Contrasting changes of snowfall in response to Temperature and Rainfall over two distinct geographic ranges of the Himalayas: A study using long-term observations

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Abstract

Snow is a major source of water and its monitoring is important for hydrological applications. It provides a large amount of meltwater to various rivers such as Indus, Ganges and Brahmaputra in the Himalayan region. Significant changes in snowfall variability play a pivotal role in climate as well as socioeconomic development. The present study investigates the temporal variability of snowfall, temperature and rainfall over Nubra (Latitude: 34.53º-35.67º N; Longitude: 76.75º-77.81º E) and Bhagirathi (Latitude: 30.33º-31.45º N; Longitude: 78.15º-79.47º E) basins in the Himalayan region using 30 years of data (1991–2020). The High Asia Reanalysis (HAR) and Climatic Research Unit (CRU) data were used to study the snowfall and maximum temperature variabilities respectively over the study basins. For rainfall, gridded rainfall data from India Meteorological Department is used. We have studied the annual and monthly variability of daily snowfall, temperature and rainfall over the two basins. Our analysis shows the declining trend (-2 mm/decade) of snowfall over the Nubra basin and slight increasing trend (0.12 mm/decade) in Bhagirathi basin from 2004. The monthly time series in maximum temperature anomaly shows a positive trend with a maximum anomaly found to be around 2K during the winter period. From the rainfall analysis, an increasing trend in annual rainfall is observed, especially Nubra basin show notable increase. Further, warming of the troposphere is found to be ~ 2–3 K, which is another important factor for reduction in snowfall. Thus positive trends in maximum temperature, rainfall and warming troposphere are the controlling factors for the declining (increasing) trend in snowfall over the Nubra (Bhagirathi) basins. Further, we have carried out the WRF simulation for the time series of snowfall. Thus, the present study shows simultaneous changes in snowfall, temperature and rainfall over the Himalayan region and assumes importance in climatic applications.

1. Introduction

Precipitation is a major element in the Earth's hydrological cycle and it is most complex (e.g., Herold et al., 2017) to estimate in the high elevation mountainous regions such as over the Himalayas (e.g., Immerzeel et al., 2015). In the high elevated mountain regions, glaciers and snowmelt make a significant contribution to the total precipitation (e.g., Barnett et al., 2005; Hasson et al., 2014; Nazeer et al., 2022). The freshwater towers of South Asia are the Hindu Kush Himalayas (HKH) that are the origin of 10 major rivers basins (Bajracharya and Shrestha, 2011), which is an essential component of the cryosphere due to the large extent of snow or ice cover (e.g., Sood et al., 2020). The HKH has great heterogeneity and significant variability in snowfall in the Karakoram and western Himalayas during the last few decades, which contribute to the shirking of glaciers and increase in glacier melt (Bolch et al., 2012; Krishnan et al., 2019; Mir et al., 2014). The recent studies showed that changes in snow extent (e.g., Kulkarni et al., 2010) of the HKH region is attributed to changing pattern of snowfall and temperature (Shekhar et al., 2010). Further, warming trends are also responsible for the changes in snowfall due to solar radiation by soot and deposition of soot on snow and glaciers (e.g., Kulkarni et al., 2002; Ramanathan et al., 2007; Lau and Kim, 2018). Moreover, the regional climate variations have a significant influence on snowfall which adversely impacts the melting of snow (Kumar et al., 2019). During the past few decades, there have been many studies on the variability of snowfall and its cover over the HKH region (e.g., Wang et al., 2008; Rikiishi and Nakasato, 2006; Immerzeel et al., 2008; Immerzeel et al., 2009; Kulkarni et al., 2010; Shekhar et al., 2010; Mir et al., 2014; Cohen et al., 2015; Viste and Sorteberg, 2015; Singh et al, 2016; Kumar et al., 2019; Sood et al., 2020; Nazeer et al., 2022). Immerzeel et al. (2009) observed a significant negative trend over the HKH region and its vicinity during winter. Menon et al. (2010) observed a declining trend of snow cover (~ 16% per decade) over the HKH region and it is closely related to air temperature (Wang et al., 2008). Rikiishi and Nakasato (2006) found that the mean annual snow cover reduced by ~ 1% per year in the Himalayas. The increasing trend in temperature has been observed over the HKH region (Immerzeel, 2008; Xu et al., 2008; Shekhar et al., 2010) with exception of the regional warming of the Karakoram range (Shekhar et al., 2010). Viste and Sorteberg (2015) used the combinations of observations with reanalysis data along with climate models for future projection of snowfall over the Himalayas. They found that with the strongest anthropogenic forcing, the climate models show the decline of annual snowfall by 30 to 70% in different basins over HKH regions by 2071–2100. In addition, Menon et al. (2010) result also suggested that the contribution of enhanced black carbon to the decline of snowfall by around 30%. The Intergovernmental Panel on Climate Change (IPCC) report (2018) also highlighted that around 64% of glaciers may be lost by 2100 in the HKH region. In the future, the HKH region will be increased by at least 0.3°C, if global warming is kept under 1.5°C (Krishnan et al., 2019).

Recent studies suggested that there is a shift in hydrological regimes of the upper Ganga basin induced by anthropogenic forcing (Swarnkar et al., 2021). Further, the HKH regions are experiencing more floods in the mountainous and downstream of Indus, Gangas and Brahmaputra river basins due to an increase in extreme precipitation events (IPCC, 2018). It is also evident that the rate of increase in temperature is faster than the global rate (Lau et al., 2010), which is one of the main drivers for the precipitation phase and leads to changes in snowfall and snowmelt distribution (Barnett et al., 2005). Monitoring and studying the temporal and spatial distribution of snowfall in high altitude river basins makes complex due to scarce or non-existent snow gauged observations. Remote sensing provides the spatial distribution of snowfall over the Himalayan region. But their temporal measurements and their retrieval accuracies over high altitude regions are limited further investigating large-scale background dynamics on the changes of daily snowfall. Therefore, the high spatial and temporal resolutions of global model/reanalysis data help to understand the rapid changes of snowfall and associated dynamics over the Himalayas. Thus, the present study uses the High Asia Refined Analysis (HAR) data for investigating the snowfall trends over the two distinct geographic ranges of Himalayas such as Nubra and Bhagirathi basins situated in the Karakoram and Great Himalaya Ranges respectively along with the India Meteorological Department (IMD) gridded rainfall data. CRU is a widely used climate dataset on a 0.5° latitude by 0.5° longitude grid over all land domains of the world except Antarctica. It is derived by the interpolation of monthly climate anomalies from extensive networks of weather station observations (Harries et al., 2020). In the present study, we have used CRU temperature data for investigating associated changes in snowfall over the two basins. Section 2 describes the study area and its importance. Data and methodology are discussed in Section 3. Results and discussion is presented in Section 4 and Section 5 presents to discuss the summary and future scope.

2. Study Area

Bhagirathi and Nubra basins are selected for this study due to the reasons that they are very important glacier regions contributing significantly to two major rivers, Ganga and Indus, and also they belong to two distinct climatic zones of the Himalayas. Nubra basin, situated in the Karakoram Himalayan Range, is dominated by Westerlies whereas South West Indian Monsoon dominates the rest of the Himalayas (Ganjoo et al., 2014). Further, Nubra basin is more arid and less wooded than the Bhagirathi.

Bhagirathi basin located in Uttarakhand State of India is part of the Central Himalayan region and falls within the Greater Himalayan Range. The Gangotri glacier, one of the largest ice bodies in the Garhwal Himalayas and the main source of the river Ganga, is located in this basin. The basin covers an area of ~ 5800 sq. km and has a mean elevation of ~ 3875 meters above sea level.

Nubra basin situated in the Ladakh region of India is part of the Western Himalayan region. With an area of ~ 4400 sq km Nubra is a highly glacierized basin, characterized by steep slopes and has an average elevation of 5150 meters above mean sea level (SAC, 2016).

3. Data And Methodology

The Weather Research and Forecasting (WRF-ARW) model and reinitialized by daily runs. Therefore, the HAR data strongly depends on the quality of global input data and as well as simulation of atmospheric processes by the WRF model (Maussion et al., 2011). Initially, it was implemented with the WRF model with a 30-km resolution model domain without a finer resolution domain (10 km) to remove inconsistencies to produce 30-km spatial resolution HAR30 dataset. A two-way nesting method was applied to run the WRF model with a high spatial resolution (10–km), called HAR10 within a broader 30-km resolution mother domain. Further details about the HAR30 and HAR10 and their differences can be found in Maussion et al (2014). The HAR data can be downloaded from http://www.klima-ds.tu-berlin.de/har/. Pritchard et al. (2010) found that HAR10 data is consistent with the in situ measurements.

We have used a gridded rainfall product from IMD available at 0.25° x 0.25° spatial resolution over two basins from 1901 to 2020 to investigate the long-term variability of rainfall (Rajeevan et al., 2006; Pai et al., 2014). There are around 6955 rain gauge stations (the highest number of stations used) that are included in this high-quality dataset. Shepard's inverse weighted distance interpolation scheme was used to convert the data into a fixed grid point (Rajeevan et al., 2006). A further detailed description of the algorithm procedures for the preparation of the data can be found in Rajeevan et al. (2006) and Pai et al. (2014). Data is arranged in 135x129 grid points. The high resolution gridded rainfall data can be accessed from https://imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html. Further, this high-resolution dataset is being extensively used in many studies and also used as input for the APHRODITE (Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation) data set. In this paper, we have extracted the daily rainfall data from 1901 to 2020 exclusively for Nubra and Bhagirathi basins. The daily maximum temperature was downloaded from CRU)gridded time-series dataset version 4.03 which provides a high-resolution on monthly time scales using land-based observations (excluding Antarctica) from 1901 to 2018 (Harris et al., 2020). Also, we have used mid-tropospheric temperature data from NOAA Climate Data Record (CDR) of Atmospheric Layer Temperatures (Mears et al., 2015) (https://www.ncei.noaa.gov/data/mean-layer-temperature-rss/access/). We have estimated the daily mean Snowfall (mm/day), Rainfall (mm/day) and maximum Temperature (^{o}K) data over Nubra and Bhagirathi basins. Further, we determined the monthly and yearly, mean values from the daily mean to investigate long-term variation in these parameters.

4. Results And Discussion

The spatial distribution of the monthly mean of daily snowfall (mm/day) derived from the HAR dataset is shown in Fig. 2. The magenta and white circle symbol indicates the locations of Nubra and Bhagirathi basins respectively shown in Fig. 1. The monthly variability of snowfall and its cover is seen in Fig. 2. From this picture, it is observed that the monthly mean daily snowfall distribution show that there is a gradual decrease from March to July (Fig. 2). Similarly, there is a gradual increase in the spatial extent of snowfall and magnitude is seen from September to February (Fig. 2). With the progression of the summer monsoon, the snowmelt contribution increases over the Himalayan region. During the winter period, western disturbances contribute significantly to the total snowfall over the Himalayan region (e.g., Mir et al., 2014). While in the summer period, the Himalayan region is dominated by the Bay of Bengal low-pressure systems (e.g., Kurita et al., 2008). Thus the decrease (increase) in snowfall has mainly been attributed to the melting (accumulating) in the summer (winter) period (e.g., Kulakarni et al., 2011). The faster rate of snowmelt is observed from May onward (Fig. 1). Due to perplexing hydroclimate changes, the variability in snowfall is not uniform over the Himalayas region, which is evident in Fig. 2. Figure 3 shows the monthly mean snowfall over (a) Nubra and (b) Bhagirathi basins from 1991 to 2020. Around 50% of reduction of monthly snowfall was noticed in Nubra basin in 2020 compared to 1991 (Fig. 3(a)) with strong interannual variability. While over the Bhagirathi basin, a slight increase of around 10% of monthly snowfall was observed from 1991 to 2020. Interestingly, there is around 50% reduction from 1991 to 2004 and an increasing trend has been observed from 2004 to 2020 (Fig. 3(b)) with varying rate of variability over the Bhagirathi basin. Over all, it shows a decreasing (slight increasing) trend is observed in the Nubra (Bhagirathi) basins. As mentioned above, Nubra located in a Karakoram Range, while Bhagirathi situated in a Great Himalayas Range. As mentioned above, Nubra is located in the Karakoram Range, while Bhagirathi is situated in the Great Himalayas Range. The geographic resident of high Asia Mountain Range forces the Nubra basin to be more dominated by winter storms and prone to the more frequent passage of midlatitude synoptic-scale systems known as the western disturbances (e.g., Dimiri et al., 2015).

Interestingly, very less monthly snowfall was observed during 2000–2001 (2008–2009) & 2006–2007(2017–2018) periods in Nubra (Bhagirathi) basins. Kulakarni et al. (2011) also noticed that the rate of decline in snowfall is more during the 2000 year. This might be due to the fewer snowfall days in that year and also increased rainfall in those periods as shown in Fig. 4, which exhibited an increasing trend.

The increased rainfall might have been caused by western disturbances. Vellore et al. (2014) noticed that the heavy rainfall associated with monsoon low-pressure system and interaction with subtropical westerly winds. But, some studies have reported a significant decreasing trend of about 1% per year in the occurrence of western disturbances (e.g., Shekhar et al., 2010; Midhuna et al., 2020). In contrast, Hunt et al. (2018) and Cannon et al. (2016) observed an increasing trend in western disturbances using ERA-Interim (European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis) and CFSR (Climate Forecast System Reanalysis)) reanalysis data. These differences can be attributed to various environmental conditions such as seasonal influences and other factors such as the impact of black carbon on snowfall (e.g., Lau and Kim, 2018) and it calls for further investigations. Further, it can contribute to the uncertainty in identifying the snowfall events in HAR10 data. However, the total precipitation (solid and liquid) does not seem to greatly differ across the region. But, there is a notable difference in rainfall in Nubra and Bhagirathi basins. In the recent decade, a rapid increase in yearly rainfall is noticed in the Nubra basin than in the Bhagirathi basin (Fig. 4).

Further, we have estimated the yearly snowfall from the monthly mean and are shown in Fig. 5. From Fig. 5(a), it was evident that the yearly snowfall is in a declining trend (-2 mm per decade) over the Nubra basin from 1991 to 2020. Maskey et al. (2011) also observed the significant decrease of winter snowfall over the Karakoram Range in the recent decades using MODIS (Moderate Resolution Imaging Spectroradiometer) satellite-derived snow product. In contrast to the Nubra basin, a slight increasing trend was observed over the Bhagirathi basin (+ 0.2 mm per decade). The temperature is one of the important factors responsible for the phase changes of precipitation (shifts from solid to liquid precipitation). The increase in temperature can cause a reduction in snowfall (e.g., Dimri and Mohanty, 2007). During the study period, the monthly maximum air temperature anomaly increased by around 3^{o}C and 2^{o}C in December month over the Nubra and Bhagirathi basins respectively (Fig. 6).

Figure 6 shows the maximum temperature anomaly during December derived from the daily maximum air temperature data from CRU data. From this picture, it is evident that the positive trend for December over the basins. However, a slight decreasing trend of maximum temperature was noticed from 2001 onwards over the Bhagirathi basin. This decreasing of temperature might have caused the increased snowfall during that period over the Bhagirathi basin as seen in Fig. 6(b). Shresta et al (1999) also observed a positive trend of temperature over the Himalayas. Bhutiyani et al. (2007) reported a significant increase in maximum Temperature by around 3^{o}C per 120 years in the north-western Himalayas. The change in daily maximum temperature is due to the global change or local urbanization, which is partly attributed to the changes in mean annual temperatures. Sinha et al. (1997) observed a rise in the temperature associated with rapid urbanization. Sabin et al. (2020) also observed the increase in annual mean temperature by 0.1°C per decade during 1901–2014 with a faster rate of 0.2°C per decade during 1951–2014 due to the increase in anthropogenic activity.

Apart from the surface daily maximum temperature, the mid-tropospheric temperature also showed an increasing trend over both the basins as seen in Fig. 7. This might be one of the contributing factors for the melting of snowfall. The increase in the mid-tropospheric temperature can be associated with the increase in absorption aerosols at high altitudes that can enhance warming (Lau and Kim, 2018). This warming in mid-troposphere can facilitate amplifying the melting of snowfall and leads to the increase in rainfall. However, the effect of black carbon on the Himalayas cryosphere, particularly on the melting of snowfall is not adequately studied. Thus, the present study lies in observing the long-term changes of snowfall over the two distinct geographical basins (Nubra and Bhagirathi) in the Himalayas region, which is essential to understand its variability to better represent these changes in regional models. Towards this, we have carried out the WRF simulation to capture the snowfall variability over the Nubra basin as a case study. Figure 8 shows the monthly times series of snowfall simulated (red colour) from WRF model and HAR data (black colour). The WRF model simulations are performed using two-domain with two-way nesting at 25 km (mother domain) and 5 km (nested domain) spatial resolution. The National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) datasets are utilized to generate initial and lateral boundary conditions for the WRF model. Various satellite and conventional observations are assimilated at 0000 UTC using variational assimilation techniques to improve initial condition (Mandal et al. 2020). The WSM6 and Kain–Fritsch schemes are incorporated for the microphysics and cumulus parameterization, respectively. Further details of the WRF model configurations and model physics schemes are described in Mandal et al. (2020). The daily forecast of the WRF model from 0000 UTC is utilized in this study. It is observed that the WRF model could be able to capture the variability in snowfall, though the magnitude differs. These differences are possible due to different model resolution, physics and global model inputs, etc. Further analysis is needed to better represent the cryospheric processes in regional climate models to understand the intricate weather dynamics over the Himalayas region, which will be carried out in the near future.

5. Summary And Conclusions

In this study, the long-term changes of snowfall are investigated using thirty years (1991–2020) of HAR data over the Nubra and Bhagirathi basins, two distinct geographical locations of the Himalayas Ranges. These basins are falls under the Karakoram and Great Himalaya Ranges and experience different weather dynamics. The important results are summarized below:

1. The estimated snowfall trend was found to be around 2 mm per decade declining over the Nubra basin from the 1991 to 2020 period.
2. Overall, a slight increasing trend was found to be over the Bhagirathi basin. However, a decreasing (increasing) trend was found during the 1991 to 2004 (2004 to 2020) period.
3. It is observed that an increasing trend of rainfall was observed over both the basins.
4. The maximum daily temperature anomaly also showed a positive trend with a maximum anomaly found to around 2K during the winter (December) period.
5. Interestingly, a slightly decreasing trend was observed over the Bhagirathi basin (from 2004 to 2020), which might have caused the slight increase in observed snowfall.
6. Analyzed the mid-tropospheric temperature which showed an increase in the middle troposphere (~ 2–3 K) and contributed to the melting of snowfall.

7. Further, carried out the WRF simulation for time series of snowfall over the Nubra basins and found to be good in agreement with HAR data.
8. Therefore, the positive (negative) trend in maximum temperature, rainfall and warming troposphere are the controlling factors declining (increasing) trend in snowfall over the Nubra (Bhagirathi, from 2004 to 2020 period) basins.

Thus, the present study brought out the contrasting changes in snowfall in response to temperature and rainfall over two different geological locations of the Himalayas Ranges using long-term datasets and assumes the importance of cryosphere climate.

Declarations

Author Contribution: Kandula V Subrahmanyam, conceived the idea and design, carried out the analysis, interpretation and wrote the original manuscript. Prashant Kumar carried out the WRF simulation for the snowfall over Nubra basin. J Srinivasulu, and MVR Sesha Sai are supervised and reviewed the manuscript.

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References

1. Bajracharya SR and Shrestha B (2011) The status of glaciers in the Hindu Kush–Himalayan region. International Centre for Integrated Mountain Development, Kathmandu
2. Barnett TP, Adam JC, Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303–309 doi:10.1038/nature04141.
3. Bhutiyani MR, Kale VS, Pawar NJ (2007) Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century, Climatic Change, 85:159–177 doi:10.1007/s10584-006-9196-1.
4. Bolch T, Kulkarni A, Kaab A, Huggel C, Paul F, Cogley JG, Frey H, Kargel JS, Fujita K, Scheel M, Bajracharya S, Stoffel M (2012) The state and fate of Himalayan glaciers. Science 336, 310e314.
5. Cohen, J, Ye H, Jones J (2015) Trends and variability in rain-on-snow events. Geophys Res Lett 42(17):7115-7122 doi:10.1002/2015GL065320.
6. Dimri AP, Mohanty UC (2007) Location specific prediction of maximum and minimum temperature over the Western Himalayas. Meteorol Appl 14:79–93.
7. Dimri AP, Niyogi D, Barros AP, Ridley J, Mohanty UC, Yasunari T et al (2015) Western disturbances: a review. Rev Geophys 53(2):225–246
8. Ganjoo RK, Koul MN, Bahuguna IM, Ajai (2014) The Complex Phenomenon of Glaciers of Nubra Valley, Karakorum (Ladakh), India. Natural Science 6:733-740

http://dx.doi.org/10.4236/ns.2014.610073

9. Harris I, Osborn TJ, Jones P and Lister D (2020) Version 4 of the CRU TS Monthly High-Resolution Gridded Multivariate Climate Dataset. Sci Data 7:109 https://doi.org/10.1038/s41597-020-0453-3
10. Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. Int J Climatol 34:623–642 doi:10.1002/joc.3711, 2014.
11. Harris IC, Jones PD (2020) CRU TS4.03: Climatic Research Unit (CRU) Time-Series (TS) version 4.03 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2018). Centre for Environmental Data Analysis, 22 January 2020. doi:10.5285/10d3e3640f004c578403419aac167d82.
12. Herold N, Behrangi A, Alexander LV (2017) Large uncertainties in observed daily precipitation extremes over land. J Geophys Res Atmos 122 (2):668–681.
13. Immerzeel WW, Droogers P, de Jong SM, Bierkens MFP (2009) Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. Remote Sens Environ 113:40–49 doi:10.1016/j.rse.2008.08.010.
14. Immerzeel WW (2008) Historical trends and future predictions of climate variability in the Brahmaputra basin. Int J Climatol 28:243–254 doi:10.1002/joc.1528, 2008.
15. Immerzeel, WW, Wanders N, Lutz AF, Shea JM, Bierkens MFP (2015) Reconciling high-altitude precipitation in the upper indus basin with glacier mass balances and runoff. Hydrol Earth Syst Sci 19 (11):4673–4687.
16. IPCC (2018) Climate change 2018: The physical science basis.
17. Krishnan R, Shrestha AB, Ren G, Rajbhandari R, Saeed S, Sanjay J, Syed MA, Vellore R, Xu Y, You Q, Ren Y (2019) Unravelling climate change in the Hindu Kush Himalaya: Rapid warming in the mountains and increasing extremes. In:Wester P, Mishra A, Mukerji A, Shrestha AB, editors. The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People. Cham, Switzerland: Springer Nature 57–97.
18. Kulkarni AV, Mathur P, Rathore BP, Alex S, Thakur N, Manoj K (2002) Effect of global warming on snow ablation pattern in the Himalayas. Curr Sci 83:120–123.
19. Kulkarni AV, Rathore BP, Singh SK, Ajai (2010) Distribution of seasonal snow cover in central and western Himalaya. Ann Glaciol 51(54):123–128 doi:10.3189/172756410791386445.
20. Kulkarni AV, Rathore BP, Singh SK, Bahuguna IM (2011) Understanding changes in Himalayan Cryosphere using remote sensing technique. Int J Remote Sens 32:601–615.
21. Kumar P, Saharwardi MdS, Banerjee A, Azam Mohd F, Dubey AK, Murtugudde R (2019) Snowfall Variability Dictates Glacier Mass Balance Variability in Himalaya-Karakoram. Sci Rep 9:18192 https://doi.org/10.1038/s41598-019-54553-9.
22. Kurita N, Hiroyuki Y (2008) The role of local moisture recycling evaluated using stable isotope data from over the middle of the Tibetan Plateau during the monsoon season. J Hydrometeorol 9:760–775.

23. Lau WKM, Kim KM (2018) Impact of Snow Darkening by Depostion of Light-Absordbing Aerolols on Snow Cover in the Himalayas-Tibetan Plateau and Influence on the Asian Summer Monsoon: A Possible Mechanism for the Blanford Hyposthesis. Atmosphere 9(11):438 doi: 10.3390/atmos9110438.
24. Lau WKM, Kim KM, Kim KM, Lee WS (2010) Enhanced surface warming and accelerated snowmelt in the Himalayas and Tibetan Plateau induced by absorbing aerosols. Environ Res Let 5, 025204.
25. Mandal AK, Ramakrishnan R, Pandey S, Rao AD, Kumar P (2020) An early warning system for inundation forecast due to a tropical cyclone along the east coast of India. Natural Hazards 103(2):2277-2293.
26. Maskey S, Uhlenbrook S, Ojha S (2011) An analysis of snow cover changes in the Himalayan region using MODIS snow products and in-situ temperature data. Clim Change 108:391–400
27. Maussion F, Scherer D, Mölg T, Collier E, Curio J, Finkelnburg R (2014) Precipitation Seasonality and Variability over the Tibetan Plateau as Resolved by the High Asia Reanalysis. J Climate 27(5):1910–1927 doi:10.1175/JCLI-D-13-00282.1.
28. Mears Carl A, Wentz FJ, NOAA CDR Program (2015) NOAA Climate Date Records (CDR) of Atmospheric Layer Temperature, Version 3.3. NOAA National Centers of Environmental Information (NCEI). Doi:10.7285/V5WQ01S4
29. Midhuna TM, Kumar P, Dimri AP (2020) A new western disturbance index for the Indian winter monsoon. J Earth Syst Sci 129(1):59
30. Mir RM, Jain SK, Goswami A (2014) Decline in snowfall in response to temperature in Satluj basin, western Himalaya. J Earth Syst Sci 124:365-382.
31. Nazeer A, Maskey S, Skaugen T, McClain ME (2022) Simulating the hydrological regime of the snow fed and glaciarised Gilgit Basin in the Upper Indus using global precipitation products and a data parsimonious precipitation-runoff model, Science of the Total Environment 802(1):149872 https://doi.org/10.1016/j.scitotenv.2021.149872
32. Pai DS, Latha Sridhar, Rajeevan M, Sreejith OP, Satbhai NS, Mukhopadhyay B (2014) Development of a new high spatial resolution (0.25° X 0.25°) Long period (1901-2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. Mausam 65(1):1-18.
33. Rajeevan M, Bhate J, Kale JD, Lal B (2006) High resolution daily gridded rainfall data for the Indian region: Analysis of break and active monsoon spells. Curr Sci 91(3):296–306.
34. Ramanathan V, Ramana MV, Roberts G, Kim D, Corrigan C, Chung C, Winker D (2007) Warming trends in Asia amplified by brown cloud solar absorption. Nature 448 (7153):575–578 https://doi.org/10.1038/nature06019
35. Rikiishi K, Nakasato H (2006) Height dependence of the tendency for reduction in seasonal snow cover in the Himalaya and the Tibetan Plateau region., 1966–2001. Ann Glaciol 43:369-377 doi:10.3189/172756406781811989.
36. Sabin TP, Krishnan R, Vellore R, Priya O, Borgaonkar HP, Singh BB, Sagar A (2020) Climate Change Over the Himalayas. In: Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A.,

Chakraborty, S. (eds) Assessment of Climate Change over the Indian Region. Springer, Singapore. https://doi.org/10.1007/978-981-15-4327-2_11

37. SAC (2016) Monitoring Snow and Glaciers of Himalayan Region. Space Applications Centre, ISRO, Ahmedabad, India, 413 ISBN: 978 – 93 – 82760 – 24 – 5
38. Shekhar MS, Chand H, Kumar S, Srinivasan K, Ganju A (2010) Climate-change studies in the western Himalaya. Ann Glaciol 51:105–112 doi:10.3189/172756410791386508.
39. Shrestha AB, Wake CP, Mayewski PA, Dibb JE (1999) Maximum Temperature Trends in the Himalaya and Its Vicinity: An Analysis Based on Temperature Records from Nepal for the Period 1971–94. J Climate 12:2775–2786 doi:10.1175/1520- 0442(1999)0122.0.CO;2.
40. Sinha RKC, Mukhopadhya RK, Chowdhary SK (1997) Trend in maximum and minimum temperature and sea level pressure over India; Intromet IIT Delhi, Hauz Khas, New Delhi.
41. Sood V, Singh S, Taloor AK, Prashar S, Kaur TR (2020) Monitoring and mapping of snow cover variability using topographically derived NDSI model over north Indian Himalayas during the period 2008–19, Applied Computing and Geosciences 8:100040 https://doi.org/10.1016/j.acags.2020.100040.
42. Swarnkar S, Mujumdar P, Sinha R (2021) Modifed hydrologic regime of upper Ganga basin induced by natural and anthropogenic stressors. Sci Rep 11:19491 https://doi.org/10.1038/s41598-021-98827-7.
43. Vellore RK, Krishnan R, Pendharkar J, Choudhury AD, Sabin TP (2014) On the anomalous precipitation enhancement over the Himalayan foothills during monsoon breaks. Clim Dyn 43:2009–2031 https://doi.org/10.1007/s00382-013-2024-1
44. Viste E, Sortberg A (2015) Snowfall in the Himalayas: an uncertain future from a little-known past The Cryosphere 9:1147–1167 doi:10.5194/tc-9-1147-2015.
45. Wang L, Gao G, Zhang Y, Sun J, Wang Z, Zhang Y, et al. (2008) Analysis of the severe cold surge, ice-snow and frozen disasters in south China during january 2008: I. Climatic features and its impact. Meteorol Mon 34:95–100 doi:10.7519/j.issn.1000-0526.2008.04.012
46. Xu ZX, Gong TL, Li JY (2008) Decadal trend of climate in the Tibetan Plateau – regional temperature and precipitation. Hydrol Process 22:3056–3065 doi:10.1002/hyp.6892, 2008.

Figures

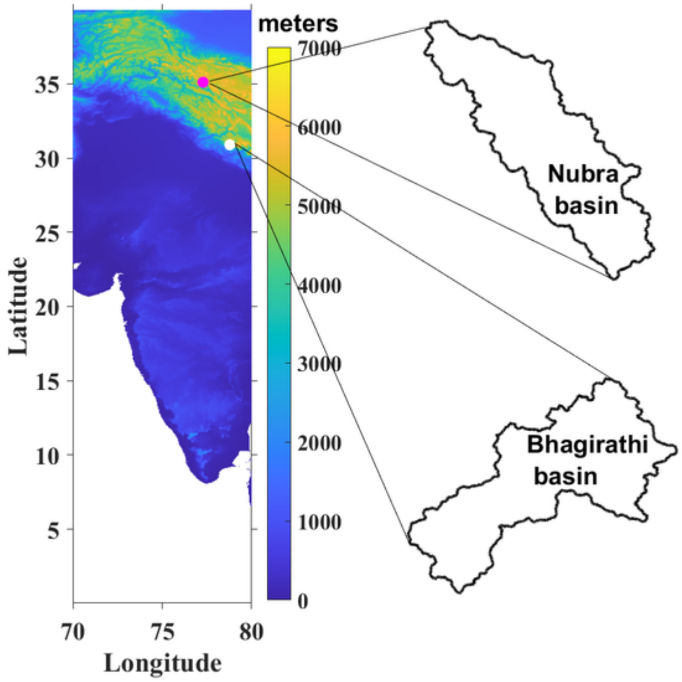

Figure 1

Digital Geographical locations of Nubra (magenta color circle) in Karakoram region and Bhagirathi basins in Great Himalaya Range (white color circle).

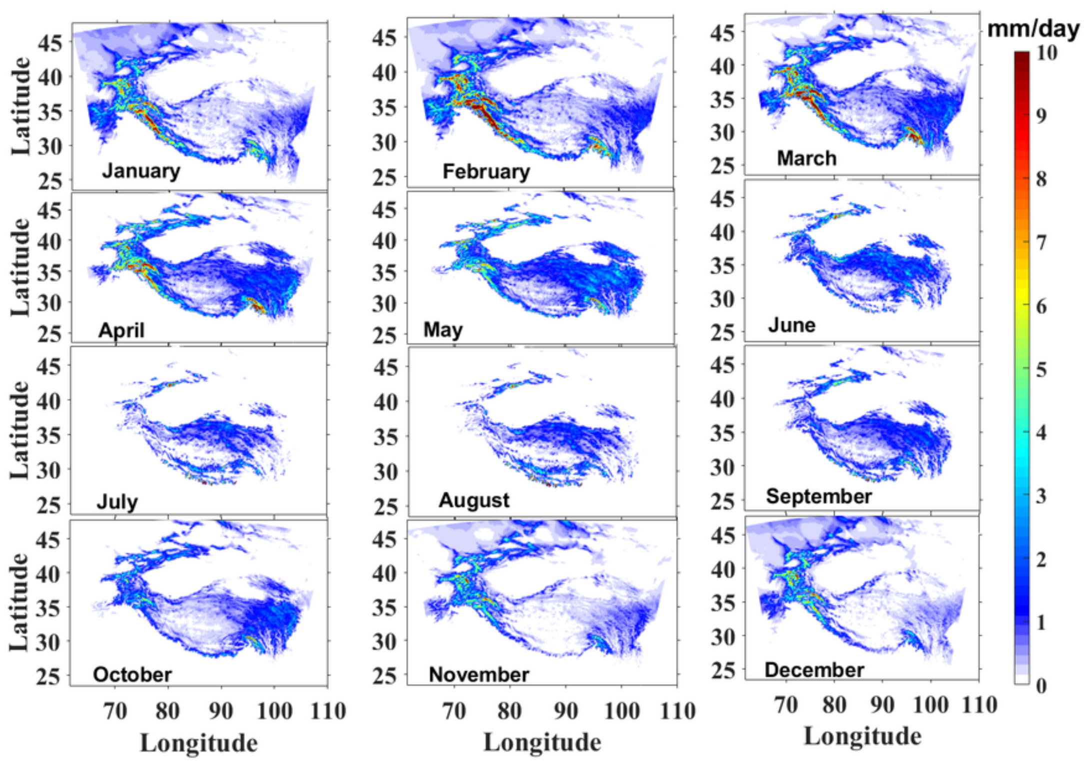

Figure 2

Spatial distribution of the monthly mean of daily snowfall (mm/day) derived from HAR dataset from 1991-2021.

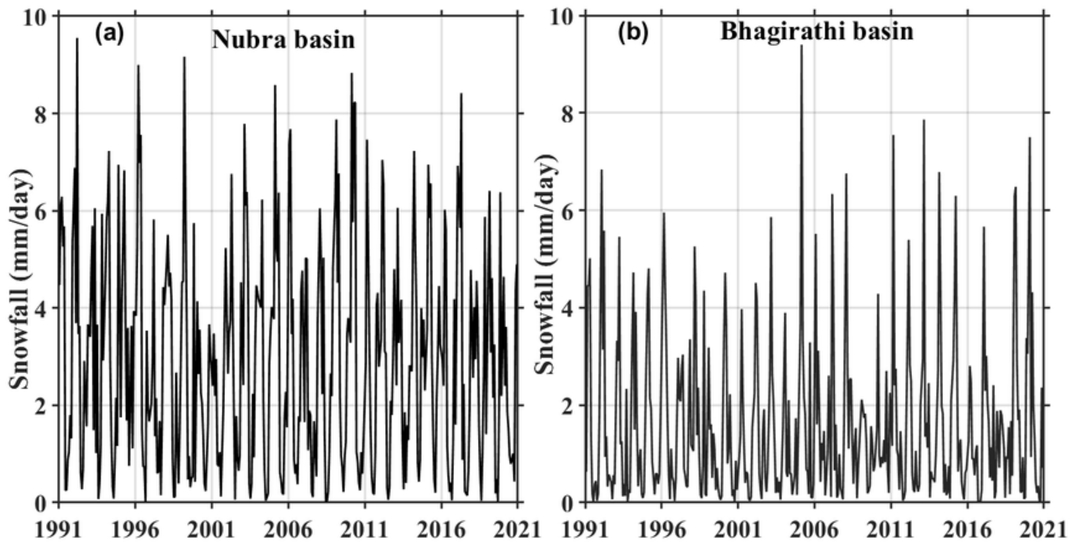

Figure 3

Monthly mean daily snowfall over (a) Nubra and (b) Bhagirathi basins respectively.

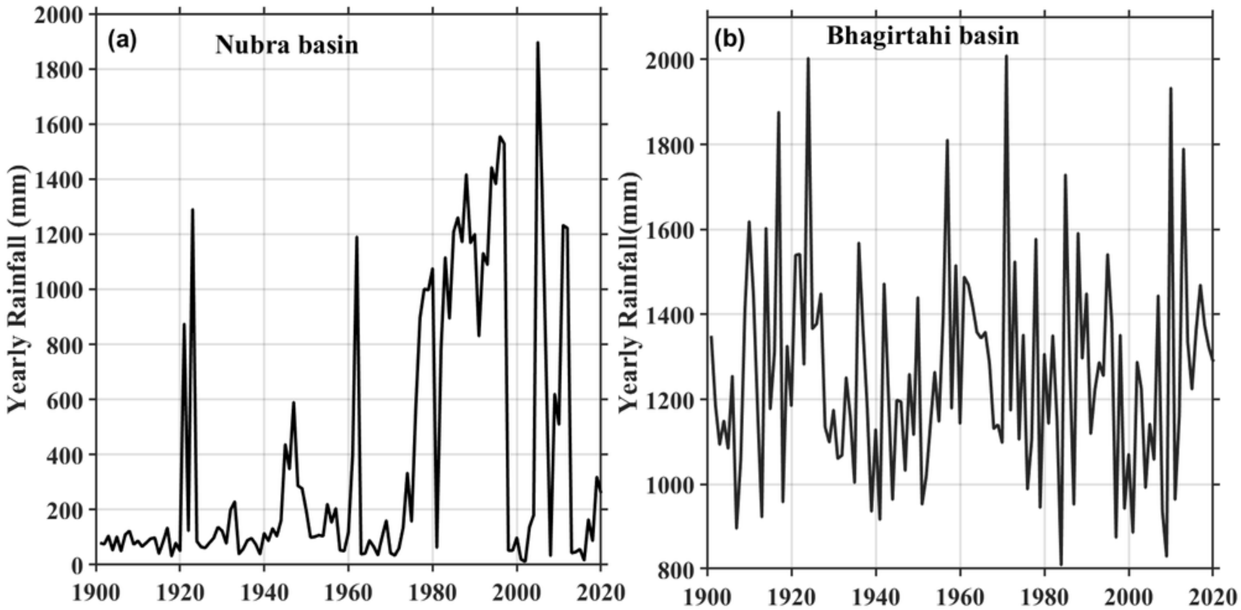

Figure 4

Yearly rainfall over (a) Nubra and (b) Bhagirathi basins respectively

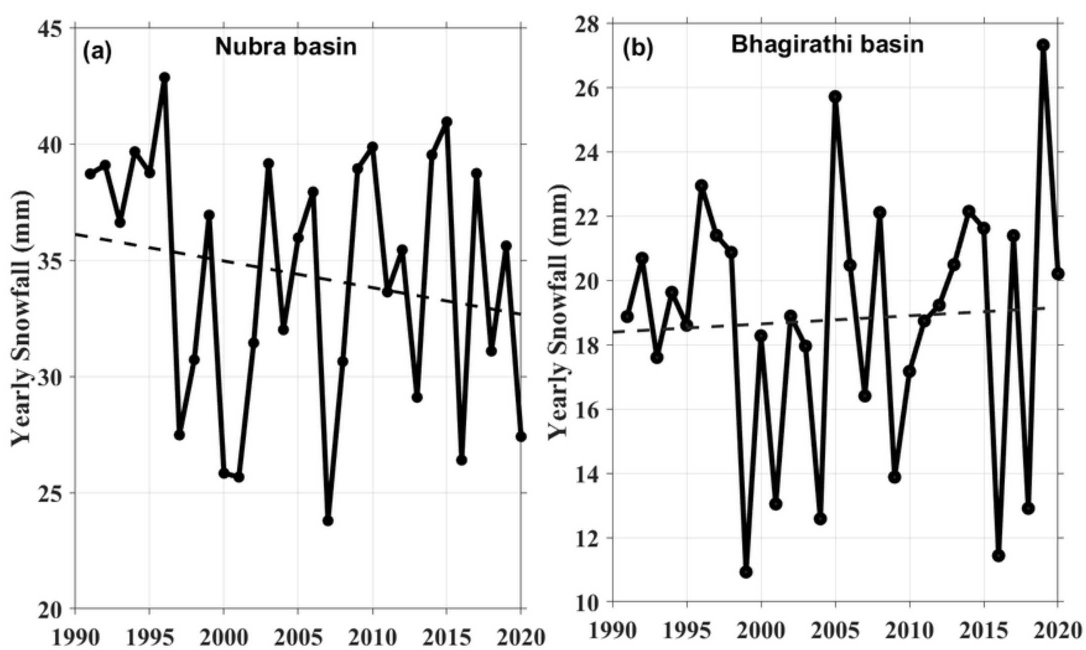

Figure 5

Yearly snowfall over (a) Nubra and (b) Bhagirathi basins respectively

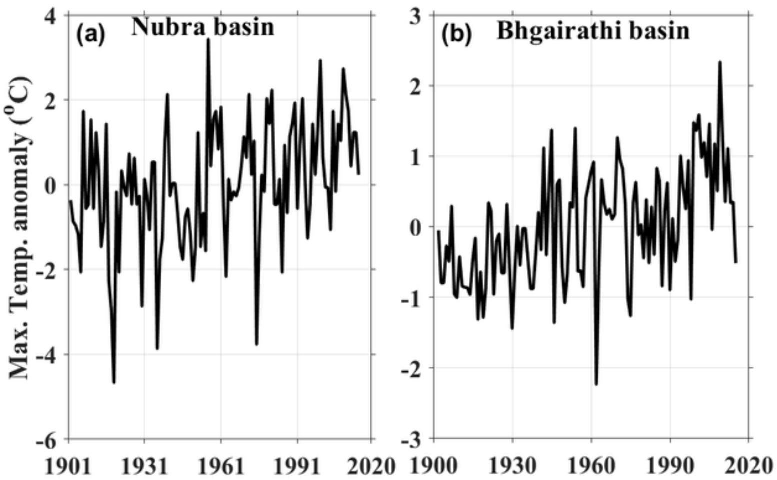

Figure 6

Maximum daily Temperature (a) Nubra and (b) Bhagirathi basins

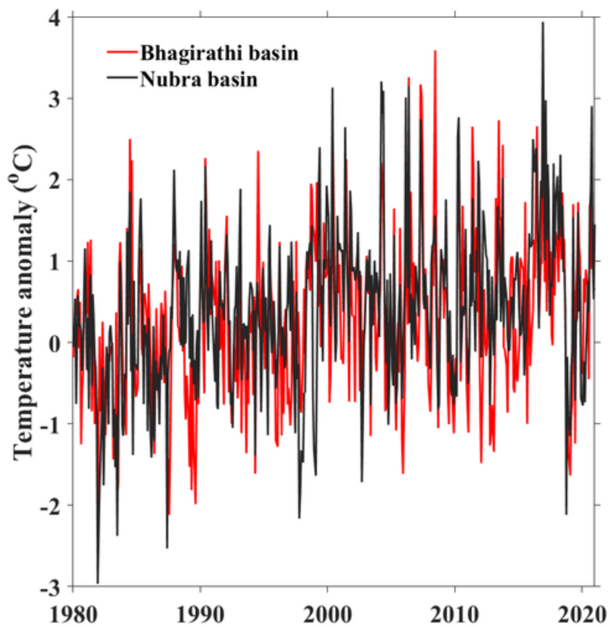

Figure 7

Mid-tropospheric Temperature over Nubra and Bhagirathi basins respectively

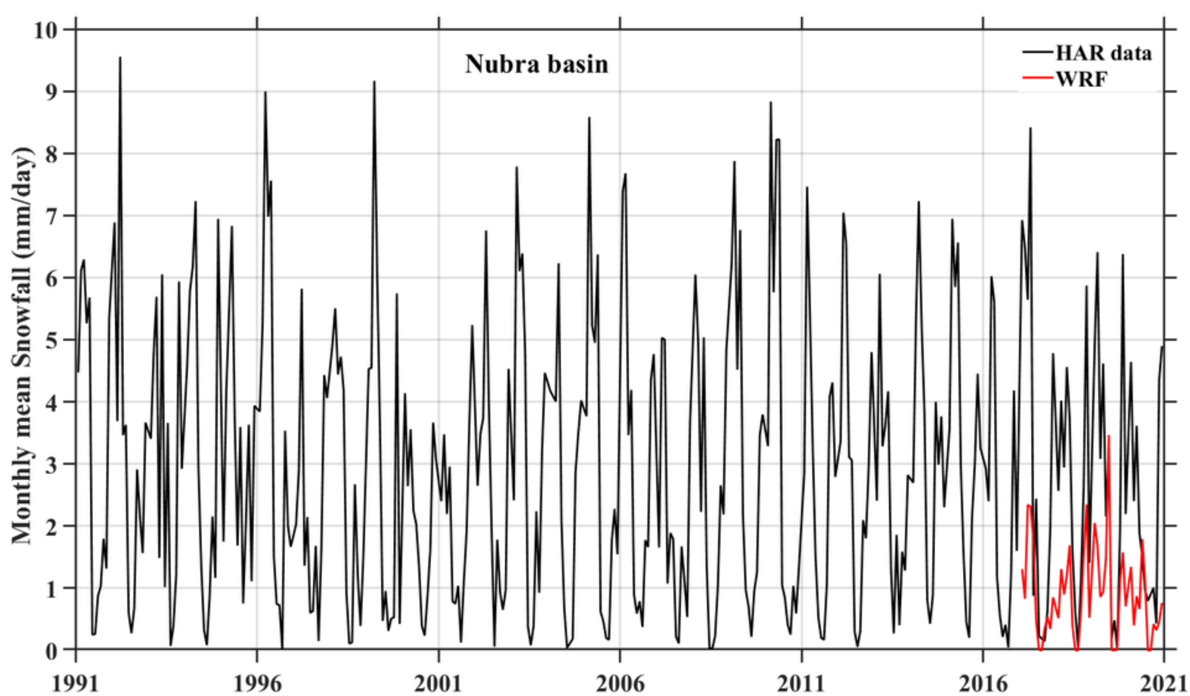

Figure 8

Monthly times series of snowfall simulated (red colour) from WRF model and HAR data (black colour).