Chapter 5
Spatial and Temporal Variability of Climate Change in High-Altitude Regions of NW Himalaya

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Abstract The high mountain areas such as the Alps, the Rockies, the Himalaya, etc. are considered as the "hotspots" over the surface of the earth where impacts of climate change are likely to be felt significantly. With regard to the Himalaya, their vulnerable ecosystem appears to have reacted to even the slightest possible changes in the temperature and precipitation conditions. The cascading effects of these changes on the vast expanse of water existing in the form of glacier ice and snow in the Himalaya, the forest cover, the health, and the socioeconomic conditions of the population inhabiting the Indo-Gangetic Plains have been the issues of serious concern.

The analyses of the temperature data collected manually at different observatories during the period from 1866 to 2012 show significant rate of warming during the winter season (1.4 °C/100 years) than the monsoon temperature (0.6 °C/100 years), due to rapid increase in both the maximum and minimum temperatures, with the maximum increasing much more rapidly. Annual rate of warming (1.1 °C/100 years) is abnormally higher than the global rate (about 0.7 °C/100 years) during this period. Not all regions of the north-western Himalaya (NWH) have reacted uniformly to the specter of climate change. Studies have confirmed significant spatial and temporal variations in magnitude of winter as well as summer warming in different ranges. While the windward side of the Pir Panjal and parts of the Greater Himalayan and Karakoram Ranges have shown statistically significant winter and summer warming, leeward sides of these ranges have not shown much change. The most remarkable finding of this study is the significant decreasing trend experienced at almost all stations above the equilibrium line (>5300 m in altitude) in winter warming as well as winter precipitation in higher reaches of the Karakoram Himalaya in the last three decades.

From the precipitation point of view, significant decreasing trends (at 95 % confidence level) in the monsoon and overall annual precipitation during the study period are indicated. In contrast, the winter precipitation has shown an increasing

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but statistically insignificant trend (at 95 % confidence level). Rising winter air temperatures have caused decreasing snowfall component and increasing rainfall component in total winter precipitation on the windward side of the Pir Panjal Range and parts of Greater Himalayan and the Karakoram Ranges. The analyses also show that although winter precipitation in the NWH has remained trendless in the last 140 years, there are significant increasing trends in the extreme snowfall events during winters and rainfall events during summers in Pir Panjal and Shamshawari Ranges in the last three decades and insignificant but increasing trends in the Great Himalayan and Karakoram Range. Decrease in winter snowfall amounts and increasing rainfall component at almost all stations have been affected to some extent by the increase in winter air temperature during this period.

The spatial and temporal variations in winter and summer warming and consequent precipitation changes in different ranges/regions of the NWH are attributed to varying scales of anthropogenic activities and growing urbanization of the areas. Decreasing temperatures in the last three decades in the Karakoram Himalaya with altitudes above the equilibrium line (>5300 m) are attributed to prevalence of permanent snow cover which appears to have influenced their microclimatology. These studies have significant bearing on the mass balance of the glaciers in the region and the hydrological behavior of various river systems in the Himalaya.

Keywords Climate change • High-altitude regions • Winter warming • NW Himalaya

5.1 Introduction

The climate in the Himalaya exercises a dominant control over the meteorological and hydrological conditions in the Indo-Gangetic Plains as majority of rivers derive significant portion of their discharge from seasonal snowmelt and/or melting of Himalayan glaciers. In view of their overall importance in the context of Indian subcontinent, the study of long-term and short-term climate changes in the Himalaya and their perilous impacts on its fragile ecosystem assumes importance. Because of the vast spread and large variations in hydrometeorological conditions in different parts and impracticability of carrying out such work for the entire Himalaya, this chapter covers the northwestern portion only, comprising of the states of Jammu and Kashmir and Himachal Pradesh (Fig. 5.1). This region, besides being influenced by, more or less, similar meteorological conditions, has a significant concentration of glaciers in its river basins and better network of meteorological stations as compared to the central and eastern Himalaya.

The climate in NWH is influenced by the western disturbances during the winter months from October to May and southwest monsoon from July to September. Precipitation during monsoon period is highest in Siwalik and Pir Panjal Ranges,

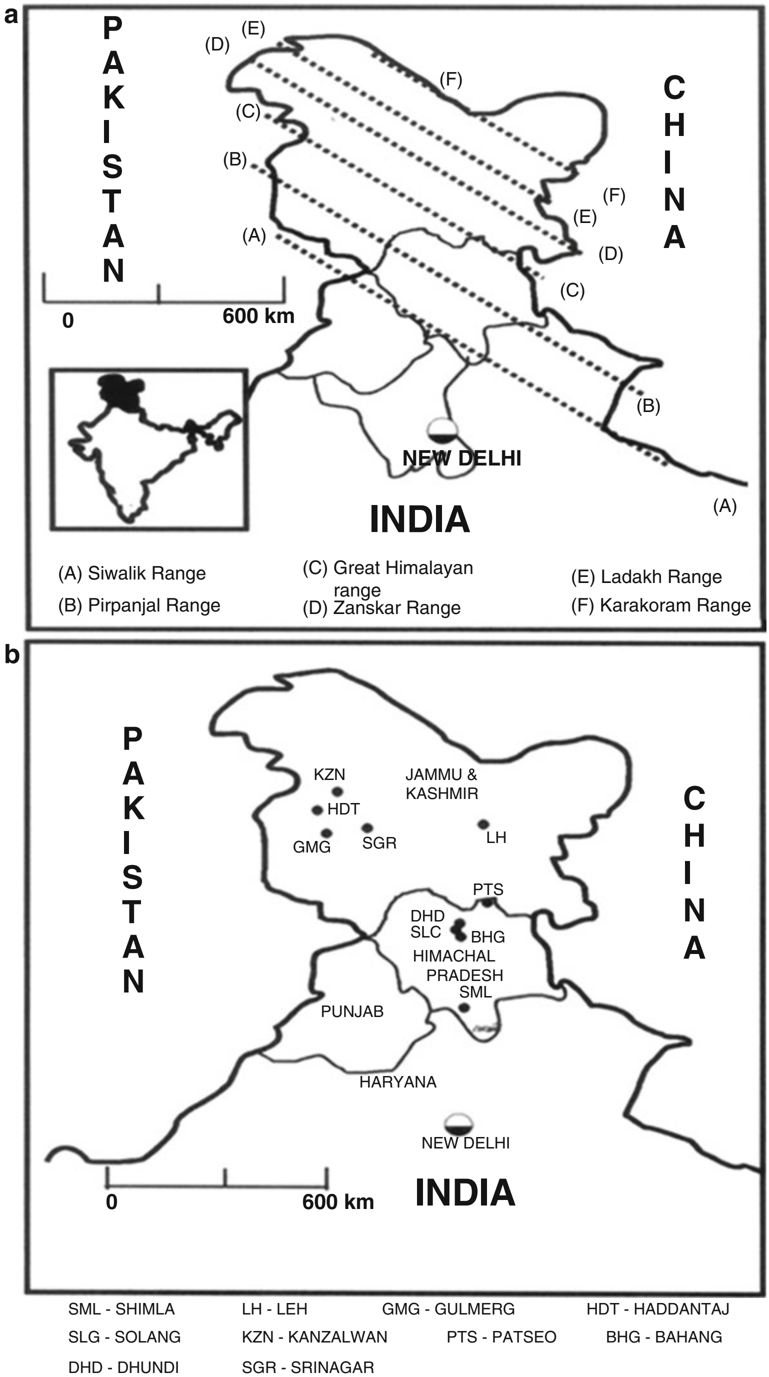

Fig. 5.1 Map of the northern western Himalaya showing approximate location of various ranges (**a**) and the meteorological stations (**b**) (Source: Bhutiyani et al. 2007)

and it reduces as one traverses northward into the Great Himalayan, Zanskar, Ladakh, and Karakoram Ranges (Rakhlecha et al. 1983). Significant variation is also observed in annual winter snowfall due to western disturbances in the NWH as various ranges in the NWH receive different amounts of snowfall ranging from about 100 to >1600 cm (snow depth). It is maximum in the Pir Panjal Range and decreases as one goes northward. Because of the variation in the mean air temperature, the changes occur in the percentage of solid precipitation (snowfall) to rainfall, duration of seasonal snow cover, snow settlement (densification) rates, and ablation rates in different ranges of the NWH (Mohan Rao et al. 1987; Bhutiyani 1992).

As compared to some studies on high-elevation regions round the globe such as by Diaz and Bradley (1997), Beniston et al. (1997), Beniston (2003), Diaz et al. (2003), and Rebetez (2004), very few studies have been carried out on the fluctuations in the climate in the Himalayan Mountains, primarily because of inaccessible terrain and inadequate database. Using the instrumental records, a few studies have examined the rainfall and temperature variations in the Nepal Himalaya and the Tibetan Plateau (Li and Tang 1986; Seko and Takahashi 1991; Borgaonkar et al. 1996) and Upper Indus Basin in Karakoram Himalaya (Fowler and Archer 2006). Temperature trends at Kathmandu in Nepal Himalaya and the Kosi Basin in Central Himalaya have been studied from the point of view of long-term trends (Sharma et al. 2000; Shreshtha et al. 2000). The precipitation and temperature trends in the western Himalaya and NWH have also been studied in the last century (Borgaonkar et al. 1996; Bhutiyani et al. 2000, 2004, 2007, 2008, 2010; Borgaonkar and Pant 2001; Yadav et al. 2004; Shekhar et al. 2010; Dimri and Dash 2012).

Based on proxy data of the ice cores from the Tibetan Plateau and tree-ring analyses from the hill regions of Uttaranchal, some authors have attempted to reconstruct the past climatic conditions during the last few centuries (Pant and Borgaonkar 1984; Liu and Chen 2000; Thompson et al. 2000).

A few studies have indicated that different regions of the NWH have not reacted uniformly to the specter of climate change and have confirmed significant spatial and temporal variations in magnitude of winter as well as summer warming in different ranges (Shekhar et al. 2010; Dimri et al. 2012). With a view to understand these aspects of climate change in NWH better, a systematic and detailed study was undertaken to analyze and evaluate temperature and precipitation trends in the NWH using instrumental data for the last 140 years. This chapter presents the results of this study.

5.2 Temperature Variations

The analyses of the temperature data show that significant increasing trends exist in annual temperature in almost all three main stations, namely, Shimla, Srinagar, and Leh in the NWH in the last century. The annual air temperature has shown an increase of about 1.1 °C during this period. Warming effect is particularly significant during the winter season. For NWH region as a whole, average winter temperature has shown an elevated rate of increase (1.4 °C/100 years) than the monsoon temperature (0.6 °C/100 years) during the period from 1866 to 2006 (Fig. 5.2). Increase in winter air temperature during the three decades is unusually high (about 4.4 °C), as compared to an average rate of about 1.4 °C/100 years in the entire last century. The "warming" in the NWH has been primarily due to rapid increase in both the maximum and minimum temperatures, with the maximum increasing much more rapidly. Consequently, the diurnal temperature range (DTR) has also shown a significantly increasing trend in both winter and monsoon seasons in the last century (Bhutiyani et al. 2007, 2010). This is in contrast to the findings of studies in the Alps and Rockies (Beniston 1997; Brown et al. 1992) and similar observations on the global scale (Karl et al. 1995), where the minimum temperatures have increased at a higher rate.

Based on the analyses of the temperature data, three different epochs/periods were identified. An episode of comparatively higher (above-average) temperatures from 1876 to 1892 was followed by three more periods of temperature variation. Below-average mean air temperature persisted from 1893 to 1939 indicating a cooler episode, followed by a period of relatively stable/average temperatures till around 1969. The periods from 1969 to 1990 and from 1991 till 2006 are characterized by above-normal temperatures indicating warmer episodes. Temperature seems to have increased at markedly different rates during these two periods. The rate of increase appears to be highest since 1991 as compared to the period prior to 1991 (Bhutiyani et al. 2010), indicating unusual warming in the last two decades. This is also confirmed by the analysis of short-term data available for seven stations for the recent decades.

With regard to variation in monthly air temperatures during winter in the last three decades, the studies have indicated nonuniform rate of increase through the winter. Although the beginning of winter (November) has shown an increasing, but statistically insignificant trend, the onset of spring (March) has been marked by substantial warming (Table 5.1).

5.3 Precipitation Variations

Certain variations have occurred in precipitation patterns on the global scale in response to rising temperatures and resultant changes in evaporation from the oceans (Srivastava et al. 1992; Fallot et al. 1997; Zhai et al. 1999). Because of its high temporal and spatial variability and high sensitivity to circulation characteristics, precipitation has rarely been studied in as much details as temperature, as an index of climatic change (Thapliyal and Kulshrestha 1991; Srivastava et al. 1992).

Present study shows a statistically significant decreasing trend (at 95 % confidence level) in the monsoon and overall annual precipitation during the study period. In contrast, the winter precipitation has shown an increasing but statistically insignificant trend (at 95 % confidence level) (Fig. 5.2). This is generally in good

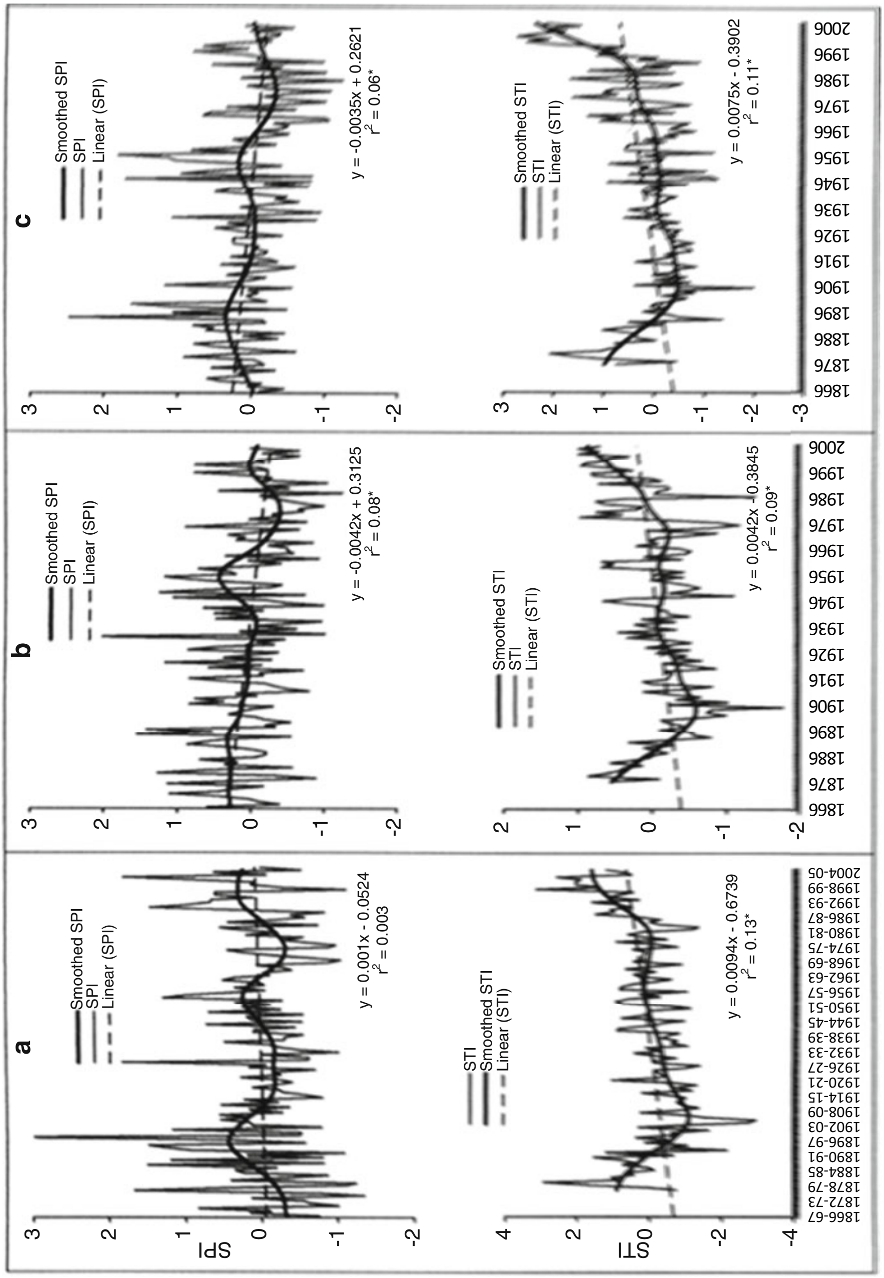

Fig. 5.2 Temporal variation of winter (**a**), monsoon (**b**), and annual (**c**) standardized precipitation index (*SPI*) and standardized temperature index (*STI*) in the northwestern Himalaya (*NWH*) during the period 1866–2006

Table 5.1 Linear trends in monthly air temperatures during winters in the NWH in the last three decades

Station	Altitude (in m)	Data span	Months					
			Nov	Dec	Jan	Feb	Mar	Apr
Bahang	2192	1977–1978 to 2009–2010	(+)	(+)	(+)[a]	(+)	(+)[a]	(+)
Kanzalwan	2440	1996–1997 to 2009–2010	(+)[a]	(+)[a]	(+)	(+)	(+)[a]	(+)[a]
Solang	2480	1996–1997 to 2009–2010	(+)	(−)	(−)[a]	(−)	(+)	(+)
Gulmarg	2800	1996–1997 to 2009–2010	(+)[a]	(−)	(−)	(+)	(+)	(−)
Dhundi	3050	1989–1990 to 2009–2010	(+)	(+)	(−)	(−)	(+)[a]	(+)
Haddan Taj	3080	1996–1997 to 2009–2010	(+)	(+)	(−)	(−)	(+)[a]	(−)
Patseo	3800	1996–1997 to 2009–2010	(+)	(+)	(−)	(+)	(−)	(−)

(+) increasing trend, (−) decreasing trend
[a]Significant at 95 % confidence level

agreement with the results of other studies carried out in western parts of Himalayan foothills (Borgaonkar et al. 1996), Nepal Himalaya (Shreshtha et al. 2000), and Upper Indus Basin in the Karakoram Himalaya (Archer and Fowler 2004). It can also be seen from the above data that during the period under study, episodes of above-average and below-average winter and monsoon precipitation almost alternated each other with a periodicity varying from 20 to 60 years. With regard to the last few decades, it is seen that whereas monsoon precipitation has remained below average from 1965 to 2006, winter precipitation has been above average during the period between 1991 and 2006.

5.4 Winter Warming and Its Relationship with Winter Snowfall

Although winter precipitation was above average during the period between 1991 and 2006, studies have shown that rising winter air temperatures have caused decreasing snowfall component in total winter precipitation. This effect is more prominent on the windward side of the Pir Panjal Range and, to a lesser extent, some portions on the leeward side. Increasing temperatures during the months of November and March during the last three decades probably point toward the late onset of winter and early advent of spring season in the NWH. The studies have also indicated that the onset of winter has been delayed by about 2 days per decade and onset of spring has been advanced by about 3 days per decade. This has effectively reduced the duration of winter and consequently the snowfall duration period by 5–6 days per decade and approximately by about 2 weeks in the last three decades (Bhutiyani et al. 2010). Identical results have also been reported from studies in Upper Indus Basin in Karakoram Himalaya (Archer and Fowler 2004), Nagaoka in Japan (Nakamura and Shimizu 1996), the Swiss Alps (Beniston 1997; Laternser and Schneebeli 2003), and Bulgarian mountainous region (Petkova et al. 2004; Brown and Petkova 2007).

Effects of winter warming in the last three decades are visible on the Eurasian landmass as a whole. Temporal variation of Eurasian snow cover area (ESCA) in March (Brown 1997, 2002) and winter mean air temperature in the NWH (Fig. 5.3) demonstrate insignificant trend in the variation of ESCA from 1922 till the late 1960s. Consequent decrease in ESCA thereafter is marked by a period of rapidly increasing winter air temperatures in the NWH, indicating a direct inverse relationship between these two parameters. Depleting snow cover area as a result of rising winter temperatures in the last three decades may have further amplified the magnitude of winter warming in the Himalaya.

Snow, being a highly reflective material, looses back a large portion of incoming radiation to the atmosphere, thus making a very small portion of energy available for transfer to the ground below. It also acts as a thermal insulator between the ground and the atmosphere, inhibiting the heat transfer between them by conduction and convection.

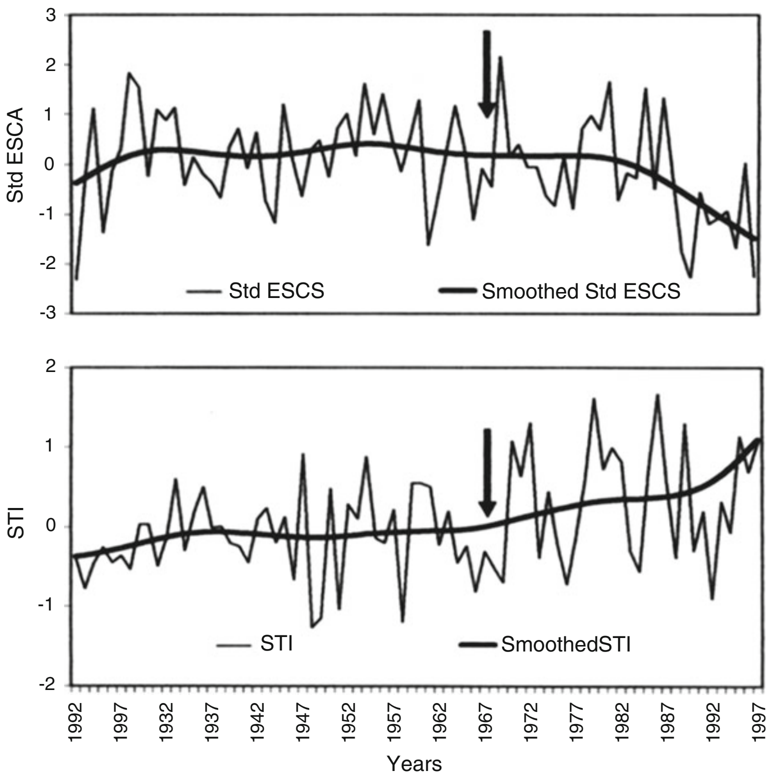

Fig. 5.3 Temporal variation of standardized Eurasian snow cover area (*ESCA*) (March) (Data Source – Brown 2002) and winter standardized temperature index (*STI*) in the northwestern Himalaya (*NWH*) during the period of 1922–1992. An onset of period of rapidly increasing winter air temperature and decreasing Eurasian snow cover is indicated by *black arrow*

As more and more land area gets exposed because of decreasing snow cover, larger amount of energy is now available for heating the ground. Consequent higher terrestrial radiation because of elevated ground surface temperatures and higher energy from incoming shortwave radiation increase the net energy balance of the area, which further raises the air temperature of the contiguous areas giving rise to a positive "feedback mechanism." This effect, which is similar to the "urban heat island" phenomenon generally associated with highly polluted cities, could be termed as "mountain heat island" effect.

Spatial study of the response of various ranges of the NWH Mountains reveals some interesting variations in warming rates in different parts of this region. While windward side of the Pir Panjal and parts of Greater Himalayan and Karakoram Ranges have shown statistically significant winter and summer warming, leeward sides of these ranges have not shown much change. This has led to significant reduction in winter snowfall amounts and rise in contribution of rain in total precipitation in this part of the Himalaya (Fig. 5.4). The most remarkable finding of this study is the significant decreasing trend experienced at almost all stations above the equilibrium line (>5300 m in altitude) in winter warming as well as winter precipitation in higher reaches of the Karakoram Himalaya in the last three decades (Fig. 5.5).

From the precipitation point of view, significant decreasing trends (at 95 % confidence level) in the monsoon and overall annual precipitation during the study period are indicated. In contrast, the winter precipitation has shown an increasing but statistically insignificant trend (at 95 % confidence level). Rising winter air temperatures have caused decreasing snowfall component and increasing rainfall component in total winter precipitation on the windward side of the Pir Panjal Range and parts of Greater Himalayan and the Karakoram Ranges. The analyses also show that although winter precipitation in the NWH has remained trendless in the last 140 years, there are significant increasing trends in the extreme snowfall events during winters and rainfall events during summers in Pir Panjal and Shamshawari Ranges in the last three decades and insignificant but increasing trends in the Great Himalayan and Karakoram Range. Decrease in winter snowfall amounts and increasing rainfall component at almost all stations has been affected to some extent, by the increase in winter air temperature during this period.

The spatial and temporal variations in winter and summer warming and consequent precipitation changes in different ranges/regions of the NWH are attributed to varying scales of anthropogenic activities and growing urbanization of the areas. Decreasing temperatures in the last three decades in the Karakoram Himalaya with altitudes above the equilibrium line (>5300 m) are attributed to prevalence of permanent snow cover which appears to have influenced their microclimatology. These studies have significant bearing on the mass balance of the glaciers in the region and the hydrological behavior of various river systems in the Himalaya.

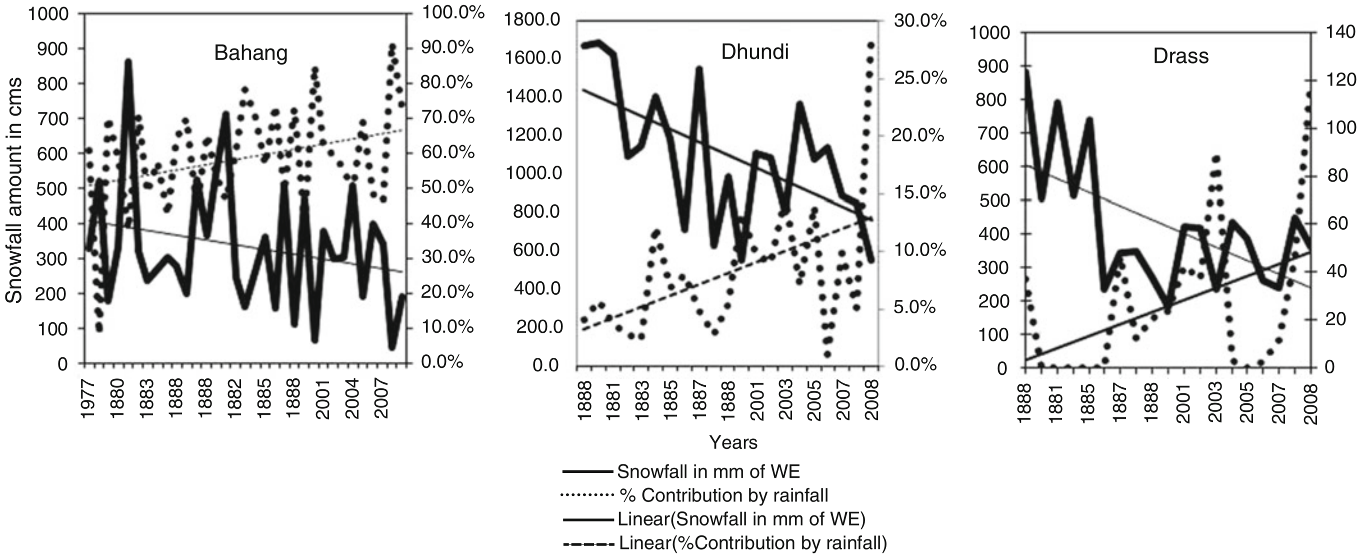

Fig. 5.4 Temporal and spatial variations of winter snowfall amounts and rainfall amounts at Behang and Dhundi in Pir Panjal Himalaya and Drass in the Greater Himalaya

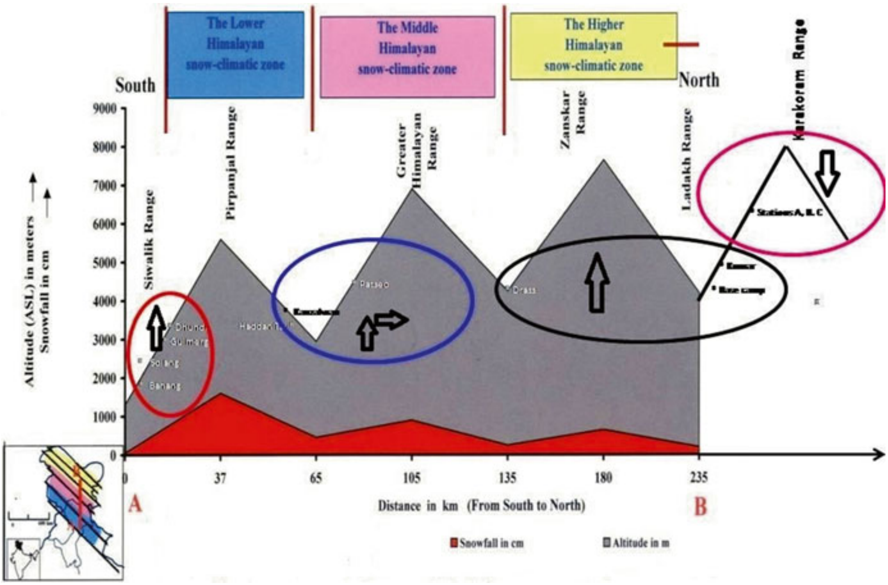

Fig. 5.5 Warming trends (winter season) in different ranges of the NW Himalayan Mountains. *Upward arrow* indicates significant rising trend, *downward arrow* indicates a significant decreasing trend, and both *arrows* together indicate a mixed response

5.5 Possible Role of Anthropogenic Activities

The studies have demonstrated that although the temperatures continued to increase from the beginning of the last century, the epochal behavior of the precipitation ensured presence of comparatively cooler and warmer periods till the early 1970s. The analysis of the diurnal temperature range (DTR) data shows regular periodicity. This periodicity, however, breaks after the mid-1970s (Bhutiyani et al. 2007).

It is evident from the foregoing discussion that some natural extra-regional factors such as the quasi-biennial oscillation (QBO) on higher frequency scale of few years and the sunspot activity on the comparatively smaller frequency scale of multi-decades appear to be largely responsible for the precipitation variation in the NWH till the early 1970s. The equatorial eastern and central Pacific sea surface temperature (SST) and the ENSO-related events had a very limited role to play in these fluctuations. Although, the temperatures continued to increase from the beginning of the last century, the epochal behavior of the precipitation ensured presence of comparatively cooler and warmer periods (Krishna Kumar et al. 1999). The periods of excess (deficient) annual precipitation, with overall increase (decrease) in cloud cover, were associated with lower (higher) temperatures, because of the decrease (increase) in net radiation balance. A remarkable feature from the standpoint of the climate change in the NWH is that these tele-connections appear to have weakened considerably in the last three decades, i.e., after the early 1970s

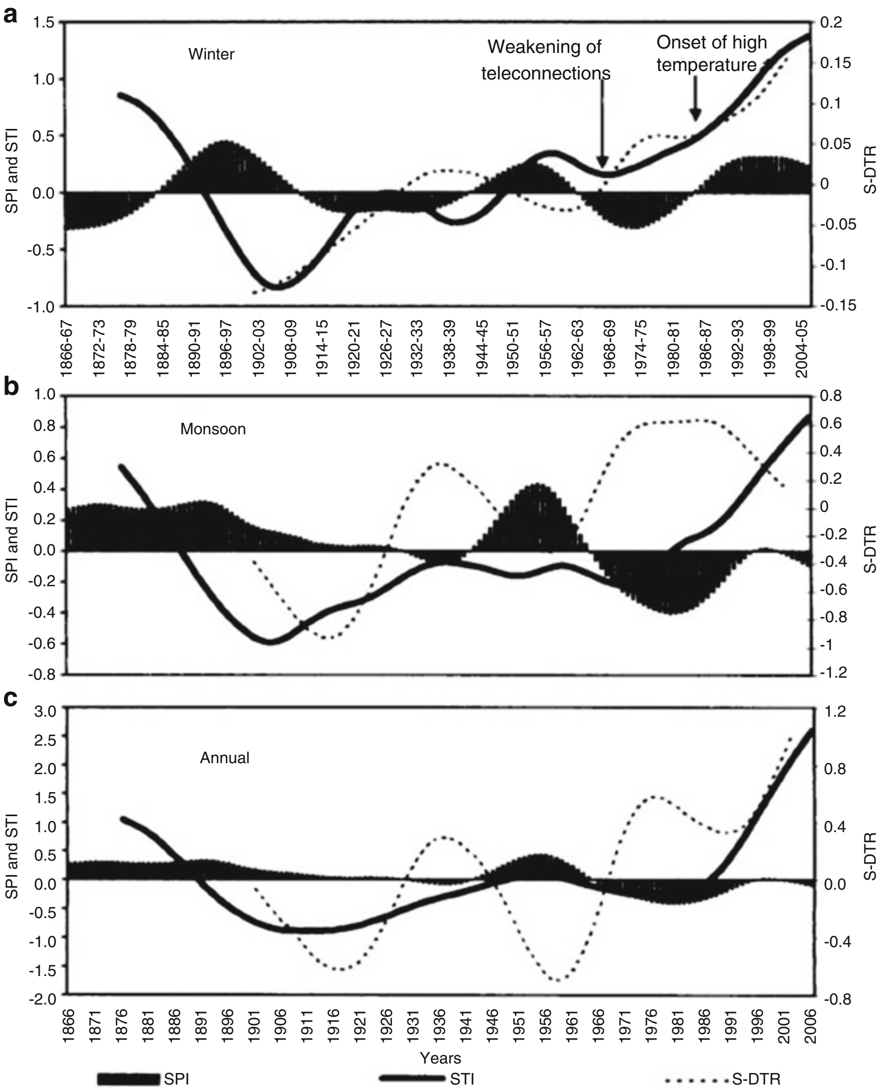

Fig. 5.6 Relationship between (**a**) winter, (**b**) monsoon, and (**c**) annual SPI, STI, and standardized diurnal temperature range (*S-DTR*) in the NWH (Source: Bhutiyani et al. 2010)

(Fig. 5.6) (Krishna Kumar et al. 1999; Baines and Folland 2007; Bhutiyani et al. 2007, 2010).

This convincingly indicates the waning effect of the natural factors in this period. The rise in air temperature has continued unabatedly in this period with both maximum and minimum temperature increasing at an alarming rate. This "warming" is unusually high, and it is difficult to be fully accounted for by the natural forcings alone, as discussed above, and there appear to be some additional factors, which may have played a significant role (Easterling et al. 1997; Crowley 2000). One of the external factors could be the increasing concentration of greenhouse gases in the atmosphere. The largest sources of the production of these greenhouse gases are the anthropogenic activities related to rapid industrialization and urbanization. Therefore, monitoring of changes in population and land use patterns and the greenhouse gases emissions may provide an insight into the probable causes of the climatic change in the NWH.

5.6 Conclusion

The study has confirmed conclusively that the climate change in the NWH is an inevitable reality today and not a myth anymore. The region has "warmed" significantly during the last century at a rate which is disturbingly higher than the global average. Unlike other high mountainous regions such as the Alps and Rockies, where the minimum temperatures have increased at a higher rate, the rise in air temperature in the NWH has been primarily due to rapid increases in both the maximum and minimum temperatures, with the maximum temperature increasing more rapidly. With regard to precipitation, statistically significant decreasing trends in the monsoon and overall annual precipitation are observed during the study period. In contrast, the winter precipitation has shown an increasing but statistically insignificant trend. Rising winter air temperatures have caused decreasing snowfall component in total winter precipitation, particularly on the windward side of the Pir Panjal Range. The studies have indicated reduction in effective duration of winter by about 2 weeks in the last three decades.

The present study has demonstrated the existence of possible tele-connections between the extra-regional factors such as the quasi-biennial oscillation (QBO), the sunspot activity, etc. and the precipitation variation in the NWH till the early 1970s in the last century. However, in the post 1970s, these links appear to have grown weaker considerably, signifying the diminishing effect of the natural forcings during this period and indicating a vital role played by other factors, such as increasing concentration of greenhouse gases in the atmosphere.

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