# Recent wintertime climatic variability over the North West Himalayan cryosphere

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**This study discusses the observed long-term (1991–2015) and short-term (1991–2000 and 2001–2015) trends in winter temperature and precipitation over Northwestern Himalaya (NWH) along with its constituents, i.e. Lower Himalaya (LH), Greater Himalaya (GH) and Karakoram Himalaya (KH). An overall warming signature was observed over NWH since maximum, minimum and mean temperatures followed rising trends with a total increase of 0.9°C, 0.19°C and 0.65°C respectively, in 25 years, the increase being statistically significant for maximum and mean temperatures. However, warming was not consistent over all zones of NWH with minimum temperature at LH showing anomalous cooling by 0.83°C (statistically significant at $\alpha = 0.05$) during 25 years. The rise in mean temperature was observed highest at GH, i.e. 0.87°C (1991–2015) followed by KH, i.e. 0.56°C, which is in agreement with observations of comparatively higher rate of glacier retreat over GH than KH as reported in several studies. Total precipitation (rainfall + snowfall) was found to increase whereas snowfall was found to decrease with concurrent significant increase in rainfall at all zones of NWH. The spatio-temporal winter climatic variations over NWH support the impact on recently reported findings on the Himalayan snow cover and glacier variations at different durations.**

**Keywords:** Climate change, cryosphere, rainfall, winter warming and precipitation.

## Introduction

MOUNTAINS cover almost 27% of the earth's continental area[1] and support approximately 26% of total world population[2]. They play a vital role in regulating circulation patterns and thus shaping the weather over an area[3,4]. The mountains of the Himalaya are active in the regulation and redistribution of water resources as they contain headwater of many major rivers like the Ganges, Brahmaputra and Indus[5]. Some studies suggest that high-elevation environments comprising glaciers and permafrost are among the most sensitive indicators of climate change[6,7]. Detailed study of climate change impacts on water resources of Asia is crucial since glacial melt runoff in the continent is expected to increase in near future, thereby prompting water scarcity in the longer run due to global warming[8]. However, many such studies are impeded by scarcity of ground-observed data due to remoteness of the region[9,10].

Several attempts to study the prevailing snow-meteorological conditions over snow-bound areas of Northwestern Himalaya (NWH) utilizing ground-observed data report rise in temperature by various extents[11–14], whereas exceptional results conclude cooling over various parts of the Himalaya like Karakoram, Upper Indus Basin (UIB) and Western Himalayas during different seasons[12,15–18]. This spatially variable climate trend is attributed to significant altitudinal range of the Himalaya. Hence, distinct climatic zones similar to those separated by wide latitudinal belts can be observed within short horizontal distances[3]. Sharma and Ganju[19] also classified NWH into three distinct snow climatic zones, viz. lower, middle and upper Himalayan zones. Moderate temperature and high precipitation having significant impact on snow properties are the main characteristics of the lower Himalayan (LH) zone. The middle Himalayan zone encompassing the Greater Himalaya (GH) has numerous glaciers and is characterized by cold temperature with precipitation usually in the form of dry snow. The upper Himalayan zone which includes the Karakoram Himalayan (KH) range is characterized by extreme cold temperature with much of the area occupied by large glacial masses. Precipitation is in the form of dry snow with fewer events of rainfall during summer, that too in the valley region[20].

The impact of global warming on the cryosphere is evident worldwide. It has been reported that the Himalayan glaciers are receding in most of the regions[21,22], except a few glaciers of Karakoram which display heterogeneity[23,24]. In addition, mass balance study of the Himalayan glaciers depicts loss in mass, i.e. negative mass balance[21,25,26], except slight mass gain reported from a few glaciers of KH[27,28]. The spatially variable response of glaciers in the Himalaya is attributed to climate and topography of the region, since it was reported that glaciers lying in the westerly influenced areas have either advanced or show stability, while debris covered glaciers are found to have stable fronts. On the contrary, those influenced by summer monsoon are unstable and retreat rates are very high for such glaciers[10]. The varying extent of snow cover area (SCA) over the Himalaya using satellite data has also been reported for different durations and

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*For correspondence. (e-mail: hs.negi@sase.drdo.in) amplified warming over snow-bound areas is attributed to snow-albedo feedback[29–32]. Moreover, anthropogenic activities and dust storms have triggered climate change and influenced the cryosphere over the Tibet-Himalayan region[33–35]. Therefore, it is important to understand the spatio-temporal variability in climatic parameters to study its impact over cryospheric regions. The aim of this study is to analyse recent long-term winter time trends (1991–2015) from field-observed maximum temperature, minimum temperature, mean temperature, diurnal temperature range (DTR) and precipitation (snow water equivalent (SWE), mm) over different zones of NWH. Further, we discuss the impact of climate change on the Himalayan cryosphere in recent decades.

## Study area

The study area is NWH and based on the winter (November–April) snow climatic conditions, this area has been categorized into three zones[19] – LH, GH and KH in this study. Snow and Avalanche study establishment (SASE), India has a network of snow-meteorological observatories spanning all climatic zones of NWH. For this study, data from 16 observatories have been considered. Figure 1 depicts the study area with locations of these observatories.

## Data and methodology

### Data

The data of winter season (November–April) for the period 1991–2015 (25 years) were analysed to study the spatio-temporal variation in climatic parameters. The parameters considered were maximum temperature, minimum temperature, mean temperature, DTR and precipitation. Mean temperature is average of maximum and minimum temperature values. DTR is the difference between maximum and minimum temperature values. For temperature variables, seasonal temperature is the average of monthly temperature values. The seasonal precipitation depicts cumulative amount of monthly precipitation values. For different climatic zones, time series of temperature and precipitation were constructed by arithmetically averaging the values of the contributing stations. Since precipitation over NWH is mostly received as a mixture of snow, sleet and liquid water, the total precipitation was converted into SWE (mm) by multiplying with the respective densities.

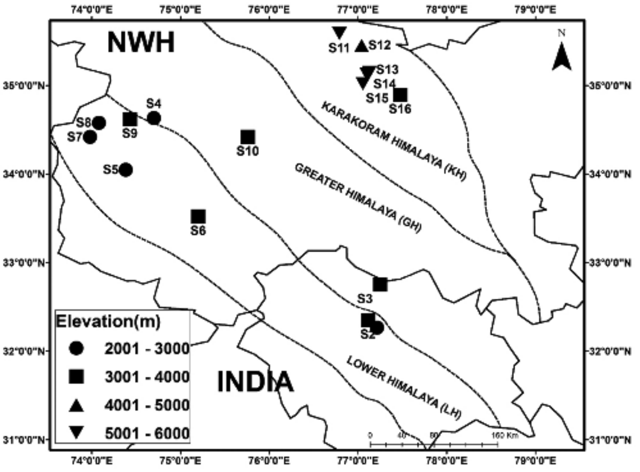

**Figure 1.** Study area, i.e. Northwestern Himalaya (NWH) with different climatic zones, i.e. Lower Himalaya (LH) and Greater Himalaya (GH), Karakoram Himalaya (KH) and locations of snow-meteorological observatories of snow and Avalanche study establishment (SASE).

### Methods

The data were tested for heterogeneities caused by factors other than climatic factors using double mass analysis[36], in which data are compared with those from a nearby station with relatively lesser number of missing records. Data gaps were filled by multiple regression using least absolute deviation (MLAD) method, which showed better estimation efficiency as reported by many researchers[37,39]. Due to orographic influences, data exhibit high spatial variability. In order to add consistency and facilitate comparison of data from different climatic zones, they were standardized prior to analysis[13]. In addition, anomalies of temperature and precipitation were computed. The time series of normalized winter temperature and precipitation time series and anomalies were computed using eqs (1) and (2) respectively.

$$\text{Normalized time series} = \frac{1}{\sigma}\left(\frac{X_i - \bar{X}}{\bar{X}}\right). \quad (1)$$

$$\text{Normalized anomaly} = \left(\frac{X_i - \bar{X}}{\sigma}\right), \quad (2)$$

where $X_i$ represents the actual time series, $\bar{X}$ the long-term mean of time series and $\sigma$ is the standard deviation of the series.

A widely used Excel template called MAKESENS generated by the Finnish Meteorological Institute[40] was used to detect and estimate trends and significance of trends. This template makes use of the popular non-parametric Mann–Kendall test for trend analysis and Sen's method for magnitude of trend. The latter estimates slope using a linear method.

## Results and discussion

### Spatial variability of climatic variables over NWH

Figure 2 *a–c* provides a comparative analysis of maximum temperature, minimum temperature and mean

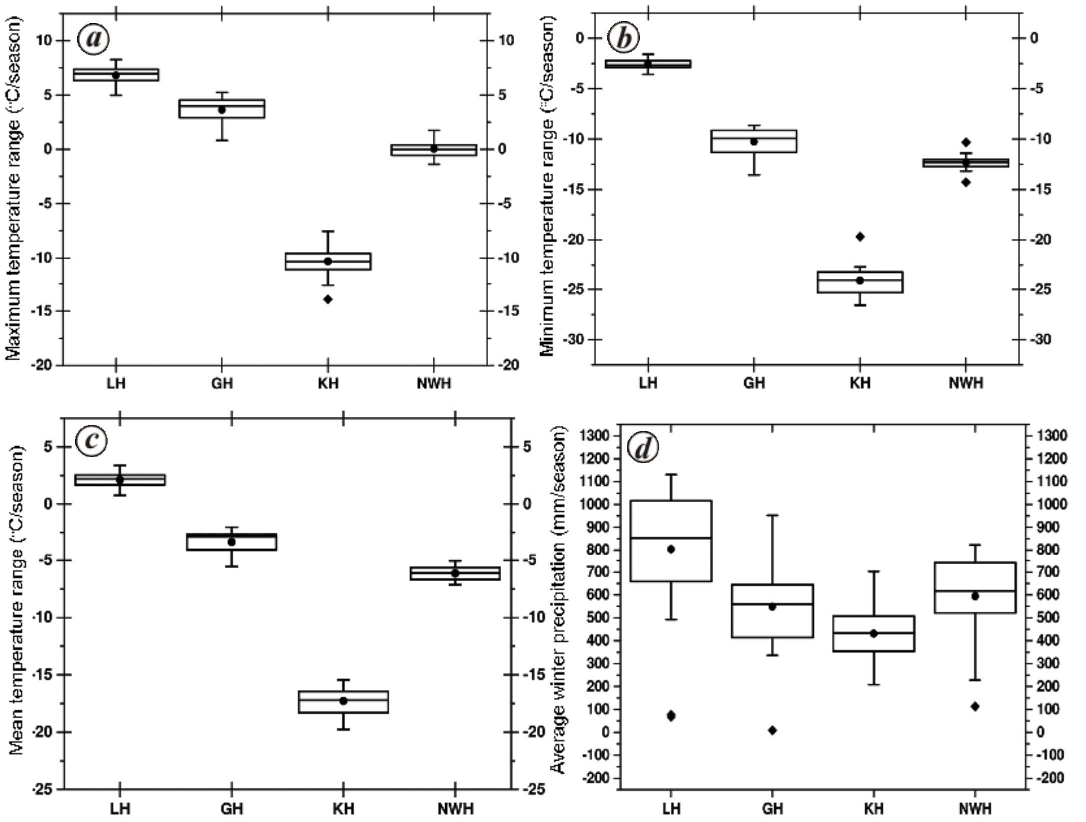

**Figure 2.** Box-charts representing values of various parameters during winter (November–April) of 25 years. ***a***, Average maximum temperature at LH, GH, KH and NWH (6.8°C, 3.6°C, –10.3°C and 0.05°C respectively). ***b***, Average minimum temperature at LH, GH, KH and NWH (–2.6°C, –10.3°C, –24.1°C and –12.3°C respectively). ***c***, Mean temperature at LH, GH, KH and NWH (2.1°C, –3.3°C, –17.3°C and –6.2°C respectively). ***d***, Average precipitation at LH, GH, KH and NWH (804, 549, 431 and 595 mm respectively).

temperature over the three NWH zones, i.e. LH, GH and KH, and overall in NWH. The average winter maximum temperature of LH, GH and KH recorded during 1991–2015 was found to be 6.8°C, 3.6°C and –10.3°C respectively. Similarly, average winter minimum temperature of LH, GH and KH recorded during this period was found to be approximately –2.6°C, –10.3°C and –24.1°C respectively. The average winter mean temperature was found to be 2.1°C, –3.3°C and –17.3°C for LH, GH and KH respectively. Hence average winter maximum, minimum and mean temperatures over NWH were approximately 0.05°C, –12.3°C and –6.2°C respectively. The spatial variability in temperature can be well observed while traversing from LH towards KH. This further substantiated by observations of varying snow albedo values over respective zones by Negi *et al.*[20]. This spatial variability in temperature values can be well explained by orographic and altitudinal effects.

Figure 2 *d* shows the spatial variability of precipitation in NWH. Average winter precipitation at LH, GH, KH and NWH during 1991–2015 was found to be approximately 804, 549, 431 and 595 mm respectively. These values are important for hydrological applications.

## *Winter temperature trends*

Figure 3 *a* depicts interannual variability of maximum temperature anomalies at LH, GH, KH and NWH during 1991–2015. Maximum temperature followed an increasing trend in all climatic zones during this period. Table 1 summarizes the climatological mean (25 years), magnitude of total change, rate of change and the respective significance levels for different temperature parameters in all the snow climatic zones of NWH. The rate of warming per year was found to be ~0.049°C, 0.031°C and 0.029°C at LH, GH and KH respectively. A significant warming was observed at LH, GH and KH, which is equivalent to approximately 1.22°C, 0.77°C and 0.72°C respectively, at different levels of significance. Consequently, maximum temperature at NWH increased by 0.90°C during the 25-year period, with per year increase of 0.036°C significant at $\alpha = 0.001$. Evidently, the increase in maximum temperature at individual zones of NWH and NWH (overall) was much higher than the global average, i.e. 0.28°C reported by Karl *et al.*[41] for the period 1951–90. However, the total rise in maximum temperature at NWH, i.e. 0.90°C was similar to that reported by Dash *et al.*[42] for

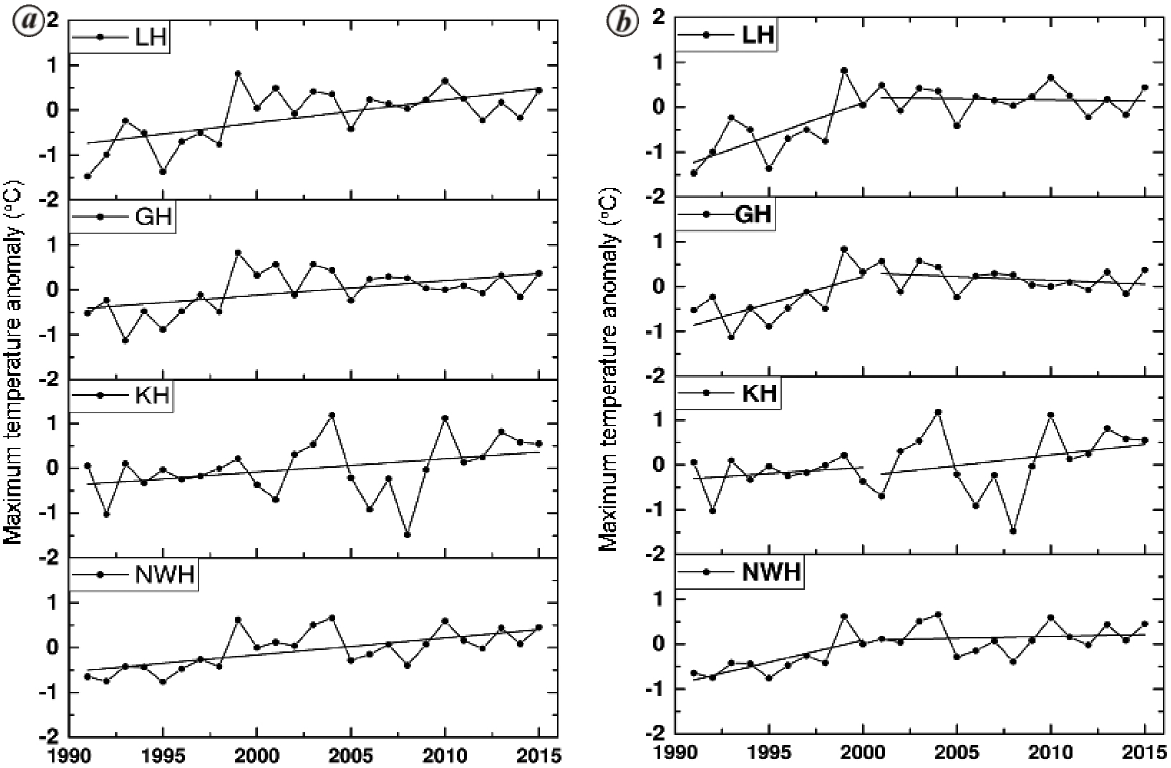

**Figure 3.** Interannual variability of average winter maximum temperature in different climatic zones of NWH. ***a***, During 1991–2015; rate of change/year (°C) at LH, GH, KH and NWH is +(0.049)**, +(0.031)*, +(0.029)* and +(0.036)*** respectively. ***b***, 1991–2000; trend at LH, GH, KH and NWH is (+)$^+$, (+), (+) and (+)* respectively; during 2000–2015, trend at LH, GH, KH and NWH is (–), (–), (+) and (+) respectively. *, **, *** and + represent statistical significance at $\alpha = 0.05$, 0.01, 0.001 and 0.1 respectively.

**Table 1.** Comparative analysis of trend and slope observed in maximum, minimum and mean temperatures and diurnal temperature range during 25 years (1991–2015) at Lower Himalaya (LH) and Greater Himalaya (GH), Karakoram Himalaya (KH) and Northwestern Himalaya (NWH)

| Temperature | Temperature parameter | LH | GH | KH | NWH |
|---|---|---|---|---|---|
| Maximum | Climatological mean (1991–2015) | 6.8 | 3.6 | –10.3 | 0.05 |
| | Total change (°C) (1991–2015) | 1.22 | 0.77 | 0.72 | 0.90 |
| | Rate of change per year (°C; 1991–2015) | +(0.049)** | +(0.031)* | +(0.029)* | +(0.036)*** |
| | Trend (1991–2000) | (+)$^+$ | (+) | (+) | (+)* |
| | Trend (2001–2015) | (–) | (–) | (+) | (+) |
| Minimum | Climatological mean (1991–2015) | –2.6 | –10.3 | –24.1 | –12.3 |
| | Total change (°C; 1991–2015) | –0.83 | 0.98 | 0.44 | 0.19 |
| | Rate of change per year (°C; 1991–2015) | –(0.033)* | +(0.039)** | +(0.018) | +(0.008) |
| | Trend (1991–2000) | (–)$^+$ | (–) | (–)* | (–)** |
| | Trend (2001–2015) | (–)* | (+) | (+)* | (+) |
| Mean | Climatological mean (1991–2015) | 2.1 | –3.3 | –17.3 | –6.2 |
| | Total change (°C; 1991–2015) | 0.37 | 0.87 | 0.56 | 0.65 |
| | Rate of change per year (°C; 1991–2015) | +(0.015) | +(0.035)* | +(0.023) | +(0.026)** |
| | Trend (1991–2000) | (+) | (+) | (–) | (+) |
| | Trend (2001–2015) | (–) | (–) | (+)* | (+) |
| DTR | Climatological mean (1991–2015) | 9.41 | 13.86 | 13.82 | 12.36 |
| | Total change (°C; 1991–2015) | 2.56 | –0.31 | 0.56 | 0.94 |
| | Rate of change per year (°C; 1991–2015) | +(0.102)*** | –(0.012) | +(0.022) | +(0.037)* |
| | Trend (1991–2000) | (+)** | (+)$^+$ | (+)* | (+)** |
| | Trend (2001–2015) | (+)$^+$ | (–) | (–) | (–) |

Increasing and decreasing trends are indicated by (+) and (–) respectively, and *, **,***, + represent statistical significance at $\alpha = 0.05$, $\alpha = 0.01$, $\alpha = 0.001$ and $\alpha = 0.1$ respectively.

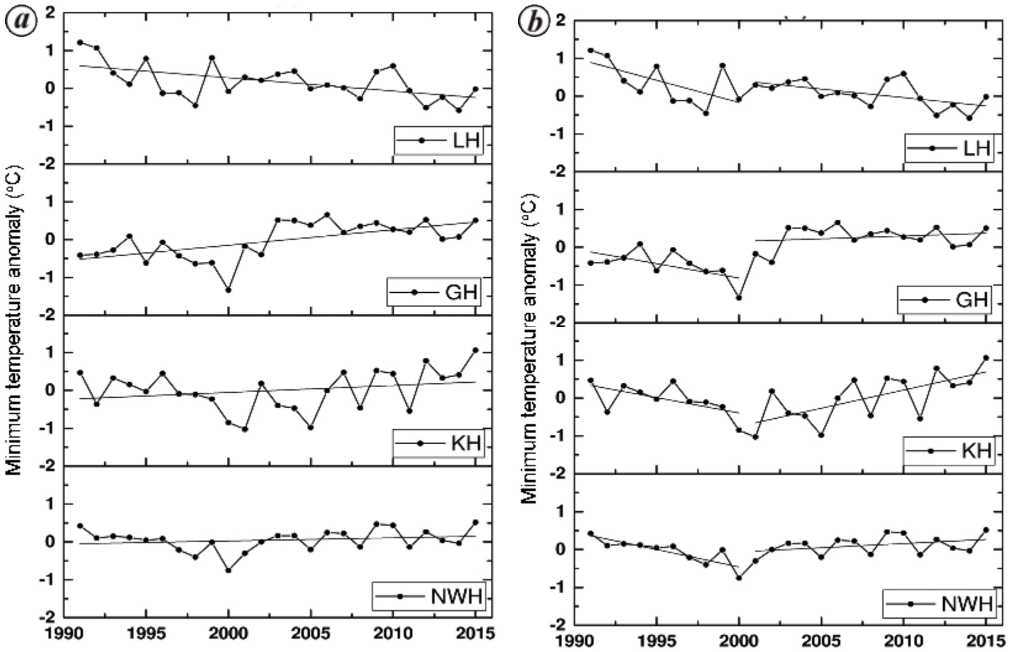

**Figure 4.** Interannual variability of average winter minimum temperature in different climatic zones of NWH. ***a***, During 1991–2015, rate of change/year (°C) at LH, GH, KH and NWH is –(0.033)*, +(0.039)**, +(0.018) and +(0.008) respectively. ***b***, During 1991–2000, trend at LH, GH, KH and NWH is $(–)^+$, (–), (–)* and (–)** respectively; during 2000–2015, trend at LH, GH, KH and NWH is (–)*, (+), (+)* and (+) respectively. *, ** and + represent statistical significance at $\alpha = 0.05$, 0.01 and 0.1 respectively.

the period 1901–2003 over Western Himalaya. Dimri *et al.*[13] also reported more pronounced warming in maximum temperature than minimum temperature. Shekhar *et al.*[12] attributed the decrease in cloud cover for this observed warming in maximum temperature at all zones of NWH, as decreased cloud cover increases daytime heating by enhancing solar influx over any area. Despite the observed warming in 25 years, it was also found that after year 2000, maximum temperature of LH and GH followed cooling trends from previously warming ones during 1991–2000. Krishnan and Ramanathan[43] also observed similar cooling in maximum temperature over India during the winter and dry season during the last three decades. They attributed surface cooling for increased emission of absorbing aerosols in the upper atmosphere which significantly reduce solar radiation reaching the surface of the earth. Figure 3 *b* shows these changing trends in maximum temperature pre- and post-year 2000. The increase in maximum temperature over KH was found consistent throughout the 25-year period (1991–2015) and during pre- and post-year 2000, which is consistent with winter warming over UIB during 1961–2000, as reported by Fowler and Archer[15]. Similar to KH, NWH also experienced warming in maximum temperature during all periods, i.e. 1991–2015, 1991–2000, 2001–15, but before year 2000 it was found significant.

Figure 4 *a* presents interannual variability of minimum temperature anomalies at LH, GH, KH and NWH during the 25-year period. Minimum temperature experienced warming in 25 years at all the climatic zones, except LH. Minimum temperatures increased by ~0.98°C and ~0.44°C for GH and KH respectively, and the increase was significant only for GH ($\alpha = 0.01$). On the other hand, LH showed a significant dip in minimum temperature by ~0.83°C ($\alpha = 0.05$). Overall, though insignificant, minimum temperature rose by 0.19°C during 25 years over NWH. Such warming in minimum temperature over Western Himalaya has also been reported earlier by Shekhar *et al.*[12] for the study period 1984/85–2007/08, Dimri and Dash[13] for 1975–2006, and Dash *et al.*[42] for 1972 onwards. The rate of warming (cooling) per year in minimum temperature at GH and KH (LH) (Table 1) was approximately 0.039°C and 0.018°C (–0.033°C) respectively. In addition, analysis of minimum temperature trends before and after year 2000 showed an interesting shift from previously decreasing to now increasing trends at GH and KH, the increase being significant ($\alpha = 0.05$) at KH only. Fowler and Archer[15] also observed similar rise in winter minimum temperature over UIB. Consequently, NWH showed warming trends in minimum temperature during the last 15 years (2001–2015). Figure 4 *b* shows these changing trends in minimum temperature pre- and post-2000. Interestingly, LH experienced significant cooling ($\alpha = 0.05$) during the last 15 years (2001–15), similar to its overall trend in 25 years.

Figure 5 *a* shows interannual variability of mean temperature anomalies at LH, GH, KH and NWH during the 25-year period. Mean temperature of LH, GH and KH during winter season increased by approximately 0.37°C, 0.87°C and 0.56°C respectively, the increase showing

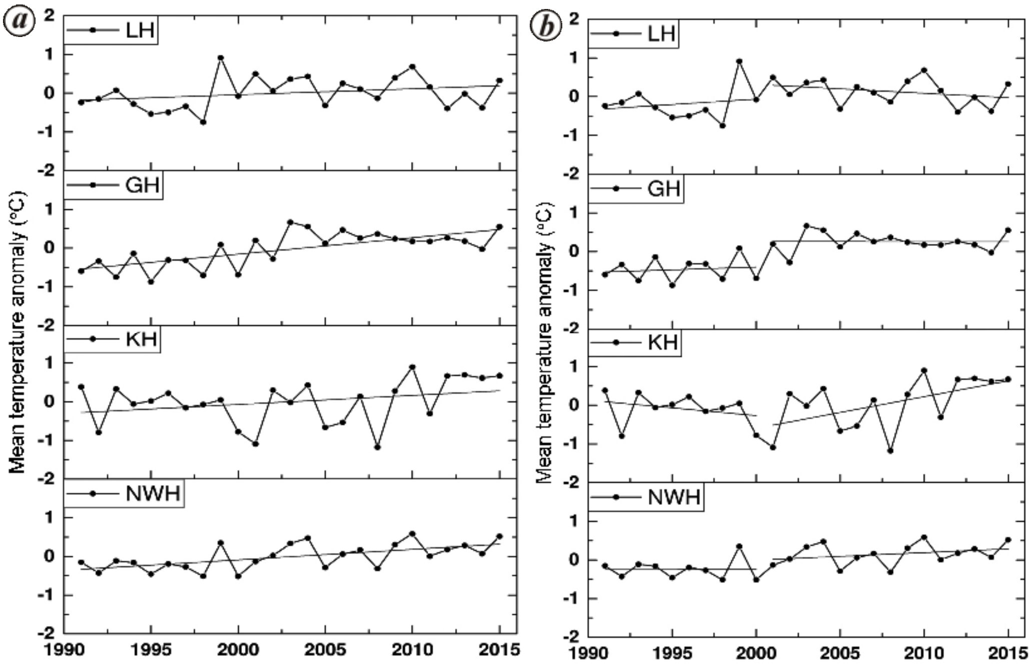

**Figure 5.** Interannual variability of winter mean temperature in different climatic zones of NWH. ***a***, During 1991–2015, rate of change/year (°C) at LH, GH, KH and NWH is + (0.015), +(0.035)*, +(0.023) and +(0.026)** respectively. ***b***, 1991–2000, trend at LH, GH, KH and NWH is (+), (+), (–) and (+) respectively; during 2000–2015 trend at LH, GH, KH and NWH is (–), (–), (+)* and (+) respectively. * and ** represent statistical significance at $\alpha = 0.05$ and 0.01 respectively.

statistical significance at $\alpha = 0.01$ for GH only. Interestingly, since highest warming was observed over GH compared to KH, the anomalous higher rate of glacier retreat over GH than KH may be a consequence of climatological forcing[21–24]. Due to warming in mean temperature in all the zones, NWH also exhibited rising mean temperature by 0.65°C significant at $\alpha = 0.01$. Similar to maximum and minimum temperature, trends in mean temperature during the last 15 years (2001–15) showed a shift from those prevailing before year 2000 for all zones of NWH (Figure 5 *b*). However, trends (2001–15) at KH (i.e. warming trend from previous cooling) showed statistical significance at $\alpha = 0.05$. Overall, mean temperature at NWH has been consistently on the rise since 1991. Also, the contribution of maximum temperature in the rise in mean temperatures was more pronounced in all climatic zones, except GH, as depicted by values of Pearson's correlation coefficient (Table 2).

Figure 6 *a* shows interannual variability of DTR anomalies at LH, GH, KH and NWH during 25-year period. DTR anomaly of LH and KH was found to increase by ~2.56°C and 0.56°C respectively, the increase being significant for LH at $\alpha = 0.001$. Table 1 shows the rate of change of DTR in all the zones during different periods. DTR over NWH increased significantly by 0.94°C ($\alpha = 0.05$) at the rate of +0.037°C/year. However, during the last 15 years (2001–15), DTR has followed a decreasing trend. The increased DTR over LH and KH can be attributed to significant warming in maximum temperature and insignificant warming in minimum temperature. Similar increase in DTR due to differential warming has been reported over India[44]. Increase in DTR and decreasing minimum temperature over western Himalaya was attributed to deforestation and land degradation[17]. DTR has shown a decrease by ~0.3°C in GH. The decline of DTR at GH could be due to rapid warming in minimum than maximum temperature. This decline in DTR over GH is consistent with decreasing global trends during the 20th century[45]. The asymmetrical warming of $T_{\min}$ over $T_{\max}$ has been attributed to factors like cloud cover[46], soil moisture[47] and precipitation[46], feedback processes[48] and land use/land cover[49]. Clouds decrease DTR by decreasing surface solar radiation and soil moisture decreases DTR by increasing evaporative cooling during daytime[46]. Figure 6 *b* depicts that the trends in DTR anomalies before year 2000 have changed from significant positive to insignificant negative after year 2000 for all climatic zones of NWH, except LH which showed consistent increase significant at $\alpha = 0.01$ before year 2000 (1991–2000) and at $\alpha = 0.1$ after year 2000 (2001–2015).

## *Winter precipitation trends*

Total precipitation increased at all climatic zones of NWH during the 25-year period as depicted in Figure 7 *a*, but the increase was found to be significant for LH at

**Table 2.** Correlation (Pearson's $R$) of mean temperature (TMEAN) with maximum (TMAX) and minimum (TMIN) temperatures of different sizes

| Correlation | LH-TMAX | LH-TMIN | GH-TMAX | GH-TMIN | KH-TMAX | KH-TMIN | NWH-TMAX | NWH-TMIN |
|---|---|---|---|---|---|---|---|---|
| LH-TMEAN | **0.820**** | 0.397* | 0.672** | 0.265 | 0.272 | –0.082 | 0.752** | 0.312 |
| GH-TMEAN | 0.725** | –0.192 | 0.741** | **0.835**** | 0.174 | 0.024 | 0.686** | 0.383 |
| KH-TMEAN | 0.073 | –0.017 | –0.161 | 0.220 | **0.839**** | 0.800** | 0.382 | 0.614** |
| NWH-TMEAN | 0.710** | 0.068 | 0.520** | 0.615** | 0.679** | 0.442* | **0.844**** | 0.660** |

Highest values are shown in bold. **Correlation is significant at the 0.01 level (two-tailed). *Correlation is significant at the 0.05 level (two-tailed).

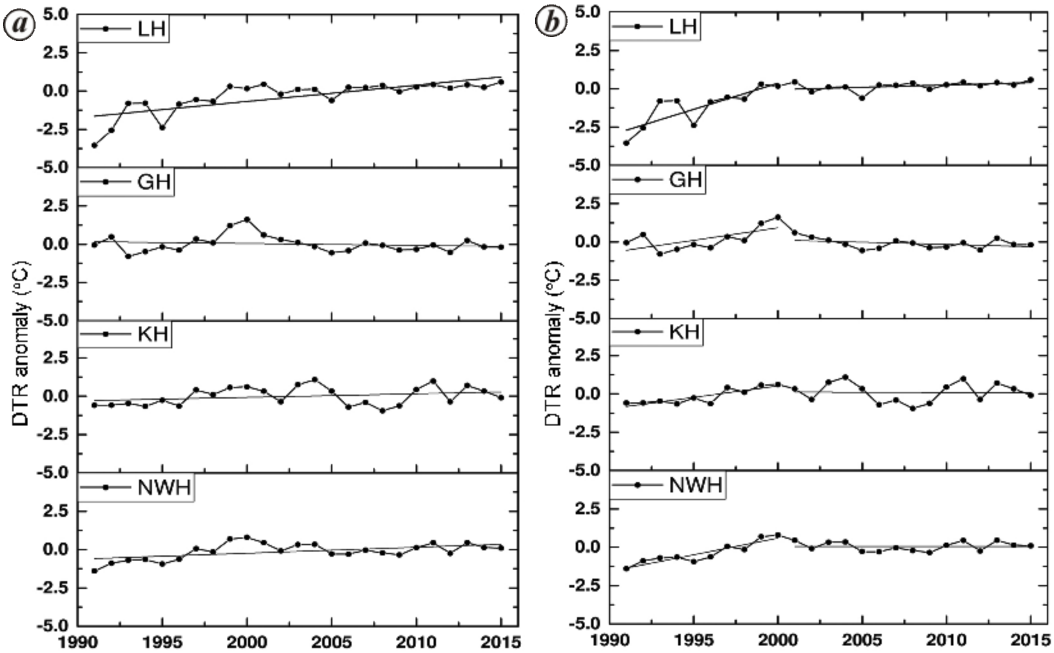

**Figure 6.** Interannual variability of wintertime DTR anomaly in different climatic zones of NWH. ***a***, During 1991–2015, rate of change/year (°C) at LH, GH, KH and NWH is +(0.102)***, –(0.012), +(0.022) and +(0.037)* respectively. ***b***, During 1991–2000, trend at LH, GH, KH and NWH is (+)**, $(+)^+$, (+)* and (+)** respectively. During 2000–2015, trend at LH, GH, KH and NWH is $(+)^+$, (–), (–) and (–) respectively. *, **, *** and + represent statistical significance at $\alpha = 0.05$, 0.01, 0.001 and 0.1 respectively.

$\alpha = 0.05$ only. The total increase in precipitation is represented as standardized precipitation anomalies. These are found to be approximately +1.6, +0.9, +0.2 and +0.9 for LH, GH, KH and NWH respectively. On the contrary, Dimri and Dash[13] reported a decrease in precipitation (SWE) over Western Himalayas during 1975/76–2006/07.

The analysis of precipitation before and after year 2000 indicated a shift in trend from positive to statistically insignificant negative for GH, KH and NWH (Figure 7 *b*). The increase in precipitation over LH was found to be consistent during all cycles, i.e. 1991–2000, 2001–15 and 1991–2015, but significance was observed during 1991-2015 only.

## *Contribution of winter rainfall to total precipitation*

As discussed in the preceding sections, temperatures are rising over all climatic zones of NWH. It was found that the effect of rising temperature has resulted in increased liquid precipitation over NWH during winter season. In order to examine spatio-temporal trends, one station from each climatic zone (i.e. S2 from LH, S10 from GH and S16 from KH) was selected randomly as representative station (Figure 1). Figure 8 *a–c* shows trends in rainfall and snowfall at LH, GH and KH respectively, during the study period. It is to be noted that the station representing KH (S16) had rainfall data of only 16 years (i.e. 2000–15). Other stations in KH are located on the top of glaciated valleys, where only solid precipitation is received[20]. Station S16 lies in the same region but at a lower altitude in the valley region where liquid precipitation was also measured after year 2000. Figure 8 indicates a decrease in snowfall but increase in liquid precipitation in all zones of NWH. The increase in rainfall is found to be significant at different significance levels over all zones (Table 3). Decrease in snowfall and increased rainfall during winter season over the Western Himalaya have also been reported earlier[13,14]. The instances of increased liquid precipitation and reduced solid precipitation are mainly attributed to rising temperatures and such climatic

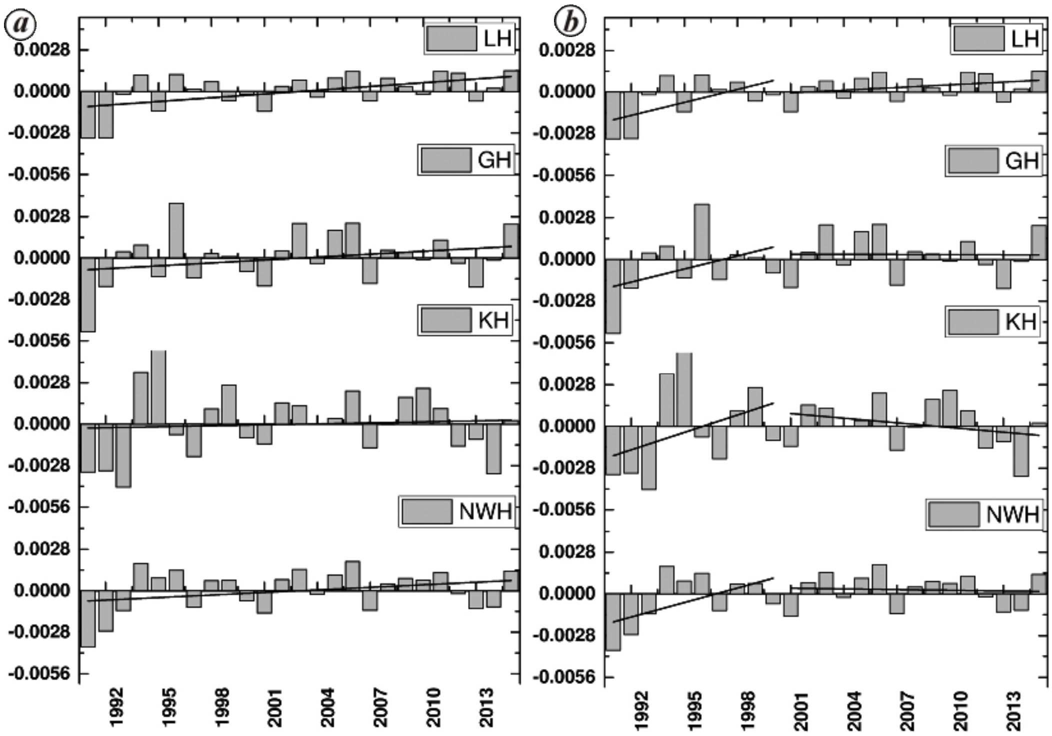

**Figure 7.** Interannual variability of winter precipitation expressed as standardized precipitation anomaly during (***a***) 1991–2015 (25 years); (***b***) 1991–2000 (10 years) and 2000–15 (15 years) in different climatic zones of NWH.

conditions are seen as an impact of El Niño[50]. On the contrary, increased (decreased) consecutive dry days (consecutive wet days) over Western Himalaya and increased prolonged dry days (PDDs) over all the ranges and altitudes of NWH have been reported[13,51]. Instances of increased frequency of extreme rainfall events and number of wet days over some stations of the Western Himalaya and Karakoram have also been reported[52,53]. This increasing tendency of extreme precipitation events has been attributed to increasing variability of western disturbances due to rising baroclinic instability of mean westerly winds over the Western Himalaya[54].

## *NWH cryosphere and climate change*

With the climatic variations in temperature and precipitation, snow cover and glaciers can either accumulate or melt, thus making the cryosphere one of the most powerful indicators of climate change. Snow and ice cover play an important role in radiation budget and act as a positive albedo feedback. Changes in snow and ice cover, in turn, affect air temperature, sea level, storm patterns, etc. NWH cryosphere manifests climate change in various ways. For instance, the decreased winter mean temperature over GH during 2001–15 according to the present study (Table 1), is in accordance with the decline in temperature over GH (after 2000) as observed by Negi *et al.*[20]; and this decline was attributed to increasing albedo in the region after year 2000. Nevertheless, before year 2000, albedo was found to decrease. In addition, mean temperature was found to be a major driving factor behind the observed changes in albedo values[20], which clearly illustrates the sensitivity of the cryosphere towards climate change.

Further, SCA investigations of the Himalaya by Menon *et al.*[55] suggest reduction in snow cover for the decade between 1990 and 2001. Whereas, significantly less declining trend in SCA of NWH was reported by Gurung *et al.*[29] for 2002–10. Immerzeel *et al.*[30] also reported no significant snow cover trends over the Himalaya between 2000 and 2008. Singh *et al.*[31] observed an increasing trend in snow cover between 2000 and 2011 over the Indus basin (part of NWH). Recently, Negi *et al.*[32] confirmed insignificant increasing trend in SCA over NWH for 2001–14. Therefore, the present study of climate change variation supports the recent findings of Himalayan snow cover variations at different durations.

The overall significant increase in mean temperature over GH and NWH (Table 1) led to overall long-term glacier retreat in GH[21,22]. Further decrease in mean temperature or slowdown in temperature rise after year 2000, suggest that most of the glaciers are in a steady state compared to the rate of retreat prior to 2001 as reported by Bahuguna *et al.*[56]. The long-term (1991–2010) albedo observations of significant decreasing trends over GH by Negi *et al.*[20] also support the high rate of glacier retreat and the insignificant increasing trend in albedo after year

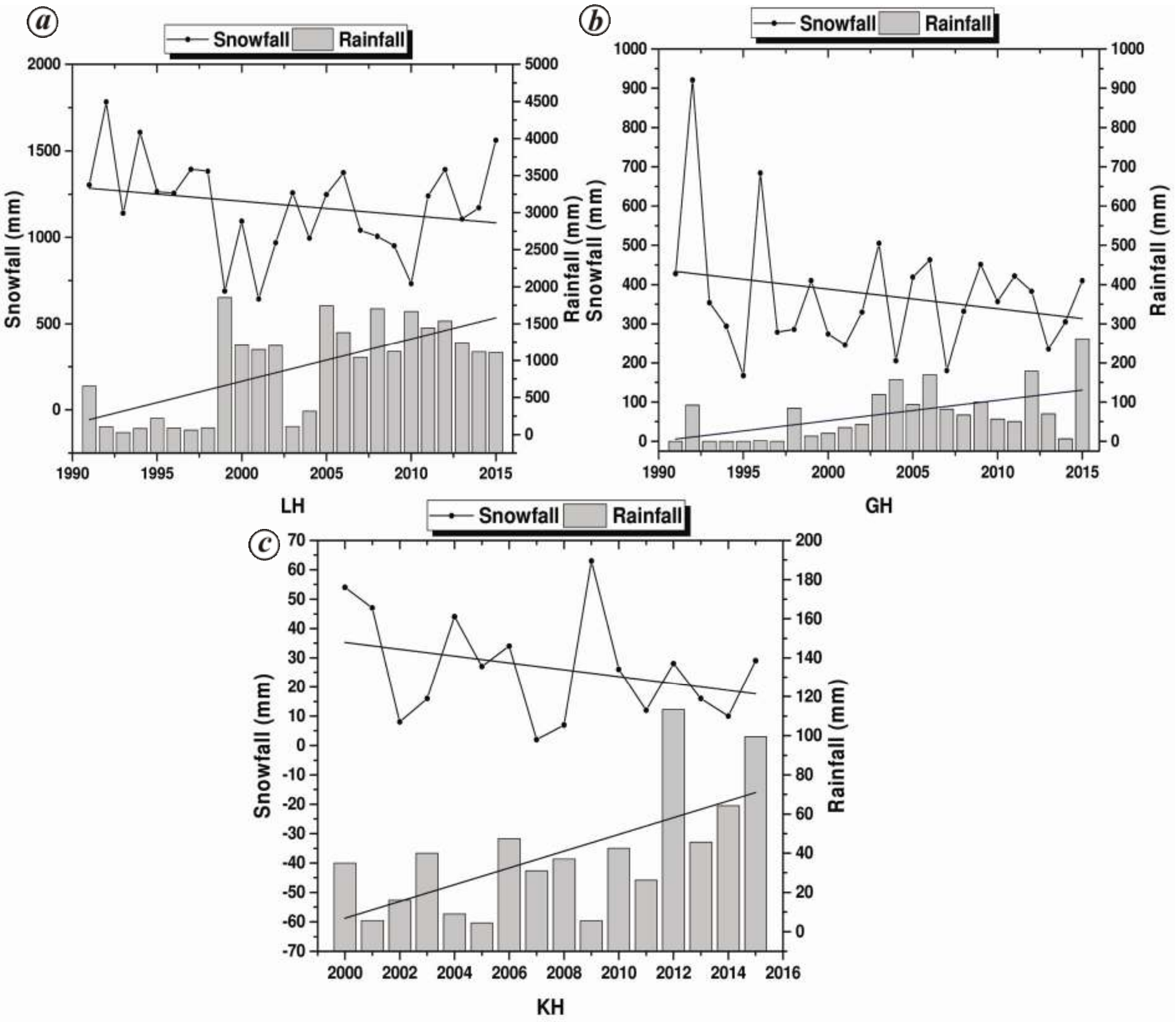

**Figure 8.** Interannual variability of wintertime rainfall along with snowfall during 25 years (1991–2015) at representative stations of (***a***) LH and (***b***) GH during 1991–2015 (25 years) and (***c***) KH during 2000–15.

**Table 3.** Comparative analysis of trend and slope observed in snowfall and rainfall during 25 years (16 years) at LH and GH (KH)

| | | Rainfall | Snowfall |
|---|---|---|---|
| LH | Trend | (+)** | (–) |
| | Slope | 57.5 | –8.3 |
| GH | Trend | (+)** | (–) |
| | Slope | 5.2 | –5 |
| KH | Trend | (+)* | (–) |
| | Slope | 4.3 | –1.2 |

Increasing and decreasing trends are indicated by (+) and (–) respectively. * and **, Statistical significance at $\alpha = 0.05$ and $\alpha = 0.01$ respectively.

2000 supports the steady state of Himalayan glaciers. Thus, winter climatic variation has an important role in governing the rate of overall glacier retreat. Recently, Sirguey *et al.*[57] found that the cumulative winter albedo strongly correlates with winter mass balance ($R^2 = 0.88$), and thus confirmed that winter snow albedo can be used as a proxy to estimate winter mass balance of the glaciers.

The increase in liquid precipitation during winter months over seasonal snow has induced enhanced melting and flood situation in Kashmir recently (5–7 April 2017). Such rising trends in liquid precipitation over snowfall, have a negative influence on the Himalayan glaciers. In addition, the frequency of hazards like avalanches and landslides is expected to increase during late winter.

## Conclusions

Wintertime variability in climatic parameters (maximum, minimum, mean temperature, DTR and precipitation) was analysed over all three snow climatic zones of NWH, i.e. LH, GH and KH during three time scales, i.e. 1991–2015 (25 years), 1991–2000 (10 years) and 2001–2015 (15 years). Impact of global warming is evident over NWH in form of rising maximum and mean temperature at all zones and NWH (overall trend). Minimum temperature is also rising over GH, KH and NWH but cooling over LH is an exception. However, maximum and mean temperature trends during last 15 years (2001–2015) depict cooling at LH and GH which could have resulted from increased aerosol emissions by anthropogenic activities and aerosols, by virtue of their absorbing nature do not allow much of incoming solar radiation reaching the earth surface leading to cooling temperature. On the contrary, KH and NWH (overall) have experienced warming during last 15 years (2001–2015) which substantiates the impact of climate change in form of global warming. However, rate of warming over GH is found to be higher than that prevailing over KH which partly explains the observance of higher glacier retreat rates over GH than KH. Precipitation (solid and liquid) has increased at all zones of NWH though significant increase is reported at LH only in 25 years. Interestingly, snowfall amount is found to have decreased whereas rainfall amount have increased in 25 years. Furthermore, precipitation at all zones except LH follows decreasing trends in last 15 years (2001–2015) which signals significant climatic change especially after year 2000. However, such observations must be validated with other sources of information depicting climate change like extent of glaciated areas and vegetation cover over different regions of NWH.

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