CHAPTER 3
CLIMATOLOGY AND TRENDS OVER CENTRAL HIMALAYA

3.1 Introduction

Generally the regional climates over the mountain region like the central Himalaya are mostly affected by the large-scale circulations. At the same time, as a land-locked region with large orography, the central Himalayan weather and climate are also affected by local processes. Thus, variability of weather and climate over central Himalaya is expected to be complex and different from those over rest of India.

In this chapter, the climatological study and the long term trend analysis of the different weather and climate parameters like rainfall, temperature, wind speed and relative humidity are carried out using the multi-source available observed data from different source. Rainfall and temperature data is taken from India Meteorological Department (IMD) gridded data, IMD Station observations, APHRODITE, NCEP/NCAR reanalysis and CMAP, while wind and humidity data are taken from NCEP/NCAR reanalysis and IMD station observation, respectively. The study area considered is termed as Central Himalyan Uttarakhand (CHU) region.
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3.2 Rainfall

It is known that in all-India scale the monsoon rainfall shows wide variability from year to year. However, the variability at different time scales (i.e. annual, seasonal, monthly and decadal) over a small region like Uttarakhand requires a separate analysis. Some studies have reported possible increase in monsoon precipitation with global warming (Meehl and Washington 1993; Meehl et al. 1996; Hulme et al., 1998); this is consistent with the basic principle that the monsoon intensifies as a result of the strengthening land-ocean thermal contrast as a result of global warming (Meehl 1994; Anderson et al. 2002).

The IPCC reported that because of the warming associated with increasing greenhouse gas concentrations it is likely to be cause an increase in Asian summer monsoon variability and changes in monsoon strength (IPCC 1996, 2001). It is also reported in earlier studies that there is no statistically significant trend in the Indian Summer Monsoon rainfall for India as a whole (Pant and Kumar 1997). It is also seen that even though the 1990s have been the warmest decade of the millennium in most parts of the world, the Indian Summer Monsoon rainfall variability has decreased drastically rather than increased (Kripalani et al., 2003).

In different parts of India, the rainfall trend also shows differently in last 150 years (Rupa Kumar et al. 1992; Sontakke and Singh 1996) so this disagreement suggests there are still many gaps in the understanding of the monsoon variability in detail. This may be a possible reason for the moderate success in monsoon forecasting (Pallava 2002; Webster et al. 1998). There is a large variation in the annual average rainfall in the Himalayas. The southern slopes of the Eastern Himalayas experience some of the highest annual rainfall totals on Earth while other areas receive as low as 50 mm in a year. Rainfall decreases from east to west (300 cm to 150 cm). The mountain ranges also influence mid latitude systems resulting in snow in Kashmir and rainfall for parts of northern India. Over Himalayas it is also observed that in the eastern Himalayas generally a prolonged monsoon season from June to October exists, with very little rain in winter. Whereas, over western Himalayas, a short monsoon season from July-August and long wet season from November-April exist.
3.2.1 Results and Discussion

3.2.1.1 Regional Analysis over CHU

The interannual variability of annual and monsoon rainfall computed from IMD gridded data are presented in figure 3.1a. Here the rainfall has been averaged over the CHU for the high resolution and local analysis of rainfall variability. Both the annual and monsoon rainfall shows a negative trend of -0.004 mm/day and -0.005 mm/day respectively. Similar analysis using APHRODITE rainfall data are presented in figure 3.1b where the annual trend is -0.006 mm/day and the monsoon trend is -0.012 mm/day. Both data shows overall decrease of rainfall in the CHU region as a whole.

![Graph showing annual and monsoon rainfall trends over CHU with equations for the trend lines: y = -0.005x + 7.708 (Monsoon), y = -0.004x + 3.504 (Annual).]
Figure 3.1: Year to year variation of the annual and monsoon rainfall over CHU with trend. The analysis is carried out using (a) IMD data (b) APHRODITE gridded data.

At monthly scale, the same analysis (presented in figure 3.2) shows a negligible positive trend during June whereas it shows negligible negative in July, August and September. Multi-scale study of the rainfall pattern is carried out over the CHU using the multi-source data like IMD, APHRODITE, NCEP and CMAP. The annual (Jan-Dec) rainfall climatology is presented in the figure 3.3, which shows that the annual rainfall climatology throughout the region is maximum about 6 mm/day.
Figure 3.2: Year to year variation of the monthly rainfall over CHU with trend. The analysis is carried out using IMD gridded data for (a) June (b) July (c) August (d) September.
Figure 3.3: Comparison of annual rainfall climatology (mm/d) from (a) NCEP (b) CMAP (c) APHRODITE and (d) IMD over CHU.
Figure 3.4: Comparison of monsoon rainfall climatology (mm/d) from (a) NCEP (b) CMAP (c) APHRODITE and (d) IMD over CHU.

The monsoon rainfall climatology is presented spatially in the figure 3.4, which clearly shows a distinction in the results from the different source, due to low resolution NCEP shows only one category and CMAP data shows hardly maximum 8mm/day. The important feature is the analysis from IMD gridded and APHRODITE data which shows that the rainfall during monsoon season (JJAS) goes up to as high as 14 mm/day in some regions of the CHU. There is a fine distribution of the rainfall structures in north and south part of the Uttarakhand region.

The eastern part generally receives more rain compare to the other region. From the above analysis, it is clear that IMD and APHRODITE data are very useful
as it shows the clear natural variability. From here onwards the study will be carried out only using the data from these two sources.

3.2.1.2 Annual and Seasonal Cycle of Rainfall

The annual cycle of rainfall climatology averaged over the CHU region is presented in figure 3.5 which compares the daily average rainfall from IMD and APHRODITE data analysis. This clearly shows a strong high in the daily rainfall during monsoon season where as IMD shows almost 2mm/day more rainfall than the APHRODITE analysis.

![Graph showing annual rainfall climatology (1951-2003) using IMD and APHRODITE data.](image)

Figure 3.5: Annual rainfall climatology (1951-2003) using IMD and APHRODITE data.

3.2.1.3 Spatial trend in rainfall

To know the pattern of rainfall within the region itself, the spatial trend of rainfall normalized to the observed standard deviation over the region, is analyzed. The spatial trend analysis of the rainfall is presented in figure 3.6 for both annual and monsoon rainfall using IMD (left panel) and APHRODITE (right panel) data. Here the linear trend for the same period i.e. 1951-2003 is computed and is presented as the % of respective SD in 53 years. The annual trend in IMD data shows negative in the south part whereas the trend is bit negative in the northern region in APHRODITE
data. In monsoon rainfall, the trend is positive on the north part of the Uttarakhand, whereas negative in the eastern and western part from both the data.

The trend in the annual scale shows that there is an increase of rainfall over the eastern Uttarakhand and a decrease in other parts. In monsoon season, the south and eastern part increases and other part shows the negative trend. Both the analysis shows that the northern Himalayan part trend is increasing in the IMD data whereas it is decreasing in the APHRODITE data. This shows that the data from two sources shows different trends which needs to be analyzed in detail by studying the anomalies where the respective climatology is used to remove the bias from each data set.

The Interannual variability of the IMD rainfall averaged over annual and monsoon season are presented in figure 3.7a and which shows there is a decreasing trend in the rainfall in annual and monsoon scale over the Uttarakhand region. The CC between annual and monsoon rainfall is about 0.89. The same analysis using APHRODITE rainfall data presented in figure 3.7b and this also shows the similar trend. Here the CC between annual and monsoon rainfall is about 0.88. There is very high correlation between annual and monsoon anomaly of IMD rainfall data and APHRODITE rainfall data.
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(a) Annual Rainfall

(b) Monsoon Rainfall

Figure 3.6: Linear trend (expressed as % of respective SD) of (a) Annual rainfall and (b) Monsoon rainfall using IMD gridded data (left panel) and APHRODITE observed data set (right panel) for year 1951-2003.
Figure 3.7: Interannual variability in annual and monsoon rainfall over CHU using (a) IMD gridded data and (b) APHRODITE data.
3.2.1.4 Station-scale analysis

The analysis of rainfall also carried out using the IMD station observations for 22 stations covering whole Uttarakhand for the period 1901-1968 to know the micro-scale i.e station scale variability within the CHU region. The mean, SD of rainfall at station scale respectively presented in the figure 3.8a and b. Also the trend of annual and monsoon rainfall measured station wise is presented in figure 3.8 (c). The linear trend is computed and normalized with the respective SD. There is clear variation in the mean rainfall distribution with Rajpur receiving maximum mean rainfall and ratio of monsoon and annual rainfall is maximum in this station and ratio is minimum in Joshimath. Similarly the variation (SD % of Mean) of rainfall varies from 15% to 50% on annual scale and 17% to 57% in monsoon season. Trend almost positive in all stations except 6 stations both for annual and monsoon rainfall. Pithoragarh shows maximum positive trend indicating there is an increase of rainfall with 2% of SD.

Following the similar methodology, we have analyzed the rainfall variation in 6 stations of Uttarakhand for recent year (1969-2007). Due to data unavailability, we are analyzing only 6 stations. These stations cover all the altitudinal ranges (274 m to 2311 m). Ratio of monsoon and annual rainfall is highest in Nainital and lowest in Mukhim. Standard deviation (% of Mean) is maximum for Mukteshwar (Figure 3.9). Four stations are showing increasing trend in rainfall in annual scale and except Mukteshwar all stations are showing increasing trend in monsoon rainfall. These trends are opposite to all Uttarakhand rainfall. In Uttarakhand as a whole rainfall trend is decreasing on temporal scale and on spatial scale, there are variations in trends.
Figure 3.8: Rainfall analysis in different stations of CHU (a) Ratio (in %) of monsoon and annual rainfall (b) Standard Deviation (% of mean) and (c) Linear trend (% of SD) for long term period (1901-1968) using IMD station data.
Figure 3.9: Rainfall analysis in different stations of CHU (a) Ratio (in %) of monsoon and annual rainfall (b) Standard Deviation (% of mean) and (c) Linear trend (% of SD) respectively for long term period (1969-2007) using IMD station data.
3.3 Temperature

The temperature over Himalayan region also controls the mountain environment as the rainfall, humidity and wind etc. directly depends on the temperature. In this study a detailed trend analysis of temperature over Himalayan region is carried out. Bhutiyani et al. (2007) shows that air temperatures in North West Himalaya rose by about 1.6°C in the last century. Due to increasing temperatures, the ice mass in the region has retreated at a rate of 0.3 to 1 meter per year, faster than the world average. The study also found that less snowfall followed by early melting of the snow has resulted in a changed water balance in the catchments. Gautam et al. (2009) showed that the mid-troposphere over west Himalayan-Gangetic region is experiencing widespread and accelerated heating particularly in May for period 1979-2007 leading to “Strengthening of land-sea thermal gradient”. The observed enhancement in troposphere heating may result in advancement of the monsoon rainfall in early summer.

3.3.1 Results and Discussion

3.3.1.1 Regional (Uttarakhand) analysis

The annual, summer monsoon and winter average of daily mean temperature for the period 1969 to 2005 are analyzed using the IMD gridded and APHRODITE and the year to year variation are presented in figure 3.10. It is observed that the temperature trend shows increase in both summer and winter as well as during the year with very insignificant trend both in APHRODITE and IMD data. The temperature over the CHU region is also studied. The annual, summer monsoon and winter climatology of temperature are presented in figure 3.11. The spatial climatology clearly shows a contrast in the temperature in north south as well as in east west part of Uttarakhand region. The mean temperature in annual scale goes up to 27°C in the south and western part both in IMD and APHRODITE data. In summer the temperature reaches upto 33°C and APHRODITE data shows a very low temp of about 8°C-9°C in the northern part of Uttarakhand, where as in IMD the temperature shows higher value.
Figure 3.10: Year to year variation of the annual, summer monsoon and winter temperature over CHU with trend analysis is carried out using (a) IMD gridded data and (b) APHRODITE gridded data.
Figure 3.11: Comparison of temperature climatology (°C) for (a) Annual (b) Summer monsoon (c) Winter. Left panel represent IMD and right panel represent APHRODITE data.
3.3.1.2 Annual Cycle of Temperature

The annual cycle (average of 1969-2005) of the area averaged temperature is presented in figure 3.12 which clearly shows there is rise of temperature in April-May and decreases in winter. The range is about as high as 28.5°C and goes as low as 11°C (Figure 3.12).

![Graph showing temperature variation over the year]

*Figure 3.12: Temperature Climatology over CHU region using IMD gridded data (1969-2005)*

3.3.1.3 Spatial trend in Temperature

In order to know the regions of increasing and decreasing temperature trend the spatial linear trend (expressed as % of respective SD) of annual, summer monsoon (JJA) and winter (DJF) temperature are analyzed using same IMD gridded data and APHRODITE data set for the common period 1969-2005. The results in figure 3.13 show there is a significant increase in the temperature over the eastern and central Himalayan region in annual and summer monsoon scale, while in winter the temperature drops indicate that there is rise in the summer temperature and fall in the winter temperature.
Figure 3.13: Linear trend (expressed as % of respective SD) of (a) Annual temperature and (b) Summer monsoon temperature (JJA) and (c) Winter temperature (DJF) using IMD gridded data (left panel) and APHRODITE data set (right panel) for year 1969-2005.
Figure 3.14: Interannual variability in annual and summer monsoon temperature over CHU using (a) IMD gridded data and (b) APHRODITE gridded data. Correlation coefficient between annual and summer monsoon is also presented here.
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The interannual variability of the annual and summer Monsoon temperature also computed and presented as the temperature anomaly expressed as % of long term mean (figure 3.14a and 3.14b respectively) for the IMD and APHRODITE data. Another interesting point of analysis is the correlation of annual and monsoon temperature IAV to know the contribution of monsoon temperature to year and for IMD data over Uttarakhand the CC is 0.51 and much more i.e 0.69 in APHRODITE data analysis.

3.3.1.4 Station Scale analysis

The station scale temperature is being studied using the IMD station level data for the period 1969-2007 and the mean, SD and the trend normalized to SD are presented in figure 3.15. It shows that there is a clearly differences in the mean and SD of temperature from station to station. The average summer monsoon temperature ranges from 20°C to 30°C and the average winter temperature ranges from 8°C to 14°C. Temperature shows increasing trend almost in all stations and in all seasons. Maximum increase in temperature is recorded in Dehradun in annual and summer monsoon season.

(a) Mean Temperature

![Bar graph showing mean temperature for different stations with labels: Annual, Summer Monsoon, Winter. The graph compares Roorkee, Dehradun, Mukhim, Nainital, Mussoorie, and Mukteshwor.](image-url)
Figure 3.15: Temperature analysis in different stations of CHU. The top, middle and bottom panels represent the Mean value, Standard deviation (% of mean) and Linear trend (% of SD) respectively for long term period (1969-2005) using IMD station data.
3.3.1.5 Maximum and Minimum temperature

Using the methodology, the analysis is also carried out for the maximum and minimum temperature using the IMD gridded daily data and its interannual variability presented in figure 3.16 and 3.17. There is slightly decreasing trend in maximum temperature in annual, summer monsoon and winter season, but in minimum temperature in all three time duration (annual, summer monsoon and winter) increasing trend is recorded, which is very interesting and very important for Himalayan region.

Figure 3.18 explains the spatial linear trend in the maximum temperature for annual, summer monsoon and winter season, which clearly shows that there is a decreasing trend in the maximum temperature at annual scale in the south and eastern Uttarakhand. Same trend is valid for the winter maximum temperature. For monsoon season almost half parts of the study area shows an increasing trend in the maximum temperature.

The trend analysis of daily minimum temperature over the Uttarakhand is presented in the figure 3.19. The spatial linear trend (expressed as % of SD) of the minimum temperature for annual, summer monsoon and winter season clearly shows that there is a strong increase in the minimum temperature of about 6-7°C at annual and summer monsoon scale in the central, south and western part, whereas the range is minimal during winter season.

The current trends in daily maximum temperature, daily minimum temperature, daily mean temperature, precipitation over different ranges of Central Himalaya have been investigated. It is observed that Deheradun and Mukteshwar stations show significant increasing trends in mean temperature. However, increasing trends in daily mean temp are seen for all the 6 station with very high value for Deheradun.
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Figure 3.16: Year to year variations of the maximum temperature in annual, summer monsoon and winter over CHU with trend. The analysis is carried out using IMD gridded data.

Figure 3.17: Year to year variations of the minimum temperature in annual, summer monsoon and winter over CHU with trend. The analysis is carried out using IMD gridded data.
Figure 3.18: Linear trend (expressed as % of respective SD) of (a) Annual maximum temperature and (b) Summer monsoon maximum temperature (JJA) and (c) Winter maximum temperature (DJF) using IMD gridded data (left panel) for year 1969-2009.
Figure 3.19: Linear trend (expressed as % of respective SD) of (a) Annual minimum temperature and (b) summer monsoon minimum temperature (JJA) and (c) winter minimum temperature (DJF) using IMD gridded data (left panel) for year 1969-2009.
3.4 Relative Humidity

Relative Humidity increases rapidly with the onset of monsoon and reaches maximum during August, when peak monsoon period sets in. Relative Humidity is minimum during the summer months (from April to June) with May being the driest month. Skies are heavily clouded during the monsoon months and for short spells when the district is affected by western disturbances. Increasing trend in the relative humidity and increasing presence of aerosols of particulate matter are most likely causes of poor visibility. Rao et al. (2004) studied the effects of urbanization on meteorological parameters over fifteen cities and concluded that in general bright sunshine hour wind speed, total cloud amount and radiation values are showing a decreasing trend while relative humidity and rainfall had an increasing trend. Dai (2006) in global study of humidity from stations, ships and buoys found statistically significant increasing trend in global and Northern Hemisphere since 1970, while trends in relative humidity were small. These trends in humidity correspond to the observed changes in temperature in a quantitatively similar way to that which would be expected due to the Clausius-Clapeyron relationship.

3.4.1 Result and Discussion

Relative Humidity (RH) all over CHU is calculated using NCEP reanalysis data. The interannual variability in the RH averaged over annual and monsoon period are presented in figure 3.20. In annual scale, RH is showing insignificantly decreasing trend (Figure 3.20a) but in monsoon season, it is showing some increasing trend (Figure 3.20b). Figure 3.21 presents the NCEP reanalysis derived Relative Humidity climatology over Uttarakhand, (a) annual and (b) monsoon for the 1948-2012, which shows the north and the eastern part experiences high humidity in monsoon as well as on annual scale.

The station scale RH is being studied using the IMD station data for the period 1969-2007 and the mean, SD (% of Mean) and the trend normalized to SD are presented in figure 3.22. Mean RH is ranges from 60-75%. Variation in RH is maximum in Mukteshwar. If we see the linear trend (% of SD), all stations are showing increase in RH except Nainital and Deheradun shows high normalized trend.
Figure 3.20: Year to year variation of the Relative Humidity in (a) annual and (b) monsoon over CHU with trend. The analysis is carried out using NCEP reanalysis data.
Figure 3.21: NCEP reanalysis derived Relative Humidity climatology over CHU (a) Annual and (b) Monsoon for the 1948-2012.
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(c)

Figure 3.22: Relative Humidity analysis in different station of CHU. The panels represent the (a) Mean value, (b) Standard deviation (% of mean) and (c) Linear trend (% of SD) respectively for long term period (1969-2007) using IMD station data.

3.5 Wind Speed

The wind speed over the mountain region is very chaotic as they frequently changes both in direction and intensity. Using the NCEP reanalysis, the annual and monsoon averaged resultant wind climatology is presented in figure 3.23, which clearly shows intense wind during monsoon season varying from 2m/s to as high as 5.5 m/s.

3.5.1 Results and Discussion

To study the seasonal variation in the wind, the annual as well as seasonal wind are studied. It is found that the monsoon season was dominated by the humid southwest summer monsoon. During the post-monsoon season, thenortheast monsoon brings dry, cool and dense central Asian airmasses to large parts of India. However, the central part of north India is less affected by this wind pattern. In general, winds spillacross the Himalayas and flow to the southeast across the country. The cold and dry weather associated with the northwesterly (coming from northwest Himalayas) is characteristic of the winter season over CHU. The seasonal wind pattern (NCEP reanalysis data) over the Indian subcontinent is presented in Figure 3.23.
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Figure 3.23: NCEP reanalysis derived resultant wind (m/s) climatology over CHU, averaged over (a) annual and (b) monsoon for the 1948-2012.

The seasonal cycle of the surface and 850 hPa resultant wind averaged over the CHU is presented in Figure 3.24, which indicates that there is a contrast in the wind at both the levels. The surface wind generally more than that at 850 hPa, the seasonal cycle is very high during monsoon and the surface wind range is about 2 m/s in annual scale and the corresponding 850 hPa wind is about 1 m/s.

Figure 3.25 presents the IAV of surface wind averaged over monsoon and annual time scale over Uttarakhand and both the time scale the IAV show a decreasing trend which is almost same for monsoon as well as annual scale.

To know the intensity climatology of wind at two vertical levels i.e., 850 hPa and 200 hPa, wind climatology (m/s) obtained from the NCEP reanalysis are presented in figure 3.26. It shows that there is not much variation in the resultant wind value but direction changes in both the cases. So the resultant wind vector climatology only over CHU region is presented in figure 3.27, which shows the annual and monsoon climatology at 850 hPa. And monsoon wind strength is more. To analyze the divergence pattern in the CHU, we analyzed the annual as well as monsoon climatology (1948-2012) of divergence of 850 hPa wind and presented in figure 3.28. It shows that wind divergence is high in north part compare to the south part in the study region, indicating the divergence to be high in monsoon season and with a flow of wind circulation from south to north.
Figure 3.24: Annual cycle of resultant wind over CHU region using NCEP reanalysis data (1948-2012)

Figure 3.25: IAV of surface wind averaged over monsoon and annual over CHU.
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Figure 3.26 (a) 850 hPa and (a) 200 hPa Wind climatology (m/s) obtained from the NCEP reanalysis; shaded regions are more than 14 m/s.

Figure 3.27: Wind vector climatology (1948-2012) obtained from the NCEP reanalysis data over CHU. Left panel shows annual and right shows monsoon climatology at 850 hPa.
3.6 Rainfall and Temperature trend in catchment scale

A study was carried out to discover trends in the rainfall and temperature pattern of the Alakananda catchment in Central Himalaya (Kumar et al. 2008). Data on the annual rainfall, monsoon rainfall for last decade, and average annual temperature over last few decades were analyzed. Nonparametric methods (Mann-Kendall and Sen’s method) were employed to identify trends. Mann-Kendall test is showing decline in rainfall and rise in temperature and these trends were found to be statistically significant at 95% confidence level for both transects. Sen’s method also confirms this trend. This aspect has to be considered seriously for the simple reason that if the same trend continues in the future, more chances of drought are expected. Impact of climate change has been well perceived by the people of the catchment and coping mechanism has been developed at the local level.

Alakananda catchment (latitude 30° to 31° N and longitude 78° 30’ to 80° E) is selected for detailed analysis as a representative area for the Central Himalaya (Fig 3.29). The Alakananda river has its sources in the Satopanth and BhagirathKharak glaciers, which rise from the eastern slope of Chaukamba (7138 AMSL) peak in Rudrprayag district of Uttarakhand state. The Alakananda River is 6th order stream (order six according to its position in a drainage network) with dendritic pattern of drainage. The catchment of Alakananda has a maximum width of 87.5Km (N-S) and length 136 Km (E-W) along the Saraswati-Vishnuganga rivers, which narrows down
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towards west and tapers off at Devprayag making its confluence with river Bhagirathi, to form the holy Ganges. The highly diversified and sharply contrasted ecological region covers practically a global range of climates under altitudinal variations of 442-7817 m. The tributary catchments of different order streams present their environmental set-up under anthropogenic modification.

Figure 3.29: Alaknanda Catchment, Central Himalaya.

The high variability of altitude in the Alaknanda catchment leads to various types of ecological zones. Considering this, the catchment area was broadly divided into three altitudinal zones i.e. 442 m to 1000 m (lower) 1000 m to 2000 m (middle) and above 2000 m (higher). The daily rainfall and temperature data was obtained from different state owned weather stations located in the Alaknanda catchment, namely Joshimath, Ukhimath, Devprayag, Srinagar, and Rudraprag (Fig. 3.29). Data have been selected for the study considering the regular period of observation as well as the quality of data. These data include rainfall for the period from 1992 to 2002 and temperature for the period from 1981 to 2002 for lower transect and from 1964 to
1997 for middle transect. Average daily rainfall and mean daily temperature was calculated for further analysis. A large part of upper transect of catchment is mostly snow covered and snowfall data of that region is not available. Hence, for climate variability only lower and middle transects were analyzed. The time series has been categorized into total annual rainfall, total monsoon rainfall, and the mean annual temperature.

3.6.1 Rainfall and Temperature patterns

A t-Test is applied to testing the significances of the differences between the mean of annual rainfall, monsoon rainfall and annual average temperature of lower transect and middle transect. The statistical test for the mean values under the assumption of finite variance showed that the differences in the mean values of annual average temperature were significant at the 95% confidence level and rainfall series were not significantly different. Other relevant statistics about rainfall and temperature data are also given in Table-3.1a and b. The mean annual rainfall in lower transect was 1050mm, whereas it was slightly higher in middle transect (1369 mm). Monsoon rains contributed about 71 and 74 per cent of total annual rainfall in lower and middle transect, respectively.

Table 3.1a: Statistics of the time series of rainfall in Alaknanda catchment

<table>
<thead>
<tr>
<th>Transect</th>
<th>Mean</th>
<th>Sd</th>
<th>Skewness</th>
<th>Median slopes</th>
<th>Confidence boundaries</th>
<th>S-value</th>
</tr>
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<tbody>
<tr>
<td>Lower (annual)</td>
<td>1050 (n=11)</td>
<td>330</td>
<td>-0.59</td>
<td>19</td>
<td>-76.725</td>
<td>3</td>
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<td>Middle (annual)</td>
<td>1369 (n=11)</td>
<td>362</td>
<td>-0.71</td>
<td>-14.8</td>
<td>-121.167</td>
<td>-5</td>
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<tr>
<td>Lower (monsoon)</td>
<td>747 (n=11)</td>
<td>218</td>
<td>-0.79</td>
<td>-17.76</td>
<td>-67.928</td>
<td>-15</td>
</tr>
<tr>
<td>Middle (monsoon)</td>
<td>1022 (n=11)</td>
<td>390</td>
<td>-0.30</td>
<td>-14.50</td>
<td>-47.463</td>
<td>-9</td>
</tr>
</tbody>
</table>

n= year (1992-2002)
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Table-3.1b- Statistics of the time series of temperature in Alaknanda catchment

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<th>Transect</th>
<th>Mean</th>
<th>Sd</th>
<th>Skewness</th>
<th>Median slopes</th>
<th>Confidence boundaries</th>
<th>S-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower</td>
<td>22.89</td>
<td>1.12</td>
<td>-0.043</td>
<td>0.1135</td>
<td>0.015</td>
<td>55</td>
</tr>
<tr>
<td>(n*=17)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle</td>
<td>15.5</td>
<td>1.64</td>
<td>-2.307</td>
<td>0.0077</td>
<td>-0.017</td>
<td>34</td>
</tr>
<tr>
<td>(n**=32)</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

n*=1981-2002 (missing years are 1992-95)
n**=(1964-1996)

3.6.2 Trend analysis using nonparametric tests

3.6.2.1 Rainfall series

As shown in Table-3.1a, the median slopes (as per Sen’s Method) for all rainfall series are negative (decreasing) except total annual rainfall in lower transect of Alaknanda valley. The Mann–Kendall S-statistics was also computed for all data series. All the time series data for total annual rainfall and monsoon rainfall has negative S-value, indicating a decreasing trend, except for annual rainfall in the lower transect of Alaknanda, which has a positive S-value, showing some increasing trend. These S-values and median slopes were statistically significant at the 95% confidence level. This indicating that annual rainfall has decreased significantly in middle transect. There was some increase in annual rainfall in lower part of valley. The trend indicated sharp decline in monsoon rains in both transects. However, increase in annual rainfall over lower transect could be due to shift in seasonal rainfall pattern in the region. In both transects, the rainfall trend is skewed negatively showing asymmetry in rainfall series.

3.6.2.2 Temperature series

The median slope (as per Sen’s Method) for average annual temperature is positive in both transects (Table-3.1b) and S-value (Mann-Kendall) is also positive, indicating an increasing trend. These S-values and median slopes of temperature were statistically significant at the 95% confidence level during the study period indicating
significance rise in temperature in the valley. Annual temperature time series data is also skewed negatively indicating asymmetry in temperature series.

3.6.3 RLWSPS results

The smoothed values obtained from the RLWSPS technique were superimposed on the plot of time series of rainfall and temperature. Figs. 3.30, 3.31 and 3.32 shows plots for annual rainfall, monsoon rainfall and average annual temperature in both transects. These plots indicate that RLWSPS smoothing confirmed the trends obtained by nonparametric tests. Annual rainfall in lower transect indicated sudden increase in year 1993 and decrease in 1998, but in case of middle transect, smoothing indicates continuous decrease in rainfall with lowest rainfall received in 2002. The smoothed values of monsoon rainfall in lower transect

![Annual Rainfall in Middle transect and Annual Rainfall in lower transect](image)

*Figure 3.30: Temporal variation of annual rainfall and RLWSPS values in Middle and Lower transect. Note: Black line shows annual rainfall amount and Blue line shows RLWSPS value.*
Monsoon Rainfall in Middle transect

Monsoon Rainfall in Lower transect

Figure 3.31: Temporal variation of monsoon rainfall and RLWSPS values in middle and lower transect. Note: Black line shows monsoon rainfall amount and Blue line shows RLWSPS value.

Average Annual temperature in middle transect

Average Annual temperature in lower transect

Figure 3.32: Temporal variation of Average annual temperature and RLWSPS values in middle and lower transect. Note: Black line shows average annual temperature and Blue line shows RLWSPS value.
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indicated a continuously decreasing trend, whereas in middle transect sharp increasing trend was followed with sharp decline. Temporal variation of annual temperature and variation of corresponding smoothed values are shown in Fig.3.32. These plots revealed that all the time series data of temperature exhibited an increasing trend in lower transect. But, in case of middle transect no specific trend was observed after smoothing. Longer duration data may be needed for making any assessment in such cases. However, the preliminary analysis done here with limited data available for the region indicated definite trends in both rainfall and temperature pattern, which were significant, as confirmed by these statistical tests. Effect of the altitude was also dominant in both parameters as suggested by these tests.

The declining trend in annual rainfall for specific period (1992-2002) is dependent on the phases of decadal monsoon oscillation. Borgaonkaret. al. (1998) suggest no significant long term trend present in 100 years but there are oscillations around the mean in the decadal data for different time spans in the Central Himalayan Region. Rainfall above normal was reported for decades 1910-1920, 1920-1930, 1950-1960 and below normal in decades 1900-1910, 1930-40, 1960-70 so if we take one mid decade to second mid decade then trend may be different. In India, long-term time series of summer monsoon rainfall and annual rainfall have no discernible trends, but decadal departures are found above and below the long time average alternatively for three consecutive decades (Kothyari and Singh 1996). Kothyari et al (1997) reported rainfall variables had a decreasing trend and temperature had an increasing trend with implication on Indian economy. These were observed to have begun around the second half of the 1960’s. Kothyari and Singh (1992) analyzed rainfall data from 1901 to 1989 and suggested a decline in number of rainy days during monsoon season. Analyses of maximum temperature data from 49 stations in Nepal for the period 1971-94 reveal warming trends after 1977 ranging from 0.06°C to 0.12°C yr⁻¹ in most of the Middle Mountain and Himalayan regions (Shrestha et al. 1994). Several countries in Tropical Asia have reported increasing surface temperature trends in recent decades. In Vietnam, annual mean surface temperature has increased over the period 1895-1996, with mean warming estimated at 0.32°C over the past 3 decades. Annual mean surface air temperature anomalies over Sri Lanka during the period 1869-1993 suggest a conspicuous and gradually increasing trend of about 0.30°C per 100 years. The warming trend over India has been reported
to be about 0.57°C per 100 years (IPCC 2001a). Analysis of rainfall and temperature data for two altitudinal transects in present study indicated a change in climate of the Alaknanda catchment in Central Himalaya. The results are in resemblance with the previous studies as quoted above for similar or longer periods in Indian and Asian region.

3.7 Conclusion

This climatology and trend analysis of rainfall, temperature, humidity and wind shows wide variation in the weather and climate at very high resolution in the complex orographical region of Himalayas. The analysis from multiple data source shows the same analysis. The annual rainfall and monsoon rainfall show decreasing trend over the region. The Interannual variability also shows decreasing trend in the rainfall in annual and monsoon scale in the CHU region. The spatial climatology clearly shows a contrast in the temperature in north south as well as in east west part of Uttarakhand region. The station scale analysis shows that there is quite variation in rainfall and temperature distribution among stations in the CHU region.

In this study so a very high resolution variability of monsoon and temperature is attempted and carried out over a big catchment area called Alkanada catchment in the central Himalaya region using the long term observed meteorological parameters. Analysis of rainfall and temperature data for two altitudinal transects indicated a change in climate of the Alaknanda catchment in Central Himalaya. The detection of trends made with use of nonparametric methods including Sen's method and Mann-Kendall test is showing decline in rainfall and rise in temperature and these trends were found to be statistically significant at 95% confidence level for both transects. The results are in resemblance with the previous studies as quoted above for similar or larger periods in Indian and Asian region.
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