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Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century

M. R. Bhutiyani · Vishwas S. Kale · N. J. Pawar

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Abstract The study reveals significant rise in air temperature in the northwest Himalayan (NWH) region by about 1.6°C in the last century, with winters warming at a faster rate. The diurnal temperature range (DTR) has also shown a significantly increasing trend. This appears to be due to rise in both the maximum as well as minimum temperatures, with the maximum increasing much more rapidly. The results are in contrast to the findings in the Alps and Rockies where the minimum temperatures have increased at an elevated rate. Conforming to the global trends, the study confirms episodes of strong warming and cooling in the NWH in the last century. Real warming appears to have started from late-1960s and highest rate of increase was experienced in the last two decades. The study also shows teleconnections between temperatures and an epochal behaviour of the precipitation till late-1960s. These teleconnections seem to have weakened gradually since then and rapidly in the post-1991 period, indicating the waning effect of the natural forcings in this period.

1 Introduction

Prevalence of varied climatic conditions that are similar to those of widely separated latitudinal belt, within a limited area, make the high mountain areas such as the Himalaya, the Alps, the Andes, the Rockies etc. the ideal sites for the study of climate change. The wide range of altitudes obtainable in these regions amplifies the variations in precipitation and temperature (Liu and Chen 2000; Thompson et al. 2000). Such regions have played a vital

M. R. Bhutiyani (✉)
Department of Geology, College of Military Engineering, Pune 411031, India
e-mail: mahendra_bhutiyani@yahoo.co.in

V. S. Kale
Department of Geography, University of Pune, Pune 411031, India

N. J. Pawar
Department of Geology, University of Pune, Pune 411031, India

role in shaping hydro-meteorological characteristics of many river basins in different parts of the world and because of their economic importance, they have been extensively studied.

Air temperature is generally recognised as a good indicator of state of climate globally because of its ability to represent the energy exchange process over the earth's surface with reasonable accuracy (Vinnikov et al. 1990; Thapliyal and Kulshrestha 1991). The ease of measurement with highly standardised thermometers and availability of long homogeneous records dating back to 1870s, further underline its importance. Many studies on temperature variation on the global scale (Jones et al. 1986a,b; Folland and Parker 1990; IPCC 2001) have established the fact that the earth's atmosphere has witnessed a significant warming in the last century. On regional scale, in mountainous areas such as the Swiss and Polish Alps, the Rockies (Brown et al. 1992; Diaz and Bradley 1997; Beniston et al. 1997; Wibig and Glowicki 2002; Beniston 2003; Diaz et al. 2003; Rebetez 2004) and the Andes (Villaba et al. 2003; Vuille et al. 2003), the studies have demonstrated significant rise in air temperatures with alarming effects on their environment. Limited number of studies in the Nepal Himalaya, some parts of the northwest Himalaya and the Tibetan Plateau region has also revealed similar trends (Pant and Borgaonkar 1984; Li and Tang 1986; Seko and Takahashi 1991; Borgaonkar et al. 1996; Pant et al. 1999; Sharma et al. 2000; Thompson et al. 2000). Contrary to the global observations, pre-monsoon cooling (March–May) has also been reported in some portions of the western Himalaya (Yadav et al. 2004).

Besides being the source of many rivers, the Himalaya exercise a dominant control over the meteorological and hydrological conditions in the Indian sub-continent. Even a minor change in their climate has a potential to cause disastrous consequences on the socio-economic survival of millions of people inhabiting the Indo–Gangetic plains. Considering their importance, this paper attempts to understand the climate change in the northwestern Himalaya (NWH) in the last century by analysing the instrumental air temperature data of two principal seasons in the NWH i.e. the winter (November–April), the monsoon (June–September) (Dhar et al. 1984; Snow and Avalanche Study Establishment (SASE) 1999) and annual air temperature.

2 Data source and methodology

2.1 Data availability

The Himalayan region is poorly studied because of inaccessibility and sparse meteorological and hydrological data. Long-term maximum, minimum and mean temperature and precipitation data for annual, winter and monsoon seasons are available from only three stations namely, Srinagar and Shimla (1901–2002) and Leh (1901–1989), spread over an aerial distance of about four to 600 km (Fig. 1). These data have been used in the present study. In addition to the above three stations, winter temperature data for seven stations spread over Jammu and Kashmir (J & K) and Himachal Pradesh in the NWH, available for varying periods in the last three decades, are also used along with the published data on the global mean air temperature (Easterling et al. 1997; http://www.noaa.com).

2.2 Data validation and testing

Attempts were made to validate the raw temperature and precipitation data by established techniques in meteorology. The gaps in the Leh temperature and precipitation series were

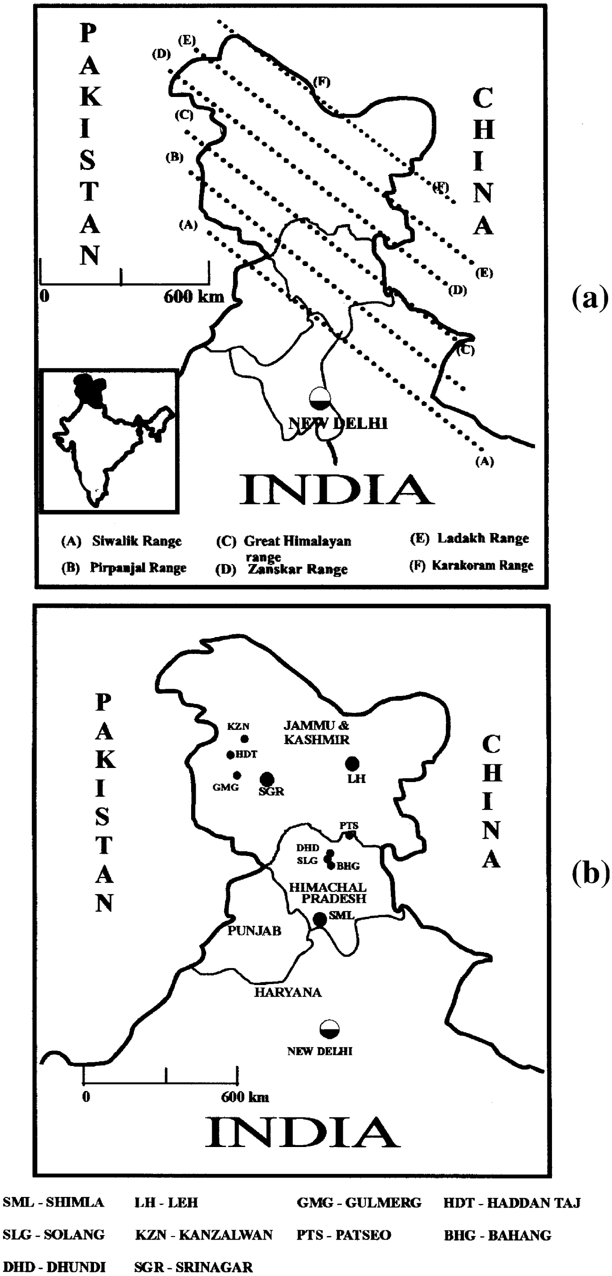

Fig. 1 Map of the northwestern Himalaya showing approximate locations of various ranges (**a**) and the meteorological stations (**b**)

filled by using temporal interpolation method (monthly value was computed as an average of the same month for a period between ± 2 years) (Mitchell et al. 1966). Because of limited number of stations spread over a vast geographical area, the data of each individual station had to be subjected to homogeneity test with other stations to ensure compatibility (Mutreja

1986; van der Made 1987). Double mass curves were plotted and simple linear regression analyses (the results presented in Table 4) on data of all three stations with each other were also carried out. The double mass curves for all three stations showed straight lines. This confirmed high temporal and spatial consistency in the inter-annual variability of temperature at all three stations. Positive bivariate correlations (statistically significant at 95% confidence level) in linear regressions (Table 4) further supported these results. The data, therefore, were considered to be of reasonably high quality to derive long-term trends in the northwestern Himalaya (NWH).

2.3 Methodology

To bring uniformity and facilitate comparison between different stations located at varying altitudes, the temperature and precipitation data were standardised by subtracting the mean and dividing by their standard deviation (Pant and Rupa Kumar 1997). In this manner, winter, monsoon and annual standardised temperature indices (STI) of mean maximum, mean minimum and average annual temperatures and standardised precipitation indices (SPI) were computed for all three stations. Similarly, mean annual winter and monsoon diurnal temperature range (DTR) data for Srinagar, Leh and Shimla were computed by subtracting the mean minimum temperature from mean maximum temperature for each station during a particular season. The DTR values were also standardised as per the method discussed above.

The extensions of STI and SPI series of Leh from 1990 to 2002 were done by adopting following method (Singh and Sontakke 2002):

1. Based on linear correlation and regression coefficients between Leh and other two stations from 1901 to 1989, Shimla STI data were selected as an independent series because of its good, positive bivariate correlation with Leh, statistically significant at 95% confidence level (r^2=0.26) (Table 4) and uninterrupted record till 2002.
2. Using the linear relationship between Shimla and Leh series, the STI and SPI values for Leh were estimated from 1901 to 1989. Standard deviations of both, original and estimated series of Leh were computed. The factor p (ratio of standard deviation of original series to that of estimated series) for each series was calculated.
3. To calculate 1-year forward extension of Leh STI series i.e. 1990, the value of STI and SPI were estimated from the linear regression equations between the Leh and Shimla series. This estimated values were inflated by their respective p factors and the final values for the year 1990 for Leh were obtained. Similar procedure was adopted for subsequent years up to 2002.

STI and SPI series for the NWH were calculated by arithmetically averaging respective records of all three main stations namely, Shimla, Srinagar and Leh (Pant et al. 1988; Shreshtha et al. 2000). Standardised DTR (S-DTR) indices for the NWH were also computed by using the method discussed above. To remove inter-annual variability, these data were smoothed using cubic spline method with 50% variance reduction frequency (Pant et al. 1988). Standard parametric and non-parametric statistical techniques such as linear regression slope and Kendall–Manny's rank test (Kendall and Stuart 1961; Mitchell et al. 1966; Pant and Rupa Kumar 1997; Pant et al. 1999) were used for trend analysis. To determine the overall increase over the past century, the b coefficients in linear regression equations, which indicate the rate of change in temperature with time, were multiplied by 100 (Pant et al. 1999). To analyse decade-to-decade variations in temperature, the decadal rates of increase/decrease were computed by linear regression slope method. To investigate periodicity, the winter, monsoon and annual STI, SPI and S-DTR series of the NWH, were subjected to power spectrum analyses (Mitchell et al. 1966; Bhalme et al. 1983).

3 Discussion of results

Tables 1 and 2 show the summary of the trend analyses and Figs. 2, 3, 4 demonstrate the plots of temporal variation of winter, monsoon and annual mean minimum, mean maximum and average standardised temperature indices (STI), respectively, with linear trends. The winter years are shown as 1901–02, 1902–03, 1903–04.... as per the standard practice (Snow and Avalanche Study Establishment 1999) in Fig. 2. This is because of the reason that unlike monsoon, the winter season extends from November of the earlier year to April of the next year and is not confined to a particular calendar year. Monsoon and annual STI series are shown with normal calendar years (1901, 1902, 1903...) in Figs. 3 and 4.

The study reveals overall increasing trends in temperatures (significant at 95% confidence level) at different rates in the last century. For the NWH as a whole, on the century scale, the annual warming rate is estimated to be about 1.6°C, with the minimum temperature rising at relatively lower pace than the maximum temperature. Warming is particularly noteworthy during the winter season (1.6°C), which compares well with the rate recorded at Nagaoka in Japan (1.35°C) in the last century (Nakamura and Shimizu 1996). The results are in good agreement with the findings of other studies on the climate change in the Himalaya. The Nepal Himalaya and Kosi Basin in the Central Himalaya in India and the Tibetan Plateau region have experienced a similar positive trend in temperature in the last century (Li and Tang 1986; Seko and Takahashi 1991; Borgaonkar et al. 1996; Sharma et al. 2000). Although, pre-monsoon cooling (March–May) has been reported in some portions of the western Himalaya during the latter part of the twentieth century (Yadav et al. 2004), it may have been nullified by an overall increase in annual air temperatures after the decade ending 1940 (Pant and Borgaonkar 1984). Besides the instrumental records, several proxy records have also provided indications of recent rise in air temperature. High-resolution ice-core data obtained from Tibet confirm the twentieth

Table 1 Results of trend analysis of average annual temperature in the NWH

Station	Data Availability	Trend Analysis	
		Kendall–Manny's non-parametric test	Linear regression coefficient *b*
Mean maximum temperature			
1. Shimla	1901–2002	(+)*	(+)*
2. Srinagar	1901–2002	(+)	(+)
3. Leh	1901–1989	(+)*	(+)*
Mean minimum temperature			
1. Shimla	1901–2002	(+)	(+)
2. Srinagar	1901–2002	(+)*	(+)*
3. Leh	1901–1989	(+)*	(+)*
Mean annual temperature			
1. Shimla	1901–2002	(+)*	(+)*
2. Srinagar	1901–2002	(+)*	(+)*
3. Leh	1901–1989	(+)*	(+)*

(+) Increasing trend * Significant at 95% confidence level

Table 2 Rates of increase of winter, monsoon and annual air temperatures in °C in the last century, computed by linear regression slope (b)

Station	Season→	Winter $b\times100$	Monsoon $b\times100$	Annual $b\times100$
Shimla	Mean maximum	2.6*	2.8*	2.4*
	Mean minimum	1.0*	−0.01	0.5
	Average annual	1.8*	1.5*	2.0*
Srinagar	Mean maximum	1.1*	0.2	0.5
	Mean minimum	1.2*	0.2	1.0*
	Average annual	1.1*	0.2	0.8*
Leh	Mean maximum	1.3*	1.0*	1.7*
	Mean minimum	0.4*	1.1*	1.3*
	Average annual	0.6*	1.1*	1.6*
NW-Himalaya	Mean maximum	1.7*	1.3*	1.6*
	Mean minimum	1.7*	0.4*	1.1*
	Average annual	1.7*	0.9*	1.6*

* Significant at 95% confidence level

century rise in air temperature. It is attributed to the anthropogenic activity in India and Nepal, which is reflected in doubling of chloride and a four-fold increase in dust concentrations in the ice-cores (Liu and Chen 2000; Thompson et al. 2000).

The results are also in conformity with the global trends and the studies in other mountainous regions of the world. The observations made in the Austrian Alps and Bavarian Alps (Auer and Boehm 1994; Diaz and Bradley 1997), Swiss Alps (Beniston 1994; Beniston et al. 1997; Beniston 2003; Rebetez 2004), French Alps (Jamelli et al. 2004), Rocky Mountains in Colorado, USA (Brown et al. 1992) and southern Andes in Argentina and Chile (Villaba et al. 2003; Vuille et al. 2003) have also shown a rising trend in air temperature in the last century.

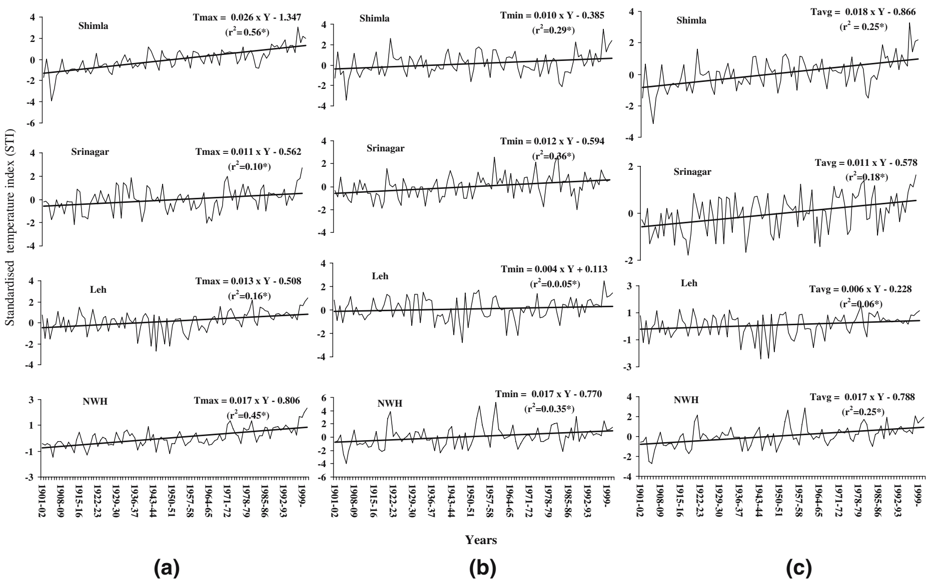

Fig. 2 Variation of mean winter maximum (**a**), minimum (**b**) and mean temperature (**c**) (STI values) in the northwestern Himalaya in the last century. (Tmax=mean maximum temperature, Tmin=mean minimum temperature, Tavg=mean winter temperature, Y=time in years)

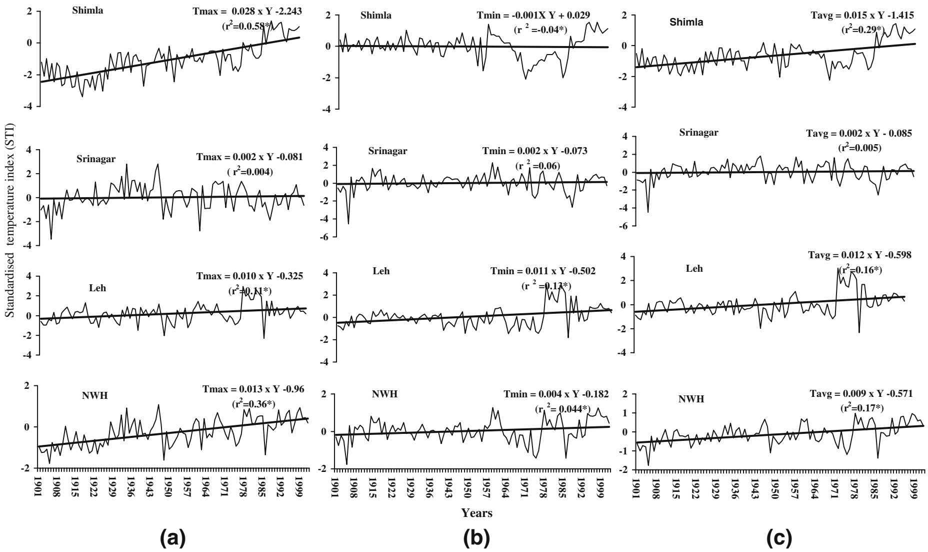

Fig. 3 Variation of mean monsoon maximum (**a**), minimum (**b**) and mean temperature (**c**) (STI values) in the northwestern Himalaya in the last century. (Tmax=mean maximum temperature, Tmin=mean minimum temperature, Tavg=mean monsoon temperature, *Y*=time in years)

Similar warming has been reported from other parts of the world such as Antarctica (David et al. 2003; Vaugan et al. 2003), former Soviet Union (FSU) (Fallot et al. 1997), parts of China (Zhai et al. 1999; Qian and Lix 2004) and plains of India (Hingane et al. 1985; Thapliyal and Kulshrestha 1991; Srivastava et al. 1992; Rupa Kumar et al. 1993). On the

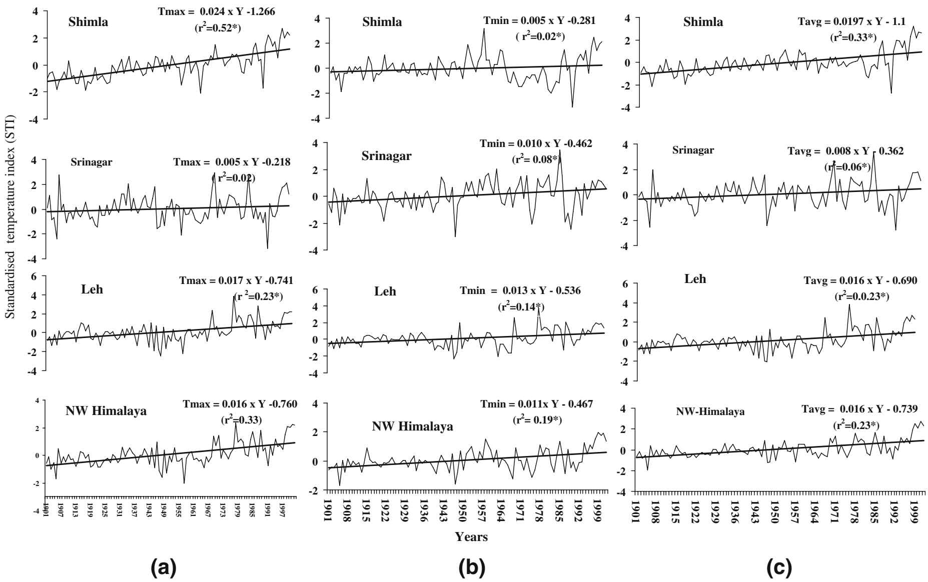

Fig. 4 Variation of mean annual maximum (**a**), minimum (**b**) and mean temperature (**c**) (STI values) in the northwestern Himalaya in the last century. (Tmax=mean maximum temperature, Tmin=mean minimum temperature, Tavg=mean annual temperature, *Y*=time in years)

global scale too, numerous studies indicate that there has been a substantial increase of about 0.5–1.1°C during the last century (Jones et al. 1986a,b; Folland and Parker 1990; IPCC 2001).

Table 2 reveals non-uniformity in the rates of increase at all stations. This may be because of dissimilarity in physiographic characteristics of the areas they represent. Shimla, which experienced significantly higher rate of warming in comparison with the other two stations, falls in the Lower snow-climatic zone (Sharma and Ganju 2000). Moreover, it is located on the Siwalik Range facing the monsoon winds directly. Leh, falling in the rain shadow zone, is situated on a wide terrace of the Indus River in the Ladakh Range of the Higher snow-climatic zone. At Shimla, the monsoon moisture regulates the temperature, while at Leh; it is the moisture deficiency that leads to aridity. Srinagar, located in Kashmir Valley in the Lower snow-climatic zone, in contrast, represents an area with a different geomorphological setting. A typically bowl-shaped Kashmir Valley, surrounded by mountains of the Pirpanjal and Great Himalayan Ranges on all sides, entraps the clouds for longer duration (Rakhlecha and Pisharoty 1986). This leads to the reduction in direct incoming radiation during the day and confinement of outgoing long-wave terrestrial radiation (OLR) during the night. Consequent increase in minimum temperature reduces the diurnal temperature range (DTR).

To ascertain whether the warming rate at a particular station and the NWH was uniform throughout the last century or not, decade-to-decade rates (season-wise) were computed. The plots given in Figs. 5, 6, 7 confirm episodic variation and demonstrate that barring the decade of 1911–1920, the temperatures rose at a comparatively lower rate till 1930. This period was followed by a cooler episode of decreasing temperatures or insignificant rise. Real warming appears to have started in the decade of 1961–1970 with a modest rate and with an exception of the decade of 1981–1990, continued till the end of the century at all stations. The warming rate appears to be highest during the period from 1991 to 2002 as

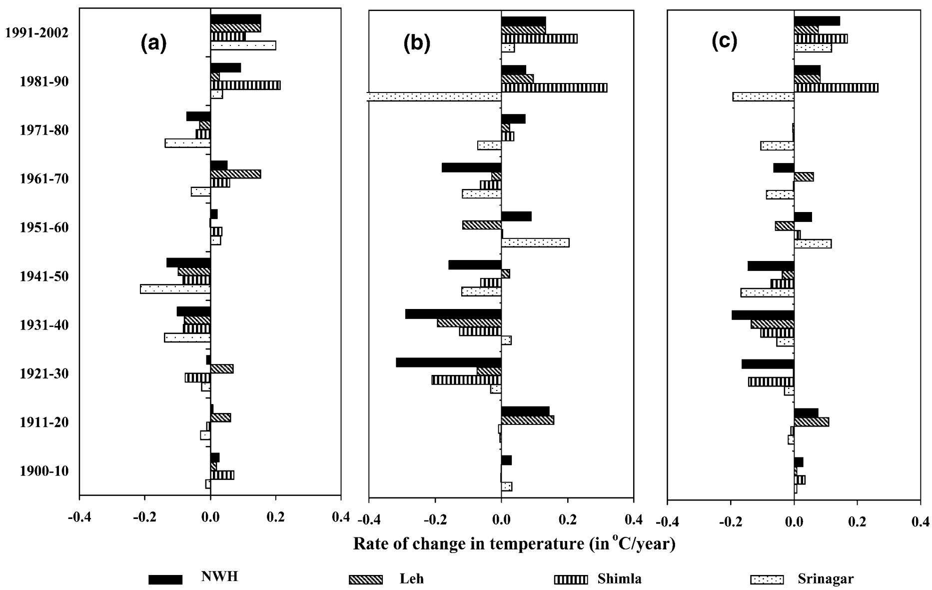

Fig. 5 Decade-to-decade change in winter mean maximum, mean minimum and average air temperatures (in °C/year) in the last century. *Positive (negative) values* indicate increasing (decreasing) temperatures. **a** Mean maximum **b** mean minimum **c** winter average

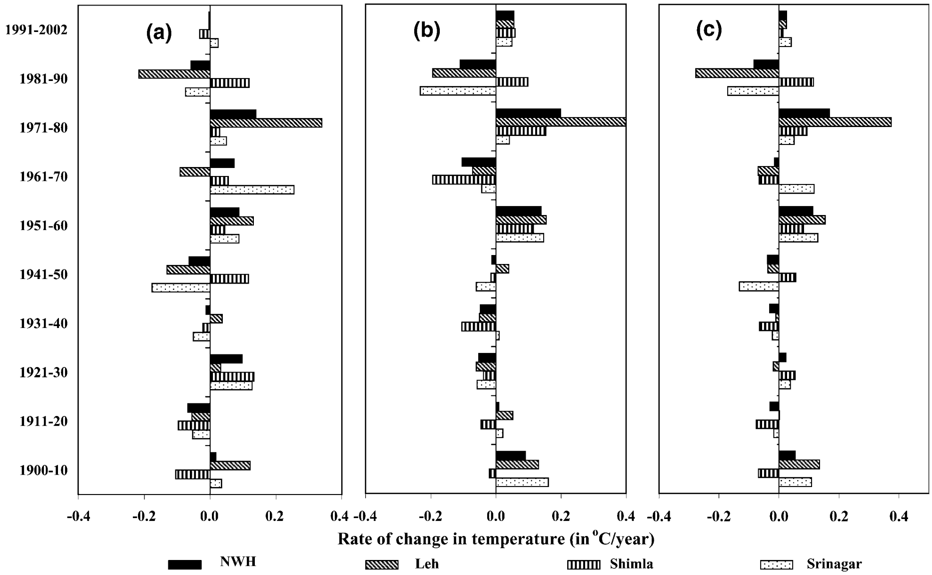

Fig. 6 Decade-to-decade change in monsoon mean maximum, mean minimum and average air temperatures (in °C/year) in the last century. *Positive (negative) values* indicate increasing (decreasing) temperatures. **a** Mean maximum **b** mean minimum **c** monsoon average

compared to the earlier period. The analyses of short-term winter data from seven more stations in the NWH using linear regressions confirmed relatively higher rate of warming in the last two decades. The results given in Table 3 show that gross rise in mean air temperature in the last two decades in the NWH is about 2.2°C, which is a far higher than

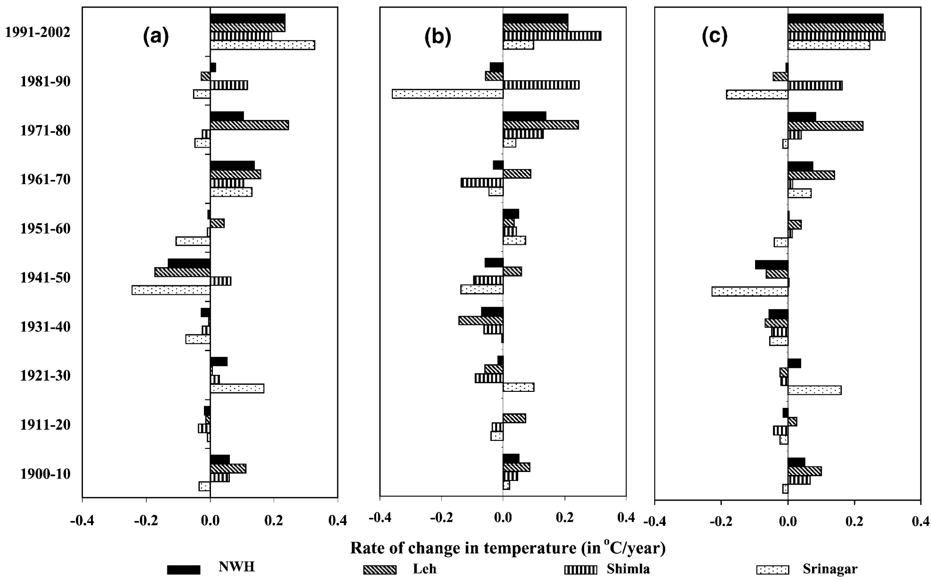

Fig. 7 Decade-to-decade change in annual mean maximum, mean minimum and average air temperatures (in °C/year) in the last century. *Positive (negative) values* indicate increasing (decreasing) temperatures. **a** Mean maximum **b** mean minimum **c** annual average

Table 3 Gross increase in winter mean air temperature in the last two decades

Temperature in °C→ Station name (Altitude in m) ↓	Mean maximum	Mean minimum	Average winter
Jammu and Kashmir			
1. Haddan Taj (3,080)	2.2*	3.2*	2.6*
2. Gulmerg (2,800)	2.2*	1.8	2.0*
3. Kanzalwan (2,440)	3.6*	−1.4	1.0
4. Srinagar (1,500)	1.0	0.0	0.6
Himachal Pradesh			
1. Bahang (2,192)	4.0*	1.8*	3.8*
2. Solang (2,480)	4.4*	2.0*	3.8*
3. Dhundi (3,050)	5.6*	1.0	3.2*
4. Patseo (3,800)	3.0*	−3.0*	0.0
5. Shimla (1,200)	2.8*	2.2*	2.4*
Average	3.2	0.8	2.2

* Significant at 95% confidence level

the rate of about 1.7°C for the entire century (computed on the basis of about 100-year data). Similar rise in air temperature in the last 20 years has been observed in the French Alps (Jamelli et al. 2004). It is also seen from the table that at majority of the stations, barring Patseo, maximum temperature increased significantly at a much faster pace in comparison to an increase in minimum temperature. The average rate of rise in maximum temperature is about four times higher (3.2°C) than the minimum temperature (0.8°C). The results are in agreement with similar estimates for the Peninsular India, where increasing mean air temperature is primarily caused by rise in maximum temperature. Minimum temperature has remained, more or less, trendless in the last century, particularly in last two decades (Hingane et al. 1985; Rupa Kumar et al. 1993; Borgaonkar and Pant 2001). These findings are in striking contrast to the results of studies conducted in the Alps (Beniston 1997; Wibig and Glowicki 2002; Beniston 2003; Schaer et al. 2004) and the Rocky Mountains in Colorado (Brown et al. 1992), which have shown that minimum temperatures have increased much more rapidly than the maximum temperatures. Even on the global scale similar results have been obtained (Karl et al. 1993; Qiang et al. 2004).

One interesting observation that has emerged from the analysis of short-term data is that the rate of increase in maximum (minimum) temperature in higher altitudes appears to be higher (lower) than the lower altitudes (Table 3), although these relationships do not appear to be statistically significant, because of data of shorter duration. Similar observation has been reported by Liu and Chen (2000) in the study of climate change in the Tibetan Plateau, where higher elevations have undergone much more warming than the lower elevations.

Conforming to the results obtained in other parts of the world (Knappenberger et al. 2001; Schaer et al. 2004; Qiang et al. 2004), the winter, monsoon and annual diurnal temperature range (DTR) in the NWH have also shown overall significant increasing trends with episodes of variation in the last century (Fig. 8).

3.1 Comparison of 'warming' in the NWH vis-à-vis global temperature

The magnitude of 'warming' in the NWH was compared with the rise in global mean air temperature to ascertain its compatibility with the global trends. Figure 9a shows the temporal variation of standardised average annual temperature indices at Srinagar, Shimla, Leh, the NWH and the global mean temperature respectively. The plots show that the warmest years have all been experienced after late-l960s with the exception of years 1991

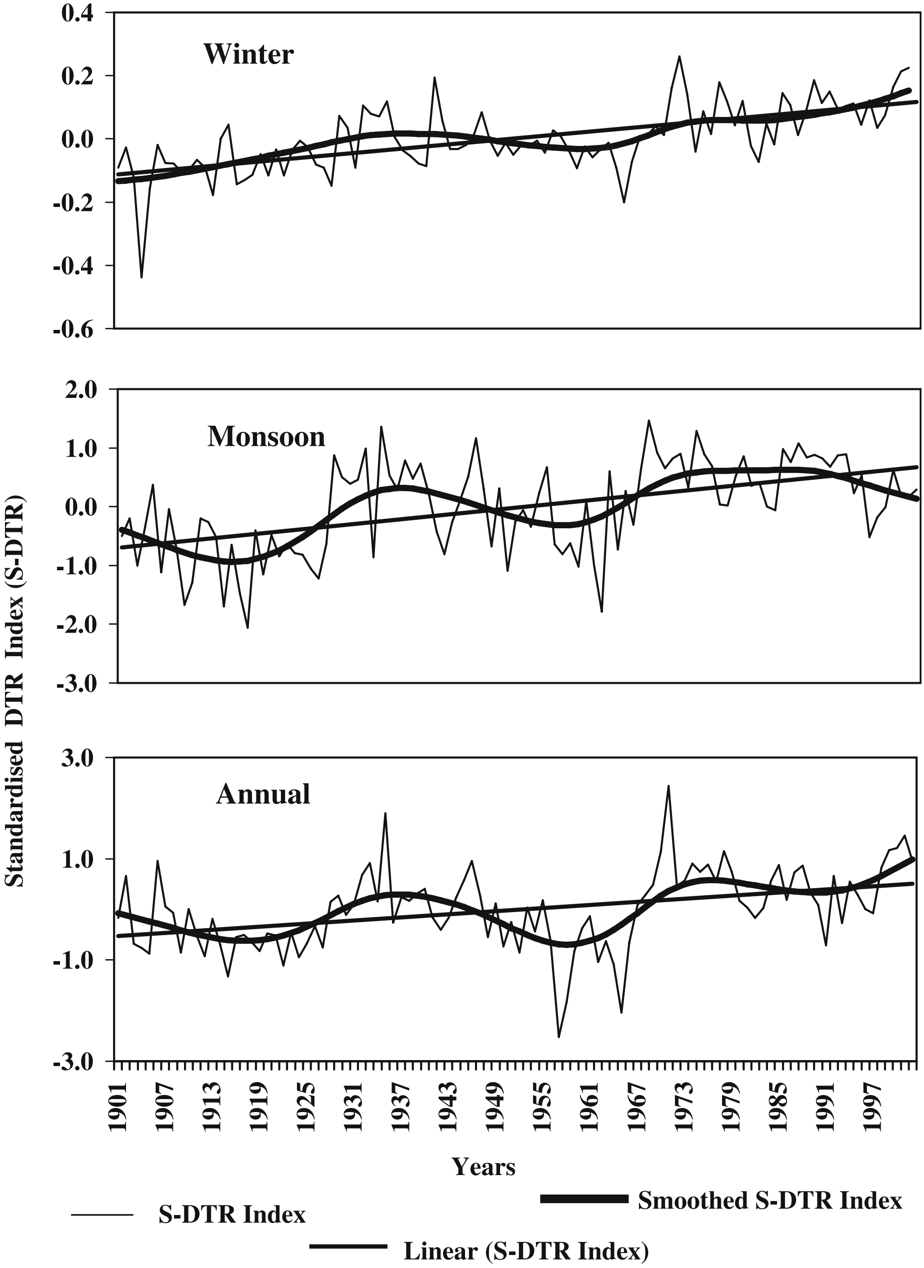

Fig. 8 Variation of winter, monsoon and annual diurnal temperature range (DTR) in northwestern Himalaya in the last century

and 1992, when a sudden drop in air temperature was recorded globally and is also reflected in STI (Standardised Temperature Index) series of the NWH. This drop in mean air temperature has been ascribed to general cooling caused by the spread of aerosols in the upper atmosphere emitted by the volcanic eruptions of Mt. Pinatubo in Philippines

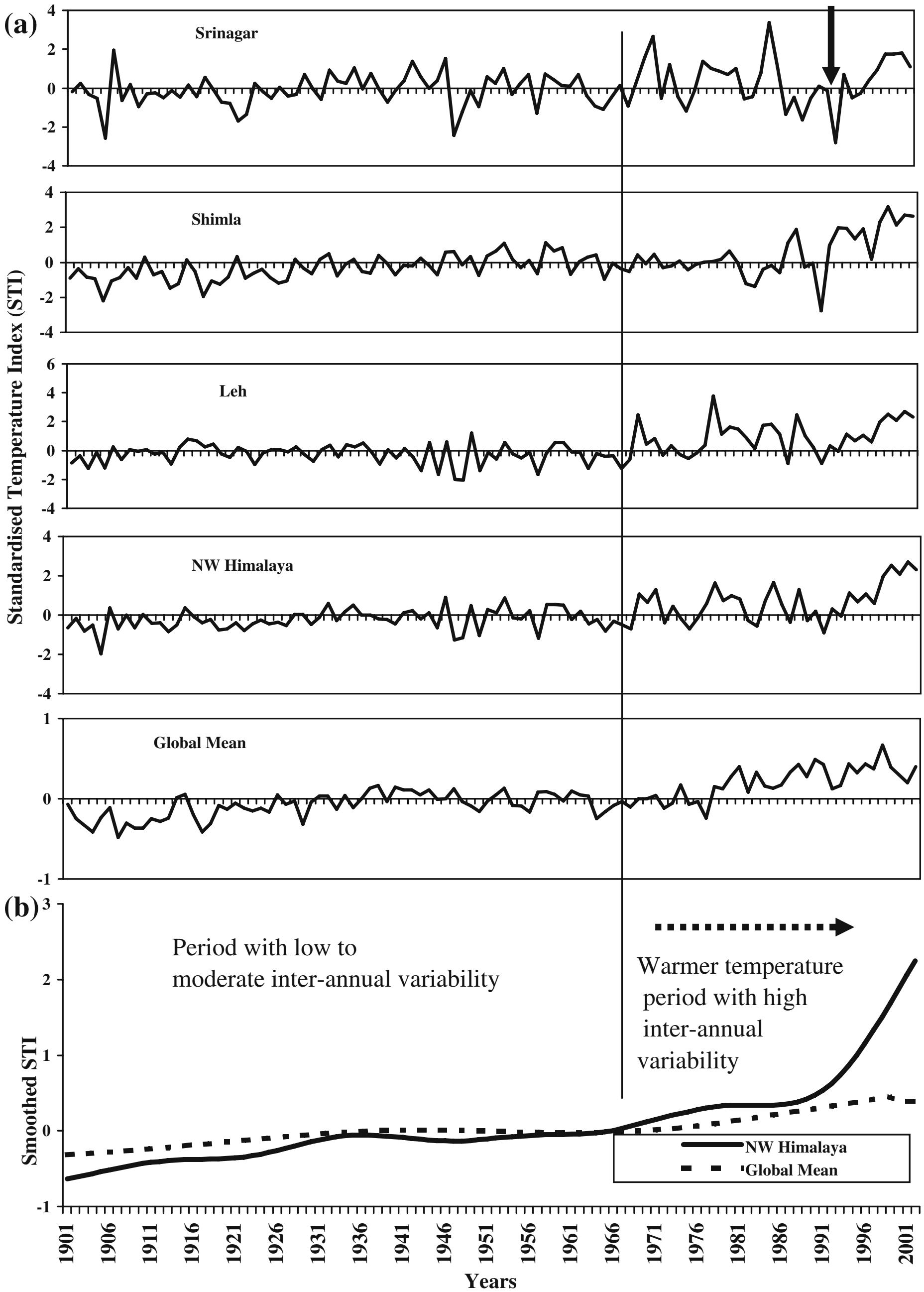

Fig. 9 Comparison of temperature variation in northwestern Himalaya (NWH) vis-à-vis the global temperature in the last century. *Black solid arrow* indicates cooling due to the effect of Mt. Pinatubo eruption

(McCornnick et al. 1995; Hansen et al. 1996; Parker et al. 1996). An interesting feature illustrated by the graph is a dramatic increase in the inter-annual variability during the post-1967 period. In comparison, the inter-annual variability of STI of Srinagar, Leh and Shimla was remarkably lower between 1901 and late-1960s which mimics the global pattern. Positive bivariate correlation coefficients (r^2) obtained in linear regressions between annual STI series of Srinagar, Shimla, Leh and the NWH and the global mean (Table 4) also indicate that the temperature variations at all these stations and the NWH are in conformity with the global trend.

Figure 9b shows the variation of global mean air temperature and the NWH (smoothed data). The graphs indicate similar epochs of temperature variation in the last century as discussed above and confirm a steeper rise in air temperature in the NWH during the last two decades.

3.2 Relationship between temperature and precipitation variation

To establish reasons for higher rate of 'warming' in the last two decades, the relationships between the winter, monsoon and annual STI, SPI and S-DTR series of the NWH in the last century were studied. The results are demonstrated in Figs. 10, 11, 12. The epochal variation in mean maximum temperature, mean minimum temperature and the DTR can be seen, more or less, in the form of sinusoidal curves. They appear to be largely coupled with the long-term precipitation variation that prevailed during these periods, indicating teleconnections in their variation. Maxima in the curve of annual SPI are seen generally to coincide with the maxima in mean minimum STI and minima in the curves of mean maximum STI and standardised DTR index till around late-1960s. This shows that the periods of excess (deficient) annual precipitation, with overall increase (decrease) in cloud-cover, were associated with low (high) maximum temperatures, high (low) minimum temperatures and lower (higher) diurnal temperature range. This may be because of the decrease (increase) in daytime direct radiation and entrapment (release) of nighttime outgoing longwave radiation during the periods of excess (deficient) precipitation, resulting in decrease (increase) in DTR values during these periods (Easterling et al. 1997; Wibig and Glowicki 2002). The oscillatory characteristics of these series are reflected in the power spectrum analyses of temperature, precipitation and diurnal temperature range. The spectral estimates of the smoothed series along with the associated values of 90, 95 and 99% confidence limits based on appropriate null continuum are shown in Table 5. It is seen from this table that a periodicity of 34 years (significant at 90% level) in annual precipitation is replicated by a strong periodicity of 34 and 68 years in the diurnal temperature range (DTR).

It is evident from the above discussion that the variations of maximum, minimum, average annual temperature and diurnal temperature range (DTR) were affected by the

Table 4 Variation of coefficients of linear correlation (r^2) between annual STI series of Srinagar, Shimla, Leh and the NWH

	Global mean	Srinagar	Shimla	Leh	NWH
Global mean	1.00	0.03*	0.26*	0.17*	0.25*
Srinagar	0.03*	1.00	0.07*	0.25*	0.53*
Shimla	0.26*	0.07*	1.00	0.26*	0.58*
Leh	0.17*	0.25*	0.26*	1.00	0.73*
NWH	0.25*	0.53*	0.58*	0.73*	1.00

* Significant at 95% confidence level

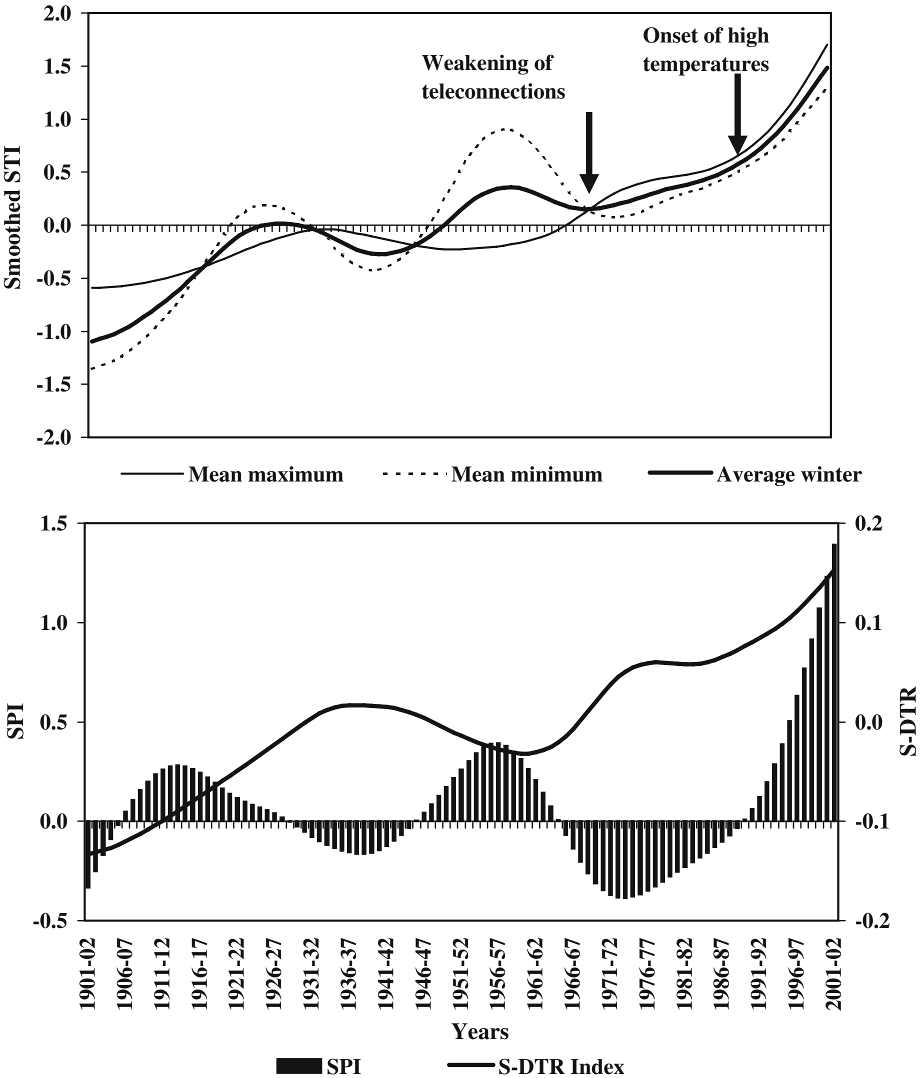

Fig. 10 Relationship between the winter standardised temperature index (STI), standardised winter precipitation index (SPI) and standardised winter diurnal temperature range (S-DTR) in the NWH

fluctuations in the annual precipitation patterns till late-1960s. The period after this was marked by deficient annual precipitation till around 1990–1991. During this period, both maximum and minimum temperatures have increased. Minimum temperature has increased at comparatively lower rate as compared to maximum temperature, leading to rise in DTR values. The period after 1990–1991 has been characterised by excess annual precipitation as seen in Fig. 12. Normally this period should have experienced lower maximum temperatures, higher minimum temperatures and reduced DTR values. Instead, both maximum and minimum temperatures have shown sizeable increase and DTR values have increased significantly during this period.

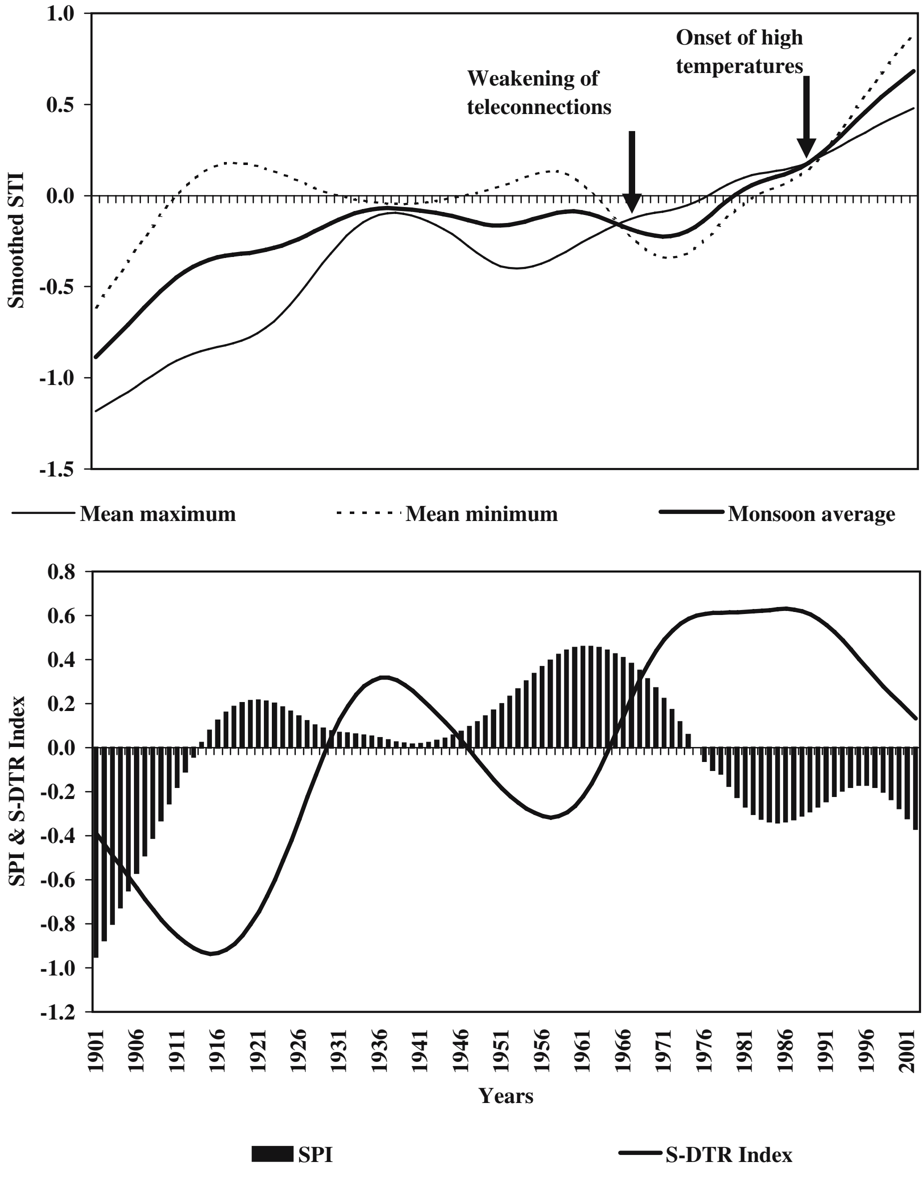

Fig. 11 Relationship between the monsoon standardised temperature index (STI), standardised monsoon precipitation index (SPI) and standardised monsoon diurnal temperature range (S-DTR) in the NWH

A remarkable feature from the standpoint of the climate change in the NWH is that the teleconnections between the variation of temperature and precipitation existing till late-1960s, appear to have weakened gradually since the late-1960s (Krishna Kumar et al. 1999) and rapidly in the post-1990–1991 period indicating the waning effect of the natural forcings in this period. Continued rise in air temperature in the post-1990–1991 period, with both maximum and minimum temperature increasing at a higher rate, makes it difficult

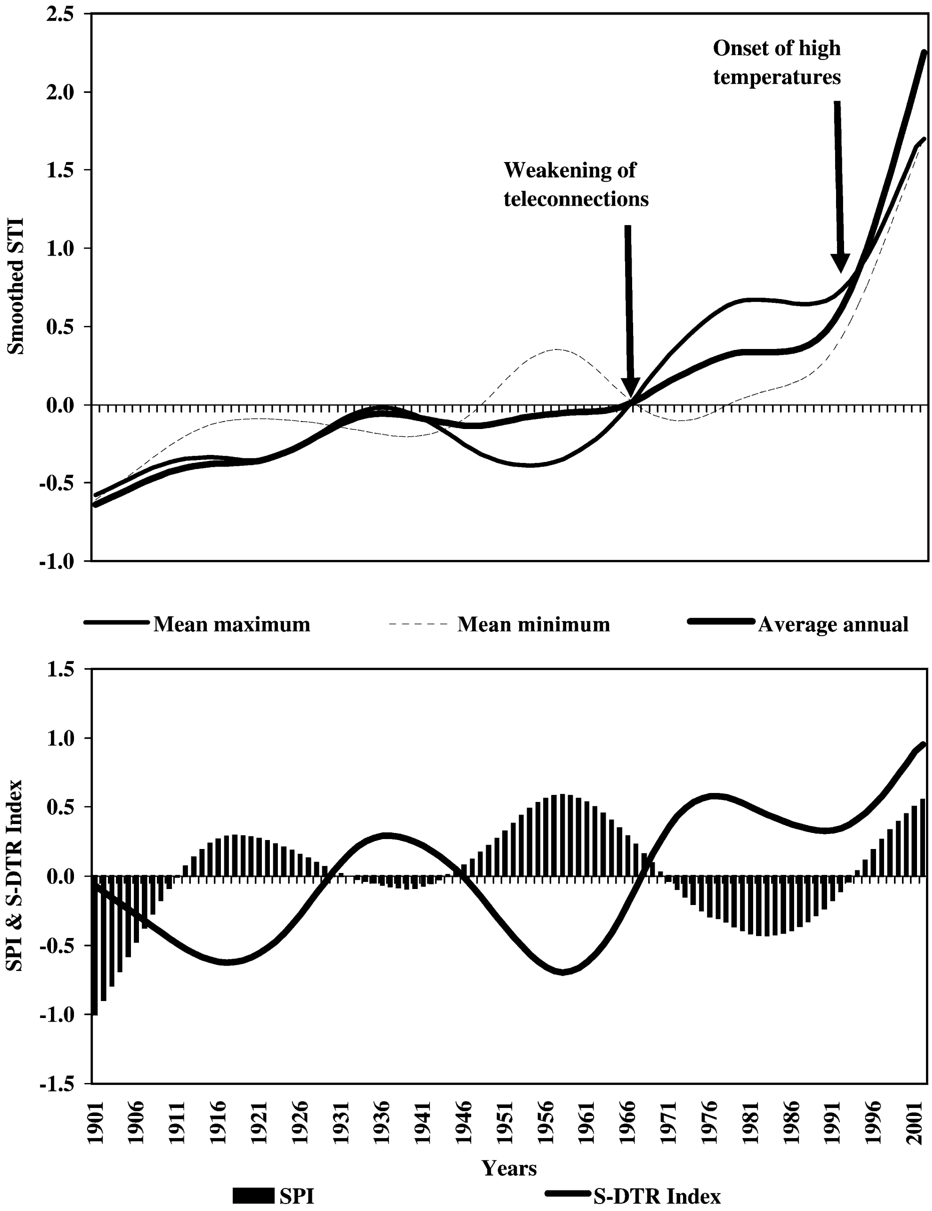

Fig. 12 Relationship between the annual standardised temperature index (STI), standardised annual precipitation index (SPI) and standardised annual diurnal temperature range (S-DTR) in the NWH

to attribute to the natural factors alone. It is, therefore, logical to conclude that some additional factors may have been responsible (Easterling et al. 1997; Crowley 2000). One of these factors could be the increasing concentration of greenhouse gases in the atmosphere related to rapid industrialization and urbanization. Monitoring of changes in

Table 5 Results of the power spectrum analyses of STI, S-DTR and SPI series of the NWH

Season	Significant cycle in years
A) Standardised temperature index (STI)	
Winter	6.6*
Monsoon	3.6**, 3.4**, 2.2*
Annual	2.3*
B) Standardised DTR index (S-DTR)	
Winter	4.4***, 2.8***
Monsoon	68***, 2.8**
Annual	34***, 2.8**
C) Standardised precipitation index (SPI)	
Winter	3.4*, 3.2*
Monsoon	4.3*, 2.8*, 2.6*
Annual	34*, 9.7*, 2.7*

* Significant at 90% confidence level, ** Significant at 95% confidence level and *** Significant at 99% confidence level

population and land use patterns and the greenhouse gases emission may provide a good insight into the probable causes of the climatic change in the NWH.

4 Conclusions

The study has confirmed that the NWH region has ‘warmed’ significantly during the last century at a rate, which is higher than the global average. Unlike other high mountainous regions such as the Alps and Rockies, where the minimum temperatures have increased at an elevated pace, the rise in air temperature in the NWH has been primarily due to rapid increases in both, the maximum as well as minimum temperatures, with the maximum temperature increasing more rapidly.

The present study has demonstrated the existence of possible teleconnections between the precipitation and temperature variation in the NWH till late-1960s in the last century. However, post-1970, these connections appear to have grown weaker considerably. It points towards the presence of other factors, which could also be playing a role. One of these could be the increasing concentration of greenhouse gases in the atmosphere.

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