WN
Qazigund	0.146	-	-	WN
Banihal	0.417	-	-	RN
Jammu	0.351*	-	-	RN
Dalhousie	0.580*	5 (12)	4.8*	RN
Dharamsala	0.637*	4 (15) 5 (15)	7.5* 6.0*	RN
Manali	0.218	2 (11)	11.0*	WN
Bhuntar (A)	0.130	3 (13)	8.7*	WN
Mandi	0.409*	-	-	RN
Bilaspur	0.542*	7 (12)	3.4*	RN
Simla	0.476*	11 (19)	3.5**	RN
Mukhim	0.268	6 (11)	3.7**	WN
Joshimath	0.390*	-	-	WN
Mussoorie	0.429*	10 (19) 11 (19)	3.8** 3.5*	RN
Tehri	0.349*	3 (8)	5.3*	WN
Dehradun	0.483*	-	-	RN
Mukteshwar	0.680*	11 (19) 14 (19)	3.5* 2.7*	RN
Nainital	0.217	-	-	WN
Pasighat	0.478*	-	-	RN
Ziro	0.678*	-	-	RN
Gangtok	0.799*	-	-	RN
Kalimpong	0.547*	18 (19) 19 (19)	2.1** 2.0**	RN
Darjeeling	0.736*	10 (19) 17 (19) 18 (19) 19 (19)	3.8* 2.2* 2.1* 2.0*	WN
Western Himalaya	0.447	6 (10) 9 (10)	3.3* 2.2*	RN
Central Himalaya	0.363*	5 (10) 6 (10)	4** 3.3**	RN
Eastern Himalaya	0.680*	2 (10)	10*	RN
All Indian Himalaya	0.623*	5 (10) 6 (10)	4* 3.3**	RN

* Significant at 0.90 confidence level, ** Significant at 0.95 confidence level

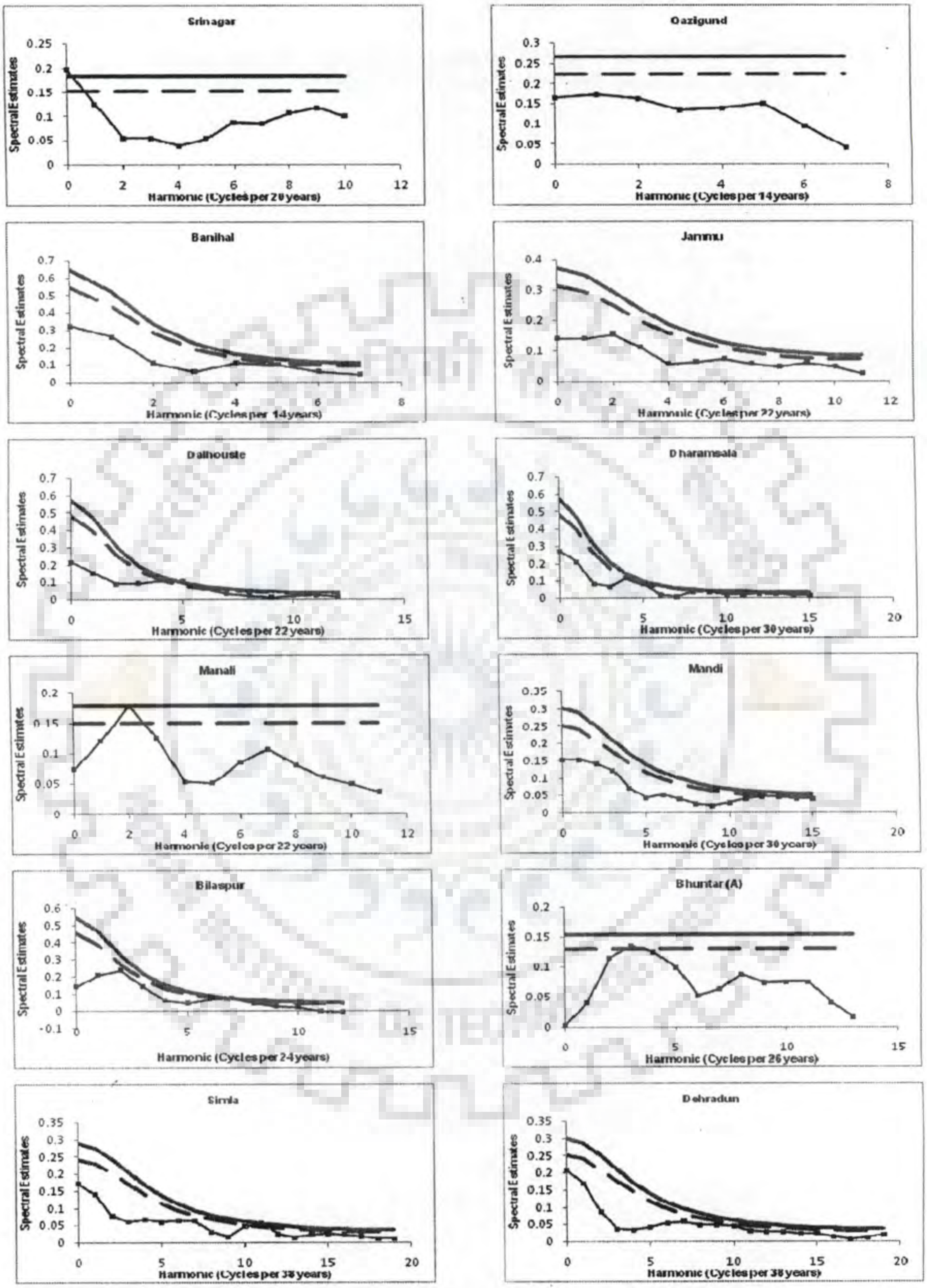

Fig. 6.2 Power spectrum plots of annual mean minimum temperature of Indian Himalayan stations. – 'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum.

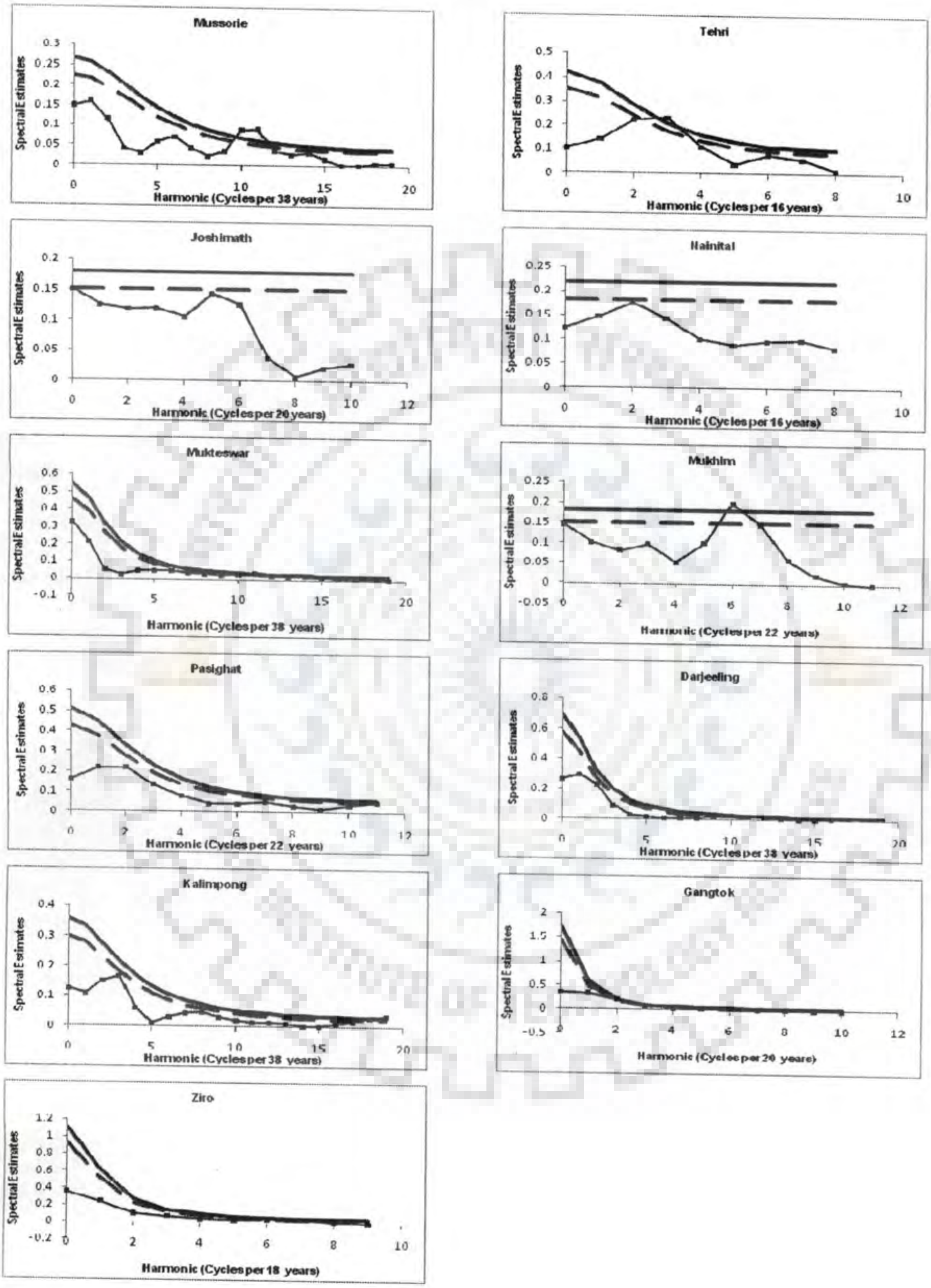

Fig. 6.2 (continued)

6.5.3 Annual Mean Temperature

On examination of results (Table 6.3 and Fig. 6.3), it could be seen that the mean temperature variations comprised all the periods taken in to account in the study. In Srinagar, Manali, Nainital and Kalimpong sun spot cycle is evident. On the other hand the QBO was present in the Darjeeling and Pasighat. Short cycles of about 3 – 4 year are observed in the Himalayan regions and in all Indian Himalaya. Jammu, Gangtok and Zero were random with respect to periodicity.

6.5.4 Annual Mean Temperature Range

Table 6.4 and Fig. 6.4 demonstrate the results obtained from the power spectrum. The cycles equal to sun spot are observed at Manali, Nainital, and Gangtok. In western and all Indian Himalaya cycles of 2.5 to 4 years were observed. While periodicity was absent in eastern Himalayas. The central Himalaya exhibited a sun spot cycle.

6.5.5 Annual Rainfall

It may be seen from Table 6.5, that the periodicity was not present in 43% of the tested series. The plot of power spectrum is shown in Fig. 6.5. Long cycles of 24-12.7 years, medium cycle of 7.6 -9.5 years and QBO are seen in the annual rainfall. Short range periodicities of 2-2.5 years were revealed over the Indian Himalaya. The computed periodicities for gridded annual rainfall are given in Table 6.6 and their power spectrum plots are shown in Fig. 6.6. All the periodicities observed in gridded annual rainfall vary in the range of 2-2.6 years, 3.1-4.9 years and 8.5 -17 years.

6.5.6 Annual Number of rainy days

The annual number of rainy days series also included all the periods considered. Regionally, periodicity for the annual number of rainy days series is characterized generally by short cycles of 2-3 years in the Indian Himalayan regions (Fig. 6.7 and Table 6.7). The long range periodicity of 38, 24 and 12 year are also found in the stations of Indian Himalaya. No periodicity was observed in central Himalayan region. In case of gridded annual number of rainy days it was revealed that the short cycle and QBO are present in most the grids and varies from 2-3.4 years, 6.8-11.3 years and 17 years over some of the grids (Table 6.8 and Fig. 6.8).

Table 6.3 Serial correlation and power spectrum analyses for the annual mean temperature. L: lag; m: maximum lag; WN: white noise; and RN: red noise

Station	r_1	L (m)	Cycle	Continuum
Srinagar	0.182	2 (10) 3 (10)	10.0** 6.7**	WN
Qazigund	0.331	2 (7)	7.0*	WN
Banihal	0.455*	4 (7)	3.5*	RN
Jammu	0.077	-	-	WN
Dalhousie	0.503*	7 (12)	3.4**	RN
Dharamsala	0.546*	5 (15) 9 (15)	6.0** 3.3*	RN
Manali	0.247	2 (11) 3 (11)	11.0* 7.3**	WN
Bhuntar (A)	0.206	4 (13) 7 (13)	6.5* 3.7*	WN
Mandi	0.280*	4 (15)	7.5*	RN
Bilaspur	0.169	7 (12)	3.4*	WN
Simla	0.221	5 (19) 6 (19) 11 (19)	7.6* 6.3** 3.5*	WN
Mukhim	0.179	6 (11) 7 (11)	3.7** 3.1*	WN
Joshimath	0.672*	3 (10) 4 (10)	6.7** 5.0**	RN
Mussoorie	0.310*	10 (19) 11 (19)	3.8** 3.5**	RN
Tehri	0.550	3 (8)	5.3**	RN
Dehradun	0.284*	10 (19)	3.8*	RN
Mukteshwar	0.372*	6 (19) 11 (19) 14 (19)	6.3** 3.5* 2.7**	RN
Nainital	0.146	2 (8)	8.0*	WN
Pasighat	0.316*	11 (11)	2.0*	RN
Ziro	0.392*	-	-	RN
Gangtok	0.631*	-	-	RN
Kalimpong	0.527*	3 (19) 8 (19)	12.7** 4.8**	RN
Darjeeling	0.684*	15 (19)	2.5*	RN
Western Himalaya	0.161	6 (10)	3.3*	WN
Central Himalaya	0.348*	5 (10) 6 (10)	4* 3.3**	RN
Eastern Himalaya	0.549*	5 (10)	4*	RN
All Indian Himalaya	0.267	5 (10) 6 910)	4* 3.3**	WN

* Significant at 0.90 confidence level, ** Significant at 0.95 confidence level

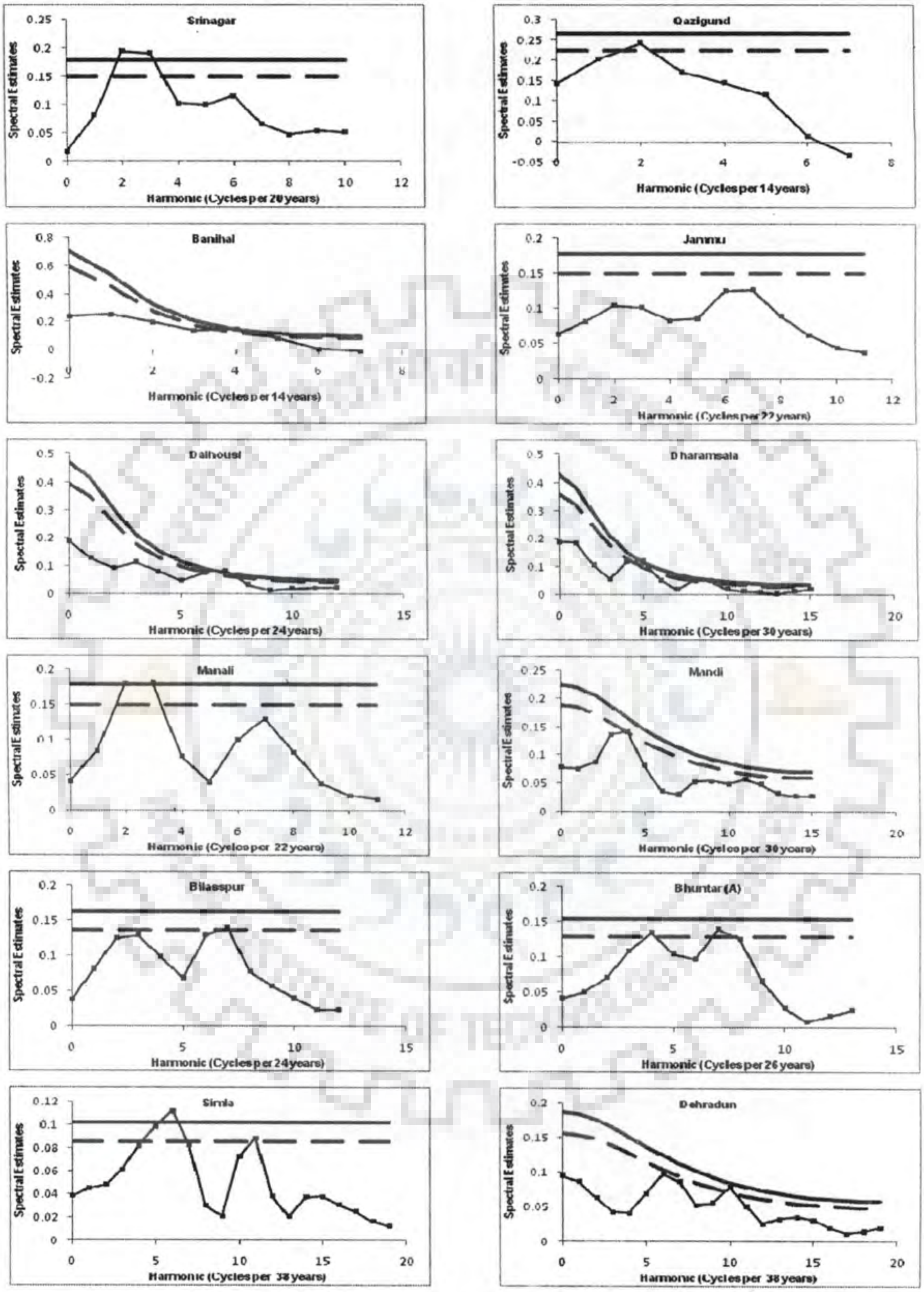

Fig. 6.3 Power spectrum plots of annual mean temperature of Indian Himalayan stations. –'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum.

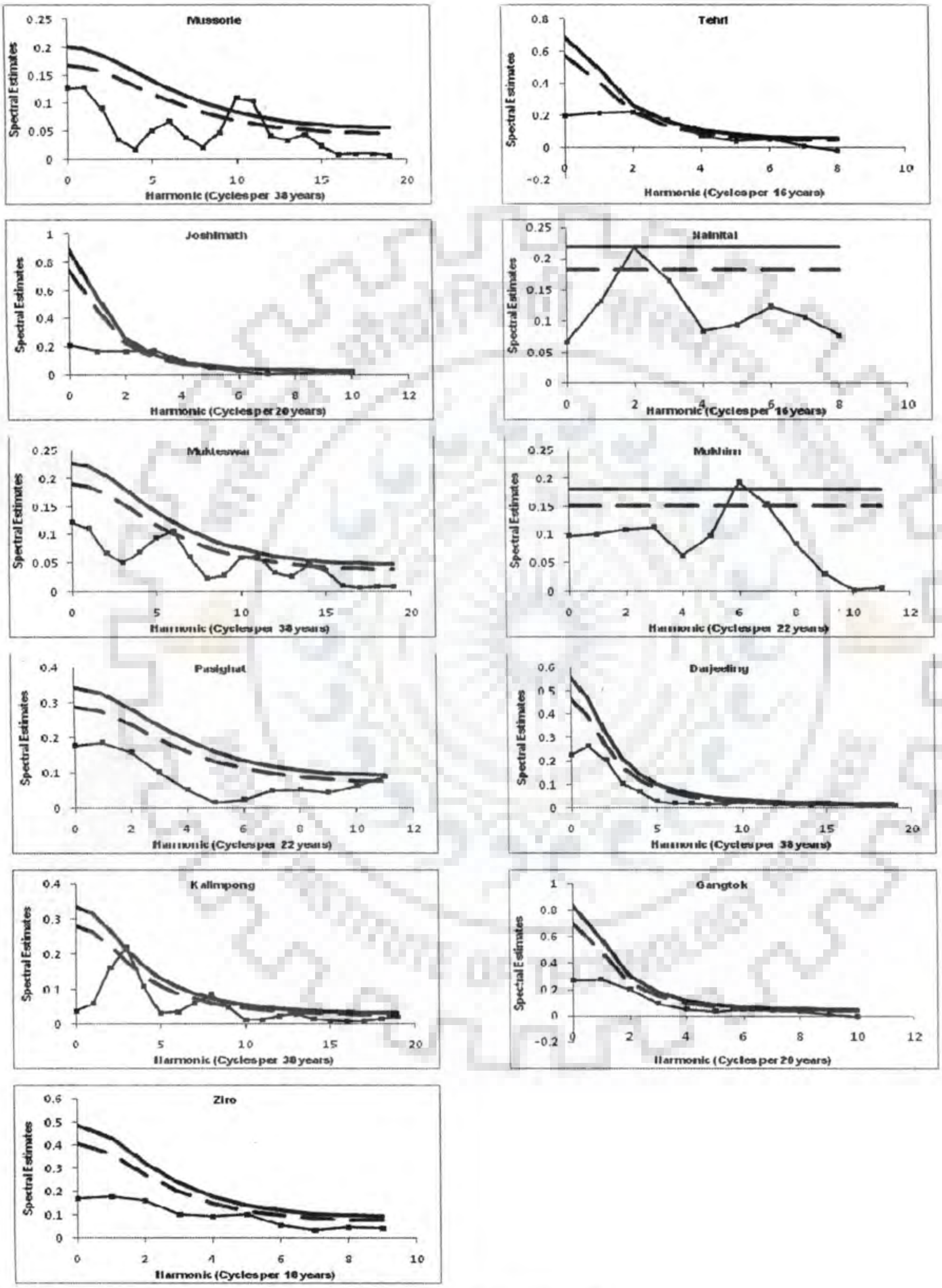

Fig. 6.3 (continued)

Table 6.4 Serial correlation and power spectrum analyses for the annual mean temperature range. L: lag; m: maximum lag; WN: white noise; and RN: red noise

Station	**r_1**	**L (m)**	**Cycle**	**Continuum**
Srinagar	0.469*	-	-	WN
Qazigund	-0.230	4 (7)	3.5*	WN
Banihal	-0.056	-	-	WN
Jammu	0.299	4 (11) 5 (11)	5.5* 4.4*	WN
Dalhousie	0.603*	4 (12) 5 (12) 6 (12)	6.0** 4.8** 4.0*	RN
Dharamsala	0.714*	12 (15) 13 (15)	2.5* 2.3**	RN
Manali	0.205	2 (11)	11.0*	WN
Bhuntar (A)	0.025	-	-	WN
Mandi	0.527*	6 (15) 7 (15)	5.0* 4.3*	RN
Bilaspur	0.547*	-	-	RN
Simla	0.827*	6 (19) 16 (19)	6.3* 2.4*	RN
Mukhim	0.503*	8 (11) 9 (11)	2.8* 2.4**	RN
Joshimath	0.490*	3 (10)	6.7**	RN
Mussoorie	0.617*	5 (19)	7.6*	RN
Tehri	-0.043	6 (8) 7 (8)	2.7* 2.3*	WN
Dehradun	0.594*	15 (19)	2.5*	RN
Mukteshwar	0.884*	16 (19) 17 (19)	2.4** 2.2**	RN
Nainital	0.279	1 (8) 2 (8)	16.0* 8.0**	WN
Pasighat	0.200	4 (11)	5.5*	WN
Ziro	0.110	-	-	WN
Gangtok	0.871*	2 (10)	10.0**	RN
Kalimpong	0.542*	9 (10) 10 (19) 11 (19) 12 (19)	4.2* 3.8* 3.5* 3.2*	RN
Darjeeling	0.798*	8 (19) 9 (19)	4.8* 4.2**	RN
Western Himalaya	0.612*	5 (10) 8 (10)	4* 2.5*	RN
Central Himalaya	0.517*	2 (10)	10*	RN
Eastern Himalaya	0.484*	-	-	RN
All Indian Himalaya	0.672*	5 (10) 8 910)	4* 2.5*	RN

* Significant at 0.90 confidence level; ** Significant at 0.95 confidence level

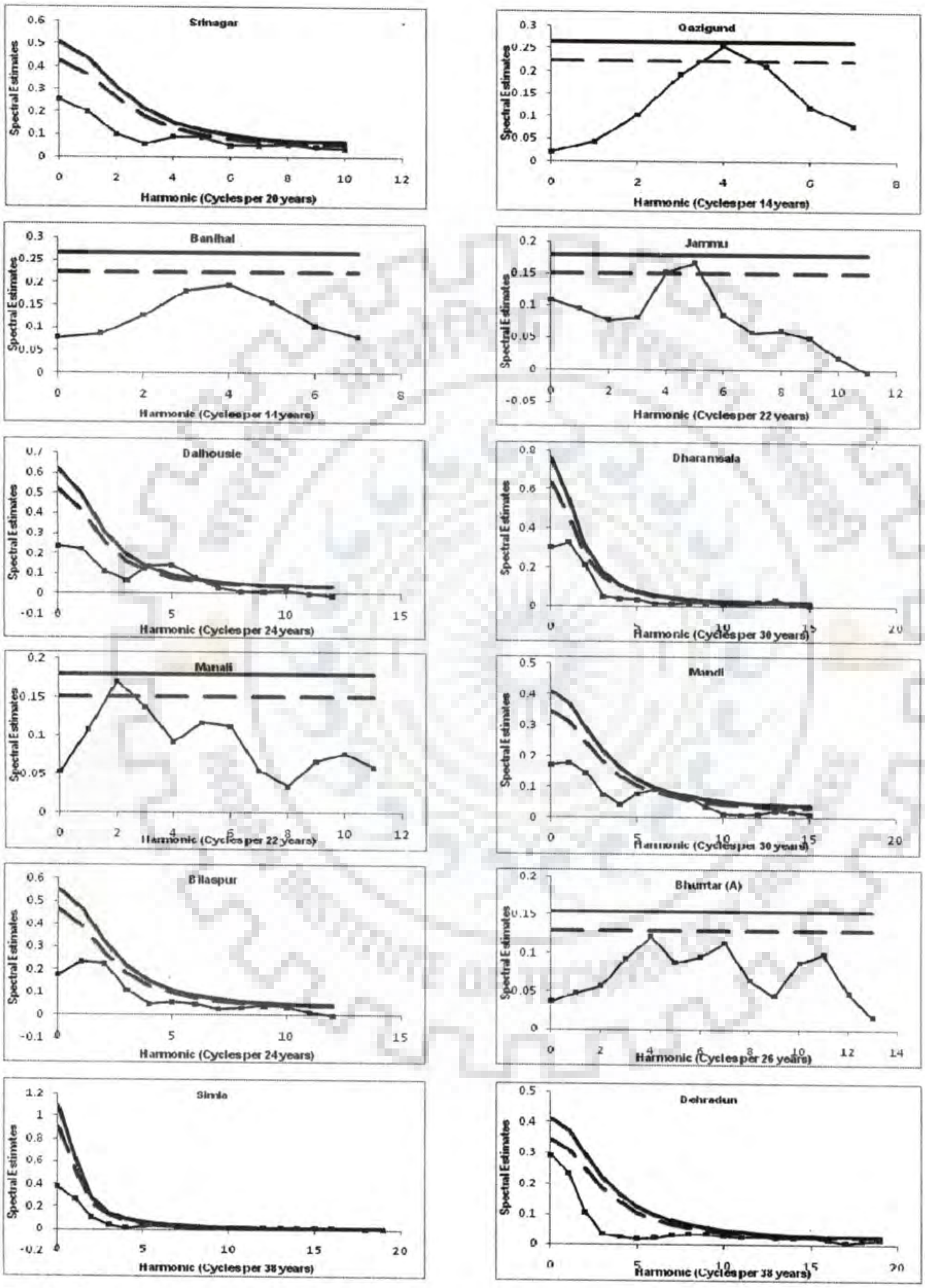

Fig. 6.4 Power spectrum plots of annual mean temperature range of Indian Himalayan stations. – 'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum.

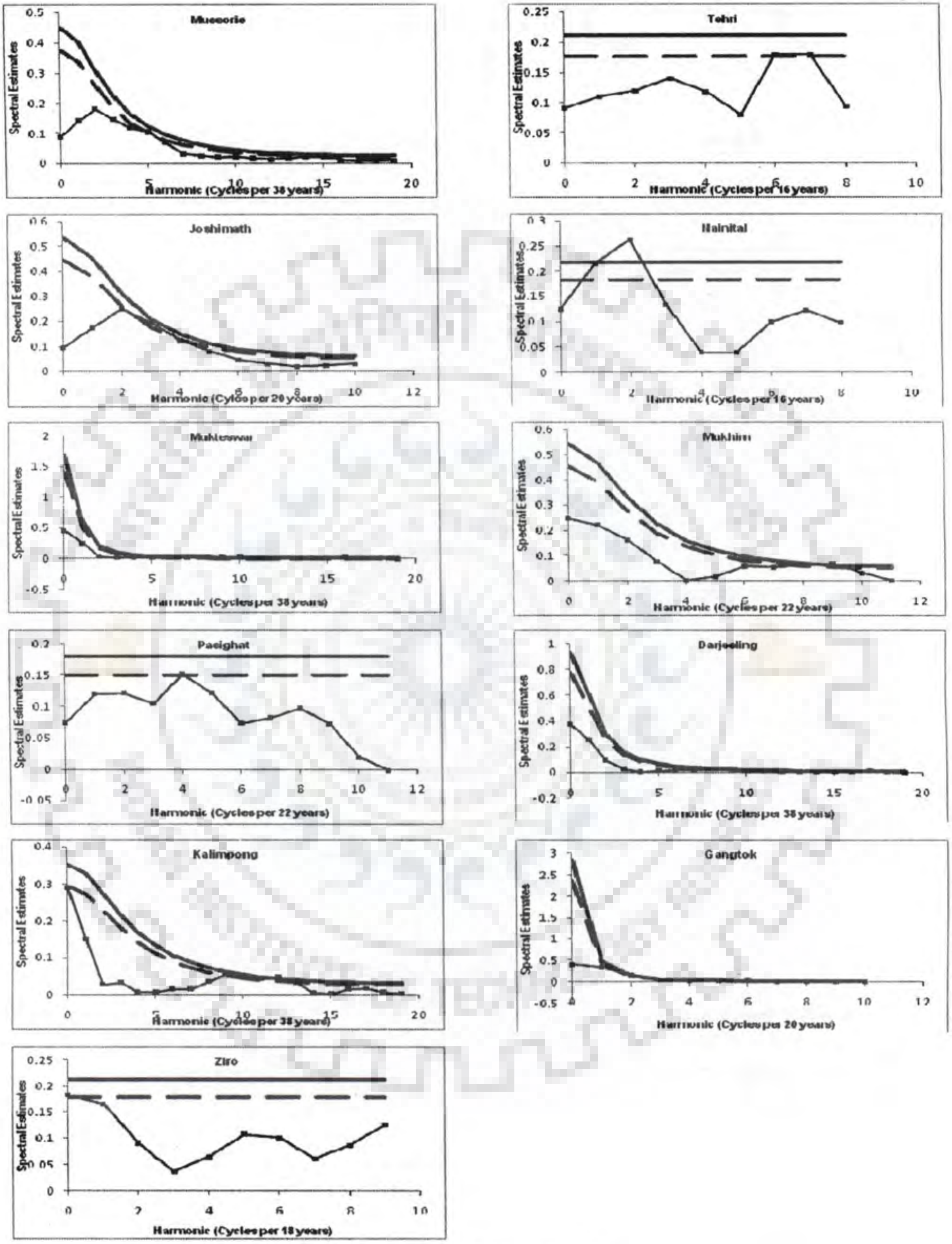

Fig. 6.4 (continued)

Table 6.5 Serial correlation and power spectrum analyses for the annual rainfall. L: lag; m: maximum lag; WN: white noise; and RN: red noise

Station	r_1	L (m)	Cycle	Continuum
Srinagar	0.032	-	-	WN
Qazigund	-0.018	-	-	WN
Banihal	0.249	-	-	WN
Jammu	-0.255	9 (11) 10 (11)	2.4** 2.2**	WN
Dalhousie	0.475*	9 (12) 10 (12)	2.7* 2.4**	RN
Dharamsala	0.021	12 (15)	2.5*	WN
Manali	0.204	1 (11) 2 (11)	22.0* 11.0*	WN
Bhuntar (A)	-0.138	10 (13)	2.6*	WN
Mandi	0.102	-	-	WN
Bilaspur	0.074	1 (12)	24.0*	WN
Simla	0.012	9 (19)	4.2*	WN
Mukhim	0.212	2 (11) 3 (11)	11.0* 7.3**	WN
Joshimath	0.434*	-	-	RN
Mussoorie	0.170	-	-	WN
Tehri	-0.150	-	-	WN
Dehradun	-0.146	16 (19)	2.4**	WN
Mukteshwar	0.107	3 (19)	12.7**	WN
Nainital	0.079	-	-	WN
Pasighat	0.153	-	-	WN
Ziro	-0.053	-	-	WN
Gangtok	-0.363	6 (10)	3.3**	WN
Kalimpong	0.127	3 (19) 4 (19) 5 (19)	12.7* 9.5** 7.6**	WN
Darjeeling	0.061	3 (19) 4 (19)	12.7** 9.5*	WN
Western Himalaya	-0.150	8 (10) 9 (10)	2.5** 2.2*	WN
Central Himalaya	-0.068	8 (10)	2.5*	WN
Eastern Himalaya	0.156	1 (10)	20**	WN
All Indian Himalaya	-0.099	8 (10)	2.5*	WN

* Significant at 0.90 confidence level; ** Significant at 0.95 confidence level

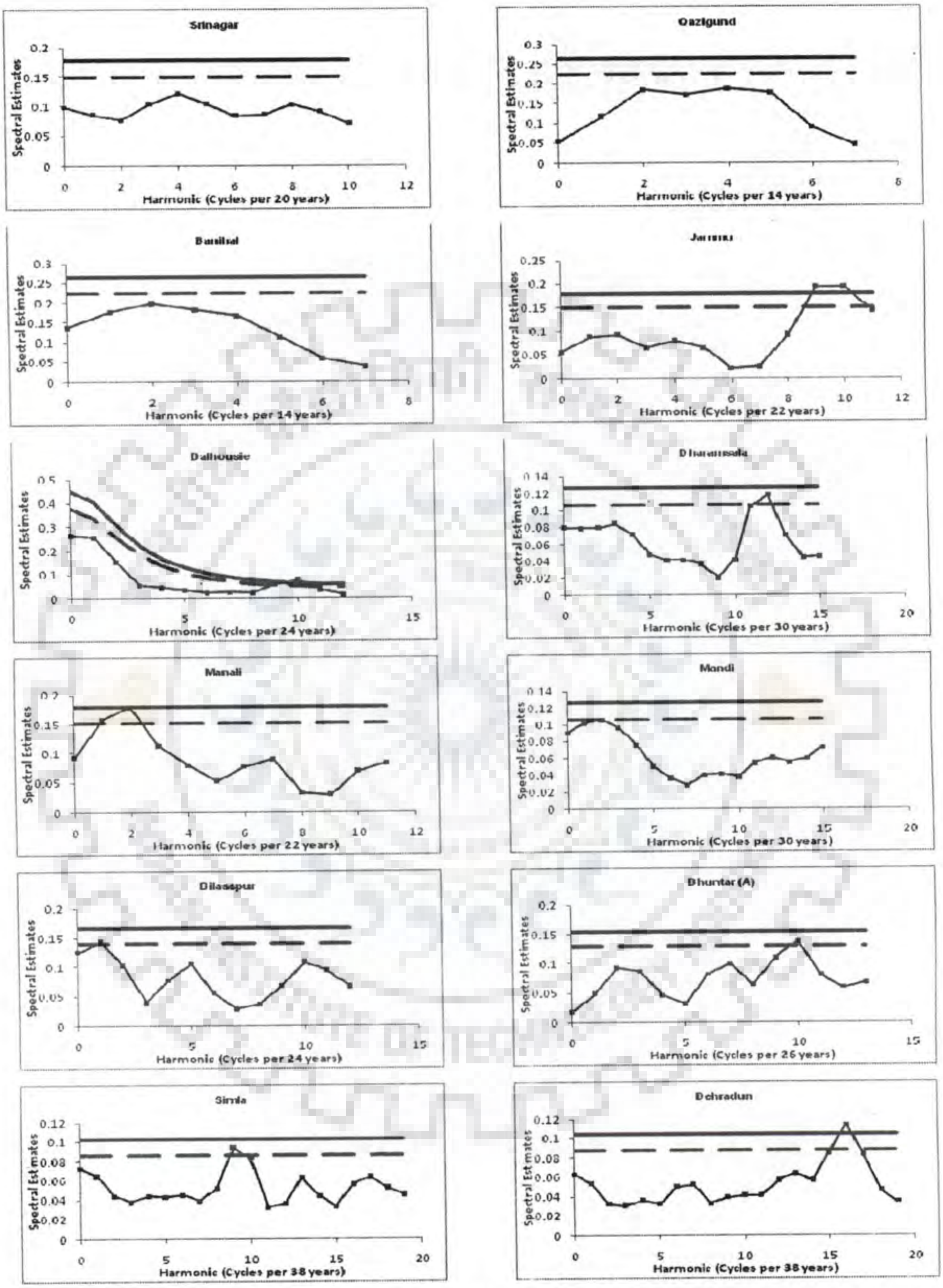

Fig. 6.5 Power spectrum plots of annual rainfall of Indian Himalayan stations. – 'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum.

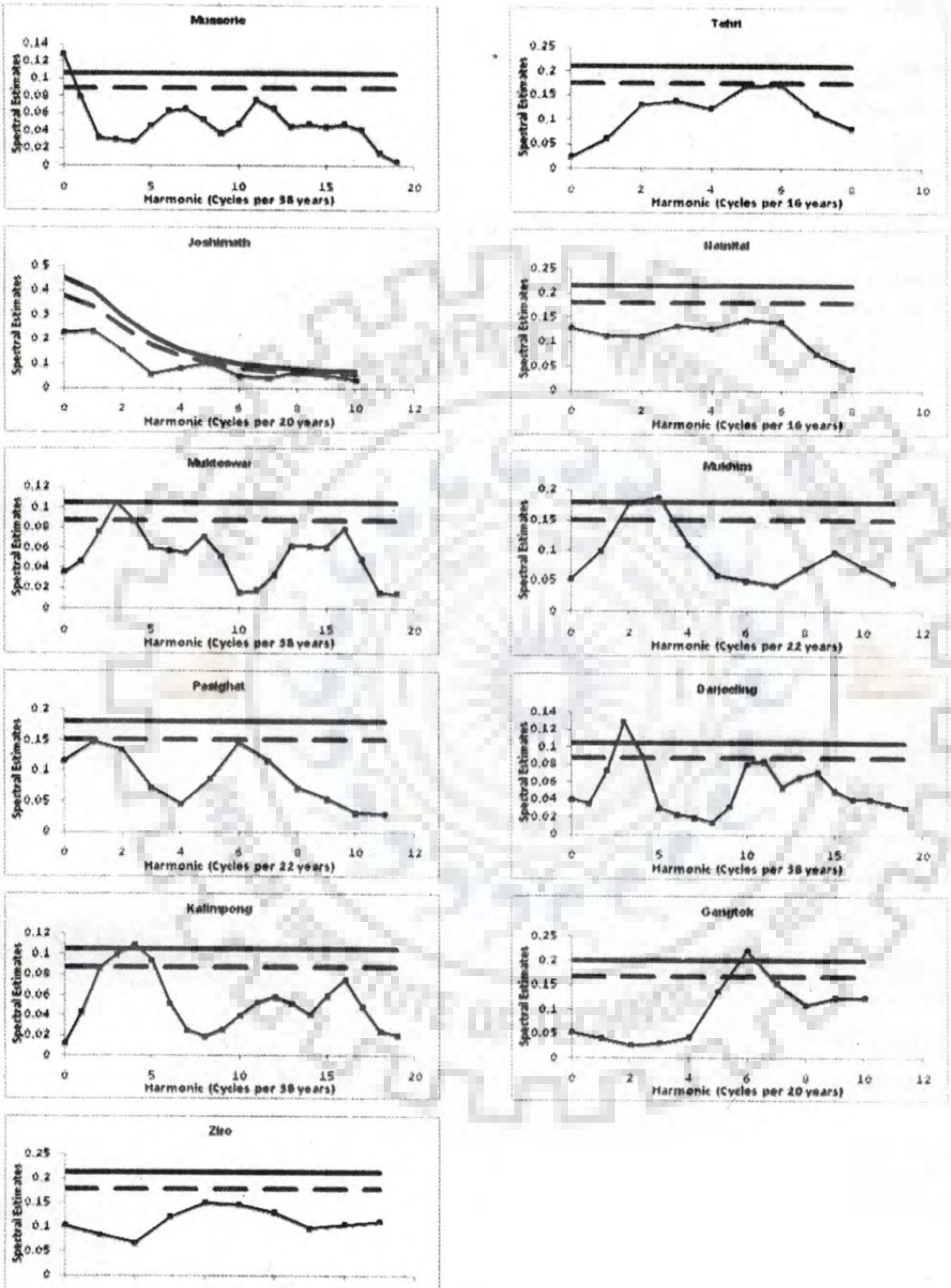

Fig. 6.5 (continued)

Table 6.6 Serial correlation and power spectrum analyses of gridded annual rainfall. L: lag; m: maximum lag; WN: white noise; and RN: red noise

Series No.	Grid Location	r_1	L (m)	Cycle	Continuum
1.	27.5N-88.5E	0.031	8(17)	4.25*	WN
2.	27.5N-89.5E	0.018	3(17) 4(17) 13(17)	11.3* 8.5* 2.6*	WN
3.	27.5N-90.5E	-0.124	3(17)	11.3*	WN
4.	27.5N-91.5E	-0.221	14(17) 15(17)	2.4* 2.3**	WN
5.	27.5N-92.5E	-0.153	7(17)	4.9*	WN
6.	27.5N-93.5E	0.028	7(17) 10(17)	4.9** 3.4*	WN
7.	28.5N-93.5E	-0.028	10(17)	3.4*	WN
8.	28.5N-94.5E	-0.101	10(17)	3.4*	WN
9.	28.5N-95.5E	-0.001	-	-	WN
10.	28.5N-96.5E	-0.007	-	-	WN
11.	29.5N-78.5E	0.138	5(17) 14(17)	6.8* 2.4*	WN
12.	29.5N-79.5E	-0.266	13(17) 14(17) 15(17)	2.6** 2.4** 2.3*	WN
13.	29.5N-80.5E	0.538*	13(17) 14(17)	2.6** 2.4**	RN
14.	29.5N-95.5E	0.014	-	-	WN
15.	30.5N-77.5E	0.629*	14(17) 17(17)	2.4* 2.0*	RN
16.	30.5N-78.5E	0.299*	-	-	WN
17.	30.5N-79.5E	0.166	-	-	WN
18.	31.5N-76.5E	0.290*	-	-	WN
19.	31.5N-77.5E	0.118	2(17) 3(17)	17.0* 11.3*	WN
20.	31.5N-78.5E	0.391*	9(17) 10(17)	3.8* 3.4*	WN
21.	32.5N-75.5E	0.099	-	-	WN
22.	32.5N-76.5E	0.409*	17(17)	2.0*	RN
23.	32.5N-77.5E	0.445*	10(17) 16(17) 17(17)	3.4* 2.1* 2.0**	RN
24.	32.5N-78.5E	0.278*	9(17) 10(17)	3.8* 3.4**	WN
25.	32.5N-79.5E	0.328*	9(17) 10(17)	3.8* 3.4**	WN
26.	33.5N-74.5E	0.282*	4(17)	8.5*	WN
27.	33.5N-75.5E	0.363*	10(17) 11(17)	3.4* 3.1*	RN
28.	33.5N-76.5E	0.325*	16(17) 17(17)	2.1* 2.0**	RN
29.	33.5N-77.5E	0.298*	10(17) 11(17) 17(17)	3.4** 3.1* 2.0*	RN
30.	33.5N-78.5E	0.443*	10(17) 14(17)	3.4* 2.4*	RN
31.	34.5N-74.5E	0.304*	4(17) 10(17)	8.5* 3.4*	WN

Table 6.6 (continued)

32.	34.5N-75.5E	0.321*	4(17) 10(17) 11(17)	8.5* 3.4* 3.1*	WN
33.	34.5N-76.5E	0.374*	10(17)	3.4*	RN
34.	34.5N-77.5E	0.364*	10(17) 17(17)	3.4** 2.0*	RN
35.	34.5N-78.5E	0.423*	10(17) 17(17)	3.4** 2.0*	RN
36.	34.5N-79.5E	0.410*	10(17)	3.4**	RN
37.	35.5N-74.5E	0.280*	4(17) 10(17)	8.5* 3.4**	RN
38.	35.5N-75.5E	0.304*	4(17) 10(17) 11(17)	8.5* 3.4* 3.1*	WN
39.	35.5N-76.5E	0.283*	4(17) 10(17) 11(17)	8.5* 3.4* 3.1*	WN
40.	35.5N-77.5E	0.312*	10(17)	3.4**	WN
41.	35.5N-78.5E	0.373*	10(17) 17(17)	3.4** 2.0*	RN
42.	35.5N-79.5E	0.393*	10(17) 17(17)	3.4** 2.0*	RN
43.	36.5N-73.5E	-0.237	12(17) 13(17)	2.8** 2.6*	WN
44.	36.5N-74.5E	0.046	12(17)	2.8*	WN
45.	36.5N-75.5E	0.217	2(17) 3(17) 4(17)	17.0* 11.3** 8.5**	WN

* Significant at 0.90 confidence level; ** Significant at 0.95 confidence level

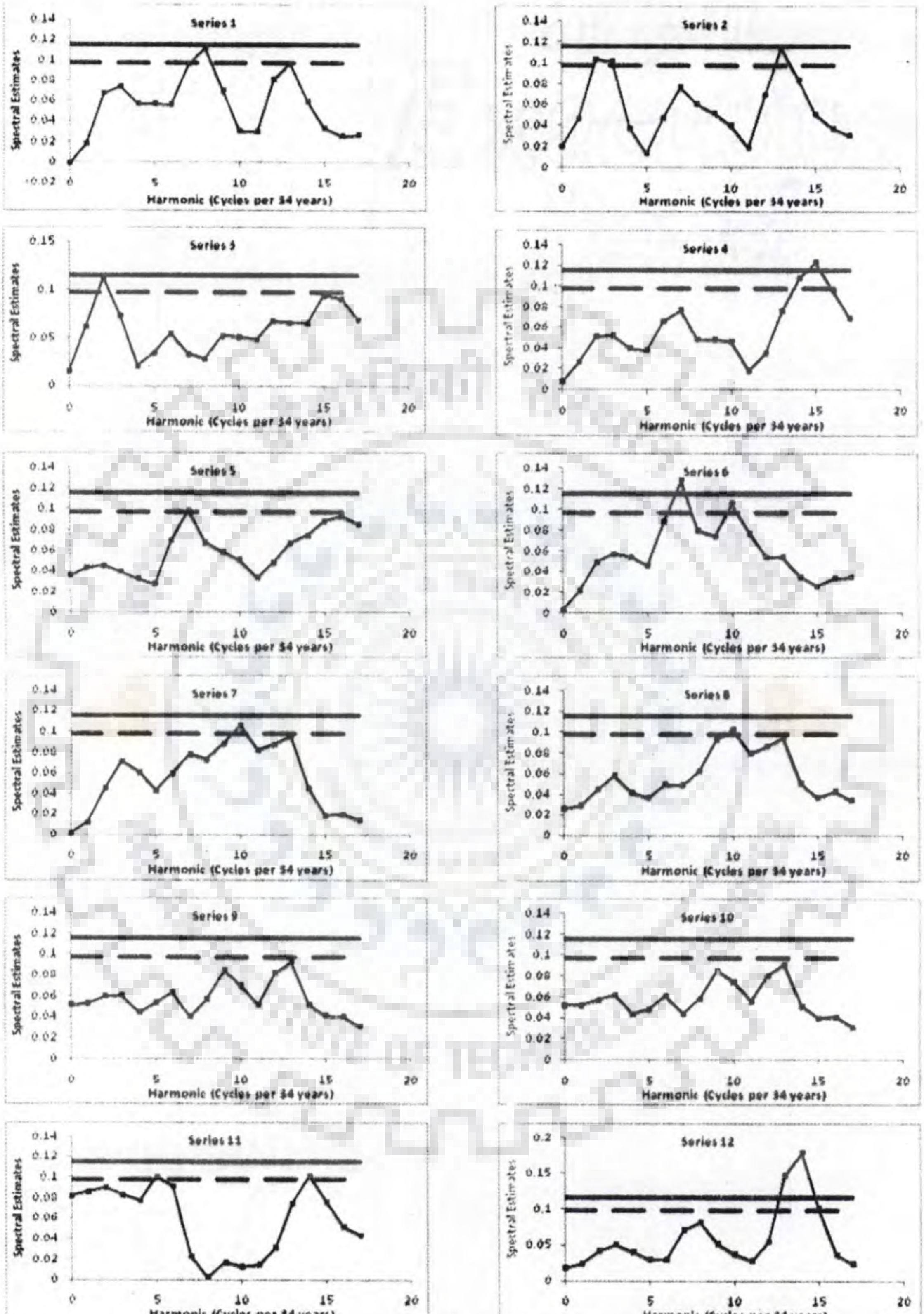

Fig. 6.6 Power spectrum plots of gridded annual rainfall of Indian Himalayan stations. – 'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum

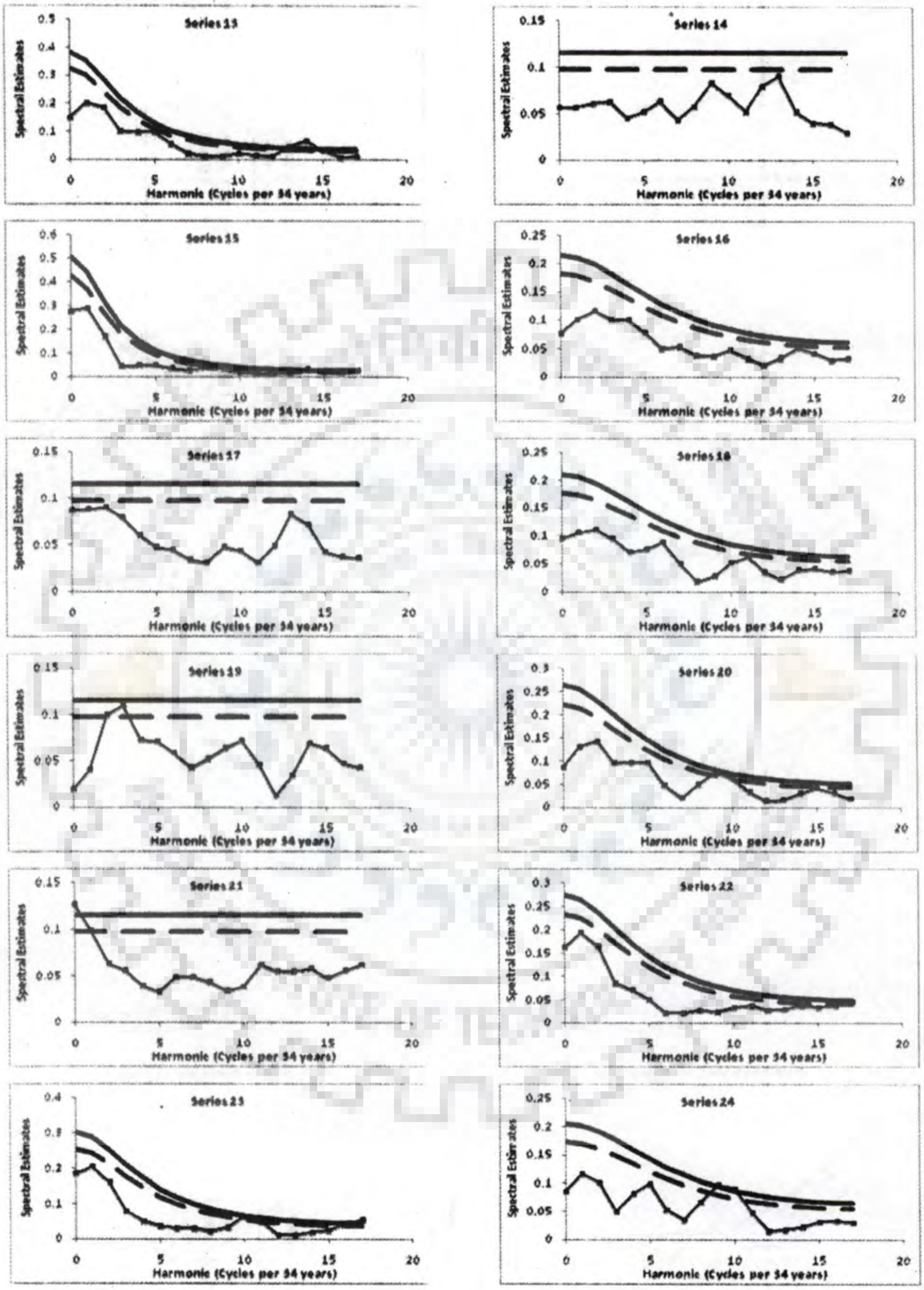

Fig 6.6 (continued)

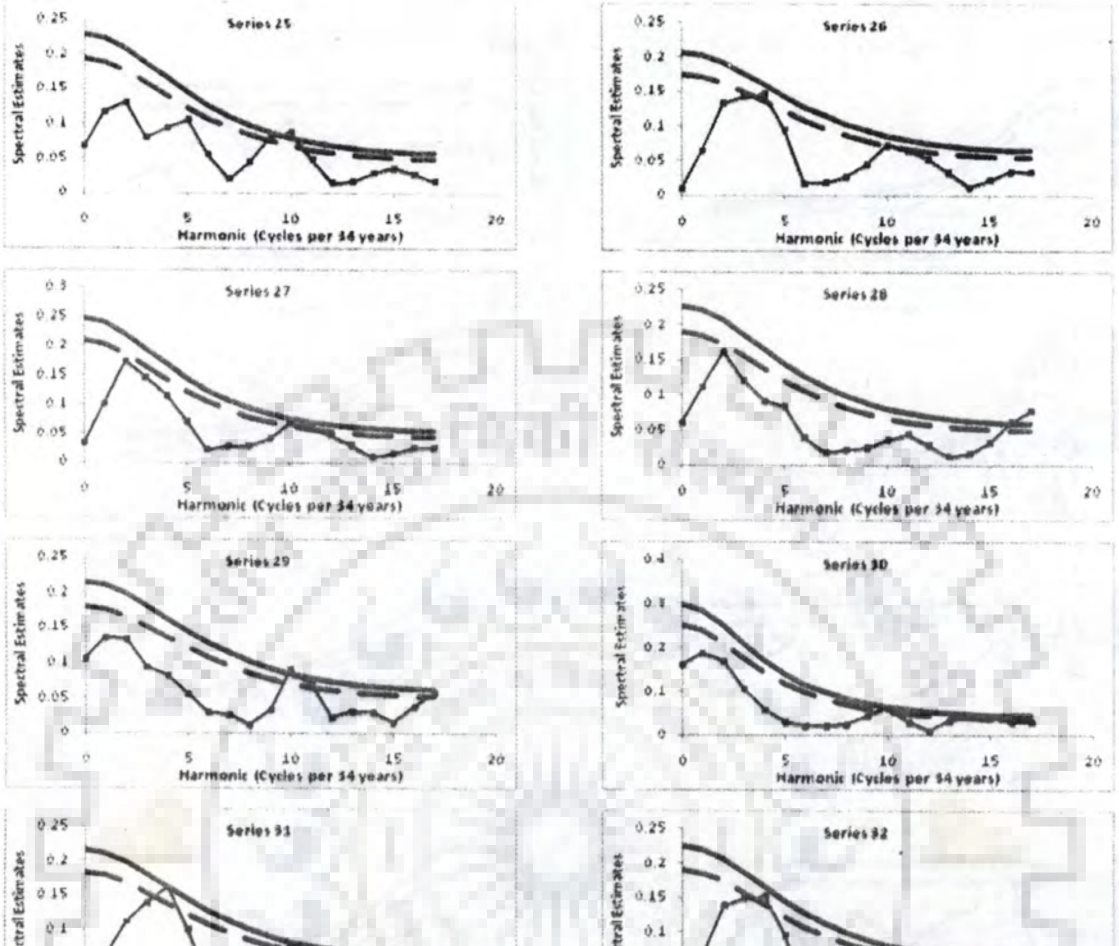

Fig 6.6 (continued)

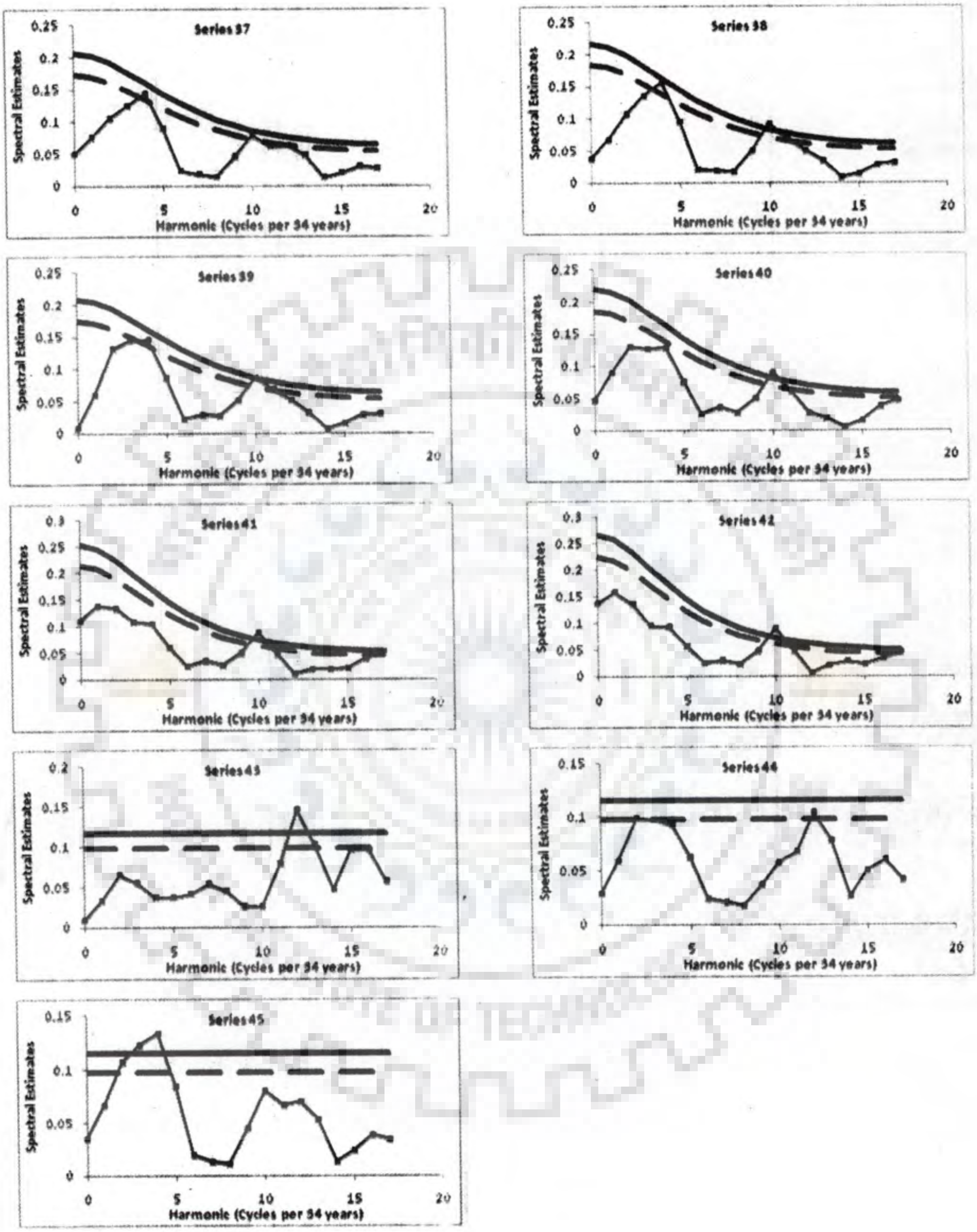

Fig 6.6 (continued)

Table 6.7 Serial correlation and power spectrum analyses for the annual number of rainy days. L: lag; m: maximum lag; WN: white noise; and RN: red noise

Station	r_1	**L (m)**	**Cycle**	**Continuum**
Srinagar	-0.150	8 (10) 9 (10)	2.5** 2.2*	WN
Qazigund	0.108	-	-	WN
Banihal	0.185	-	-	WN
Jammu	0.032	5 (11)	4.4*	WN
Dalhousie	0.468*	10 (12)	2.4*	RN
Dharamsala	-0.207	12 (15) 13 (15)	2.5* 2.3*	WN
Manali	0.238	1 (11) 2 (11)	22.0** 11.0*	WN
Bhuntar (A)	-0.084	-	-	WN
Mandi	0.3828*	-	-	RN
Bilaspur	-0.085	-	-	WN
Simla	0.215	1 (19) 2 (19) 3 (19)	38.0* 19.0** 12.7*	WN
Mukhim	0.222	3 (11) 4 (11)	7.3* 5.5*	WN
Joshimath	0.325*	4 (10)	5.0*	WN
Mussoorie	0.099	-	-	WN
Tehri	0.026	2 (8) 3 (8)	8.0* 5.3*	WN
Dehradun	-0.046	-	-	WN
Mukteshwar	0.019	15 (19) 16 (19)	2.5* 2.4**	WN
Nainital	0.175	-	-	WN
Pasighat	-0.173	7 (11)	3.1	WN
Ziro	0.005	-	-	WN
Gangtok	-0.394	6 (10) 7 (10)	3.3** 2.9*	WN
Kalimpong	0.608*	-	-	RN
Darjeeling	0.120	11 (19) 12 (19) 13 (19)	3.5* 3.2** 2.9*	WN
Western Himalaya	-0.285	8 (10) 9 (10)	2.5** 2.2**	WN
Central Himalaya	0.031	-	-	WN
Eastern Himalaya	0.022	6 (10) 7 (10)	3.3** 2.8**	WN
All Indian Himalaya	-0.171	4 (10)	5*	WN

[*] Significant at 0.90 confidence level; ** Significant at 0.95 confidence level

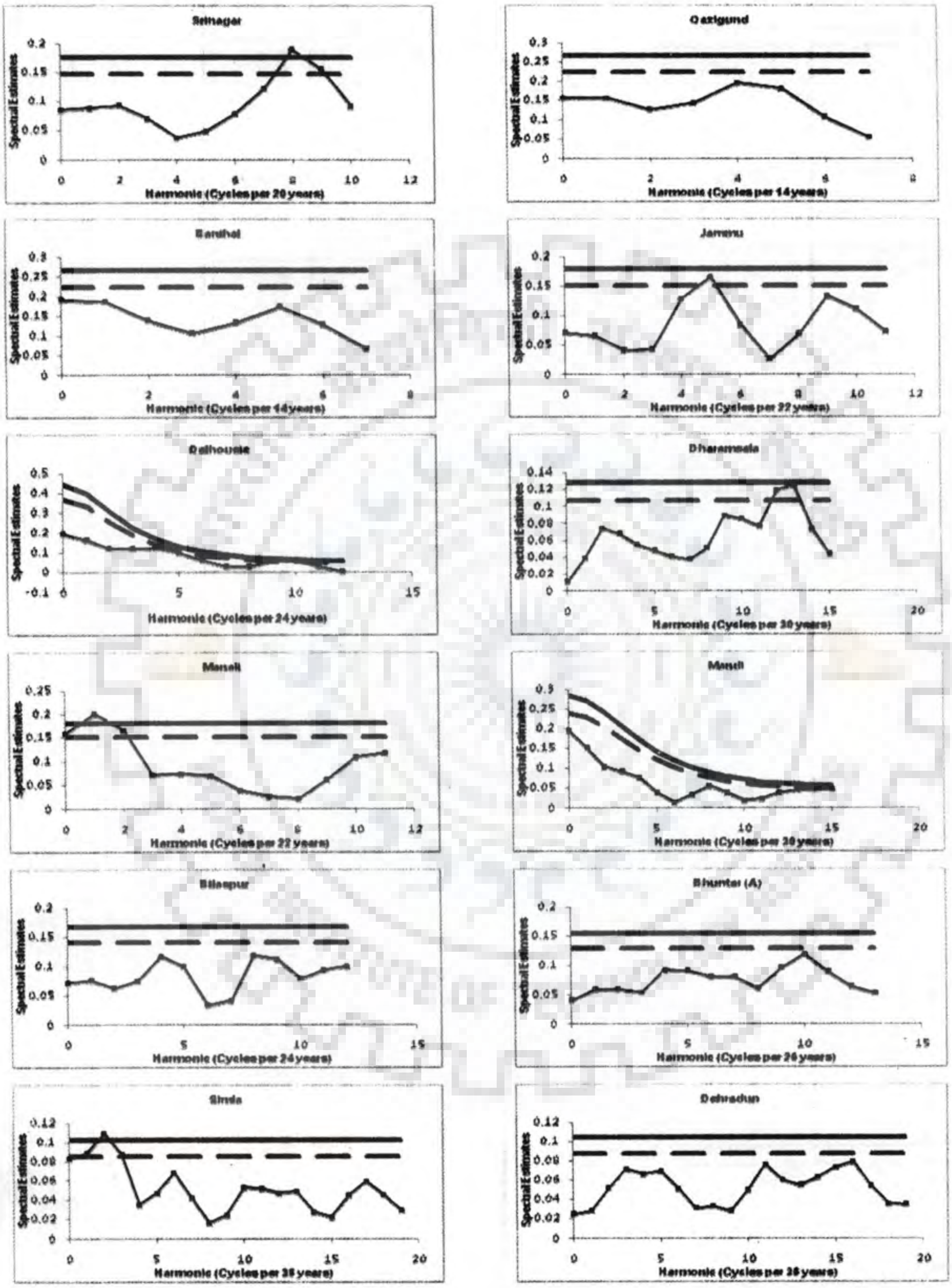

Fig. 6.7 Power spectrum plots of annual number of rainy days of Indian Himalayan stations. – 'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum.

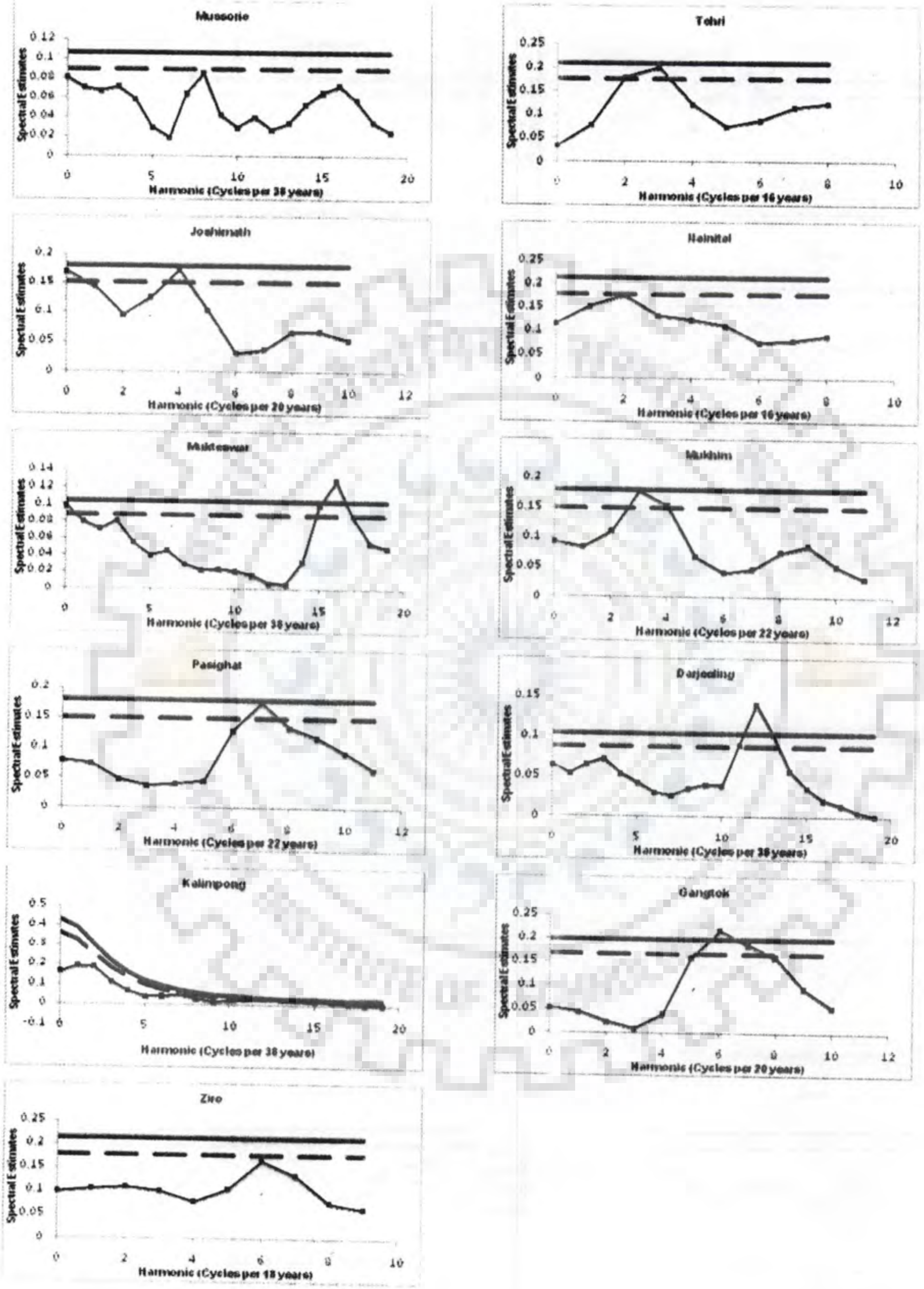

Fig. 6.7 (continued)

Table 6.8 Serial correlation and power spectrum analyses of gridded annual number of rainy days. L: lag; m: maximum lag; WN: white noise; and RN: red noise

Series No.	Grid Location	r_1	L (m)	Cycle	Continuum
1.	27.5N-88.5E	0.043	3(17) 11(17)	11.3* 3.1*	WN
2.	27.5N-89.5E	-0.022	10(17) 11(17)	3.4* 3.1*	WN
3.	27.5N-90.5E	0.004	-	-	WN
4.	27.5N-91.5E	0.050	-	-	WN
5.	27.5N-92.5E	-0.090	-	-	WN
6.	27.5N-93.5E	-0.142	13(17) 14(17)	2.6** 2.4*	WN
7.	28.5N-93.5E	-0.169	5(17) 13(17)	6.8* 2.6**	WN
8.	28.5N-94.5E	-0.115	9(17) 10(17) 13(17)	3.8* 3.4* 2.6*	WN
9.	28.5N-95.5E	-0.094	10(17)	3.4**	WN
10.	28.5N-96.5E	-0.151	10(17)	3.4**	WN
11.	29.5N-78.5E	0.366*	5(17) 13(17) 14(17) 17(17)	6.8* 2.6* 2.4* 2.0*	RN
12.	29.5N-79.5E	0.088	-	-	WN
13.	29.5N-80.5E	0.511*	14(17)	2.4**	RN
14.	29.5N-95.5E	-0.106	10(17)	3.4*	WN
15.	30.5N-77.5E	0.228	1(17)	34.0**	WN
16.	30.5N-78.5E	0.182	5(17)	6.8*	WN
17.	30.5N-79.5E	0.339*	13(17) 14(17)	2.6** 2.4*	RN
18.	31.5N-76.5E	0.159	5(17) 6(17)	6.8** 5.7**	WN
19.	31.5N-77.5E	0.103	-	-	WN
20.	31.5N-78.5E	0.386*	12(17)	2.8*	RN
21.	32.5N-75.5E	-0.064	1(17) 13(17) 14(17)	34.0* 2.6* 2.4*	WN
22.	32.5N-76.5E	0.310*	2(17)	17.0*	RN
23.	32.5N-77.5E	0.469*	17(17)	2.0**	RN
24.	32.5N-78.5E	0.330*	-	-	WN
25.	32.5N-79.5E	0.465*	-	-	RN
26.	33.5N-74.5E	0.474*	10(17)	3.4*	RN
27.	33.5N-75.5E	0.215	1(17) 2(17) 3(17)	34.0* 17.0** 11.3**	WN
28.	33.5N-76.5E	0.398*	16(17)	2.1*	RN
29.	33.5N-77.5E	0.523*	17(17)	2.0**	RN
30.	33.5N-78.5E	0.549*	-	-	RN
31.	34.5N-74.5E	0.386*	-	-	RN
32.	34.5N-75.5E	0.314*	-	-	RN
33.	34.5N-76.5E	0.434*	16(17)	2.1*	RN
34.	34.5N-77.5E	0.510*	11(17) 17(17)	3.1* 2.0**	RN
35.	34.5N-78.5E	0.517*	11(17) 17(17)	3.1* 2.0**	RN

Table 6.8 (continued)

36.	34.5N-79.5E	0.508*	10(17) 17(17)	3.4* 2.0*	RN
37.	35.5N-74.5E	0.383*	13(17)	2.6**	RN
38.	35.5N-75.5E	0.267*	-	-	RN
39.	35.5N-76.5E	0.247	1(17) 2(17) 3(17)	34.0* 17.0** 11.3*	WN
40.	35.5N-77.5E	0.432*	17(17)	2.0*	RN
41.	35.5N-78.5E	0.529*	17(17)	2.0*	RN
42.	35.5N-79.5E	0.506*	10(17) 17(17)	3.4* 2.0*	RN
43.	36.5N-73.5E	0.156	1(17) 2(17) 13(17)	34.0* 17.0* 2.6*	WN
44.	36.5N-74.5E	0.308*	12(17) 13(17)	2.8** 2.6**	RN
45.	36.5N-75.5E	0.301*	13(17)	2.6*	RN

* Significant at 0.90 confidence level; ** Significant at 0.95 confidence level

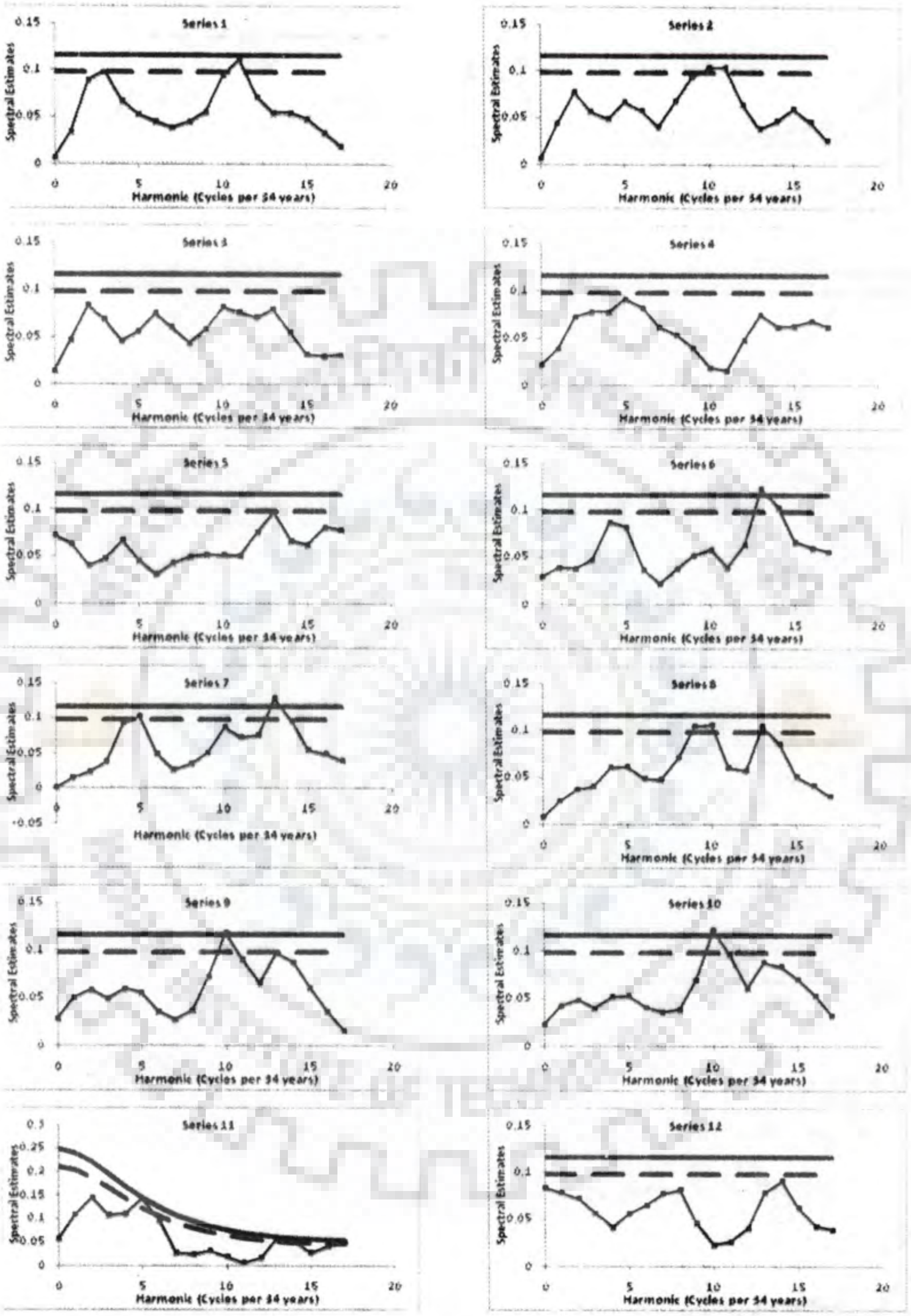

Fig. 6.8 Power spectrum plots of annual number of gridded annual number of rainy days of Indian Himalayan stations. – 'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum

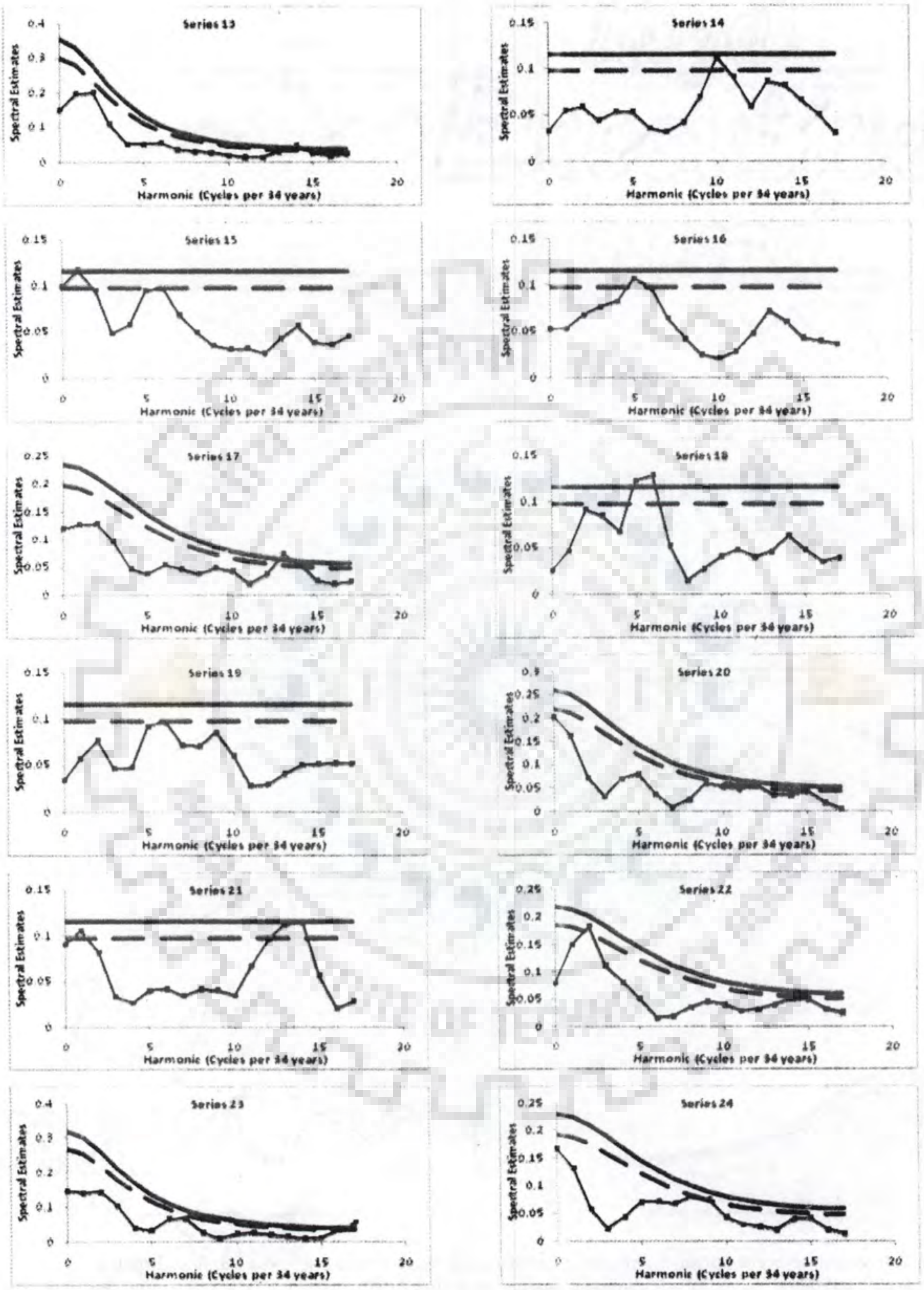

Fig 6.8 (continued)

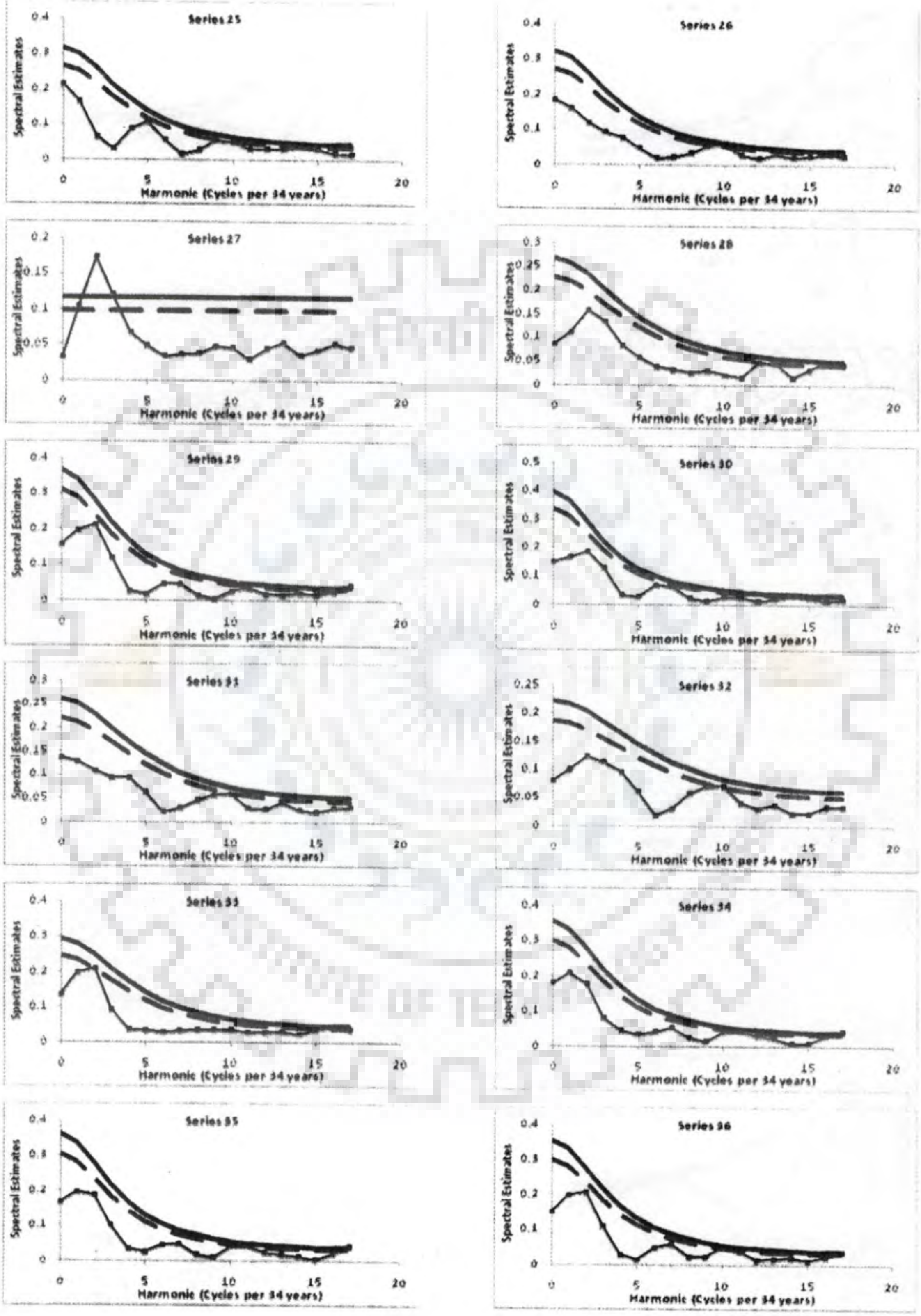

Fig 6.8 (continued)

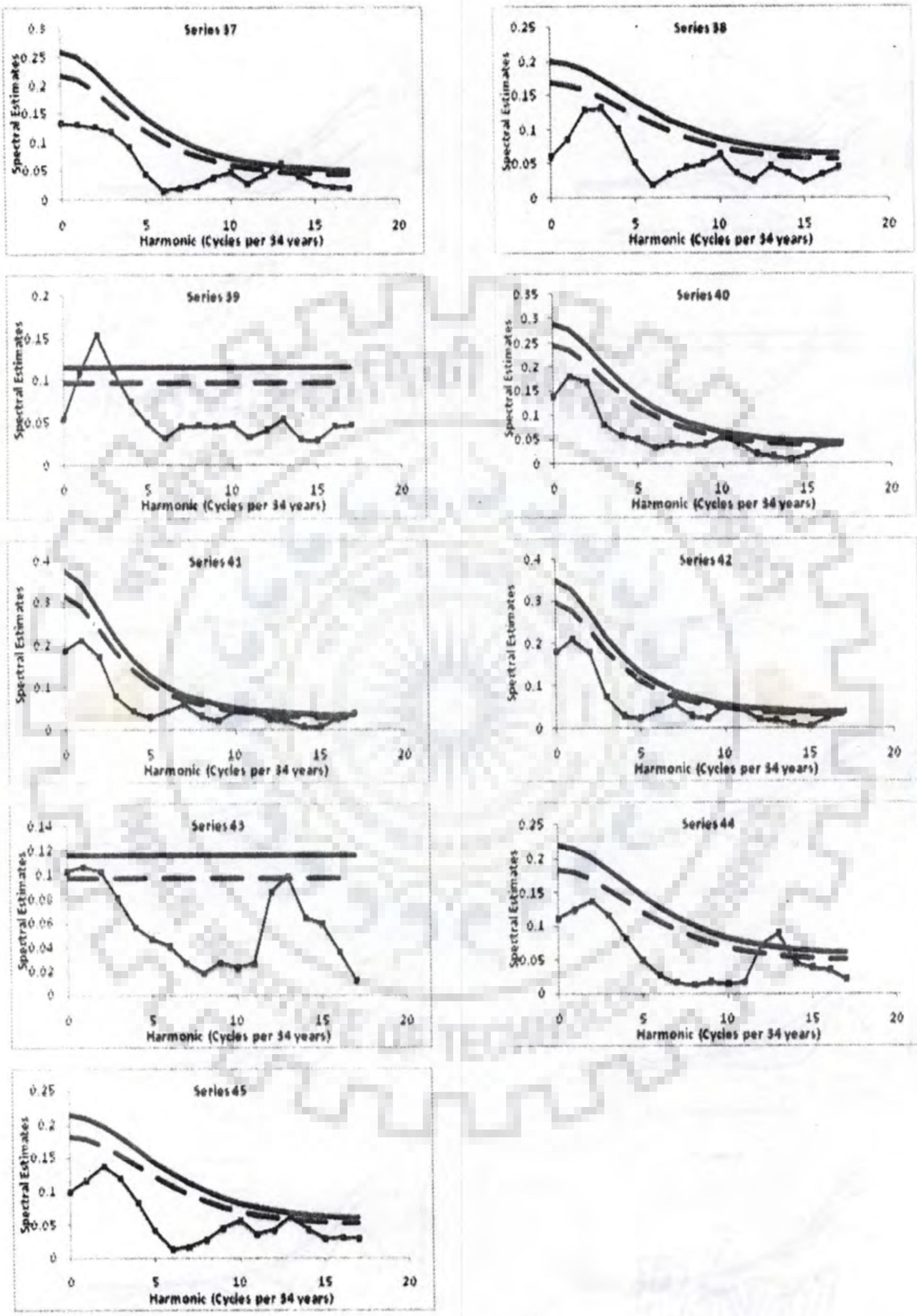

Fig 6.8 (continued)

6.5.7 Mean Wind speed

When stations are examined as a whole, the variations of the annual wind speed series was found to contain all the cycles (Table 6.9 and Fig. 6.9). The presence of short cycles outnumbered the long period cycles. However, some stations exhibit existence of long range periodicity. In few stations sun spot cycle of 19, 12.7 and sunspot cycle was seen. On regional basis except central Himalaya all other regions including all Indian Himalaya cycles of 5-10 years were observed.

Table 6.9 Serial correlation and power spectrum analyses for the annual mean wind speed L: lag; m: maximum lag; WN: white noise; and RN: red noise

Station	**r_1**	**L (m)**	**Cycle**	**Continuum**
Dalhousie	0.745*	-	-	RN
Dharamsala	0.450*	10 (15) 11 (15) 12 (15)	3.0** 2.7** 2.5*	RN
Bhuntar (A)	0.856*	4 (13) 5 (13)	6.5* 5.2**	RN
Mandi	0.662*	9 (15) 10 (15)	3.3* 3.0*	RN
Simla	0.688*	3 (19)	12.7**	RN
Joshimath	0.662*	9 (10)	2.2*	RN
Mussorie	0.444*	8 (19)	7.6*	RN
Tehri	0.622*	3 (8) 4 (8)	5.3** 4.0*	RN
Dehradun	0.452*	11 (19)	3.5*	WN
Mukteshwar	0.505*	16 (19) 17 (19)	2.4** 2.2**	RN
Nainital	0.460*	3 (8) 4 (8)	5.3** 4.0**	RN
Pasighat	0.563*	-	-	RN
Ziro	0.774*	5 (9) 6 (9)	3.6** 3.0**	RN
Gangtok	0.868*	2 (10) 5 (10)	10.0** 4.0*	RN
Kalimpong	0.835*	11 (19) 12 (19) 13 (19)	3.5* 3.2** 2.9**	RN
Darjeeling	0.939*	2 (19) 14 (19) 15 (19)	19.0* 2.7* 2.5**	RN
Western Himalaya	0.716*	2 (10)	10**	RN
Central Himalaya	0.429*	8 (10) 9 (10)	2.5* 2.2**	RN
Eastern Himalaya	0.785*	2 (10) 3 (10) 8 (10)	10** 6.7** 2.5*	RN
All Indian Himalaya	0.753	3 (10) 4 (10)	6.7* 5*	RN

* Significant at 0.90 confidence level; ** Significant at 0.95 confidence level

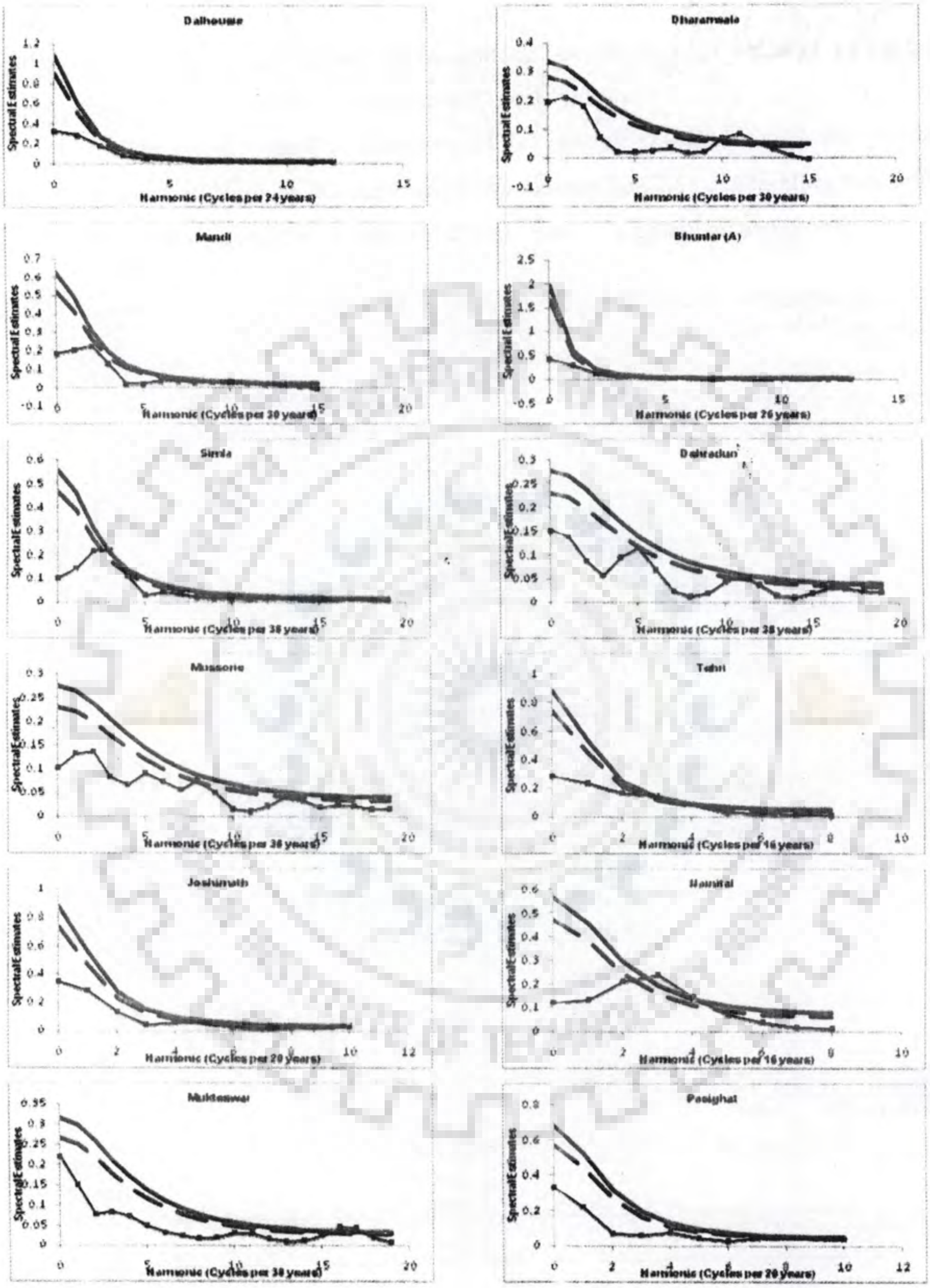

Fig. 6.9 Power spectrum plots of annual mean wind speed of Indian Himalayan stations. – 'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum.

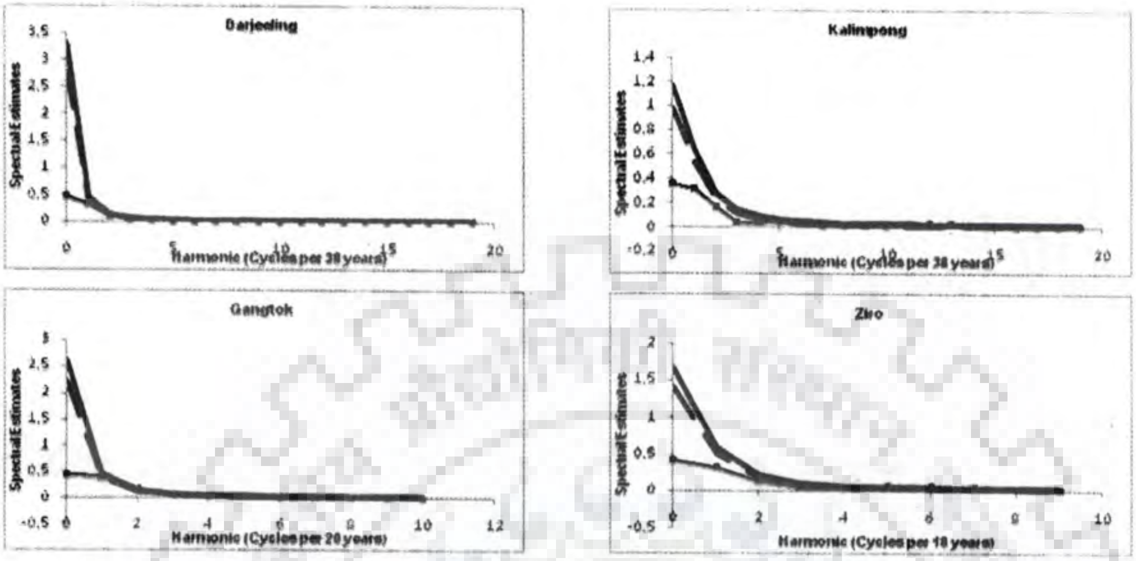

Fig. 6.9 (continued)

Since, in some of the stations and Himalayan regions the periodicity of the sunspot cycle was observed. In order to see that the cycles are actually corresponds to sun spot cycle or not, the sunspot numbers were downloaded from http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt for 1959-1990 and are subjected to power spectrum analysis. The plot of power spectrum is shown in Fig. 6.10. The analysis clearly indicates presence of significant periodicities of 11 ± 1 years and 6.6 ± 1 years. Therefore, the stations exhibited sunspot cycles in different climatic variables are actually present.

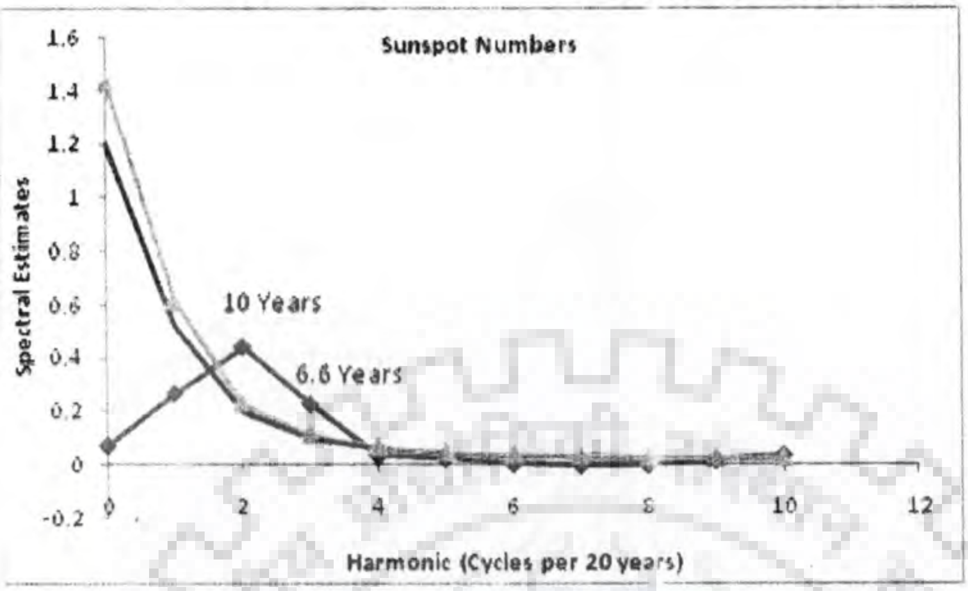

Fig. 6.10 Power spectrum plot of annual sunspot numbers for 1959-1990. – 'null' ('white' or 'red noise') continuum, (------, ——) 90 and 95 Confidence limits of the chosen continuum.

6.5.8 Discussion on Periodicity

The power spectrum analysis indicates that significant periodicities are present in climatological variables. The determined periodicities are dominated by the QBO and short-range cycles. In some cases existence of sunspot cycles (11 ± 1 years) was revealed and same has been verified by the power spectrum analysis of sun spot numbers. In India very limited studies have been found in the literature and mostly dealt with the periodicity in rainfall. The present findings of presence of QBO and sunspot cycle are comparable with the results obtained for different Indian stations (Jagannathan and Bhalme, 1973; Jagannathan and Parthasarathy, 1973; Parathasarathy and Dhar, 1975; Basak and Sengupta, 1998). The present findings are in close agreement with the findings of Bhutiyani, et al. (2010) for western Himalaya except for periodicity of 68 years. The probable reason for the observed periodicities has been the response of sunspot cycle and the anomalous behavior of certain circulation features associated with the different sunspot epochs that suggest that the real cause-effect in the solar-weather relationships may be traceable to changes introduced in the atmospheric circulation. The geographical patterns of how these energetically minute changes in the solar features could be linked to the energetically large changes in the atmosphere are still major questions to be answered. The relationship could not be found with global teleconnections and require further study with more length of records.

CHAPTER 7

STUDY OF EFFECT OF CLIMATE CHANGE ON THE HYDROLOGICAL REGIME OF A TYPICAL HIMALAYAN BASIN

7.1 INTRODUCTION

In Chapters 4, 5 and 6 it is evident that short-term dependence, trends and periodicity is present in the climatological variables of the Indian Himalaya. This indicates that climate of the Indian Himalaya is not stable and some changes have taken place. Whether, these changes have any influence on the river discharge has been studied by selecting a Satluj River basin in the western Indian Himalayas. The major river systems of the Indian subcontinent, Brahmaputra, Ganga and Indus, which originate in the Himalaya, are expected to be extremely vulnerable to climate change because of the substantial contributions from snow and glaciers into these river systems. In spite of high vulnerability, studies related to trend analysis of the Himalayan River are lacking.

In this chapter, the annual and seasonal trends in the discharge, temperature, rainfall and snowfall has been analysed for the Satluj basin (Western Himalaya). Attempts have also been made to investigate the impact of climate change on the timing of centre volume dates and peak date of the discharge.

7.2 REVIEW OF LITERATURE

7.2.1 Impacts on water resources – Global context

Water is fundamental to human life and many other social, economic and industrial activities. It is required for agriculture, industry, ecosystems, energy, transportation, recreation and waste disposal (Frederick and Gleick, 1999). Therefore, any changes in hydrological system and water resources could have a direct effect on the society, environment and economy. There are very complex relations between climate, hydrology and water resources. Climatic processes influence the hydrologic processes, vegetation, soils and water demands (Kaczmarek et al., 1996).

Precipitation is the main driver of variability in the water balance over space and time. Change in precipitation could have very important implications for hydrology and water resources

(IPCC, 2001b). Floods and droughts primarily occur as a result of too much or too little of precipitation. Various empirical and model studies suggest that the trends in precipitation vary in space and time over the globe, with a general increase in mid- and high latitudes in the northern hemisphere and a general decrease in the tropics and subtropics in both hemispheres. Increasing temperatures mean decreasing proportions of precipitation as snowfall. Snow may cease to occur in areas where snowfall currently is marginal. This would have substantial implications for hydrological regimes (IPCC, 2001b).

Warmer temperature increases the water holding capacity of the atmosphere (Cline, 1992; IPCC, 2001b); which generally results in an increased potential evaporation, i.e. evaporative demands. However, the actual rate of evaporation is constrained by water availability. The amount of water stored in the soil influences directly the rate of actual evaporation, ground water recharge and generation of runoff (IPCC, 2001b).

Changes in River flows from year to year have been found to be much more strongly related to precipitation changes than to temperature changes (IPCC, 2001b). The patterns of changes in River flow are broadly similar to the change in annual precipitation, i.e. increases in high latitudes and many equatorial regions, but decreases in mid-latitudes and some subtropical regions (IPCC, 2001b). Generally, increase in evaporation means that some areas may experience reduction in runoff despite some increases in precipitation. The real impacts of climate changes vary with catchment characteristics. For example, the streams with smaller catchments are generally more sensitive to these changes (IPCC, 2001b).

Under climate change, many River systems show changes in the timing and magnitude of seasonal peak and low flows. For example, peaks tend to occur earlier due to earlier snowmelt in cold climate zones. Although there is widespread consensus that climate changes cause substantial impacts on hydrology and water resources, the magnitude and direction of these impacts vary in space and time (Cohen et al., 1996).

Many Rivers maintaining flows through the summer season are supported by glaciers. Snow and glaciers supply at least one-third of the water used for irrigation in the world (Singh and Singh, 2001). Higher temperatures will increase the ratio of rain to snow; accelerate the rate of snow- and glacier-melt; and shorten the overall snowfall season (Frederick and Gleick, 1999). Since the end of the Little Ice Age, the temperatures have been generally increasing (Oliver and Hidore, 2003) and the majority of the world's glaciers are retreating (IPCC 2001b). Orlemans and Hoogendorn (1989) have reported that 1 K temperature change leads to a change of equilibrium-line altitude (i.e. the altitude where the accumulation of a glacier equals to its ablation) of 130 m in the Alps. Increasing temperature shifts the permanent snowline upward. This could cause a significant reduction of water storage in the mountains, which is likely to pose serious problems of water availability to many people living in the hills and downstream (Kulkarni et al., 2004).

7.2.2 Impacts on Water Resources – the Indian Himalayan Perspectives

Singh et al. (1995) and Singh and Kumar (1997b) studied precipitation distribution in the mountainous basins located in different parts of Himalayan region. In these studies main emphasis was laid to study the effect of altitude on precipitation distribution.

Mirza et al. (1998) analysed precipitation series of Ganges, Brahmaputra and Meghana River basins of Himalayan region and found that precipitation in the Ganges basin is stable. Precipitation in one subdivision in the Brahmaputra basin shows a decreasing trend and other shows an increasing trend. One of the three subdivisions in the Meghana basin shows increasing trend while another shows an increasing trend. The persistent was found to be absent in precipitation series in the Ganges basin but it was present in two common subdivisions in the Brahmaputra and Meghna basins.

7.2.3 Snow and Glacier Studies

Long-term records on glacier fluctuations on the global scale indicating mass loss/retreat of mountain glaciers support evidence of change in the climate in the past 100 years (Letréguilly and Reynaud, 1990). Streamflow in most of the Himalayan Rivers is minimal in winter and early springs because flows decrease rapidly after the monsoon rains (Kattelmann, 2003).

The effect of climate change on snow water equivalent, snowmelt runoff, glacier melt runoff and total streamflow and their distribution was examined for the Spiti River by Singh and Kumar (1997a). The snow water equivalent reduces with an increase in air temperature. The projected increase in air temperature (T+1 to T+3 °C) did not reveal any significant changes in the snow water equivalent. An increase of 2 °C in air temperature reduced annual snow water equivalent in the range of 1 to 7%. Changes in precipitation caused proportional changes in snow water equivalent. It was further revealed that an increase of 2 °C in air temperature enhanced annual snowmelt runoff, glacier melt runoff and total streamflow in the range of 4-18%, 33-38% and 6-12%, respectively. The seasonal analysis of total streamflow indicated that an increase in air temperature produces an increase in the pre-monsoon season followed by an increase in the monsoon season.

Singh and Kumar (1997b) mentioned that snowfall increases linearly with elevation in the greater Himalayas. The ratio of snowfall to annual precipitation varies linearly with altitude. All stations of Satluj and Beas basin recorded more than 60% snow contribution to annual precipitation. Further, the Extrapolated relationship indicated that snow and rain contribute equally at about 2000 m and all the precipitation occurs as snow above 5000 m.

Snow and glacier melt forms an important part of annual runoff of many Himalayan Rivers. The snow and glacier contribution into annual flows of major Rivers in the eastern Himalayas is about 10% but more than 60% in the western Himalayas (IPCC, 2001b).

Dry season runoff of these Rivers is largely comprised of snow and glacier melts, which is the main source of water for irrigation, hydroelectric power and drinking water supply for the population downstream (Singh and Singh, 2001). Increasing temperature would lead to reduction in snow and glacier volume and thereby reduction in water availability in the Himalayas. In addition, reduction in Himalayan snow cover would lead to heavier monsoon in the Indian sub-continent (Khandekar, 1991; Meehl, 1994) that would increase the likelihood of floods.

Singh and Jain (2002) attempted to estimate the average contribution of snow and glacier melt runoff to the annual flows of the Satluj River (Indian part) at Bhakra Dam using water balance approach for 10 years (October 1986 – September 1996).The average contribution of snow and glacier melt in the annual flow of Satluj River at Bhakra was found to be about 59%, the remaining 41% being from rain, showing that snow and glaciers provide a substantial contribution of snow melt runoff would be higher than 59% due to higher percentage of snow covered area in the total area.

Singh and Bengtsson (2003) prepared snow depletion curves for the warmer climate scenarios (T+1, T+2, T+3 °C) for the Satluj basin in the western Himalaya and compared with snow covered area of the present climate. Their study revealed that under a warmer climate scenario, the melting of snow is accelerated and snow cover disappeared at a faster rate compared to present climatic conditions. The retreat of snow covered area is simulated to be ahead of present climate by 20, 31, and 40 days for the T+1, T+2 and T+3 °C scenarios, respectively. From their study it was found that reduction in melt from the lower part of the basin owing to a reduction in snow covered area and shortening of the summer melting season and, in contrast, an increase in the melt from the glaciered part owing to larger melt and extended ablation period. The impact of climate change was found to be more prominent on seasonal rather than annual availability. Reduction of water availability during the summer period may have severe implications on water resources of the region because of high demand of water during this period.

Singh and Jain (2003) used a conceptual snowmelt model to simulate daily streamflow for the Satluj River basin in the western Himalayan region and observed that most of the peaks in the straemflow were generated by rainfall. However, prolonged high flows were generated by the melting of snow. The results further suggested that more than two-thirds of annual flow is generated from snowmelt runoff. The seasonal distribution of streamflow indicated that about 60% of annual flows were generated during the summer season and about 75% of the summer flow was obtained from snowmelt.

Singh and Bengtsson (2004) in another study of Satluj River basin showed that the melt rate at a point will increase in the warmer climate and the extension of glaciers will reduce, if snow precipitation does not increase. If snow precipitation increases much, the glaciers may grow in size even in a warmer climate.

Changes in snowfall pattern have been observed in the Himalayas and almost 67% of the glaciers have retreated in the past decade (IPCC, 2001b). The Gangotri glacier in the western Himalayas has been retreating by about 30 m /yr. The Pindari glacier in Uttar Pradesh of India retreated by 2,840 m during 1845-1966 with an average retreat rate of 135.2 m /yr (Shrestha, 2005).

Negi et al. (2009) have evaluated accumulation and ablation pattern of snow cover in Pir Panjal and Shamshawari ranges of Kashmir valley by monitoring the snow cover using multi-temporal WiFS sensor data of IRS-1C/1D satellites between November and April 2004-05 to 2006-07 . The study showed that snow cover undergoes number of variations during the winter in Kashmir valley and overall reduction in seasonal snow cover during the monitoring period was revealed. Further, March onwards considerable melting was observed in all regions.

More recently Shekhar et al. (2010) studied snowfall patterns in the western Himalayan range and revealed a decrease in total seasonal snowfall of 280 cm over the entire western Himalaya between 1988/89 to 2007/08. The snowfall decreased by ~ 280, 80 and 440 cm over the Pir Panjal, Shamshawari and Greater Himalaya ranges, respectively. The decreasing trend in total seasonal snowfall over the Karkoram range is only ~40 cm.

7.2.4 River Discharge Studies

The Himalayan Rivers are expected to be very vulnerable to climate change because snow and glacier meltwater make a substantial contribution to their runoff (Singh, 1998). However, the degree of sensitivity may vary among the River systems. The peak melting season in the Himalayas coincides with the summer monsoon season, any intensification of monsoon or accelerated melting would contribute to increased summer runoff that ultimately would result in increased flood disasters (IPCC, 2001b). The increase in temperature would shift the snowline upward, which reduces the capacity of natural reservoir. This situation would increase the risk of flood in the Himalayan region.

An impact assessment study for a number of Himalayan basins contributing to the Ganges showed that changes in mean runoff in different sub-basins ranged from 27 to 116% in a climate forced by doubling CO_2 concentrations (Mirza, 1997). Shifts in the timing and intensity of the monsoon, and the manner in which the Himalayan range intercepts the available precipitable water content of the atmosphere, will have major impacts on the timing and amount of runoff in River basins such as the Ganges and Brahmaputra was indicated by him.

The impact of climate change using the HadRM2 climate change scenario on the current availability of water resources in 12 River basins of India has been studied using Soil and Water assessment Tool (SWAT) water balance model (MoEF, 2004). It was observed that the impacts are different in different catchments. The increase in rainfall due to climate change does not result in an increase in the surface runoff as is generally predicted. Though an increase in precipitation is projected for the Mahanadi, Brahmani, Ganga, Godavari, and Cauvery basins for the climate change scenario, the corresponding total runoff for all these basins has not increased. In the remaining basins, a decrease in precipitation is projected. The resultant runoff for the majority of cases except for the Narmada and Tapi, is projected to decline.

Bhutiyani et al. (2008) carried out trend analysis of four northwestern Himalayan Rivers for a longer period of record. They revealed significant decrease in the annual and monsoon discharge of Satluj despite increasing temperatures and average monsoon precipitation. Their study indicated decreasing contribution of glaciers to the discharge and the glaciers are disappearing gradually. Further, the annual maximum series of peak discharge revealed significant increasing trends in Satluj, Chenab and Ravi Rivers and significant decreasing trend in the Beas River in northwestern Himalaya.

7.2.5 Impacts on Water Resources – the Neighboring Himalayan Perspectives

Aizen et al. (1997) observed a decrease in snow cover in all the altitudinal belt at Tien Shan. Annually the maximum snow thickness and snow duration decreased by 10 cm and 9 days, respectively. The maximum (minimum) decrease of 0.36 (0.012) cm/year was observed at altitude above 2000 m in the western region. The warm season runoff showed decrease in the value at all altitudes. Significant decrease of 0.10, 0.05 and 0.06 $m^3/s/year$ in central region above and below 2000 m and; in western region above 2000 m, respectively was revealed from their analysis. The annual runoff follows the same significant trends with different magnitude. On Tien Shan region as a whole significant decrease in seasonal and annual runoff was also found.

A runoff sensitivity analysis by Mirza and Dixit (1997) showed that a 2°C rise in temperature would cause a 4% decrease in runoff, while a 5°C rise in temperature and 10% decrease in precipitation would cause a 41% decrease in the runoff of the Ganges River near New Delhi.

Westmacott and Burn (1997) reported that over the Churchill-Nelson River basin the magnitude of hydrologic events decreased over time while snowmelt runoff events occurred earlier. The only exceptions to this behavior were the spring mean monthly streamflow values which exhibited increasing trends due to the potential for snow melting during this period.

River discharge is influenced by climate, land cover and human activities (Sharma et al., 2000a), and it is difficult to disaggregate the climatic impact from non-climatic impacts on River discharge. However, River discharge analysis for 1947-1994 in the Koshi Basin in eastern Nepal showed a decreasing trend particularly during the low-flow season. Sharma et al. (2000b) through a sensitivity analysis of River runoff in the same basin showed that the runoff increase was higher than the precipitation increase assuming temperature constant and an increase in temperature of 4°C assuming precipitation constant would cause a decrease in runoff by two to eight percent.

Archer (2003) explored the relationship between climatic variables and streamflows for three basin in the Upper Indus Basin in Pakistan and showed that the summer volume governed by melt of glaciers and permanent snow, melt of seasonal snow (control by winter and spring precipitation) or winter and monsoon rainfall. He has obtained good correlation between streamflow and temperature and precipitation at valley sites.

Studies of Li et al. (2004) for trends in annual natural runoff in Yellow River basin showed slight decreasing trend in precipitation and a strong reduction of annual runoff. The similarities observed in trends and patterns in natural runoff and precipitation implied that changes in natural runoff may be related to changes in annual precipitation.

The annual runoff of the Alkananda River in the western Himalayas increased by 2.8% /yr for 1980-2000, whereas that of Kali Gandaki River in Nepal Himalayas increased by about 1% annually for 1964-2000 (Shrestha, 2005). Glacier retreat has immediate implications for downstream flows in the Himalayan Rivers. In Rivers fed by glaciers, the runoff first increases as more water is released by melting due to warming. As the snow and glacier volume gets smaller and the volume of meltwater reduces, dry season flows will decline to well below present levels (Shrestha, 2005).

The impact of manmade activities in terms of soil conservation measures on the stream flow of Wuding River basin, a tributary of the yellow River of China for the period 1961-1997 was evaluated by Li et al. (2007). The analysis indicated a significant down ward trend in annual stream flow after 1972, which corresponds to increased soil conservation measures adopted in the basin. Further, on comparing the stream flow pattern for the splitted period i.e. 1961-1971 and 1972-1997, the annual stream flow during the period 1972-1997 was 31% as compared to 1961-1971 period (period before the starting of soil conservation work). It was revealed from their study that climatic variability accounts for 13% whereas soil conservation measures were responsible for 87% of the total reduction in mean annual stream flow. This clearly indicates that human activities are the major cause in reducing the natural stream flow.

Hewitt (2005) reported that some glaciers of the central Karakoram are growing and attributed this to the higher elevations and distinct climatic regimes of these glaciers. He found an increasing trend in winter temperature which he concluded was not critical for these higher glaciers. Glaciers are melting in the eastern Himalaya due to local warming effects, such as increased fossil fuel burning and deforestation.

Yang et al. (2005) analysed reconstructed time series of annual discharge of the Yangtze River basin and found a significant decreasing trend inspite of slight increase in precipitation and melt water. The discharge had decreased by 8.2% from 1865 to 2004. The decreasing trend in discharge was attributed to human activities especially increasing consumption of water.

Sharma and Shakya (2006) analysed different aspects of discharge (annual and seasonal flows, extremes flows, monthly hydrograph) of Baghmati River at Nepal and revealed that mean yearly flow and monsoon season flow in the Bagmati River has decreased significantly. However, post-monsoon and pre-monsoon seasonal flows were more or less constant. A late shifting of peak in hydrograph by one month, decrease in instantaneous maximum discharge and increase in instantaneous minimum discharge was revealed from their study.

Zhang et al. (2006) investigated temporal trends in annual maximum discharge at Yichang, Hankou and Datong representing upper, middle and lower reaches, respectively of Yangtze River. The linear slope indicated a downward trend of 6.53 for the whole annual maximum series at Yichang while increasing trend of 93.4 was found at Hankou station.

Fu et al. (2004) indicated that stream flow is sensitive to both precipitation and temperature. For small precipitation increases (less than 13%), the stream flow percentage change is less than the precipitation change for the yellow River.

Zheng et al. (2007) investigated changes in stream flow regime of four headwater catchments of the Yellow River basin during the period 1956-2000. The results of their investigation showed that annual stream flow decreased in all the four catchments with the decreasing precipitation in the monsoon (wet) season. The reason for the reduction in stream flow is attributed mainly due to reduced precipitation in monsoon season. They indicated that rising temperature may lead to more snowmelt from the permanent snow packs and glaciers, the increasing snowmelt runoff would be offset by runoff reduction due to decreased precipitation and hence, increasing temperature had a limited impact on runoff.

7.3 STUDY AREA AND DATA USED

7.3.1 Description of Satluj River Basin

The Satluj River basin upstream the Bhakra Reservoir (Indian part) located in the western Himalayan region is selected to study the impact of climate change on water resources of Indian Himalaya. The Satluj River rises from the lakes of Mansarover and Rakastal in the Tibetan plateau at an elevation of more than 4500 m and forms a part of the Indus River system. In the lower part of the basin only rainfall is experienced. The topographical setting and availability of abundant water provides a huge hydropower generation potential in this River. Several hydropower schemes exist and more are planned for this River. The Bhakra Dam, the oldest dam in India, is situated on this River in the foothills of the Himalayas. This dam is considered a boon to north India both for hydropower production and irrigation. The total drainage area of the Satluj River up to Bhakra Dam is about 56,874 km^2. The area of the present study basin (Indian part) is about 22,275 km^2, including the whole catchment of the Spiti basin (a major tributary of the Satluj). The altitude of the basin varies from about 500 m to 7000 m. About 57% area of the basin lies between 3600 and 5400 m altitude, and only a very small area lies above 6000 m. Owing to large differences in seasonal temperatures and the great range of elevation in the basin, the snowline is highly variable, descending to an elevation of about 2000 m during winter and receding to above 5000 m after the summer season.

7.3.2 Climate of Satluj River Basin

This River basin is characterized by diversified climatic patterns. The westerly weather disturbances deposit nearly all the precipitation during the winter months in the upper part and middle part of the basin and most of the precipitation falls in the form of snow in this season. The major part of the basin area lies in the greater Himalayas where heavy snowfall takes place. The monsoon rains have little influence in the greater Himalayan range, where the annual rainfall is about 200 mm (Singh and Kumar, 1997b). Part of the Satluj River is within the middle and outer Himalayan range for which the annual rainfall is about 700 and 1300 mm, respectively (Singh and Kumar, 1997b). The rainfall is not uniformly distributed and mainly concentrated in the lower part of the basin. Reliable information on snowfall and its distribution is not available for the whole basin.

Depending on the climatic conditions of the basin, the seasonal snowpack which are developed during winter, starts melting around March month and depletes either fully or partially during the forthcoming summer season. The runoff produced from the upper part of the basin is mainly due to the melting of snow, whereas in the lower part it is the contribution of rainfall. The middle and upper parts of the basin have contributions from both rain and snowmelt. As the altitude within the basin increases, the rain contribution to stream flow reduces but snowmelt contribution increases. Runoff is dominated by snowmelt-induced runoff above 3000 m altitude, whereas above 4000 m there is also glacier melt contribution in summer. The contribution of rain and to the stream flow varies with time. Stream flow receives higher contributions from snowmelt during summer, whereas in the monsoon period rainfall contribution exceeds the snowmelt contribution to stream flow. The average contribution to annual runoff from melting of snow and glaciers is estimated to be about 60% (Singh and Jain, 2002).

7.3.3 Data Used

The observed daily maximum and minimum temperatures (mean temperature – derived) of six stations, rainfall data of eight stations and snowfall data of four stations were used in the present study. The River discharge is measured at the River basin outlet Bhakra and also at the upstream Namagia. Difference in discharge of these two stations provided the discharge from the study area. The meteorological, hydrological and snowfall data were made available by Bhakra Beas Management Board (BBMB), Nangal Township (Punjab), India. The BBMB is the organization responsible for data collection and operation of Bhakra Dam. The locations of the meteorological stations used in the present study are shown in Figure 7.1 and the details about the stations in

Table 7.1. The altitude of the meteorological stations used in this study varied from 518 to 3639 m. Because of the limited data availability the study was carried out for a uniform period of 17 years i.e. from 1985 to 2002.

Table 7.1 Hydrometeorological data and elevation of different stations used in the study. Rainfall (P), Temperature (T), Discharge (Q), Snowfall (SN)

Station	Elevation (m a.s.l.)	Hydrometeorological variable
Bhakra	518	P,T,Q
Suni	625	P
Kasol	661	P
Rampur	1066	P,T,Q
Kalpa	2439	P,T,SN
Namgia	2910	P,T,SN
Rakchham	3130	P,T,SN
Kaza	3639	P,T,SN

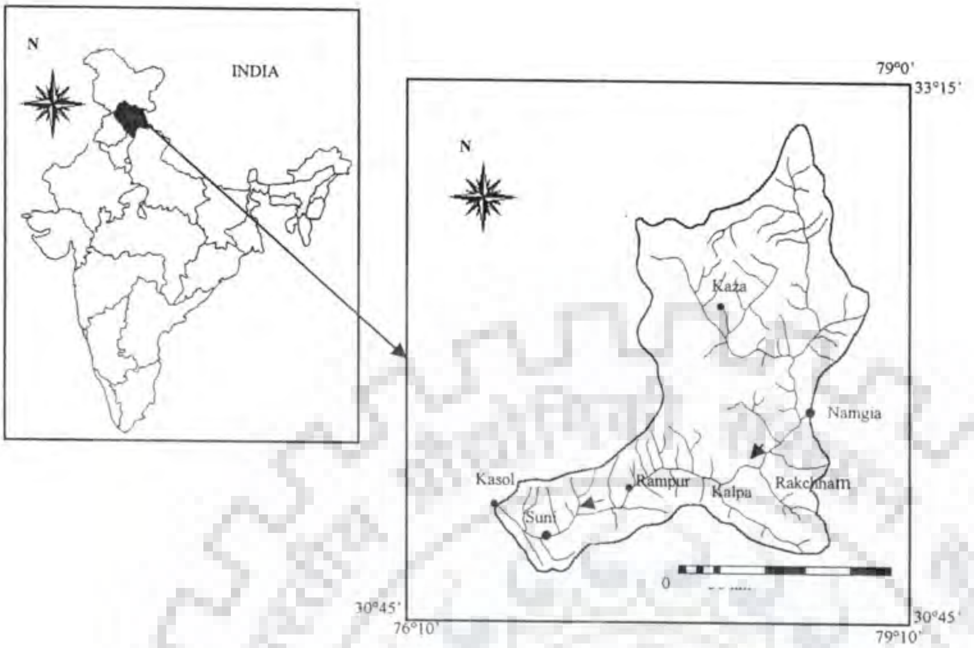

Fig. 7.1 Location map of Satluj Basin upstream Bhakra Dam (Indian part) with location of hydrometeorological stations.

The monthly and annual averages for all the climatological variables of all the stations were calculated and presented in Table 7.2 to 7.6. The average annual mean temperature had a variation from 2.8 °C at Kaza to 24.1 °C at Bhakra with a mean value of 12.5 °C (Table 7.4). The average annual mean temperature is slightly lower in comparison to the overall mean of the Indian Himalayan stations. In regard to the precipitation variation, it may be seen from Table 7.5 that precipitation is confined to low altitude stations. The high altitude stations receive precipitation mainly in the form of snowfall. The maximum depth of snowfall was recorded at Rakchham while Namgia recorded minimum snowfall depth (Table 7.6).

Table 7.2 Monthly and annual averages of mean maximum temperature for the stations of Satluj River basin

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bhakra	20.7	23.1	28.2	34.7	38.6	38.1	33.8	32.5	32.5	30.7	27.3	22.5	30.2
Rampur	18.1	19.8	23.7	29.2	33.2	34.2	32.7	31.7	31.2	29.0	24.5	19.7	27.2
Kalpa	4.2	5.4	9.4	15.7	20.1	23.1	23.0	21.8	20.7	17.8	13.2	7.8	15.2
Namgia	4.6	6.9	11.0	17.5	22.1	25.7	27.8	26.7	25.0	19.5	14.5	8.0	17.4
Rakchham	3.9	5.3	7.7	12.2	17.0	19.5	19.9	19.1	17.2	13.3	10.1	6.1	12.6
Kaza	-7.1	-9.6	-6.5	0.6	12.9	19.6	23.9	25.3	21.4	14.1	8.0	0.6	8.6
Mean	**7.4**	**8.5**	**12.3**	**18.3**	**24.0**	**26.7**	**26.8**	**26.2**	**24.7**	**20.7**	**16.3**	**10.8**	**18.5**
Max	**20.7**	**23.1**	**28.2**	**34.7**	**38.6**	**38.1**	**33.8**	**32.5**	**32.5**	**30.7**	**27.3**	**22.5**	**30.2**
Min	**-7.1**	**-9.6**	**-6.5**	**0.6**	**12.9**	**19.5**	**19.9**	**19.1**	**17.2**	**13.3**	**8.0**	**0.6**	**8.6**

Table 7.3 Monthly and annual averages of mean minimum temperature for the stations of Satluj River basin

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bhakra	9.2	10.8	14.3	19.5	23.6	24.8	23.9	23.5	22.4	18.5	14.3	10.5	17.9
Rampur	4.5	6.2	9.3	13.4	17.5	20.5	22.3	21.8	19.3	13.6	8.7	5.1	13.5
Kalpa	-4.0	-3.4	-0.2	4.3	7.8	11.5	13.8	13.3	10.2	5.2	1.8	-1.5	4.9
Namgia	-5.6	-3.4	0.0	5.3	8.2	12.3	15.5	14.6	11.2	4.7	0.9	-3.0	5.1
Rakchham	-9.0	-8.0	-4.8	0.5	4.2	7.5	11.0	10.8	6.4	0.3	-2.7	-6.2	0.8
Kaza	-18.6	-20.6	-17.4	-10.9	1.4	8.4	12.8	14.3	10.6	2.9	-4.9	-12.2	-2.8
Mean	**-3.9**	**-3.0**	**0.2**	**5.4**	**10.4**	**14.2**	**16.6**	**16.4**	**13.4**	**7.5**	**3.0**	**-1.2**	**6.6**
Max	**9.2**	**10.8**	**14.3**	**19.5**	**23.6**	**24.8**	**23.9**	**23.5**	**22.4**	**18.5**	**14.3**	**10.5**	**17.9**
Min	**-18.6**	**-20.6**	**-17.4**	**-10.9**	**1.4**	**7.5**	**11.0**	**10.8**	**6.4**	**0.3**	**-4.9**	**-12.2**	**-2.8**

Table 7.4 Monthly and annual averages of mean temperature for the stations of Satluj River basin

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bhakra	15.0	17.0	21.2	27.1	31.1	31.4	28.9	28.0	27.4	24.6	20.8	16.5	24.1
Rampur	11.3	13.0	16.5	21.3	25.3	27.4	27.5	26.7	25.3	21.3	16.5	12.5	20.4
Kalpa	0.2	1.0	4.6	10.0	13.9	17.3	17.5	17.5	15.5	11.5	7.5	3.2	10.0
Namgia	-0.5	1.7	5.5	11.5	15.1	19.0	21.3	20.7	18.1	12.1	7.7	2.4	11.2
Rakchham	-2.6	-1.4	1.4	6.3	10.6	13.5	15.4	14.9	11.8	6.8	3.5	-0.1	6.7
Kaza	-12.8	-15.1	-11.6	-5.1	7.2	14.0	18.4	19.7	15.4	8.5	1.5	-5.8	2.8
Mean	**1.8**	**2.7**	6.3	**11.8**	17.2	**20.4**	**21.5**	**21.3**	**18.9**	**14.1**	**9.6**	**4.8**	**12.5**
Max	**15.0**	**17.0**	21.2	**27.1**	**31.1**	**31.4**	**28.9**	**28.0**	**27.4**	**24.6**	**20.8**	**16.5**	**24.1**
Min	**-12.8**	**-15.1**	-11.6	**-5.1**	7.2	**13.5**	**15.4**	**14.9**	**11.8**	**6.8**	**1.5**	**-5.8**	**2.8**

Table 7.5 Monthly and annual averages of rainfall for the stations of Satluj River basin

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	Monsoon	% of annual
Bhakra	43.0	55.1	45.5	24.9	43.7	104.8	418.0	388.0	198.5	30.8	14.3	44.6	1411.3	1109.3	78.6
Suni	51.5	67.1	69.7	42.9	70.4	122.7	218.0	195.0	105.6	27.1	15.3	42.1	1027.4	641.3	62.4
Kasol	51.4	62.3	56.2	34.8	65.2	144.9	338.5	374.8	140.3	33.7	14.7	40.3	1357.1	998.5	73.6
Rampur	48.5	68.8	88.3	38.9	59.4	63.5	137.8	136.4	83.0	22.1	13.9	30.4	790.8	420.6	53.2
Kalpa	0.9	0.9	28.7	54.8	74.2	41.2	43.4	56.0	58.4	35.1	4.9	1.0	399.5	199.0	49.8
Namgia	0.3	0.6	10.0	26.2	20.8	8.8	17.0	15.8	9.5	10.7	1.4	0.7	121.8	51.1	42.0
Rakchham	0.0	0.0	0.0	19.2	27.1	28.0	49.1	48.7	32.8	15.4	0.0	0.0	220.2	158.5	72.0
Kaza	0.0	0.0	0.2	0.0	8.3	13.7	43.4	33.5	20.4	2.4	0.0	0.0	121.7	110.9	91.1
Mean	**24.4**	**31.8**	**37.3**	30.2	**46.1**	**65.9**	**158.1**	**156.0**	**81.1**	**22.2**	**8.1**	19.9	**681.2**	**461.2**	**65.3**
Max	**51.5**	**68.8**	**88.3**	54.8	74.2	**144.9**	**418.0**	**388.0**	**198.5**	35.1	**15.3**	44.6	**1411.3**	**1109.3**	**91.1**
Min	**0.0**	**0.0**	**0.0**	0.0	8.3	**8.8**	17.0	**15.8**	9.5	2.4	**0.0**	**0.0**	**121.7**	**51.1**	**42.0**

Table 7.6 Monthly and annual averages of snowfall for the stations of Satluj River basin

Station	Nov	Dec	Jan	Feb	Mar	Apr	Total
Kalpa	20.5	42.8	93.7	133.0	146.3	28.4	464.6
Namgia	3.4	17.8	27.4	45.5	52.7	5.6	152.4
Rakchham	18.8	43.0	65.6	106.4	150.6	54.8	439.2
Kaza	11.2	31.4	54.8	89.2	135.1	54.2	375.9
Mean	**13.4**	**33.8**	**60.3**	**93.5**	**121.2**	**35.7**	**358.0**
Max	**20.5**	**43.0**	93.7	**133.0**	**150.6**	**54.8**	**464.6**
Min	**3.4**	17.8	27.4	**45.5**	52.7	5.6	**152.4**

7.4 METHODOLOGY

For proper understanding of physical impacts of climate change on water resources the trend analysis (MK trend test and Linear regression test) of temperature (mean temperature, mean maximum and mean minimum temperatures), rainfall, snowfall and River discharge are attempted using HYDROSPECT software. The details of the methodology have already been described in Chapter 5 under sub-section 5.4.1 however, for its completeness the same is described as below:

7.4.1. Resampling Technique (Radziejewski and Kundzewicz (2000)

Resampling offers an alternative way to compute the significance levels of tests results. It may allow us to use a test even if its assumptions are not satisfied by the series like uncorrelated series. Resampling works by generating many random time series with distribution identical to that of the time series. The test results obtained for the original time series are compared with to those obtained for the random series and significance is evaluated based on this comparison. Random series are generated either by permuting the series (sampling its value without replacement) or by sampling its values with replacement (bootstrapping). Radziejewski and Kundzewicz (2000) have developed HYDROSPECT software package for detection of trends in a climatolgical time-series by incorporating several test and suggested that results obtained from resampling are probably more valid than without resampling. The method is now the preferred method for detecting trend in climatological series (Kundzewicz and Robson, 2000). Therefore, in this study, the climatological variables at annual and seasonal time scales were subjected to MK trend detection test with resampling (bootstrapping) techniques and the magnitude of trend was estimated with linear regression using HYDROSPECT software (Radziejewski and Kundzewicz, 2000).

7.4.2 Mann-Kendall Test

In HYDROSPECT software Mann-Kendall test can only be applied to a series of ranks or ranked deviations from the median. So the raw data were pre-processed and ranks were calculated using the inbuilt option in the software. The test statistic displayed is Kendall's sum (commonly denoted as S) divided by the square root of its variance under the hypothesis of independent and identically distributed observations. The test statistic equals

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \qquad (7.1)$$

where, x_j are the sequential data values, n is the length of the data set and

$$\operatorname{sgn}(t) = \begin{cases} 1, & for\, t > 0 \\ 0, & for\, t = 0 \\ -1, & for\, t < 0 \end{cases} \qquad (7.2)$$

The value of S indicates the direction of trend. A negative (positive) value indicate falling (rising) trend. Mann-Kendall documented that when $n \geq 8$, the test statistics S is approximately normally distributed with mean and variance as follows:

$$E(S) = 0 \qquad (7.3)$$

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \qquad (7.4)$$

where, m is the number of tied groups and t_i is the size of the i^{th} tie group. The standardized test statistics Z is computed as follows.

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & for\, S > 0 \\ 0 \quad , & for\, S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, & for\, S < 0 \end{cases} \qquad (7.5)$$

The HYDROSPECT software displays the Z score and associated significance level for the chosen bootstrap sampling (1000 in this case) and; as an option it also displays Kendall's *tau*.

The significance level is valid under the null hypothesis of independent and identically distributed observations. For linear regression test it gives correlation coefficient, significance level and the change in slope value.

7.4.3 Interpretation of Hydrospect Results (Radziejewski and Kundzewicz (2000)

Hydrospect returns the values of the test statistic and of the significance level actually achieved. High value of the actual significance level means that the hypothesis of a lack of change is rejected in the light of evidence. If the significance level returned by Hydrospect is 99% (tantamount to 1% in another convention), there is a high chance that a change exists in the hydrological time series subject to analysis. A value of significance equal to 99.3% means that a change is detected at the 95% (or 5%) significance level and at the 99% significance level, but not at the 99.9% (or 0.1%) level. For the present trend analysis the interpretations were made at 90% significance level.

7.5 RESULTS AND DISCUSSION

7.5.1 Temperature trends

7.5.1.1 Mean Temperature

The annual mean temperature is increasing in all most all the stations except Bhakra where it is decreasing (Table 7.7). Both the trend determination techniques indicated significant rise of annual mean temperature at Rampur, Kalpa, Namgia and Rakchham. The highest rate of rise of 1.82 °C/decade was observed at Namgia which also receive winter precipitation in the form of snow. The basin scale analysis also indicates significant warming of the Satluj River basin with significant rise of 1.17 °C/decade in annual mean temperature. The individual stations and basin wide analysis point towards warming of Satluj River basin during the period of study. Fig. 7.2 shows the normalized mean temperature for the Satluj River basin. The warming trend in the mean temperature is clearly visible. On seasonal basis the pre-monsoon temperature exhibited warming at majority of the stations with significant trends at four stations out of six with a greater rise of 2.70 °C/decade at Namgia. The warming was significant in winter, monsoon and post-monsoon seasons at different stations. Basin wide analysis reveal that mean temperature in all the four seasons was rising but it was significant in pre-monsoon, monsoon and post-monsoon seasons only.

Warming of western Himalaya was reported by many researchers (Bhutiyani et al, 2007; Dash et al., 2007; Shekhar et al., 2010) with varying estimates of rising. For the whole Satluj River basin the estimated rise in annual mean temperature by about 1.17 °C/decade compares well with the reported rising trend of ~2.0 °C during 1984-85 to 2006-07 for the western Himalaya by Shekhar et al. (2010). In neighboring country China, about 70% of the stations in Yellow River basin of indicated significant warming trends (Fu et al., 2004). In contrast to present finding of warming of mean annual temperature, the Upper Indus Basin, Pakistan indicated cooling of mean annual temperature between 1961-1990 (Fowler and Archer, 2006). The mean winter temperature increase of 0.23 °C/decade is in close agreement with the findings of Bhutiyani et al. (2007) who computed a rise of 0.17 °C/decade for the northwestern Himalaya. The warming of winter season was also reported by Fowler and Archer (2006). Since, "the period from 1991 to 2006 was characterized by above normal temperatures indicating warmer episodes" (Bhutiyani, et al., 2007) the present warming trend is in conformity of the statement. Although, pre-monsoon cooling was reported in some portions of the western Himalaya (Yadav et al., 2004), Upper Indus Basin in Pakistan (Fowler and Archer, 2006) the present study estimated a rise in the temperature. The monsoon season temperature rise of 1.20 °C/decade was on the higher side as compared to the estimates of 0.09 °C/decade by Bhutiyani et al. (2007).

Table 7.7 MK trend test and linear slopes for mean temperature during 1986-2002.

Station	MK test					Linear slope (°C/decade)				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Bhakra	(-)	(+)	-	-	-	**-1.13**	**+0.81**	-0.50	-0.56	-0.38
Rampur	+	(+)	+	(+)	(+)	+0.12	**+1.62**	-0.13	+0.53	**+0.49**
Kalpa	(+)	(+)	+	(+)	(+)	+1.03	**+1.54**	+0.15	**+0.91**	**+0.88**
Namgia	(+)	(+)	(+)	(+)	(+)	**+2.19**	**+2.70**	**+1.11**	**+1.32**	**+1.82**
Rakchham	+	+	+	-	(+)	+0.93	+1.21	+0.11	-0.16	**+0.57**
Kaza	-	-	(+)	(+)	+	-1.52	-0.92	**+3.26**	**+4.36**	+1.20
Satluj Av.	+	(+)	(+)	(+)	(+)	+0.23	**+1.03**	**+1.20**	**+1.30**	**+1.17**

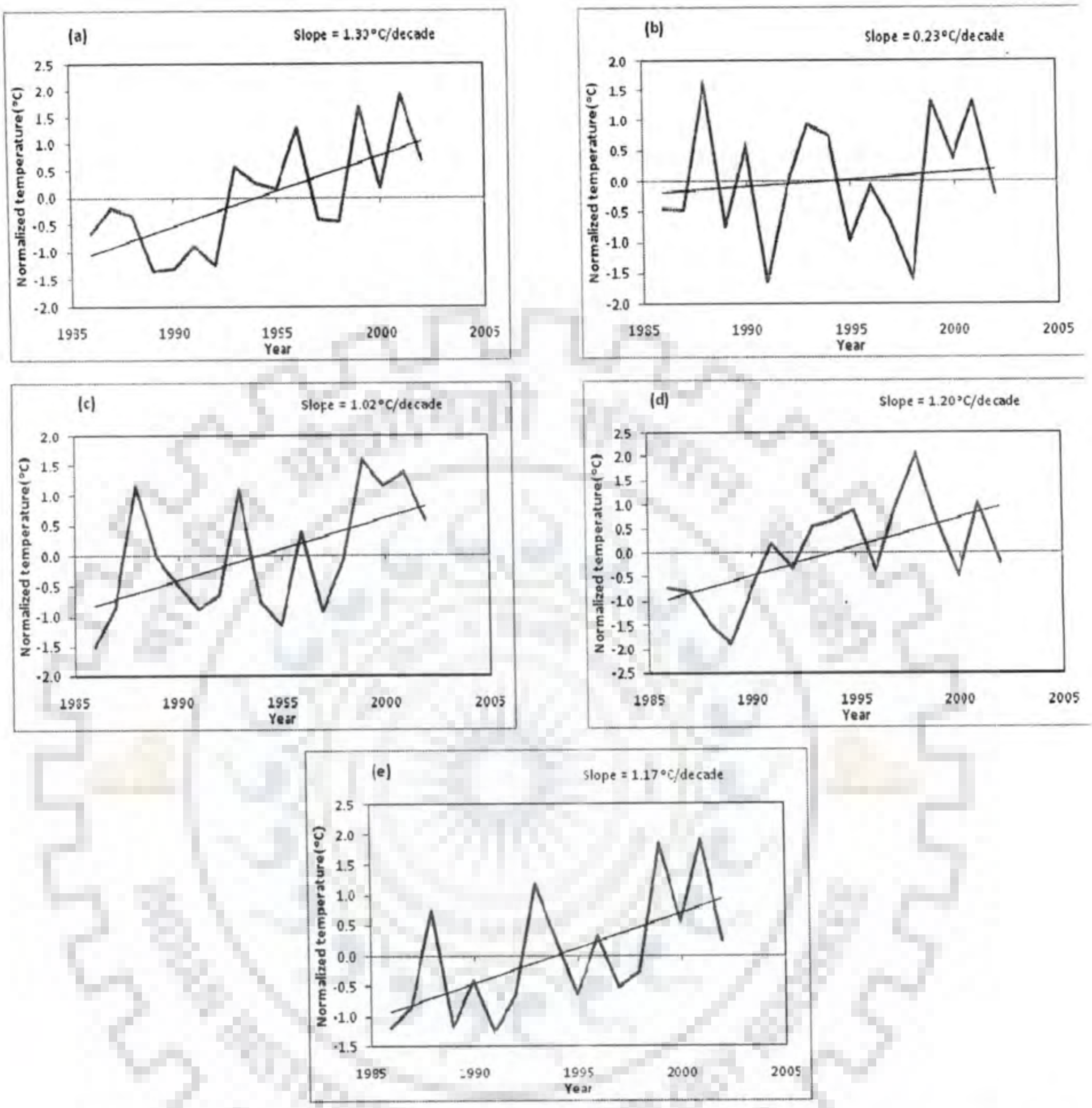

Fig. 7.2 Normalized mean temperature variation and fitted linear slope line for (a) Post-monsoon (b) Winter (c) Pre-monsoon (d) Monsoon (e) Annual at Satluj River basin

7.5.1.2 Mean Maximum Temperature

In case of annual mean maximum temperature all the stations shows rising of temperature with significant rise at three stations by both the trend detection methods. Bhakra did not follow the trend of other stations and exhibited a fall in temperature (Table 7.8). Namgia showed the highest warming of 2.34 °C/decade followed by Rampur with 0.94 °C/decade. On basin scale, no significant warming was noticed. The seasonal analysis of mean maximum temperature exhibited warming of all stations in pre-monsoon but was significant at three stations barring Kaza where cooling was observed. In winter, monsoon and post-monsoon seasons also significant rise in the temperature was found. The seasonal maximum rate of rise of 3.48 °C/decade was recorded at Kaza in monsoon season followed by 3.38 °C/decade at Namgia in pre-monsoon season.

An increase in mean maximum temperature was also observed by Bhutiyani et al. (2007), Dash et al. (2007) and Shekhar et al. (2010) in the western Himalaya. The rate of increase in maximum temperature in higher altitudes appears to be greater than the lower altitudes are in conformity with the findings of Bhutiyani et al. (2007). Increase in annual maximum temperature was also reported in other neighboring Himalayan countries (Shrestha et al., 1999; Fu et al., 2004; Fowler and Archer, 2006). Basinwide warming of winter season was also well supported by the findings of Fowler and Archer (2006) and Shrestha et al. (1999). In contrast to the findings of Shtrestha et al. (1999) who found lowest rate of increase, the present study observed a faster rate of increase during pre-monsoon season.

Table 7.8 MK trend test and linear slope for mean maximum temperature during 1986-2002.

Station	MK test					Linear slope (°C/decade)				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Bhakra	-	+	-	-	-	**-1.47**	+0.65	-0.87	**-1.47**	-0.72
Rampur	+	(+)	+	(+)	(+)	**+0.89**	**+2.48**	-0.17	+0.81	**+0.94**
Kalpa	+	(+)	-	(+)	(+)	+0.83	**+1.74**	-0.07	+0.77	**+0.77**
Namgia	(+)	(+)	(+)	(+)	(+)	**+3.22**	**+3.38**	**+1.28**	**+1.61**	**+2.34**
Rakchham	-	+	-	+	+	-0.11	+1.1	-0.20	-0.27	+0.17
Kaza	-	-	(+)	(+)	+	-2.03	-1.86	**+2.90**	**+3.48**	+0.59
Satluj Ave.	+	(+)	(+)	(+)	(+)	+0.22	**+1.25**	**+0.49**	**+0.81**	**+0.67**

7.5.1.3. Mean Minimum Temperature

In contrast to the decreasing trends in mean minimum temperature in the western Himalayas and in the entire Indian Himalayas, the annual mean minimum temperature analysis shows increasing trend in all the stations. However, four stations indicated significant increasing trend. Kaza has warmed by 1.98 °C/decade during the study period (Table 7.9). The most noticeable feature of trend is the significant rising of temperature at five stations during pre-monsoon season. Since, 1986, the basinwide increase of annual mean minimum temperature is much higher than the increase of mean maximum temperature. The increase in annual mean temperature may be attributed to the greater rise of mean minimum temperature (0.90 °C/decade) than the mean maximum temperature (0.67 °C/decade). Bhutiyani et al. (2007) have similar findings of increasing minimum temperature. Fu et al. (2004) revealed rising of mean minimum temperature but Fowler and Archer (2006) found a decline in the annual mean minimum temperature as compared to the mean maximum temperature. The present estimates of the rise of minimum temperature are closely related with the results obtained by Shekahr et al. (2010). The increase in the mean maximum and mean minimum temperature has narrow down the temperature range and are supported by the findings of other studies RupaKumar et al. (1994), Jhajharia and Singh (2010) for India, and Karl, et al. (1993), Easterling et al. (1997) and Jones (1999) of narrowing down the temparature range.

Table 7.9 MK trend test and linear slope for mean minimum temperature during 1986-2002

Station	MK test					Linear slope (°C/decade)				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Bhakra	(-)	(+)	+	+	+	**-0.80**	**+0.97**	-0.18	+0.42	+0.03
Rampur	(-)	(+)	+	+	+	**-0.69**	**+0.72**	-0.06	+0.29	+0.03
Kalpa	+	(+)	+	(+)	(+)	+0.93	**+1.36**	**+0.49**	**+1.07**	**+0.90**
Namgia	(+)	(+)	(+)	+	(+)	**+1.34**	**+1.99**	**+1.40**	**+0.99**	**+1.47**
Rakchham	(+)	(+)	+	-	(+)	**+1.99**	**+1.24**	+0.46	-0.02	**+0.96**
Kaza	-	-	(+)	(+)	(+)	-1.06	-0.07	**+4.23**	**+5.22**	**+1.98**
Satluj Ave.	+	+	(+)	(+)	(+)	+0.28	**+1.03**	**+1.05**	**+1.34**	**+0.90**

7.5.2 Trends in Rainfall

The results of the trend analysis for rainfall are given in Table 7.10. It may be noted from the table that annual precipitation has decreased in all the stations barring station Rakchham where significant increase was observed. Bhakra exhibited maximum decrease of 16.73 cm/decade during the study period. The average annual rainfall over the entire basin also shows very small decrease in the magnitude. Seasonal analysis over the period of study gave mixed results. Both increase and decrease were observed. However, significant falling trends were found in winter and pre-monsoon season. Average seasonal rainfall over the entire basin was also decreasing.
Precipitation is the main variable in regulating the River flow and its decrease greatly affects the pattern of River discharge. The decline in the precipitation was also observed in other study basins. A decrease in precipitation was observed in the Brahmaputra basin (Mirza et al., 19998). In Yellow River basin (Fu et al., 2004) statistically significant increasing or decreasing trends were found to be absent. Fig. 7.3 shows normallized average precipitation with fitted linear slope line for the Satluj River basin. Decreasing trends in the seasonal and annual precipitation was clearly reflected by the trend line. Some high fluctuations were also seen in the precipitation series suggesting episodic nture of precipitation. The estimated decrease in precipitation vary from ~ 0.08 in winter to ~ 0.05 cm/decade in pre-monsoon.

Table 7.10 Trend analysis of rainfall for Satluj basin

Station	MK test					Linear slope (cm/decade)				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
Bhakra	-	-	+	(-)	-	-5.37	-1.80	-5.93	-3.61	-16.73
Suni	(-)	+	+	-	-	**-5.33**	-1.07	+6.22	-1.56	-1.73
Kasol	-	+	-	-	-	**-6.32**	+0.22	-0.30	-3.54	-9.94
Rampur	-	-	+	-	-	-0.71	-3.77	+3.08	-2.03	-3.43
Kalpa	-	-	+	-	-	-0.12	**-6.26**	+2.98	-1.75	-5.15
Namgia	-	-	-	-	-	-0.04	**-3.33**	-0.23	+0.14	-3.46
Rakchham	+	-	+	-	(+)	+0.00	+0.18	+2.76	+0.66	+3.59
Kaza	+	+	-	+	-	+0.00	+0.25	-1.57	+0.49	-0.83
Satluj Ave.	-	-	-	-	-	-0.08	-0.05	+0.01	-0.04	-0.04

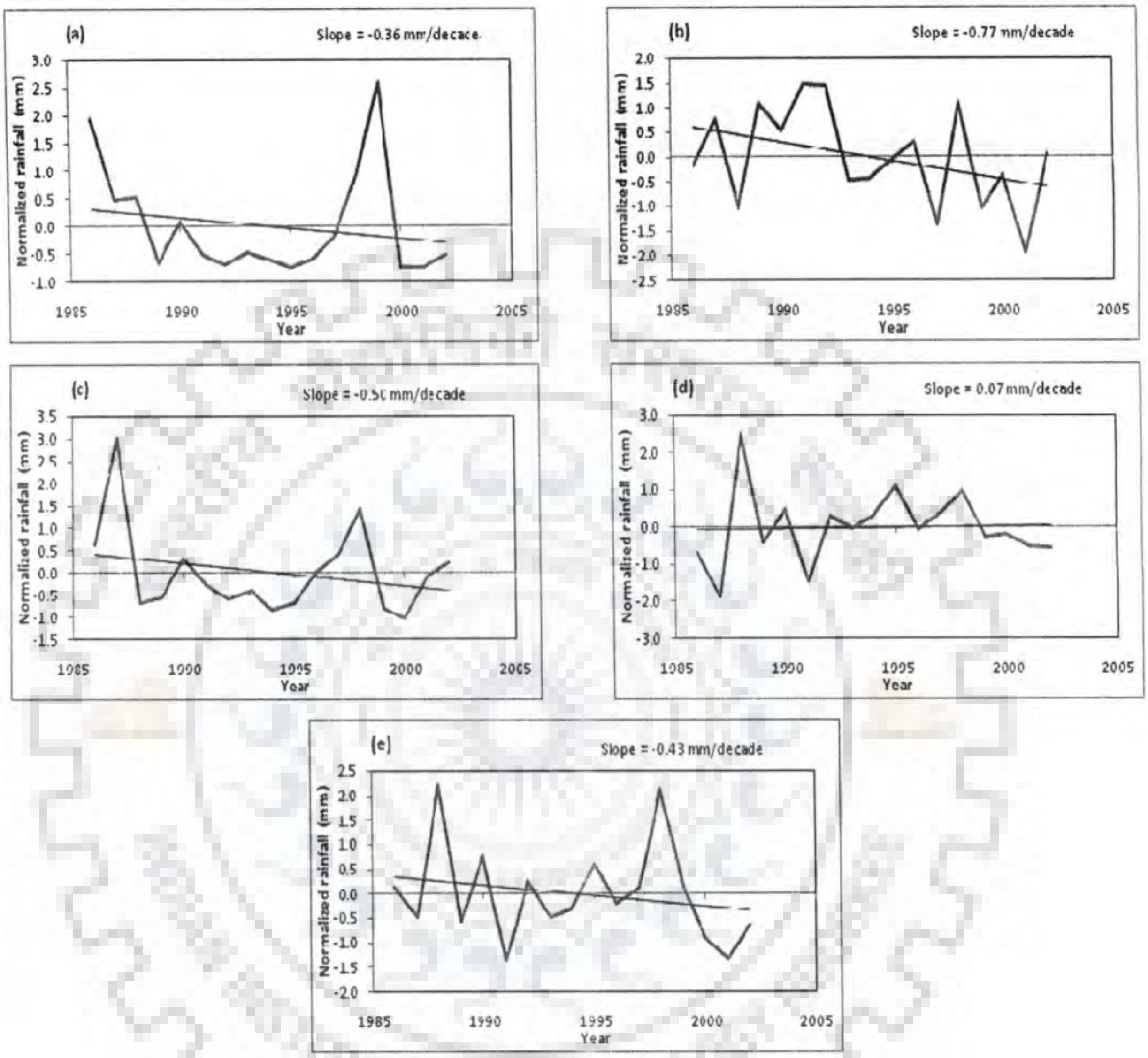

Fig. 7.3 Normalized precipitation variations with fitted linear slope line for (a)Post-monsoon (b) Winter (c) Pre-monsoon (d) Monsoon (e) Annual at Satluj River basin

7.5.3 General trends of Temperature and Precipitation in the Satluj River Basin (1986–2002)

The observed annual temperature in the whole Satluj River basin shows an increasing trend from 1986 to 2002 (Fig. 7.4). In 2002, the annual temperature was 11.5 ° C, nearly 1.5 °C higher than the interannual level for 17 years. The observed annual precipitation in the whole Satluj River basin, at the same period, indicates a decreasing trend, in contrary to that of temperature. In 2002, the annual precipitation was as low as 557 mm, just about 22% of the interannual level for 17 years.

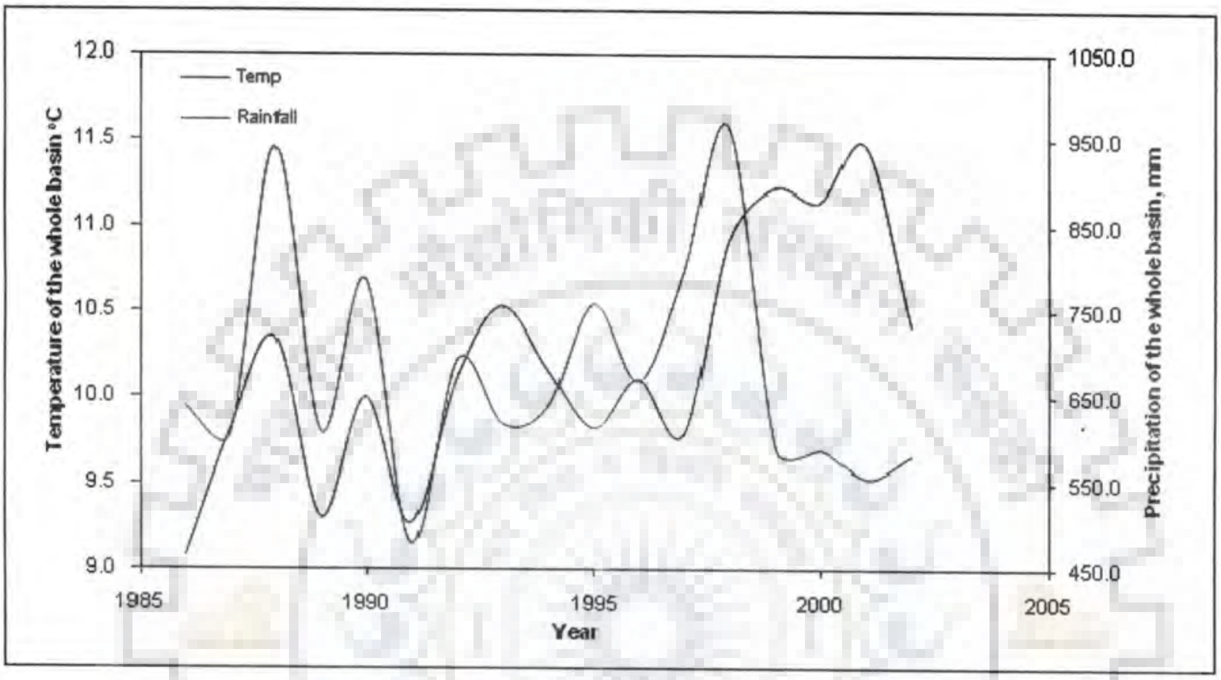

Fig. 7.4 Annual mean temperature and precipitation variations in the Satluj River basin

7.5.4 Snowfall Trends

Fig. 7.5 shows total snowfall variations with linear slope of the trend. The trend test results are presented in Table 7.11. Both the trend detection methods indicates decrease in total snowfall in all the stations irrespective of the altitude. However, significant decreasing trends were observed at Kalpa and Namagia. The estimated decrease varies from 3.36 at Rakchham to 12.67 cm/decade at Kalpa. The total snowfall over the entire basin also revealed significant decrease of 8.16 cm/decade during 1986-2002. The retreat of Himalayan Glaciers due to an increase in summer temperature was reported by Hasnain (2002). The summer warming was observed over the Satluj River Basin and reduction in snow fall may be attributed due to increase in summer mean temperature.

Table 7.11 Snowfall trends during winter time in Satluj River basin

Station	MK test	Linear slope (cm/decade)
Kalpa	(-)	**-12.67**
Namgia	(-)	**-6.07**
Rakchham	-	-3.36
Kaza	-	-10.53
Satluj Ave.	-	**-8.16**

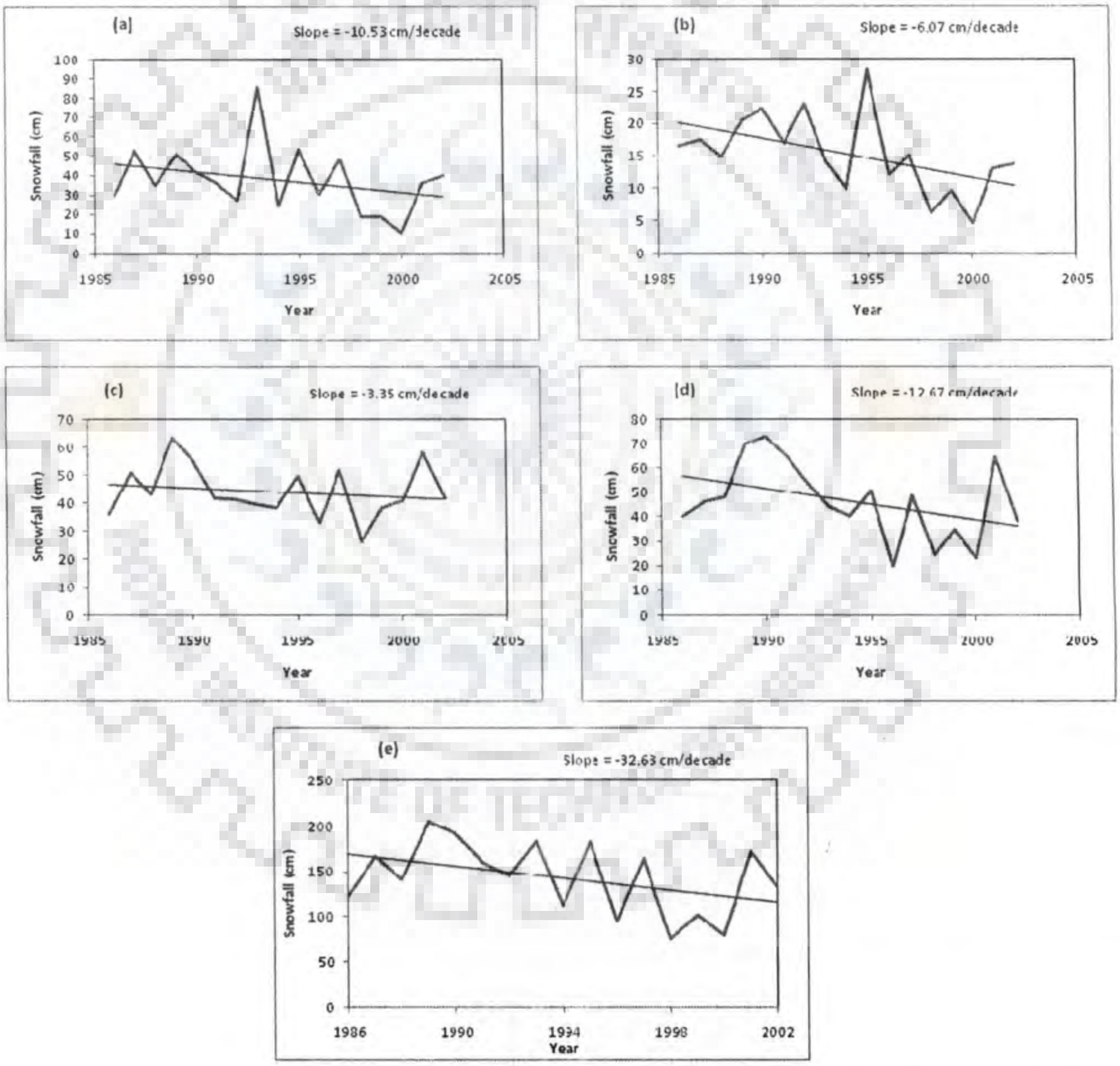

Fig. 7.5 Snowfall variations at different stations: (a) Kaza (b) Namgia (c) Rakchham (d) Kalpa (e) Total snowfall at Satluj

Since, rising winter temperature may affect the winter snowfall pattern (Bhutiyani et al., 2010) the mean winter temperature is correlated with the total snowfall and are shown in Fig. 7.6. It was found that the total snowfall is negatively correlated with the mean winter temperature at Kalpa, Namgia and Rakchham and positively correlated at Kaza. The decrease in snowfall in the western Himalaya is also reported by by Bhutiyani et al. (2010), Shekhar et al. (2010). In Tien Shan basin also decrease in snowfall was observed in all the altitudinal belt (Aizen et al., 1997). Increasing temperature would lead to reduction in snow (Khandekar, 1991). The results of present study also found an increase in temperature and decrease in snowfall. The negative correlation of temperature with snowfall totals are in close agreement with the findings of Bhutiyani et al. (2010).

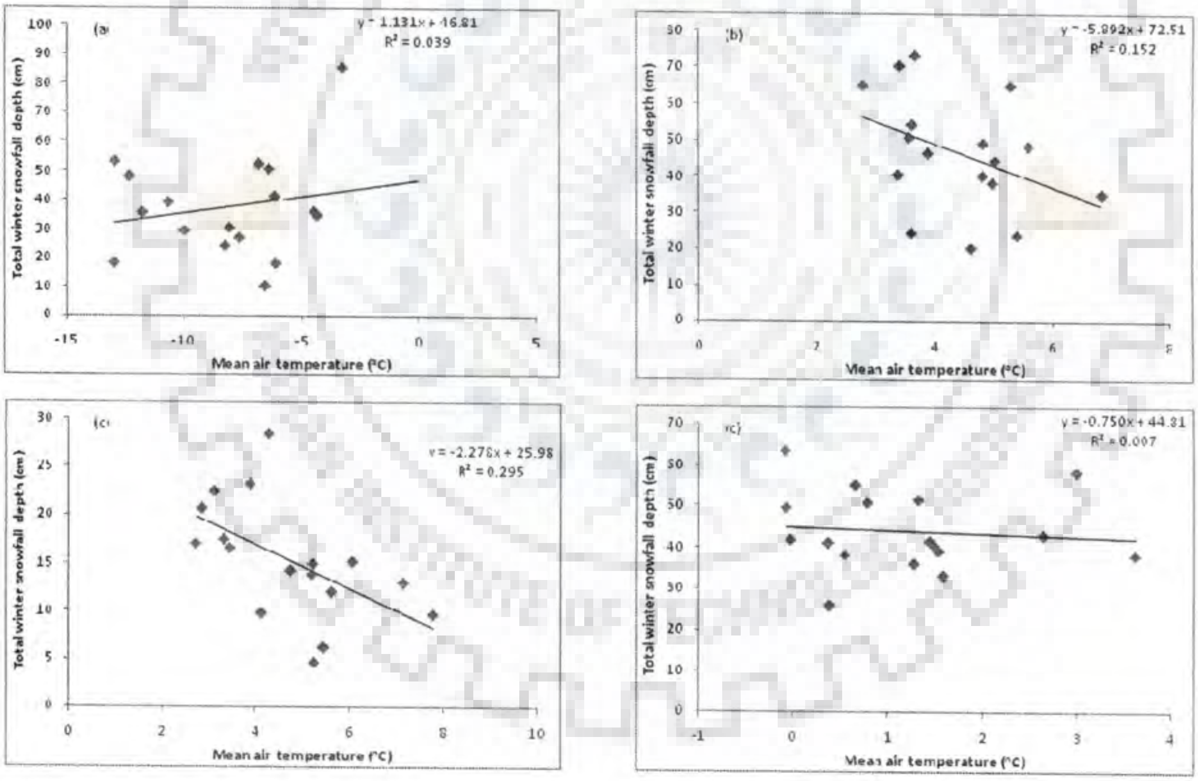

Fig. 7.6 Relationship between the total snowfall depth and winter mean air temperature during 1986-2002 at four stations Kaza (a), Kalpa (b), Namagia (c) and Rakchham (d) in Satluj River basin.

7.5.5 Trends in River Discharge

The MK trend and linear regression tests results are given in Table 7.12 and the normalized series of discharge measured at Bhakra is depicted in Fig. 7.7. The decreasing trends in the annual and seasonal discharge is evident from the table and figures except pre-monsoon where a slight insignificant increase was observed. The MK test result show statistically significant decrease in discharge in monsoon season, however, the linear slope show insignificant decrease. The magnitude of decrease was highest during monsoon (-0.80 m^3/s/decade) followed by annual discharge (-0.62 m^3/s/decade) suggest that over the years the discharge is reducing in the Satluj River.

Table 7.12 MK trend test result and linear slope of discharge at Bhakra during 1986-2002.

Season	MK test	Slope (m^3/s/decade)
Winter	-	-0.23
Premonsoon	+	+0.01
Monsoon	(-)	-0.80
Annual	-	-0.62

- decreasing; + increasing; bracketed term signifies significant trends

On both the annual and seasonal scales, it was found that discharge is decreasing. Such a decrease is possible primarily because of two reasons. First, the temperature is rising and secondly both liquid and solid precipitation is decreasing. Singh and Kumar (1997a) showed that an increase of 2 °C in air temperature would reduce the amount of annual snow water equivalent by 1-7%. A runoff sensitivity analysis by Mirza and Dixit (1997) also showed that a 2 °C rise in temperature would cause a 4% decrease in runoff, while a 5 °C rise in temperature and 10% decrease in precipitation would cause a 41% decrease in the runoff of the Ganges River near New Delhi. Archer (2003) reported that high altitude large glacierised catchments have summer and annual runoff that is strongly dependent on the seasonal temperature, while middle altitude catchments have summer flow predominantly defined by preceding winter precipitation. Further, he revealed a negative correlation between temperature and runoff on middle-altitude (snow fed) catchments. The runoff regime of foothill catchments is mainly controlled by rainfall, predominantly in winter but also during the monsoon (Archer, 2003). Inspite of increasing temperature and an average monsoon precipitation a significant decrease in monsoon and annual discharge at Satluj River was revealed by Bhutiyani et al. (2008). However, the annual runoff of the Alkananda River in the western Himalayas increased by 2.8%/yr for 1980-2000, whereas that of Kali Gandaki River in Nepal Himalayas increased by about 1% annually for 1964-2000 (Shrestha, 2005). In contradiction to the findings of Shrestha (2005) a decreasing trend in annual discharge in large basins like the Karnali and Koshi with no significant changes in the Narayani basin was observed (Sharma, 2005). He inferred that declining trends were due to a trend of lower monsoon flows thereby implying less monsoon precipitation across the high mountains. In China declining trend of 6.53 for the Yichong (Zhang et al., 2006), 8.2% from 1865-2004 in Yangtze (Yang et al., 2005), Yellow basin from 1991-2000 (Zheng et al., 2007) was also observed. Apart from climatic factors land use will also influence the hydrologic regime. Yang et al. (2005) attributed human activities as a reason for the decrease in discharge. Li et al. (2007) also revealed that soil conservation works are responsible for 87% in the reduction annual stream flow.

7.5.6 Extreme Flows

The trend of extreme flows, i.e., instantaneous maximum and instantaneous minimum flows was also analyzed. Fig. 7.8 shows the scatter plot fitted with linear regression line of the annual maximum and minimum instantaneous discharges observed at the basin outlet. It indicates that the instantaneous maximum discharge has the tendency to decrease and it is decreasing at the rate of 361.9 m^3/s/decade which means that the magnitude of the flood is decreasing. Similarly instantaneous minimum discharge of the basin is also decreasing (4.25 m^3/s/decade) which suggests reducing water availability during the driest time.

The trend analysis of annual maximum and minimum instantaneous discharges revealed a decrease during 1986-2002. However, Bhutiyani et al. (2008) have observed a significant increase in the annual maximum series of annual peak flood discharge of the northwestern Himalaya. In Baghmati River basin of Nepal a decrease in maximum flow and an increase in minimum flow were observed (Sharma and Shakya, 2006).

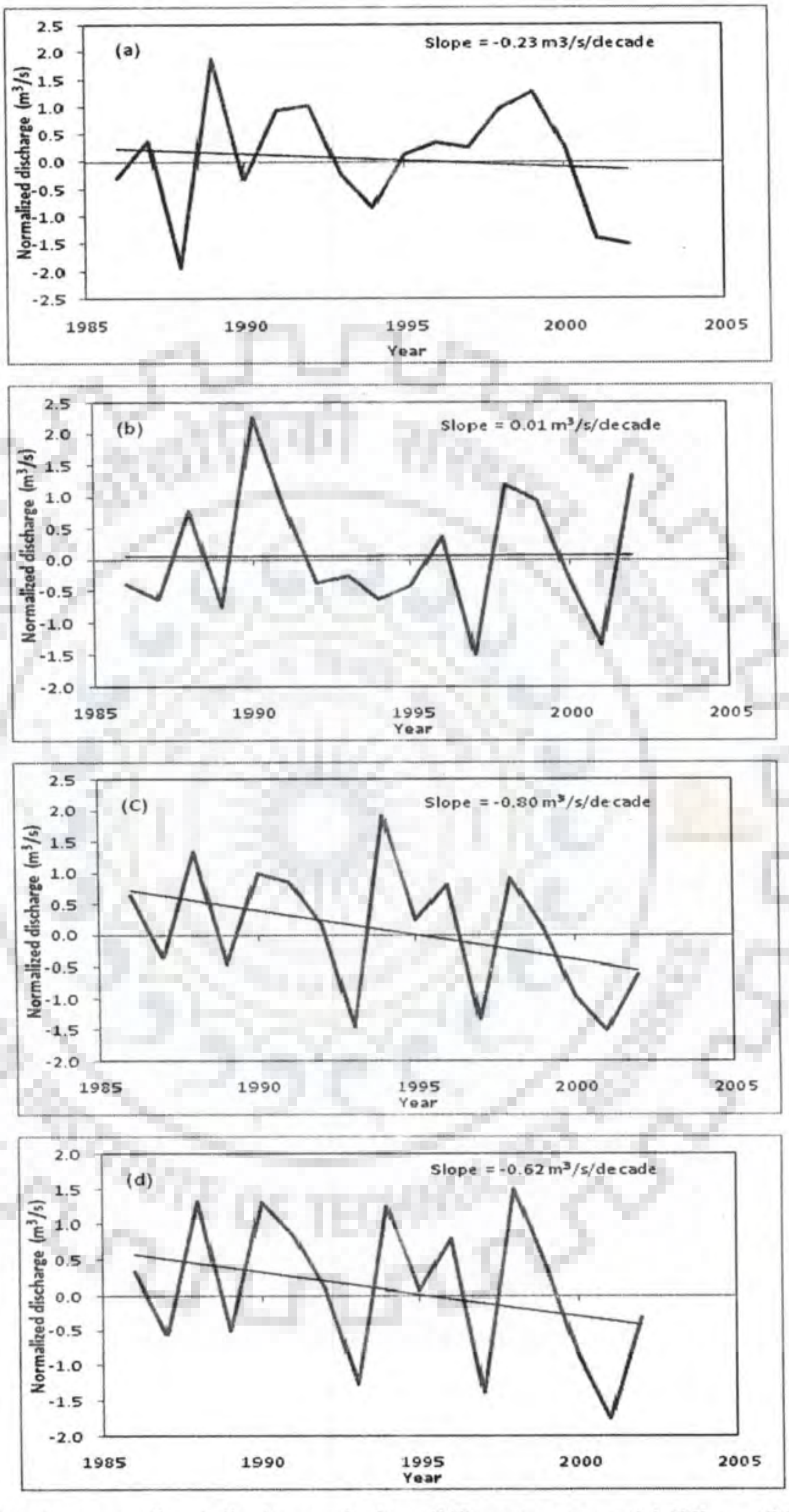

Fig. 7.7 Variation in normalized discharge during different seasons (a) Winter (b) Premonsoon (c) Monsoon (d) Annual in Satluj River basin.

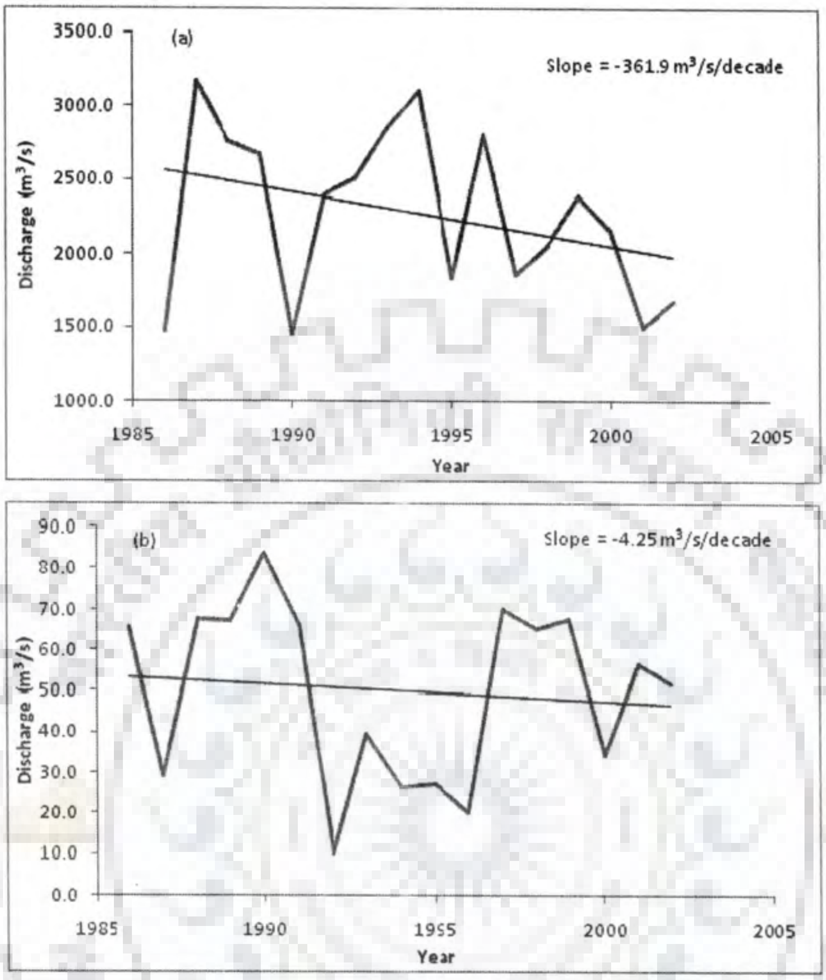

Fig. 7.8 Variation in annual extreme flows: (a) Maximum (b) Minimum with fitted linear slope line

CHAPTER 8

CONCLUSIONS AND SCOPE FOR FURTHER WORK

6.1 General

Mountains are among the regions most sensitive to climate change. Climate change is affecting the temperatures, amount of snow and ice in the Himalayan region as well as rainfall patterns in the densely populated downstream regions. Some of the most visible indicators of climate change, such as the widespread retreat of glaciers that has been observed from polar to tropical regions in recent decades, come from mountain areas.

The Indian Himalayas, the originating point of many important rivers, plays a vital role in controlling the weather of India. Despite this fact, the climate of Indian Himalayas is less studied because of its inaccessibility and hilly terrain that makes the data on meteorological and hydrological variables scarce. Therefore, the present study was under taken to provide base line information of temporal and spatial climatic variability over the Indian Himalayas. The effect of climate change has also been assessed for the Satluj River basin of western Himalayas, where more recent data of climatological variables are available.

In the present study, monthly data of maximum and minimum temperatures, mean temperature, temperature range, point rainfall and grid rainfall, number of rainy days and mean wind speed for Indian Himalayas and maximum and minimum temperature, mean temperature, rainfall, snowfall and river discharge for Satluj River basin have been analysed.

6.2 Conclusions

Based on the analysis of these data pertaining to Indian Himalayas, the following conclusions may be drawn:

(i) Based on the dependence analysis, it was found that the series of climatological variables are short-term dependent and it is more pronounced in the high altitude. On spatial basis, more dependence has been observed in the eastern Himalayas.

(ii) The periodicity analysis shows that the observed periodicities are lying outside the quasi-biennial oscillation (QBO) region at 3.3, 5 and 6.7 years in the Indian Himalayas. In some cases the observed periodicities in the climatological variables coincide with the periodicity of sunspot numbers.

(iii) The western and central regions and all Indian Himalayas show negative trends in annual mean temperature. In central Himalayas a very high cooling rate of -0.5^0 °C/decade during the period 1959-1990 has been observed. It was also observed that the mean and minimum monsoon, pre-monsoon and annual temperatures show a consistent cooling in the period 1959-1990 over the entire Indian Himalayas while the maximum post-monsoon temperatures are increasing.

(iv) Overall minimum temperatures are decreasing on annual, pre-monsoon and monsoon basis with annual cooling rate of -0.57 °C/decade. The significant decrease in minimum temperature has resulted in widening of difference between maximum and minimum temperatures.

(v) Trend analysis of temperature data in Satluj River basin indicate significant warming of maximum, minimum and mean temperatures on annual, pre-monsoon, monsoon and post-monsoon basis. A warming of minimum temperature conflicts with the cooling of minimum temperature in western Himalayas.

(vi) The rainfall records for the period 1959-1990 reveal statistically significant decrease in monsoon precipitation over the Indian Himalayas. However, on annual basis this decrease is insignificant. Gridded rainfall also indicates significant decrease in annual and monsoon rainfall during 1952-2003 period. The analysis of number of rainy days show significant increase in pre-monsoon and decrease in monsoon season, respectively and indicate shift in the occurrence of rainfall regime in the Indian Himalayas. Grid based analysis also indicate significant increase of rainy days in pre-monsoon and significant decrease in annual, monsoon and post monsoon rainy days.

(vii) Statistically significant decrease in wind speed was observed in the Indian Himalayas. The decrease was more pronounced at low altitudes.

(viii) Based on the results of spatial analysis, overall significant decreasing trends in the mean temperature, rainfall, number of rainy days and mean wind speed in the western and central Himalayas are observed on annual basis.

(ix) All the four snowfall gauging stations of Satluj River basin show decreasing trends. The decreasing rates are high and statistically significant at two stations. The basinwide analysis also indicates significant decreasing trend in snowfall during 1986-2002. Although these snowfall gauging stations indicated significant warming in all temperature variables but the snowfall totals were negatively correlated with the mean temperature.

(x) Discharge analysis shows that the monsoon discharge of Satluj River basin is decreasing by 0.80 m^3/s/decade and this has resulted in decrease in discharge on annual basis at a rate of 0.62 m^3/s/decade. On annual basis, the maximum and minimum flows have been found decreasing and suggest reduction in the magnitude of flood during monsoon and availability of water during dry period.

6.3 Limitations of the study

(i) The climatic data used in this study are very limited in terms of number of stations as well length of data. It is very possible that the above conclusions might change with time, as use of recent data may modify the reported scenario on the climatic variability in Indian Himalayas.

(ii) Lack of sufficient meteorological data from Himalayas has been a major handicap in drawing conclusions on the impact of climate change on the snowfed river basin. Due to non-availability of multisensoral satellite coverage of entire Himalayas a detailed examination of the glacier dynamics and associated phenomena like Glacier Lake Outburst Floods (GLOFs) could not be taken up.

6.4 Scope for further work

(i) A denser network of meteorological stations with longer period of records especially for the period beyond 1990 should be utilized for the study of climatic change in the Indian Himalayas.

(ii) It is believed that climate is changing due to deforestation, population increase and change in the living style. This aspect should be explored further for the Indian Himalayas by utilizing land use/land cover and population data.

(iii) The reasons of rising and falling trends in various climatological variables need further critical examination in light of the atmospheric pollution like aerosols, Indian Ocean sea surface temperatures and Siberian snow cover etc.

(iv) Conflicting results about the trends in temperature over western Himalayas (1959 - 1990) and Satluj River basin (1986-2002) have been obtained. Hence, there is a strong need of revision of study over the common data period i.e. 1986-2010.

(v) Studies on dependence and periodicity in climatological variables may be conducted for Indian Himalayas with longer period of records and the influence of external forcings like ENSO, NAO and Sunspot numbers may be explored.

(vi) More studies regarding the impact of climate change on water resources are required in order to segregate the climatic impacts from non-climatic impacts on the river runoff in Indian Himalayas. Because of the diverse topographical, physical and environmental characteristics of the region, the impact may vary from basin to basin. Therefore, more representative basins should be studied for the identification of possible impacts of climate change on water resources including physical and socioeconomic dimensions.

(vii) More analyses of climatological variables including daily and sub-daily observations are necessary using different tools and models. Indian Himalayas' rugged topography, especially wide altitudinal variation within a relatively short horizontal distance makes it difficult to apply the General Circulation Models (GCMs). Therefore, the development of a regional circulation models appropriate for Indian Himalayas orographic characteristics by scaling down the GCM is necessary in order to model its future climate.

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