



High-altitude meteorology of Indian Himalayan Region: complexities, effects, and resolutions

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Abstract The Himalaya, by virtue of its location and stupendous height, acts as a great climatic divide and regulates meteorological conditions in the subcontinent regions of South Asia. However, the associated complexities and their effects are yet to be resolved to understand the meteorology of the Indian Himalayan Region (IHR). In this review volume, we synthesize the results and inferences of several studies carried out in the IHR using in situ data, remotely sensed data, and model-based meteorological observations. Results provide insights into climate change, scientific gaps, and their causes in deciphering meteorological observations from the last century to recent decades and envisage impacts of climate change on water reservoirs in the future. Warming trend of air temperature, in contrast to global temperature, has been projected in recent decades (after 1990) with a greater warming rate in the maximum temperature than the minimum temperature. This drifting of air temperature from the beginning of last century accelerates the diurnal temperature range of the

Himalayas. An elevation-dependent warming trend is mostly perceived in the northwest Himalayan region, implicating an increased warming rate in the Greater Himalaya as compared to the lower and Karakoram Himalaya. No definite trends of precipitation have been observed over different regions of the IHR, suggesting heterogeneous cryosphere-climate interaction between western and central Himalaya. In this review, we have tried to emphasize to the scientific community and policy-makers for enhancing the knowledge of physical and dynamical processes associated with meteorological parameters in the Himalayan terrain.

Keywords Meteorology · Temperature · Precipitation · Glaciers · Runoff · Climate change · Indian Himalayan Region

Introduction

The Himalaya is popularly known as the ‘Third Pole’ or ‘Water Tower of South Asia’ as it hosts the sources of three world’s largest and life-supporting rivers—the Indus, Ganges, and Brahmaputra. The nourishment of billions of people of the South Asian region relies on these river systems (Bolch et al., 2012; Immerzeel et al., 2010). Earlier studies show that the glacier changes and manifestation of climate change in the Hindu-Kush Himalayan (HKH) region are comparable with the other glacierized region of the world. For example, worldwide warming signals and

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declining trend of precipitation are also seen in this region (Shrestha et al., 1999; Bhutiyani et al., 2007, 2010; Zemp et al., 2009; Shekhar et al., 2010; Dimri & Dash, 2012). However, at the local scale, reported mass gains in the Karakoram unit (Hewitt, 2005; Käab et al., 2012) and some other catchments (e.g., Chenab basin) are debatable (Gaddam et al., 2016). Thus, understanding the processes driving the climate and their subsequent impact on downstream flow regime is crucial in the IHR.

The western Himalaya is much nourished by mid-latitude westerlies, known as the western disturbances (WDs), whereas central Himalaya is strongly impounded by both climatic systems—Indian summer monsoon (ISM) and WDs (Thayyen & Gergan, 2010). The atmospheric conditions are thermodynamically affected by the complex terrain of the Himalayas that acts as a physical barrier for the circulation of air for ISM as well as WDs. Chalise and Khanal (2001) suggested that the spells of summer monsoon are highly variable over different regions of the Himalaya, lasting 8 months (March–October) for eastern Himalaya, 4 months (June–September) for central Himalaya, and 2 months for western Himalaya, implicating the weakening of monsoon from east to west of the Himalayan arc. Kennett and Toumi (2005) observed that moist southerly originating from the Bay of Bengal has been impacted significantly by the Himalayan terrain and amplifies the circulation of the monsoon in summer season. Similarly, high-altitude regions of the Himalayas interact with the strong winds of the subtropical jet stream (Moore, 2004) in the winter season. Consequently, the topography of the Himalayas modulates the atmospheric circulations and in turn regulates the weather conditions at the regional scale.

The HKH region encompasses the largest glacierized areas in the lower latitudes of the globe. Contrary to the Alps and Rockies, the topographic setting (shape, size, and latitudinal range) and glaciations of the Himalayan glaciers are highly variable (Immerzeel et al., 2013; Kaser et al., 2010). The uneven terrain of the Himalayas affects the meteorological parameters at the local to regional scale (Liu & Chen, 2000; Singh et al., 2005). Therefore, extensive investigations of meteorological dataset play a pivotal role to understand numerous aspects, viz. natural hazards (i.e. landslides, avalanches, flash flood, and cloudburst) (Das et al., 2012), weather

conditions (Singh et al., 2005), availability of water reserves and drought problems (Kumar et al., 2014), and glaciations, runoff, and sediment transfer processes (Jain et al., 2003). In recent decades, we have seen the most devastating disaster, known as the Kedarnath tragedy (June 2013), which occurred due to extreme precipitation events in the Mandakini River Basin (Dobhal et al., 2013). Similarly, a more recent event (7 February 2021) in the Rishi Ganga Basin, central Himalaya, has believed to be happened due to breaking of hanging glacier accompanied by abrupt changes in the weather conditions (Sain et al., 2021), but there existed uncertainties because of the lack of meteorological data around the catchment. Though the projection of glacial responses to climate change is thought-provoking under complex terrain and harsh weather conditions of the Himalayas, these local events necessitate the strengthening of the meteorological database to outline proper development planning in the Himalayan hilly terrain and to reckon the glacial input to water resources.

Over the past few years, numerous research has been carried out on glacier dynamics using in situ and remotely sensed data and on probable consequences of mass wasting to runoff in the IHR (Dobhal et al., 2008; Kesar et al., 2010; Bolch et al., 2012; Azam et al., 2014; Kulkarni et al., 2007; Kumar et al., 2019; Pratap et al., 2015). However, these studies could not pay attention to meteorological aspects in their research despite the linkages of glacier dynamics with meteorological drivers. Singh et al., (2016) attempted to review meteorological conditions in the IHR, but they could not focus on all meteorological parameters except temperature and precipitation. Similarly, in recent times, Azam et al. (2014) highlighted the interaction of some climate parameters with glacier dynamics and in turn hydrological regimes. The focal objective of the present study is to review the past and current status of meteorological research based on the compilation of the glaciological studies excluding many studies reported by the Geological Survey of India (GSI), which are not yet published. We attempt to delineate the trends of climate changes and their consequences on glaciation processes using various indicators like temperature, precipitation, relative humidity, wind speed and direction, solar radiation fluxes, and vapour pressure. The present study aims to:

- Deliver an inclusive and a unified contribution to meteorological studies in the IHR
- Discuss numerous scientific gaps, causes, and constraints on meteorological research
- Highlight the crucial role of in situ observations for validation and calibration of other results and models
- Emphasize the need to change the strategy to mitigate hazards caused by extreme climatic events in the IHR based on results of the in situ and model-based analysis with good confidence

Research works have structured into many folds: first, the article describes the study area and its hydro-meteorological importance. The “[Convolutions of meteorological research](#)” section highlights the convolutions and constraints in the observations of meteorological parameters in the IHR. The “[Temperature scenarios](#)”, “Near-surface temperature lapse rate (NSTLR)”, and “[Precipitation scenarios](#)” sections comprise the various results and their variability in the most studied parameters (temperature and precipitation). Besides these parameters, the “[Missing meteorological data at a large scale](#)” section and its sub-sections signify the research on other numerous meteorological parameters to approach a conclusion with good confidence. Finally, the study illustrates (“[Glacier-climate interaction](#)” and “[Hydro-meteorological interaction](#)” sections) the glacier response to climate change and their impact on hydrological regimes.

Study area

The Himalaya is the world’s youngest and greatest mountain chain that hosts the highest peak covered with snow. The Indian Himalayan Region (IHR), a part of the Himalaya, encompasses ~2500 km length and ~250–300 km width between the Indus and the Brahmaputra river systems, covering the total geographical area of ~5.13 lakh km² (~16.2% of the total area of the country). It lies between latitudes 26° 20' and 35° 40' North and between longitudes 74° 50' and 95° 40' East (Fig. 1). Physio-graphically, it starts from Shiwaliks (known as foothill of the Himalaya) in the south and extends up to Tibetan Plateau in the north (Trans Himalaya), linking about 95 districts

of India. The Greater Himalaya, Lesser Himalaya, and Shiwaliks are three prominent units of the IHR, which extends almost without interruption along its length and are distinguished by major fault lines. The IHR spans over 10 hill states, Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, Arunachal Pradesh, Meghalaya, Nagaland, Manipur, Mizoram, and Tripura, and partial hill regions of 2 states, Assam and West Bengal of the Indian Republic. The northernmost range of the IHR is popularly known as Karakoram Range that extends up to Pakistan and China. Three mountain ranges, namely, south Karakoram, Zaskar, and Pir Panjal, lying parallel to each other are climatically significant. The IHR forms the northern boundary of the country and acts as potential barriers for precipitation, substantially affecting the Indian summer monsoon (ISM). Thus, it governs the change in regional climate that impact agricultural, societal, and environmental sectors of the country.

Convolutions of meteorological research

Long-term, high-resolution, and year-round meteorological records are rare in the glacial environment of the Himalayas. In the IHR, the observation of meteorological parameters was mostly conducted at Western Indian Himalaya (WIH) followed by the Central Indian Himalaya (CIH). Although most of the studies in the WIH were carried out using data from manual observatories (MOs), that could not provide sole insights into weather conditions at the local and global scale. Further, such observations from the Eastern Indian Himalaya (EIH) were yet not documented, putting a huge scientific gap. The exclusive summaries of meteorological studies in the IHR are shown in Table 1.

Several MOs have been established at or below the snout position (~4000 m asl) to assess the meteorological conditions of the Himalayan glaciers (Palazzi et al., 2013). The meteorological data available from MOs are believed to be inadequate and taken for a short period, mostly recorded during the summer months in the IHR (Table 1). In contrast, recently, the use of Automatic Weather Station (AWS) has offered an opportunity to record the continuous long-term meteorological parameters, which are more reliable to predict and forecast the synoptic weather conditions.

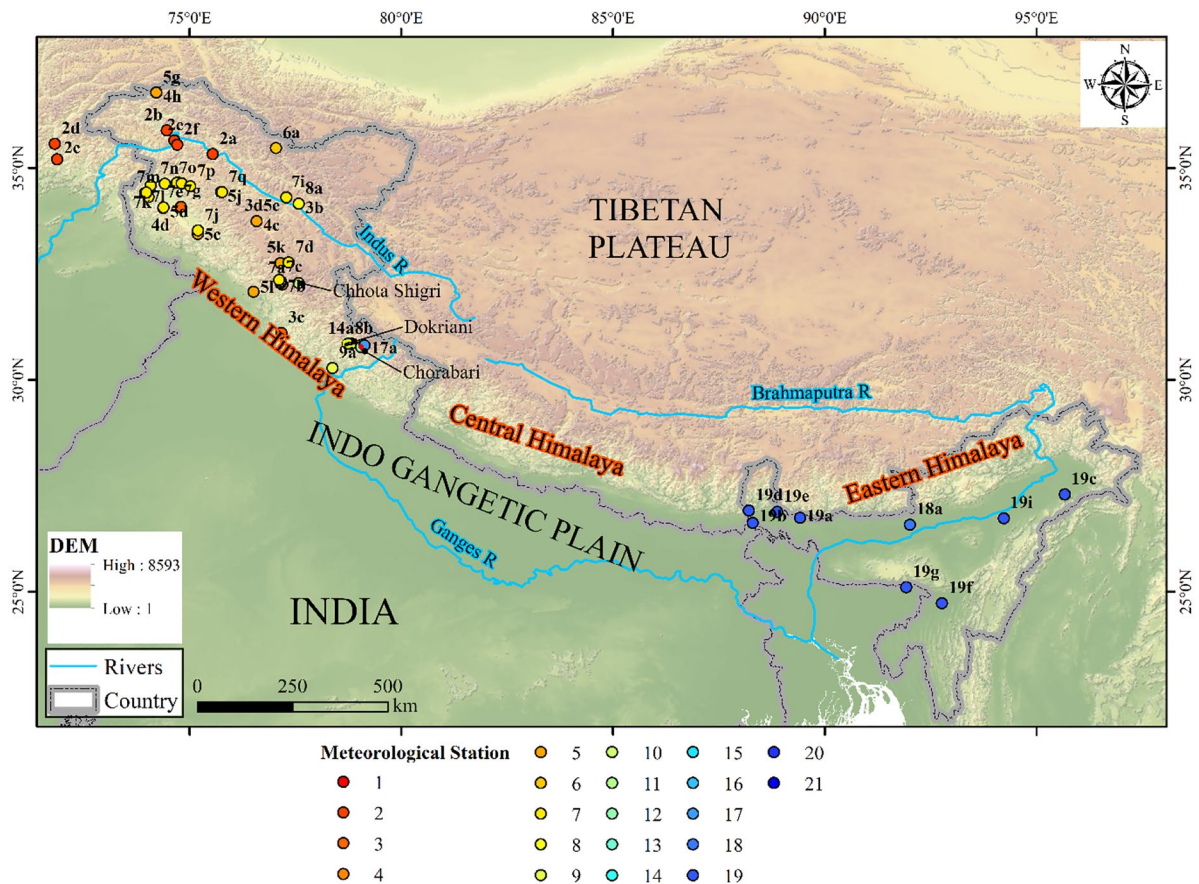


Fig. 1 Pictorial map showing the boundary of the Indian Himalayan Region (IHR), geographical locations, river basins, and most studied glaciers (Chhota Shigri, Dokriani, and Chorabari) in this region. The locations of weather stations (automatic

weather stations and manual observatories) are highlighted by point colour mark ($n=21$) from which data were used in the past studies. The number given for meteorological stations are shown by superscript on respective reference in Table 1

Yet, very few AWSs with a large spatial separation have been installed in the IHR due to poor approachability on complex terrain, harsh weather conditions, and high costs of positioning a series of observatories (Fujita & Sakai, 2014). This has posed major difficulties to project the entire extent of climatic patterns as well as point information over the mountainous regions. Consequently, the trend associated with glacier-climate interactions has yet remained underway in the Indian Himalaya as compared to the other glaciated terrains of the world such as the Alps, the Rockies, and the Andes (Fowler & Archer, 2006).

Rainfall measurements by using rain gauges are generally considered more reliable and used to correlate with other datasets from AWSs and remote sensing-based data series. The dense network of

rain gauges is rarely seen in the IHR as compared to worldwide data. Furthermore, constraints like frequent calibration of instruments (like AWS) installed with MOs and proper gauge location significantly affect the quality of data. In contrast to manual data, the AWS provides continuous data of rainfall, but they are prone to considerable errors because it fails to take care of mixing of little solid precipitation with rainfall in the tipping bucket during summer monsoon. Thus, the accuracy of measurement of precipitation in the basin can be portrayed by integrating rainfall data from the MOs and AWSs. This will also provide an opportunity to cross-calibration data received from an independent source of information. For an instant, Yadav et al., (2019) developed a correlation between manually collected data and AWSs

Table 1 Exclusive summary of weather station installed in the IHR and their observed dataset

IHR	Study site	No of stations	Elevation (m asl)	Station type, (observation type)	Study period	Measured/ derived variables	Concise remarks	References
Western Indian Himalaya (WIH)		9	-	M (S)	1226–2000	T	Cooling effect of T_{min} than T_{max} in pre-monsoon season (March to May) during the late twentieth century	¹ Yadav et al., (2004)
		7	480–3506	M (S, Y)	1961–2000	T, P	A consistent cooling for T_{avg} and T_{min} in the summer and warming trend in T_{max} in the winter	² Fowler and Archer (2006)
		10	1587–3800	M	1866–2006	T, P	Decadal temperature increment ~ 0.06 °C (monsoon), 0.14 °C (winter) and 0.11 °C (annual); warming of 1.6 °C during last century with dominant in winter season	³ Bhutiyani et al., (2007, 2010)
		11	2192–3250	M (S)	2007–2008	T, P	In the same climatic zone, T, P, & SD can be estimated by using similar parameters of the neighbouring regions (Barnes objective analysis)	⁴ Joshi and Ganju (2012)

Table 1 (continued)

IHR	Study site	No of stations	Elevation (m asl)	Station type, (observation type)	Study period	Measured/ derived variables	Concise remarks	References
	Siachen Glacier	18	< 5000	M (S)	1984–2007	T, P, CC	Rise of seasonal temperature ($T_{avg} \sim 2^{\circ}\text{C}$, $T_{max} \sim 2.8^{\circ}\text{C}$, $T_{min} \sim 1^{\circ}\text{C}$), trendless in frequency of western disturbances, yet decreasing trend of snowfall days in warming climate; amount of cloud decreases with the increase in maximum temperature	⁵ Shekhar et al., (2010)
		6	-	M (S, Y)	1975–2006	T, P	Contrasting winter temperature trend; increasing trend of mean precipitation in the ablation zone and reverse is seen in the transition and accumulation zones	⁶ Dimri and Dash (2010)
	Western Himalayan region	16	2192–3800	M (S)	1975–2006	T, P	Significant increasing trend of air temperature (T_{max} , T_{min} and T_{avg}) in the winter; slightly decreasing and inconsistent trend of precipitation	⁷ Dimri and Dash (2012)
	Ganglass catchment, Ladakh Himalaya	3	3500, 4700, 5600	M ₁ M ₁ M ₂	2010–2013	T	Mean monthly temperature range: -21.0 to 22.5°C ; shallower lapse rate in the winter and steeper in the summer due to arid conditions	⁸ Thayyen and Dimri (2014)
	Naradu Glacier, WH	-	4512–5600	Giovanni data-base (S, Y)	1985–2009	T	Decadal warming: T_{max} : 0.56°C , T_{min} : 0.65°C , T_{avg} : 0.60°C	⁹ Kumar et al., (2014)

Table 1 (continued)

IHR	Study site	No of stations	Elevation (m asl)	Station type, (observation type)	Study period	Measured/ derived variables	Concise remarks	References
Central Indian Himalaya (CIH)	Chhota Shigri Glacier; Chandra Basin	2	4863, 4670	A ₃ , (S, Y) A ₃ [*] , (S, Y)	2009–2013 2012–2013	T, RH, P, K _↓ , L _↓ , K _↑ , μ, θ, p	T _{DM} ~ -22.0 to 7.3 °C; RH ~42–68%, P~680 mm (W _{inter}), ~32 mm (pre-monsoon); μ ~2.5– 5.5 ms ⁻¹ ; K _↓ ~33–299 Wm ⁻² ; T and P both serve as a key driver in control- ling the mass balance	¹⁰ Azam et al., (2014, 2016)
	Chorabari & Dokriani Glaciers	2–3	2760, 3820, 2540, 3763, 4364	A ₁ , (S) A ₂ , (S) A ₁ , (S) A ₂ , (S) A ₃ , (S)	2011–2012	T, P, μ	Overall same meteorological conditions for both glaciers macroscopically, but controlled by many other factors (e.g. slope, aspect and topography) at micro-scale	¹¹ Kesarwani et al., (2012)
Central Indian Himalaya (CIH)	Chorabari Glacier	2	2760, 3820	A ₁ , (S, A) A ₂ , (S, A)	2011–2013	T, RH, K _↓	Variation trend of mete- orological Parameters with altitude: quadratic for air temperature, logarithmic for relative humidity, and linear for global and diffuse radiation	¹² Karakoti et al., (2017)
	Din-Gad catchment, Bhagirathi Basin	3	2540, 3483, 3763	M ₁ , (S) M ₂ , (S) M ₂ , (S)	1994, 1998–2000	T, P, SD	Mean monthly temperature range: -21.0 to 22.5 °C; shallower lapse rate in the winter and steeper in the summer due to arid conditions	¹³ Thayyen et al., (2005)

Table 1 (continued)

IHR	Study site	No of stations	Elevation (m asl)	Station type, (observation type)	Study period	Measured/ derived variables	Concise remarks	References
	Din-Gad Catchment, Bhagirathi Basin Gangotri Glacier, Bhagirathi Basin	3	2540, 3483, 3763	M ₁ , (S) M ₂ , (S) M ₂ , (S)	1998–2004	T, P, RH	Mean monthly temperature: -4.6 to 18.6 °C; lowering of lapse rate due to a moisture influx during winter and monsoon	¹⁴ Thayyen and Dimri (2014)
		1	3800	M ₁ , (S)	2000–2003	T, RH, P, SD, μ ,	T _{DM} : T _{max} ~ 14.7 °C, T _{min} ~ 4.1 °C and T _{avg} ~ 9.4 °C, RH ~ 77 – 83% ; P (mean seasonal) ~ 260 mm; $\mu \sim 12.6$ kmh ⁻¹ (daytime) and 3.0 kmh ⁻¹ (night-time); SD \sim maximum in May followed by October	¹⁵ Singh et al., (2005)
	Gangotri Glacier, Bhagirathi Basin	1	3800	M ₁ , (S)	2000–2008	T, P	Overall decreasing trend in the areal extent of the seasonal snow cover area; an increase in rainfall amount during summer; a decrease in snowfall days; an increase in rainfall days and rising trend of average temperature	¹⁶ Negi et al., (2012)
		1	3900	M ₁ , (S, A) A ₁ , (S, A)	2000–2012 2012–2013	T, P, μ , K \downarrow , K \uparrow , α	T _{AM} : T _{max} $\sim 11.1 \pm 0.7$ °C, T _{min} $\sim -2.3 \pm 0.4$ °C; decadal increase ~ 0.9 – 0.05 °C; $\mu \sim 3.3$ – 6.5 kmh ⁻¹ ; K _{AM} ~ 366 Wm ⁻² (top of the atmosphere) and 136 Wm ⁻² (at the surface)	¹⁷ Gusain et al., (2015)

Table 1 (continued)

IHR	Study site	No of stations	Elevation (m asl)	Station type, (observation type)	Study period	Measured/ derived variables	Concise remarks	References
	Brahmaputra Basin	-		RG from CRU TS 2.1 dataset (S, A)	1900–2002	T, PT, P	Increasing trend in temperature at an average rate of 0.6 °C/100 year, with the largest increase in spring; no clear trends in precipitation; accelerated seasonal T & P in twenty-first century and sharp increment of downstream discharge	¹⁸ Immerzeal (2008)
Eastern Indian Himalaya (EIH)		8	40–1158	M ₁ (S)	1960s/1970s–2000	T, SD	Decadal change: T _{avg} ~ 0.2–0.8 °C, T _{max} ~ 0.1–0.9 °C, T _{min} ~ 0.1–0.6 °C; trendless for temperature in the winter and pre-monsoon and increasing trend during monsoon and post monsoon	¹⁹ Jhajharia and Singh (2011)
Himalayas		-		RCM	twenty-first century	T	Decadal change: T _{avg} ~ 0.2–0.8 °C, T _{max} ~ 0.1–0.9 °C, T _{min} ~ 0.1–0.6 °C;	²⁰ Dimri et al., (2018)
Indian Himalaya Region		-	-	RG (S)	1901–2003	T, PT	Decadal warming of T _{max} ~ +0.9 °C and T _{min} ~ 0.19 °C, equally sharp rise over the past 3 or 4 decades	²¹ Dash et al., (2007)

Symbols of meteorological parameters and other factors are employed as Z elevation/elevation range, observation type (S seasonal/temporary, Y year-round), station type {A - AWS (A₁, A₂, and A₃), M - MOs (M₁, M₂, and M₃); suffix 1, 2, and 3 shows location of a meteorological station far below, nearby, and above the snout position, respectively}, RG reanalysed grid, DM daily mean, AM annual mean, T temperature, RH relative humidity, P precipitation, u wind speed, μ wind direction, K_↓ incoming short-wave radiation, L_↓ incoming longwave radiation, K_T outgoing radiation, α albedo, SD sunshine duration, p = atmospheric pressure, CC cloud cover, e evaporation, RCM regional climate model, CRU climate research unit. Studies mentioned in the eastern Himalaya are restricted to the lower reaches rather than high-altitude areas

data for the Dokriani Glacier Catchment (DGC) and found insignificant statistical errors (mean absolute percentage error (MAPE) < 12%) between these two different observations. Further, in the case of snow cover area (SCA), most of the in situ or remote sensing-based observations were confined to river basins at lower elevation levels, and none of the studies has yet focused on the glacier basin where such studies are required to understand the effects of higher elevation, vastness of snow cover, proximity to the glacier on snow depletion, and accumulation patterns.

Similarly, radiation indices are difficult to be assessed from the manual observatory, which is the major challenge for exploring the surface energy balance (SEB). This becomes even worse as dynamics of crevasses, supra-glacier channel, and avalanches in the ablation zone are the main challenges towards the installation of AWSs over the glacier surface. Owing to this, very few studies on the variability of radiation fluxes and their importance in the SEB are reported in glacierized basin.

Considering these facts, recently, many agencies and organization have focused to establish several observatories in the IHR. Indian Meteorological Department (IMD) is one of the leading agencies for the collection of climate data and has a rich network of Conventional Manual Observatories (CMOs) and AWSs installed over India including high-altitude IHR. Other government agencies like the Central Water Commission (CWC) and Snow and Avalanche Study Establishment (SASE) have also established meteorological observatories (manned and AWSs) to assess the weather conditions and hydrological prospects. To obtain continuous dataset with long time series, AWSs have been installed in the Naradu and Chhota Shigri glacierized catchments in the western Himalaya. A network of six AWSs is being operated in the Chorabari and Dokriani Glaciers Catchments since 2011 under the Himalayan Glaciological programme at the Centre for Glaciology at Wadia Institute of Himalayan Geology (WIHG), Dehradun, where continuous and reliable meteorological data is being obtained.

Temperature scenarios

The entire measurement settings and concise results for air temperature in the different region of the IHR

and Himalayas are presented in Table 1 and Fig. 2 (decadal change). The analysis, based on in situ and microwave dataset, reveals that the WIH experienced a rise in the average temperature (T_{avg} : 0.5–0.9 °C/decade) in the last century (1900–2010) with an accelerated rate of temperature after 1970 (Dash et al., 2007, Kothawale and Kumar, 2005, Gautam et al., 2010). Similarly, Diodato et al., (2012) suggested that Himalayan areas, including Tibetan Plateau (TP), have been warming during recent decades (1971–2005) with a faster rate (0.5 °C in annual average T_{max}) than any other period in the last century. Thus, observed asymmetric ranges of temperature could be attributed to large-scale Indian summer monsoon (ISM) anomalies and unprecedented global warming during the last few decades.

In the Northwest Himalaya (NWH), Bhutiyani et al., (2007) suggested a warming trend ranging from 0.11 to 0.16 °C per decade with a faster rate of winter warming during 1876–2006 and an accelerated rate of warming after a period of 1990 to 2009. A little higher (0.23–0.43 °C per decade) winter warming with a substantial increase of T_{max} (1.1–2.5 °C) was also reported in the recent decades (1975–2006) (Dimri & Dash, 2010). Warming trend of the NWH was supported by the several studies reported in the upper, middle, and lower regions of the Indus basin (Fowler & Archer, 2006; Khattak et al., 2011; Singh et al., 2008). Consequently, significant variation in temperature in the different units of the WIH was clearly seen, but they have shown a similar trend of temperature for a particular period.

Apart from in situ observations, many other proxies (Geospatial Interactive Online Visualization and Analysis Infrastructure (GIOVAI), tree ring chronology, etc.) showed overall warming trends with more pronounced minimum temperature (T_{min}) as compared to maximum temperature (T_{max}). Accordingly, warming winter season has been seen in the recent decades (Borgaonkar et al., 2009; Dimri & Dash, 2012; Kumar et al., 2014). While, in the pre-monsoon season of the late twentieth century, T_{min} declined at a three-fold higher rate than T_{max} , indicating a cooling trend (Yadav et al., 2004). Fowler and Archer (2006) reported a consistent cooling for T_{avg} and T_{min} in the summer and warming in T_{max} in the winter. Winter warming is indicative of enhanced precipitation as rain compared to snow, but it is limited to certain elevations. The observed variation in summer

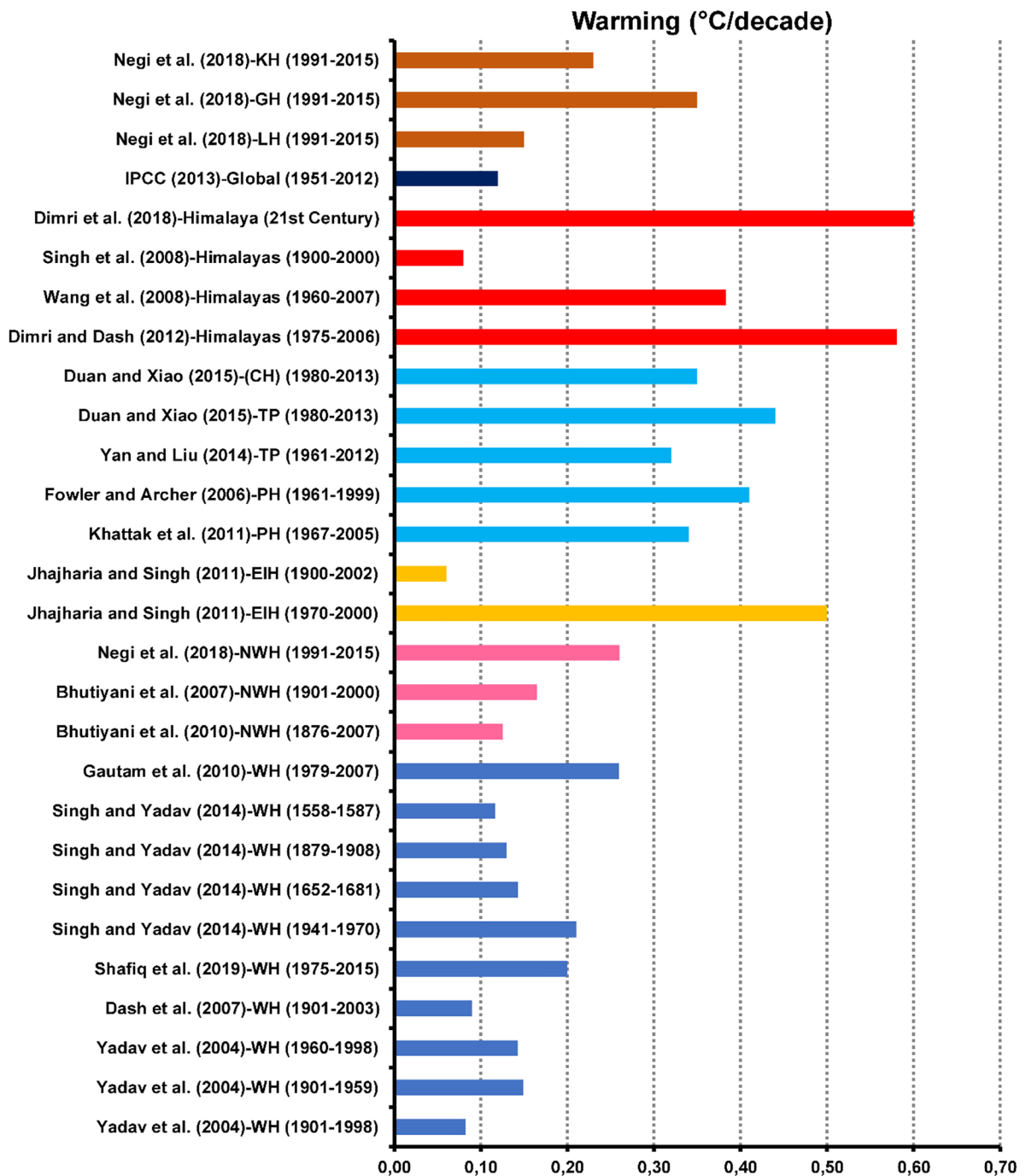


Fig. 2 Summary of temperature trend observed by numerous studies in different parts of Indian Himalayan Region. Warming trend is compared with global (dark blue colour) and important studies (blue colour) from other parts of the Himalayas (Pakistan, China). The endmost orange colour shows the variation of air temperature with elevations of different regions

(lower, higher, and Karakoram) of the Himalayas. WH Western Himalaya, NWH Northwestern Himalaya, EIH Eastern Indian Himalaya, PH Pakistan Himalaya, TP Tibetan Plateau, CH China Himalaya, LH Lower Himalaya, GH Greater Himalaya, KH Karakoram Himalaya

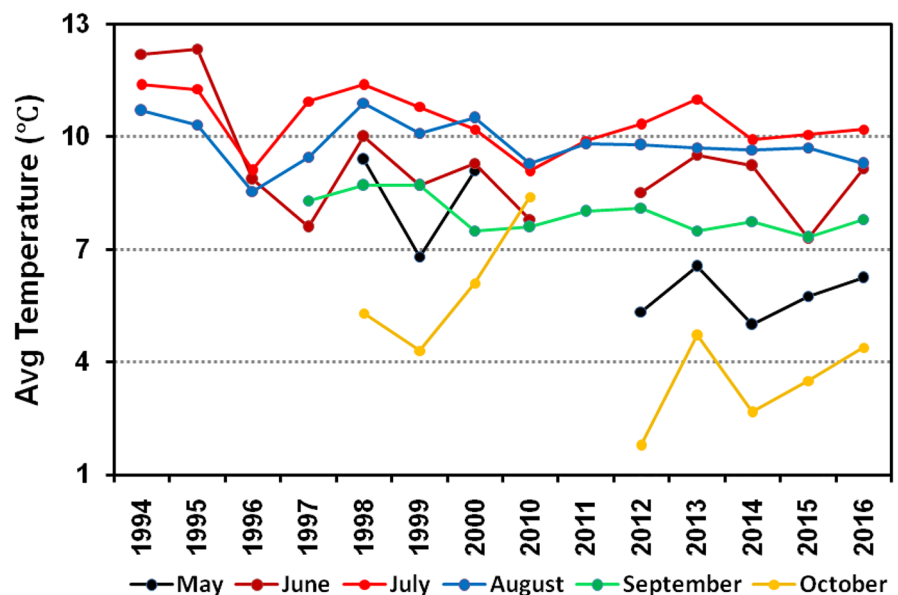
and winter temperature considerably impacts seasonal runoff; for example, the cooling effect declines the runoff from glacier-fed catchment, while it may be reversed for the snow-fed catchments because of higher albedo effect. An accelerated warming trend has also been observed in the recent decades over the other parts of the Himalaya such as Nepal and China Himalayas (Shrestha et al., 1999; Shangguan et al., 2009) (Fig. 2).

In the central Himalaya, the temperature-based study is not sufficiently available as reported for the WIH. In the lower reaches of the Doon valley, a little higher warming trend (~ 0.49 °C/decade) was reported using data from a manual observatory (1967–2007) (Singh et al., 2013). Yadav et al., (2019) observed a significant change in the average temperature (0.1–0.3 °C) of the Dokriani Glacier Catchment (DGC) from the last 2 decades. A few studies over glacierized catchments in the CIH suggested that the distribution of temperature in the same climatic zone was almost homogeneous for the same elevation ranges (Kesarwani et al., 2012; Singh et al., 2007; Thayyen & Dimri, 2014). To address the seasonal variability at a local level, the air temperature (1994–2000) of the most studied DGC were compared to the recent results to observe the seasonal changes (Fig. 3). Finding showed remarkable changes in air temperatures during early and ending months of the ablation period, typically in June,

while insignificant changes in air temperature were observed during 3 months (July, August, and September) (Fig. 3). In 1996, air temperature declined abruptly and then re-established to nearly constant rate till the present study period. These facts show that the onset time and magnitude of the ISM circulation over the central Himalayas had changed in recent decades in the central Himalayas. Thus, understanding the changing pattern of the ISM circulation is very important to develop new managing strategies for water resources, particularly for the drier period.

The air temperature in the Eastern Indian Himalaya (EIH) has poorly investigated owing paucity of the dataset. However, considering a part of the greater northeast Indian region and other regions of the Himalayas, many attempts were made to envisage the temperature trend over EIH. For example, a 1 °C warming trend with sharp changes in the T_{\min} was examined by Dash et al., (2007) from 1901 to 2003 using the reanalysed gridded method. The rise in temperature (0.1–0.9 °C per decades) is also supported by Jhajharia and Singh (2011) in the recent decades. Similarly, several studies in different regions of eastern Himalaya reported a warming trend in the last century (Fig. 2). Towards this, the gridded dataset has revealed a basin-wide warming pattern ($T_{\text{avg}} \sim 0.6$ °C/100 year) in the Brahmaputra basin of EIH and Tibetan Plateau (1901–2002) (Immerzeel, 2008).

Fig. 3 Variation of air temperature in monsoon season (May–October) from most studied Dokriani Glacier Catchment, central Himalaya since 1994



Finally, the analysis based on temperature data reveals a warming trend over the Indian Himalaya with higher spatio-temporal variability in T_{\max} , T_{\min} , and T_{avg} . Studies suggest that climate over high-altitude Himalaya is controlled by various factors like elevation, slope, aspect, vegetation cover, and rain shadow zone that substantially amplify or dampen the meteorological parameters. It is interesting to note that the Himalayas experienced a regular rise of the average temperature of ~ 0.85 °C during 1885–2012 with a decadal increment of 0.05 °C, in response to the average global temperature of 0.74 ± 0.18 °C during 1906–2005 (IPCC, 2007). Consequently, the projected temperatures have warmed the IHR to a greater extent than the global average, particularly since 1990 (Fig. 2). These warming trends may be attributed to deforestation, industrialization, and anthropogenic activities (IPCC, 2007; Shrestha & Aryal, 2011; You et al., 2013). This trend could influence biodiversity, glacial retreat, and water availability, which might pose challenges to adaptation in the IHR. Further, the Greater Himalayas has been warming faster than the Lower and Karakoram Himalayas in recent decades (Fig. 2).

Among the meteorological variables, the temperature is one of the most studied parameters in the IHR (Table 1) where most of the data series were observed at a seasonal scale from MOs. However, intra-seasonal variability at monthly and daily scales were rarely available, which reflects the lack of precise projections of local weather conditions. New et al., (2002) suggested progressively higher warming with an elevation over the entire Greater Himalayan region, which is, by and large, similar to those from the Nepal and Tibetan Plateau (Shrestha et al., 1999). Thus, the paucity of elevation-dependent warming data in the CIH and the EIH has put constraints to our understanding of the surface-atmosphere interactions like water vapour-cloud and snow-albedo interactions and aerosol forcing.

The T_{\min} is an essential component that directly influences the precipitation regimes in the high-altitude catchments (Snehmani et al., 2015), though it is least constrained so far in the IHR. The variability of minimum temperature provides pieces of information about the intensity of western disturbances, especially in the western Himalayas. Warming of winter is associated with higher T_{\min} than T_{\max} , which may prompt the faster retreat of glacier mass. Thus, it should be focused

to investigate the spatio-temporal variability of T_{\min} in understanding the response of climate change on water storage capacity. Furthermore, due to the warming trend, most of the precipitation appears as a form of rain in several regions of the IHR, which shorten the winter season. This broadly affects the river profile, natural hazards, agricultural field, terrestrial ecosystem, and people's livelihood.

The IHR has been facing a long series of meteorological observation at higher elevations. Projected temperature using the regional climate model (RCM) may not provide reliable results owing to the complex topography and reactions to the greenhouse effect over the Himalaya. In such situations, reanalysed gridded method and tree ring chronology may be helpful proxies to estimate basin-wise temperature and can be calibrated for accuracy assessment in the region where data are available. In addition, recently, the advent of T-logger has provided good opportunities to obtain high-resolution data with a cost-efficient solution for monitoring the high-altitude catchment (Fig. 4). Many researchers employed T-logger whose data records are significantly correlated with AWS' data (Petersen & Pellicciotti, 2011; Steiner & Pellicciotti, 2016). However, in the IHR, none of the studies was carried out using T-logger records. Thus, a dense network of T-logger will be helpful for long time series data at low deploying cost on and off the glacier surface to characterize environmental and glacier behaviour precisely.

Near-surface temperature lapse rate (NSTLR)

The rate of change of temperature with altitudes in the free atmosphere is known as 'standard environmental lapse rate (SELR)' or 'free-air lapse rate' (Marshall et al., 2007). It is approximated to be 6.5 °C km^{-1} covering a range between 4 and 9 °C km^{-1} worldwide, depending on air-mass characteristics (Barry & Chorley, 2009). Considering the sensor specification and mountain terrain as a physical barrier for air circulation, the variation of temperature with elevation measured, typically at a height of 2 m, using a sensor enclosed by a radiation shield is referred to as near-surface temperature lapse rate (NSTLR) and is appropriately employed by several researchers (Blandford et al., 2008; Marshall & Losic, 2011; Pratap et al., 2013; Yadav et al., 2019). Despite the importance

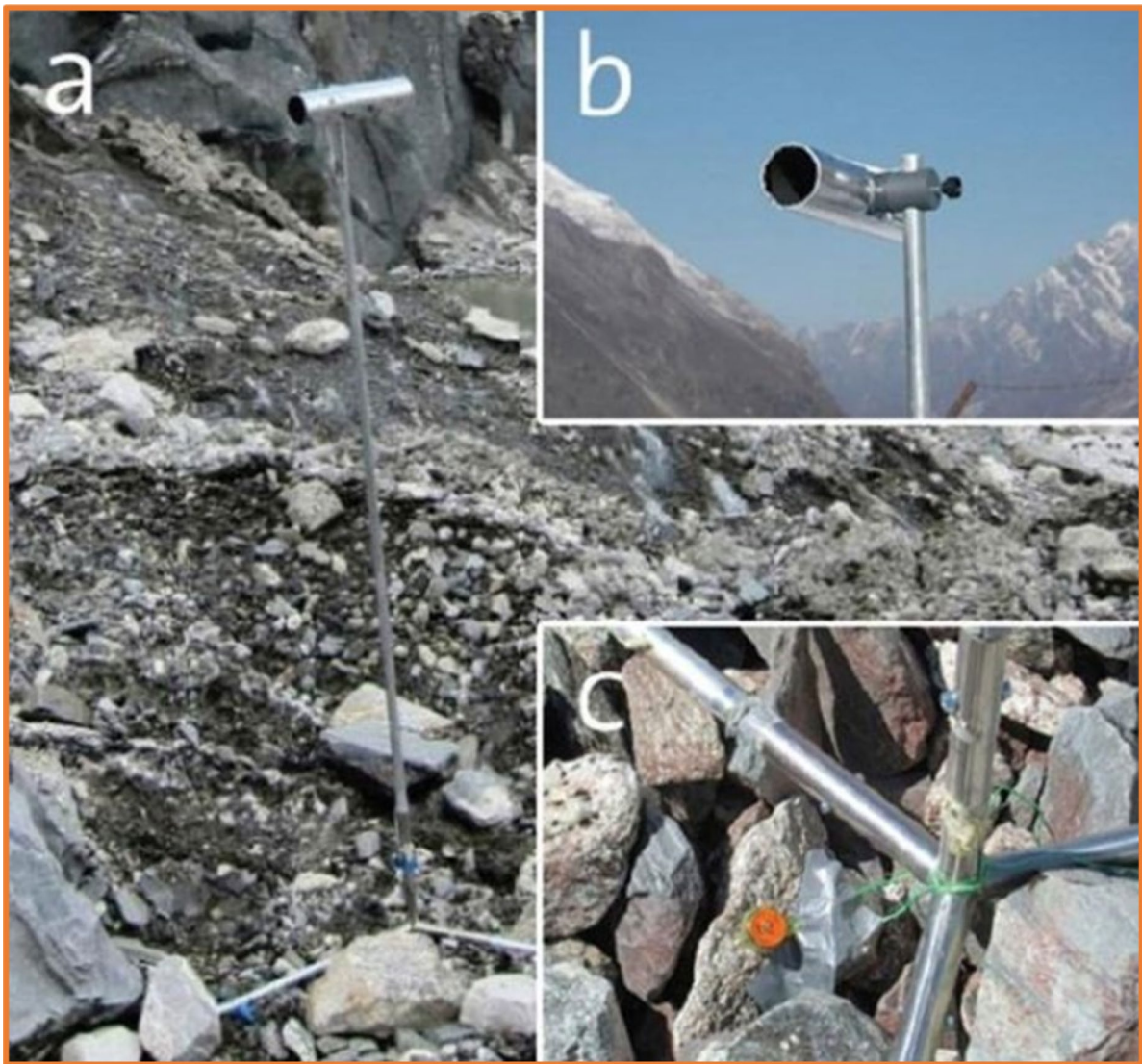


Fig. 4 Design and installation of T-Logger over glacierized catchment: **a** near-surface air temperature is measured at 2 m above the ground surface by the sensor enclosed in a cylinder shielded with aluminium foil to protect from solar radiation

and settled in a line along the valley; **b** surface sensor is tied to a rock and fastened to the base structure; **c** sensor without shielding (Steiner & Pellicciotti, 2016)

of the NSTLR, the estimation of NSTLR, as well as its linkages with meteorological parameters, has poorly been examined in the IHR. We have analysed the NSTLR at seasonal and annual scale in the IHR, including some important studies from other Himalayan regions (Fig. 5). Each of the years is classified into four seasons: winter (DJF – December, January, February), pre-monsoon (MAM – March, April), monsoon (JJAS – June, July, August, September),

and post-monsoon (ON – October, November) as suggested by Yadav et al., (2019) for the Himalayan region. Results show a high spatio-temporal variability ($3.5\text{--}11.5\text{ }^{\circ}\text{C Km}^{-1}$) in the NSTLR on basin-wide to regional scales in the Himalaya (Fig. 5), which is in the range $3.0\text{--}10.8\text{ }^{\circ}\text{C km}^{-1}$ as suggested by De Scally (1997). Typically, pre-monsoon and monsoon season show significant variations in the NSTLR in different parts of the Himalayas. Most of the studies show a

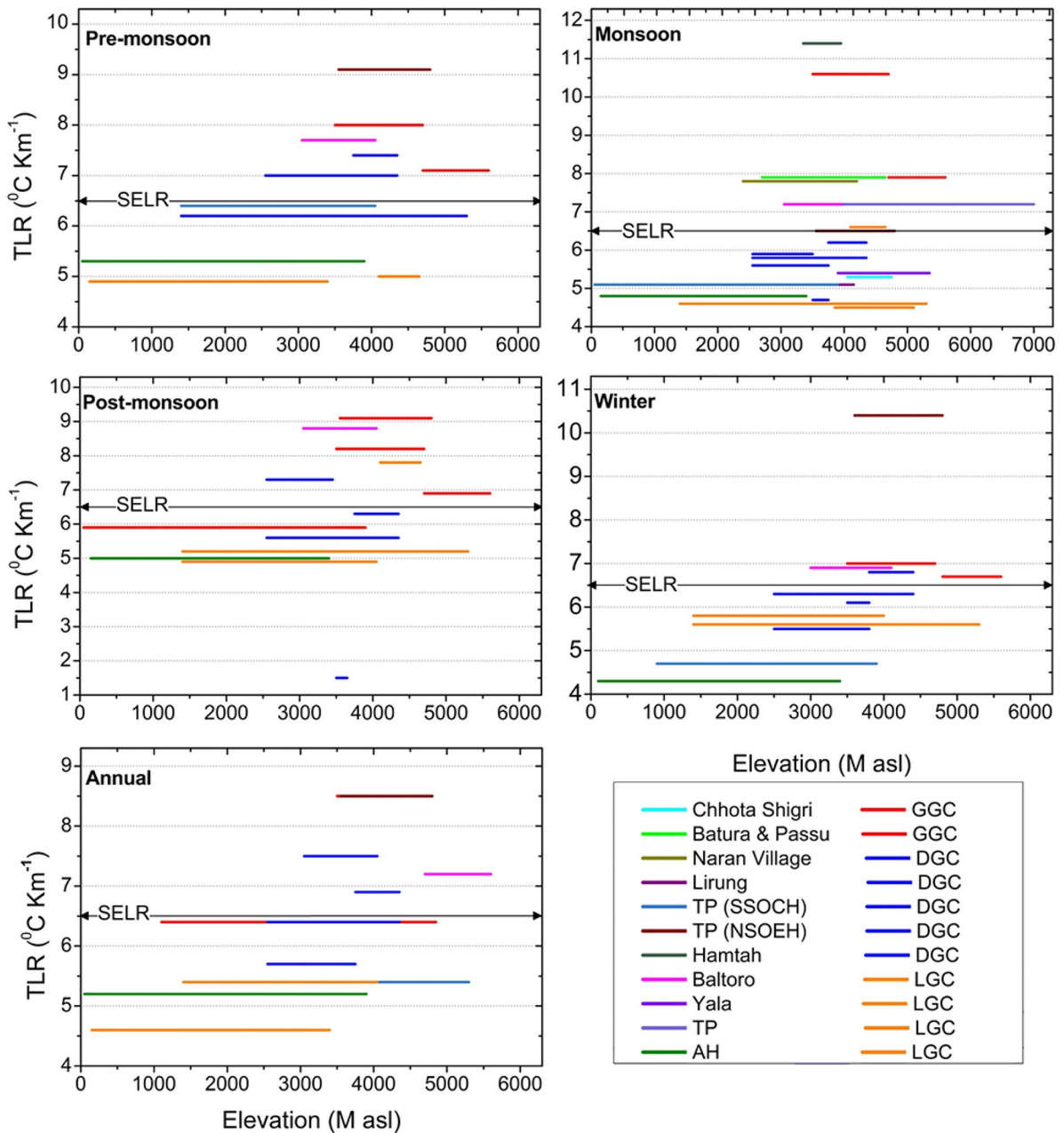


Fig. 5 Seasonal variation of near-surface temperature lapse rate in Hindu-Kush Himalayan (HKH) Region. DGC Dokriani glacier catchment, TP (SSOCH) Tibetan Plateau (southern slope of central Himalaya), NSOEH Northern slope of eastern Himalaya, LGC Lirang Glacier Catchment, LGC Langtang

Glacier Catchment, GGC Ganglass Glacier Catchment, western Himalaya. Standard environmental lapse rate is shown by arrow, providing deviation of lapse rate carried out in different regions

shallower lapse rate in the monsoon season (Fig. 5), which resulted in uniform distribution of air temperature over the catchment due to release of latent heat in the condensation process. This phenomenon

is referred to as ‘monsoon lowering’ (Thayyen & Dimri, 2014). Interestingly, the NSTLR was found close to or below the SELR during winter months for all the Himalayan regions except for the Northern

slope of eastern Himalaya (NSOEH) of the Tibetan plateau (Fig. 5), where significant heterogeneities in winter air temperature were seen due to impact of western disturbances. The Langtang and Lirang Glacier Catchment and Nepal Himalaya experience shallower lapse rate, by contrast to other regions, indicating that the distribution of air temperature is nearly homogeneous. The annual NSTLR of the most studied DGC in the IHR ranged from 5.2 to 6.4 °C km⁻¹ (Pratap et al., 2013; Thayyen et al., 2005; Yadav et al., 2019). Thayyen and Dimri (2014) highlighted the role of orography-moisture interaction in the distribution of air temperature in the two glacio-hydrological regimes-monsoon dominated DGC in the central Himalaya and cold-arid climate dominated Ganglass Glacier Catchment (GGC) in the western Himalaya. High variability in daily lapse rate (1.9–9.0 °C km⁻¹ in DGC and 2.8–17.0 °C km⁻¹ in GGC) is indicative of the heterogeneous distribution of atmospheric circulations along the Himalayan arc.

High variability in the NSTLR over the various regions of the Himalayas (Fig. 5) reflected that the SELR might not be a reliable proxy in establishing the glacio-hydrological modelling. Understanding air temperature variability and its association with glacier melt is very important for water resources, especially for the livelihood of the people inhabiting nearby the glacierized catchment. Further, the NSTLR studies at a diurnal scale provide important inputs about heat fluxes between glacier surface and atmosphere, but hourly temperature data are sparse in the IHR. Therefore, we need to establish a large network of AWSs for continuous and reliable dataset for a better understanding of temperature variability for future perspectives.

Precipitation scenarios

Precipitation as rain or snow is a temperature-dependent parameter that plays an imperative role to understand the meteorology and hydrology of the regions. The increased warming trend affect the moisture content in the atmosphere and hence increase the global mean precipitation ~1.1 ± 1.5 mm per decade over 1901–2005 (Basistha et al., 2009). Such precipitation trends over the Indian subcontinent were substantially investigated, displaying diverge scenarios at

the regional and local scale (Srivastava et al., 1992; Kripalani and Kulkarni, 1997; Singh et al., 2007).

Rainfall distribution

Spatio-temporal heterogeneities in precipitation are very common in the IHR. By contrast to the warming trend over the WIH, a seasonal trend of precipitation was inconsistent; for example, a substantial decrease in rainfall in monsoon season was reported by several researchers during the last century (Bhutiyan et al., 2010; Dash et al., 2007; Kumar et al., 2005; Sontakke et al., 2008). The plausible reasons for monsoon lowering in the WIH could be weakening of global monsoon circulation (Chase et al., 2003; Pant, 2003), or global climate shift (Baines & Folland, 2007), deforestation (Kothyari et al., 1997; Nair et al., 2003), and increasing levels of aerosol concentrations due to anthropogenic activities (Ramanathan et al., 2001). The WIH mainly receives precipitation from mid-latitude westerly disturbances (WDs) during winter months, which considerably delivers solid precipitation over the north and central part of the Himalayas (Hatwar et al., 2005; Yadav et al., 2009). Few studies indicate intra-regional differences with decreasing patterns of winter rainfall over the WIH (Dimri & Dash, 2010; Guhathakurta & Rajeevan, 2008; Pant et al., 1999). Contrary to these observations, Fowler and Archer (2006) reported an increasing trend of rainfall in the upper Indus Basin (1961–1999), but it was not consistent (Khattak et al., 2011).

In the Garhwal region of the IHR, spatially coherent trend of precipitation was not seen at the decadal and centennial scale. Besides, this region experienced some extreme event of rainfall (e.g. 70 mm rainfall in 1 h in 2012 and 250 mm rainfall in 52 h in 2013), during 2008–2013 (Khandelwal et al., 2015). Kedarnath tragedy that occurred on 16 June 2013 in the Mandakini River Basin is one of the most devastating events in recent decades. Such an event is attributed to huge precipitation (~325 mm in 1 day) induced by a convergence of the WDs and ISM (Bhambri et al., 2016; Dobhal et al., 2013).

The varied precipitation trend from the west to the central part of Himalaya can be attributed to geological, topographical, and biological interactions with weather systems (Sharma & Ganju, 2000). The eastern Himalaya receives precipitation mainly from the ISM weather system in the monsoon months. Studies

have forecasted some events of maximum annual rainfall in the eastern and northeastern regions of India (> 500 mm), while semi-desert (shadow zone) like conditions were seen in the northwest region of the Himalaya. Humid air masses of variable magnitude strike to the orographic barriers, generating a strong convection that leads to high rainfall over eastern and central Himalaya. Despite the orography, the influence of the atmospheric circulations over the ISM and WDs plays important roles in shaping the precipitation gradient from west to east of the Himalayan arc.

Impact of rainfall is manifested as a term of erosional activity, flash floods, drought, and other many disasters (e.g., landslides, glacial lake outburst, and collapse of moraine dam) over the high mountain region (Bookhagen & Burbank, 2006). These events contribute a significant amount of sediment load to the rivers, for example, Ganga, 329 m/y; Brahmaputra, 597 m/y; and Indus, 100 m/y (Subramanian, 1993). Therefore, the study of rainfall intensity and its frequency is very crucial for making a strategy for proper functioning of power station in wake of changing sediment transfer rate from the rivers originating from the Himalayan terrain. Furthermore, most of the contributions (~70%) in the headwaters of the river basin take place from snow/ice melt during summer season. Thus, the monsoon lowering restricts the glacier melts, which is prone to an acute drought in the downstream areas. Several events induced by rainfall and related risks in the IHR are still unknown, because of limited forecasting capacities. Rainfall data measured below the snout may not be utilized for the studies of other catchments owing to high variability. It is thus essential to follow up with more investigations in the high-altitude catchments.

Variability in snowfall

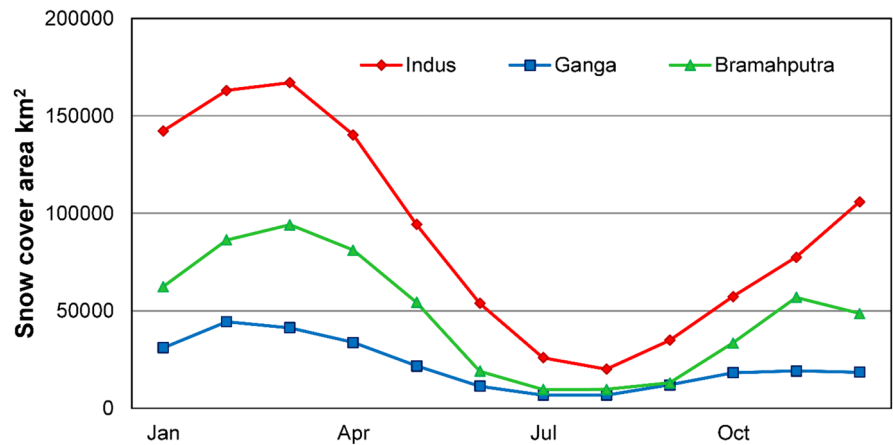
Variability in air temperature and rainfall greatly impacts the snow and ice cover, thus making the cryosphere one of the prevailing indicators of climate change (Negi et al., 2018; Rohrer et al., 2013; Shrestha et al., 1999). Numerous studies suggested an inverse relation between snow cover and the ISM rainfall over western Eurasia while a proportional relationship over eastern Eurasia (Hahn & Shukla, 1976; Dey & Kumar, 1983; Blanford, 1884; Sikka, 1999; Zhao & Moore, 2004). The inverse correlation

may be attributed to high albedo, melting of snow and formation of clouds during spring and summer period. In addition, positive net radiation sums affects the snow depth (Rohrer et al., 2013).

Satellite-based remote sensing data and ground observations through river basins have outlined the prevailing effect of topography, latitude/longitude, and little attention of impact of weather conditions over the SCA variability (Baral & Gupta, 1997; Jain et al., 2009; Pandey et al., 2013; Kour et al., 2016; Rathore et al., 2015; Rikiishi & Nakasato, 2006). During the last 3–4 decades, several snow-related observations coupled with meteorological data explore that seasonal snowfall has declined in response to accelerated warming trend in different parts of western Himalaya (except Karakoram Range) (Gurung et al., 2011; Immerzeel et al., 2009; Menon et al., 2010; Mir et al., 2015b; Sharma et al., 2012; Shekhar et al., 2010). Towards this, about 16% decline in the annual SCA across the HKH region was projected by Menon et al., (2010). In contrast, some studies revealed increasing annual SCA trends (Kour et al., 2016; Shafiq et al., 2019; Tahir et al., 2016), which may be resulted due to asymmetric influence of WDs, and large variability in the topography (Immerzeel et al., 2009; Singh et al., 2014). It is important to note that the timing of snow cover peak is highly variable due to the effect of weather systems at the same time, thereby fluctuating snow line altitudes (Kripalani et al., 2003). In this region, the reported annual snowfall during winter months ranged from 100 to 1600 cm with the highest snowfall in the Pir Panjal ranges. Higher ranges of this region sustain relatively lesser snowfall due to terrain characteristics (Bhutiyan et al., 2007). However, the WIH experienced a higher average snow cover than that of the CIH due to the effect of mean elevation and circulation pattern of winter WDs (Bookhagen & Burbank, 2010).

In the upper Ganga Basin, central Himalaya, the distribution of the snow cover with elevations varied significantly (14–21% in the lower and 2–3% in the higher elevation zones). It also varied temporally with a maximum in the winter season followed by spring season, while minimum SCA was found during monsoon season (Joshi et al., 2015). Similar variation in the seasonal SCA was also reported in the WIH due to low temperatures and frequent snowstorm in winter and increased temperature in monsoon season (Singh et al., 2018). In addition, the spatio-temporal variability of snow

Fig. 6 Spatio-temporal variation of snow cover in three major river basins—the Indus, Ganga, and Brahmaputra during accumulation and ablation period (2000–2011) (Singh et al., 2014)

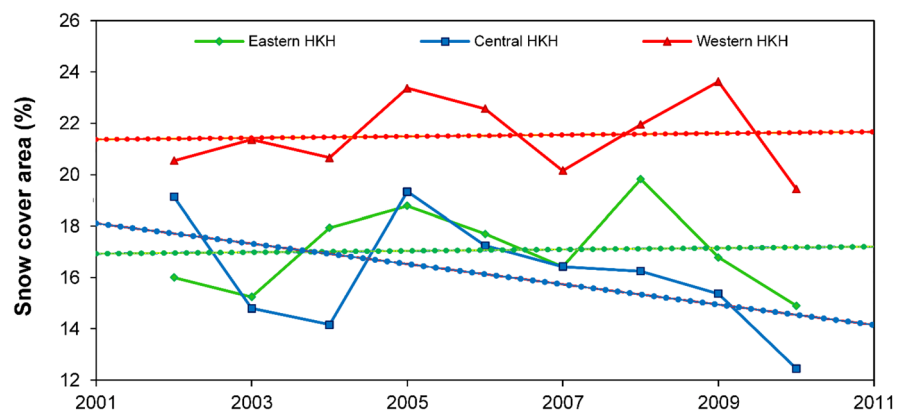


cover was conducted over three major basins—the Indus, Ganga, and the Brahmaputra for 12 years (2000–2011) (Singh et al., 2014). Results showed that snow cover was reduced to 10.41%, 11.32%, and 8.10% in respective basins during ablation period. All these basins lying in the different climatic zone show a similar pattern of SCA variability during accumulation and ablation months; however, their magnitudes are substantially different (Fig. 6). Further, during the same period (November–December), an increasing trend was noticed for the Indus basin, while the other two basins show a decreasing trend. SCA variability represents the onset/offset of the accumulation and ablation period for a particular year; for example, the least ablation period has shown for the Indus whereas prolonged period for Ganga basin. It is important to note that the observed SCA trend across the entire HKH region reflected a declining trend in the central HKH, while the western and eastern region experienced

an increasing SCA trend (Fig. 7) (Gurung et al., 2011).

In summary, an inconsistent pattern of precipitation has persisted over different regions of the Himalayas and is mainly controlled by orographic and thermo-dynamical processes induced by the ISM and the WDs. Careful investigations and scientific attention are required to depict the precipitation trend and its adequate validation using data from numerous sources such as MOs, AWSs, remote sensed, and TRMM-derived data. In this region, remote sensing studies have highlighted mostly the SCA and depletion curves in the past decades, whereas estimation of snow water equivalent (SWE) using satellite dataset is poorly investigated. A suitable selection of remote sensing data is imperative for describing the distribution of snow cover. Most of the studies over SCA carried out at regional scale using Moderate Resolution Imaging Spectroradiometer (MODIS) data having resolution ~500 m and has frequent return period

Fig. 7 Recent trend of snow cover area in different regions of the Hindu-Kush Himalayas (HKH) (Gurung et al., 2011)



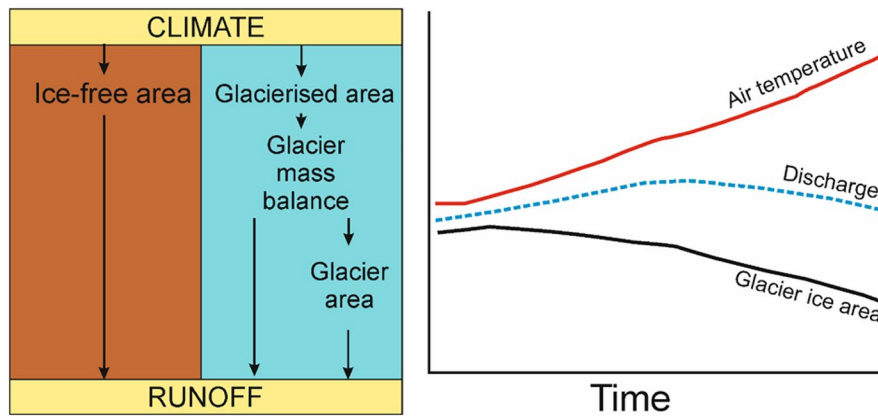


Fig. 8 Climate-runoff interaction over ice-free and ice-covered areas of partially glacierized catchments. The direct impact of climate can be seen as reductions of glacier mass and in turn its area; hence, climate directly affects the discharge regime

(8 days) (Kour et al., 2016; Mir et al., 2015a; Negi et al., 2010; Sharma et al., 2012). This dataset provides good results for the basin of large areas. On the other hand, Yadav et al., (2020) suggested the utilization of Landsat data for small catchment because of its high spatial resolution (30 m) as compared to MODIS data. Despite the limitations of the MODIS and Landsat dataset, snow filtering and blended technology coupled with passive microwave data should be adopted to re-establish more precise SCA maps for the IHR regions. It is here important to mention that recent developments of cloud-free MODIS snow cover products by integrating the existing algorithms (spatial, temporal, spatio-temporal, and multi-source fusion) will provide qualitative data (Li et al., 2019). Moreover, in response to spatial distribution, this review brings attention to monitoring snow depth to a large extent using a snow probe or other types of equipment.

Missing meteorological data at a large scale

In the IHR, temperature and precipitation are widely investigated, while other parameters (i.e. RH, wind speed and direction, radiation fluxes, evaporation), despite being an important role in understanding climate change, water storage, groundwater replenishment, and flood control, have not been examined at the appropriate scale (spatial and temporal). The

over a longer period. General thought to highlight how air temperature influences the glacier ice area and discharge through time (Collins et al., 2013) have witnessed

paucity of meteorological data has hampered the efforts not only to delineate present weather conditions but also to understand risk factors for future water resources. A brief description of underestimated meteorological parameters for research purposes is as follows.

Relative humidity (RH)

Seasonal variation in the RH plays an important role in the forecasting of weather conditions (Yadav et al., 2020). An early study (2009–2013) from the semi-arid region of Chhota Shigri Glacier and western Himalaya has shown that the RH was higher in the monsoon months with a maximum in August, while winter months experience lower RH (Azam et al., 2014). Further, this study suggests that sharp changes in the RH are indicative of the onset of a new season; for example, the RH increased/decreased suddenly in the mid-June/end of September depicts the arrival of the monsoon/winter season. In the central Himalaya, maximum RH was observed in July month followed by August, implicating the greater impact of the ISM in this region than WIH (Thayyen et al., 2005; Thayyen & Dimri, 2014). Relative humidity is considered to be a function of air temperature. Therefore, the extrapolation of temperature data using NSTLR from lower to the higher elevations with a good level of confidence may provide the trends of RH with elevations. However, the inverse relation of the RH

with air temperature as reported by Kesarwani et al., (2012) over Chorabari Glacier Catchment is not valid for all the temporal extent; for example, in the winter months, RH is lowered with a decrease of temperature. Spatially, RH was larger at high elevations than lower reaches of the catchment. To date, only a few insights on this aspect are developed in the IHR. Yadav et al., (2019) attempted to fulfil the paucity of RH data in the high-altitude Himalaya by using Tetans' equation, which can appropriately be utilized in the areas where only temperature data are available. Therefore, RH can either be explored by installing a dense network of observatories or computed by using Tetans' equation in the vicinity of in situ data.

Wind speed and wind direction

Several processes like cloud formation, moisture transportation, accumulation, and ablation of glaciers in the high-altitude regions are primarily affected by the wind regime. Toward this, Azam et al., (2014) suggested that wind was highly varied in the Chhota Shigri Catchment with strong in the winter season and weak in the monsoon season. Wind speed remains almost invariant during monsoon, while significant variation is seen in the winter. This reflects that the monsoon lowers the wind speed in the catchments.

In the central Himalaya, similar seasonality was observed in Gangotri Glacier Catchment with an annual mean of 4.7 ± 0.8 km/h for 2000–2013 (Gusain et al., 2015; Singh et al., 2005). At the diurnal level, average wind speed is more dominant (about four times) during daytime (~ 12.6 km/h) compared to night-time (3 km/h). Further, the change in the direction of the wind was seen after the sunrise and late evening. During monsoon season, most of the blow tends to northwest, i.e. from valley to upper reaches of mountain slope (i.e. Katabatic wind) (Singh et al., 2005). Generally, radiation fluxes control the wind speed and direction. The intense influx of radiation during daytime heats the mountain slope; hence wind blows upslope the valley accelerating the formation of cloud, while night-time radiation shows the cooling effect leading the blow of wind down the valley slopes (i.e. anabatic wind). A similar pattern is also identified in the other high mountain catchments of the world (Whiteman, 2000).

Overall, the wind regime in the IHR is localized and depends upon geographic settings and large-scale circulations. Thermally driven diurnal patterns of wind are common in the mountain catchment, but at this level, data availability is rare in the IHR. Further, the effect of wind on precipitation pattern (rain/snow) was poorly investigated. There is no alternative for observing the wind speed without installing the AWSs or manual observatories.

Radiative fluxes and sunshine duration

The comprehensive knowledge of radiative fluxes and their coupling with an atmosphere is important to observe the glacier behaviour as a form of mass wastage/gain; nevertheless, the published records to understand the sources and sinks of energy balance are sparse in the IHR. However, some noteworthy attempts to estimate radiative fluxes and energy balances have been conducted over Chhota Shigri Glacier (Azam et al., 2014), Pindari Glacier (Singh et al., 2020) in the western Himalaya and Gangotri Glacier (Gusain et al., 2015), and Chorabari Glacier (Karakoti et al., 2017) in the central Himalaya (Table 1). Findings from published research evince that incoming short-wave radiation was maximum in the pre-monsoon season and minimum in the monsoon season in both regions, indicating a good coherence with the RH variability, while incoming long-wave radiation was maximum during monsoon season. Reflected short-wave radiation is higher in winter than in other seasons. We have also observed that most of the observatories in the IHR were operating over moraine or soil, which could not provide data with the required reliability for surface energy balances of the glaciers. Moreover, some installed observatories could not provide all components of radiation fluxes.

Very little information is reported for the sunshine duration (SD) over the biodiversity-rich IHR. In the absence of cloud cover data, the SD is used to define the envelope of cloudiness over the catchment. In the Gangotri Glacier Catchment, the SD was highly variable in monsoon months (May–October), ranging from 4.0 to 7.2 h, with a maximum in May followed by October (Singh et al., 2005). August experienced minimum SD because of the rainiest month. One of the studies from the north region shows a decreasing trend of the SD at monthly and seasonal time scales, which may be a potential cause for decreasing the

diurnal change in temperature in north India (Jhajharia & Singh, 2011). Further, a decreasing trend of the SD is possibly due to the blocking of incoming solar radiation resulting in the increase in cloudiness over the north region for the maximum period. Results support solar dimming phenomena as proposed by Kumari et al., (2007). Therefore, variation of the SD may be used as a proxy to illustrate a warming trend due to increasing anthropogenic activities.

Evaporation and vapour pressure

Evaporation is considered an important parameter of the hydrological cycle and plays a paramount role in water balance and streamflow studies (Singh et al., 2005). It is controlled by many meteorological variables such as temperature, RH, precipitation, and wind velocity. Higher values of evaporation are attributed to low relative humidity, high sunshine hours, and high wind speed, particularly in pre-monsoon season, but reverse conditions lower the evaporation in the peak monsoon season. One of the studies from the Gangotri Glacier shows that the average seasonal evaporation was ~641 mm, which increases with elevation (Singh et al., 2005). Seasonal variation in these parameters will help to understand the glacier dynamics during different seasons and need to work on these aspects. No observations were recorded for vapour pressure.

Glacier-climate interaction

The effect of climate change on the Himalayan's glacier is an important issue for public as well as scientific interest. However, insufficient observational data impeded our attempts to trace the drivers that control the glacier mass balance (MB). Morphodynamical changes (i.e. length, area, volume, and thickness) of the glacier have delayed response to climate change. In contrast, the surface mass balance of the glacier responds quickly to climate changes and thus regarded as good climate change indicators. The sensitivity of glacier towards climate change is primarily predictable by the change in temperature, but precipitation also plays an important role. Finding shows that central and eastern Himalayan glaciers are gaining mass from summer monsoon and so-called summer accumulation type, while glaciers

of northwestern Himalaya receive mass from western disturbances (Bolch et al., 2012) Sakai et al., (2015), based on temperature scenarios, reported following two ways of sensitivity of surface mass balance to temperature change:

If $10 < \Delta T < 20$ °C, region is highly sensitive.

If $20 < \Delta T < 20$ °C, region is relatively less sensitive.

This sheds light on why Karakorum Range shows less sensitivity to climate change as compared to the rest of the Himalayan region. Subsequently, the EIH and the CIH are more sensitive to climate change than WIH and Karakorum (Fujita, 2008). In the IHR, such studies are few in numbers at a large scale due to a lack of meteorological data. However, some noteworthy studies suggest that the glacier mass goes on decreasing with an increase of temperature and decrease in precipitation (Garg et al., 2021; Azam et al., 2014; Bhutiyan et al., 2010; Dash et al., 2007; Dimri & Dash, 2012). Towards this, Yadav et al., (2020) have worked on another aspect and reported that variations of transient snow lines are mostly coherent with isotherms altitudes of the Dokriani Glacier during ablation period, while isotherms altitudes deviate largely from snowline in the accumulation period, indicating that snowfall is an event-based phenomenon and controlled by local (e.g. RH, radiation fluxes, wind speed, and direction) and global factors (e.g. weather circulations). Fowler and Archer (2006) reported that Karakoram Himalaya receives greater mass than mass wastage, which shows the weaker sensitivity to warming. With their contesting views, Fujita and Ageta (2000) suggested that the monsoon-dominated glaciers are more sensitive to temperature change, which lead to extend the ablation period by melting the solid precipitation. Cloud cover (CC) over the mountain catchment is temperature-dependent, which decreases with the increase in maximum temperature (Shekhar et al., 2010). In recent decades, in response to the increasing trend of temperature, cloudiness is reduced in the summer, thereby depleting the glacier mass. Fluctuations in maximum and minimum temperature influences the ablation and accumulation of glacier mass; Bashir et al., (2017) suggested that the amount and duration of ablation are declined with a decrease of T_{\min} and T_{\max} , indicating a significant cooling effect on summer. Avalanche-fed glaciers have small accumulation

areas because of the transport of glacier mass down through avalanche cone. They are more sensitive to warming and precipitation as rain or snow during summer season (Benn et al., 2012).

The surface energy balance (SEB), a point scale measurement of energy, has improved our understanding of glacier-climate linkages. Out of several components of the SEB, the net flux of shortwave radiation is a key component of the energy source that controls the melting of glacier mass (Pellicciotti et al., 2008). Net long-wave radiation acts as a sink and is a measure of surface-atmosphere coupling. Turbulent fluxes are generally supposed to be secondary flexes but play a dominant role in the energy exchange between glacier surface and atmosphere (Hock & Holmgren, 2005) and utilized to reflect extreme melting processes (Fausto et al., 2016; Thibert et al., 2018). Like the net radiation, sensible turbulent fluxes are always positive over debris-free areas. During peak monsoonal activity, considerable energy exchange takes place in terms of positive latent heat fluxes between glacier surface and atmosphere by the process of condensation and re-sublimation, whereas negative latent heat flexes show the dominance of the sublimation process under drier summer and the absence of monsoon activity. Therefore, the glaciers of northwestern Himalaya, Karakorum, and Tibetan Plateau indicate loss of mass due to sublimation under drier conditions (Collier et al., 2013; Zhu et al., 2015).

Considering the components of the SEB, the long-term ground observations of meteorological parameters over glacier surface are very useful. In the IHR, most of the AWSs is located on supraglacial surface or ground moraines in the ablation zone because of stability issues. Only one study by Azam et al., (2014) is available, which relates the dynamics of the MB with the SEB through the change of surface albedo over Chhota Shigri Glacier in the western Himalaya. Towards resolution, a mask with four legs structure can be used during the melting process, which provides stability of the AWS over the glacier surface. Such set up of meteorological observatory are found worldwide (Klok & Oerlemans, 2004; Oerlemans, 2000). Such settings are not available in the IHR and need to be set up on the glacier surface. Such a constrain has hampered our comprehensive knowledge about the glacier-climate interactions.

Hydro-meteorological interaction

Himalaya is a major source of fresh water supply for the people residing downstream areas of south Asia. The total discharge through glacier varies temporally at different scales (daily, seasonal, annual, and century) and affected by geometrical (glacierized area/volume), geographical, and meteorological (temperature and precipitation) factors (Singh et al., 2016). The large area contributes to a greater amount of glacier melt in the river basin (Kaser et al., 2010). Immerzeel et al. (2015), based on gridded dataset, suggesting that large glacier can be sustained if the amount of precipitation is substantial at high altitudes.

Discharge is intrinsically related to temperature and precipitation and, in turn, glacier MB. Generally, glaciological balance year with less negative MB corresponds to the year having relatively high precipitation and low discharge and vice versa; however, this relation is not valid for all the glaciers of IHR. For example, reverse correlation is observed for Chhota Shigri and Dunagiri Glacier lying in Chandra and Dhauliganga Basins, respectively. Thus, discharge characteristics of a basin cannot be directly attributed to changing climate conditions, but it also depends upon the source of precipitation. In general, Xu et al. (2009) suggested that streamflow of all the major rivers of the HKH region have been increasing, depending upon temperature and precipitation. For instance, the stream flows in the Satluj and Beas have increased than that in the Chenab and Ravi River Basins. In addition, Singh et al., (2008) compared the streamflow in the Ganges and the Indus River Basins of central and western Himalaya, respectively, and observed that both river basins indicate an increasing trend of streamflow, with slightly less in the latter. This suggests that temperature and precipitation in these basins would increase in the future. Evapotranspiration is another important process of the hydrological cycle, mainly governed by temperature, and affects water availability downstream. An attentive trend of variation of temperature with glacier area and discharge is presented in Fig. 8.

The contribution of glacier and snowmelt to total discharge varies with the river basins in the IHR. Mukhopadhyay and Khan (2015) reported that snowmelt contribution to total discharge is dominant in the western Himalaya as compared to the Karakoram Range where the river basin (e.g., Upper

Indus basin) is greatly nourished by glacier melt. These two diverse contributions are linked with the temperature and precipitation pattern of the respective regions. Temperature rise accelerates the phase change directly from snow to rain, thereby contributing to the runoff (Yadav et al., 2019). Also, discharge characteristics can be understood in terms of albedo amount. The lesser the albedo, greater is the chance of absorption and hence increased melting of glacier mass. Several studies reported that glacier melt in the river basin of Himalaya will usually increase up to 2050 and then has expected to be decreased (Immerzeel et al., 2013; Lutz et al., 2014; Shea & Immerzeel, 2016; Soncini et al., 2015; Tahir et al., 2016). However, associated uncertainties due to volumetric differences in glaciers restrict the clear projection of the river discharge. Overall, runoff regimes and their seasonal variability is a function of glacier mass turnover and its wastage is associated with variability in meteorological parameters, like temperature and precipitation. Therefore, the availability of meteorological and discharge data become central to our understanding in broader perspectives.

In recent decades, several glacio-hydrological models based on meteorological variables and empirical relationships were proposed to identify the discharge characteristics in the different regions of the Himalaya (Lutz et al., 2014; Mukhopadhyay & Khan, 2014; Ragetti et al., 2015; Thayyen & Gergan, 2010). Most of the models used temperature and precipitation data to quantify the contribution of glacier melt in the total discharge. However, the effect of debris, wind speed, radiation fluxes, and sublimation is not incorporated in the model development, which may introduce uncertainties in the estimated discharge. Earlier studies (Pratap et al., 2015) suggest that knowledge about the debris effect is crucial for the understanding of mass wastage and hence the generation of discharge through glaciers. Further, spatial distribution of precipitation at point scale is essential, which demands the dense network of meteorological observatories.

Concluding remarks

With increasing societal relevance, the understanding of meteorological attributes has promptly grown up in recent years. However, the spatio-temporal coverage of meteorological parameters is still scarce in the

Indian Himalayan Region (IHR) compared to several mountain ranges of the world. In light of this, the present study brings attention to the following conclusions and recommendations:

1. Study illustrates the observational analysis to deciphering trends of meteorological parameters. Studies in the western Himalayan region indicate the considerable increasing trends of minimum, maximum, and average temperature with more warm events than cold events.
2. The trend of diurnal temperature change is non-symmetric in all units of the IHR, which are more prominent during daytime compared to nighttime; however, certain spells of warm nights are increasing during winter season. High variability in temperature needs to be investigated at the local scale, i.e. sub-regional and basin level to make out the land-use heterogeneity.
3. Precipitation, unlike temperature, shows a large spatio-temporal incoherence in all regions of the IHR. This may be resulted due to the sparse distribution of observatory and due to highly variable events controlled by climatic sources such as Indian summer monsoon (ISM) and western disturbances (WDs). Thus, warming trend leads to the shifting of phase of precipitation (rain vs snow), which could be very important for socio-environmental perspectives as it is linked with the span of seasons and corresponding ecosystems.
4. Warming trend and reduction of solid precipitation can substantially affect the hydrological cycle, including the melting of glacier, sea-level rise, land use, slope stability, sediment load downstream, and other natural phenomena. This warrants us to investigate the meteorology of the IHR in all their aspects by opting for the latest instrument and technologies.
5. Temperature-precipitation trend will affect the source of water availability. Further, associated error in the forecasting of weather conditions may be assessed by knowing the glacier-climate interaction. Towards this, a fair understanding of controlling factors of the variability of glacier mass, flow rate and timing, moisture, and energy input is imperative for the water management and future adaption at the local scale.
6. The exact ways of glacier response to climate change are still unclear, especially where they

are expected to undergo a transition to debris-covered glaciers, while others will melt totally. Thus, the present review emphasizes meteorological attributes and their variability at a local and regional scale to emerge out of future glacier recession in the IHR. It is crucial to re-scrutinize the strategies for the adaption under changing pattern of climate change.

7. Lack of meteorological data and knowledge on the cryospheric unit remains a key barrier for not only defining sustainability of water resources locally but also in formulating a valid river flow affecting the global sea levels. Thus, it may be extremely relevant for understanding the impacts of climate change on the cryosphere and hydrosphere of the IHR.
8. We recommend establishing a dense network of meteorological stations, more possibly over the glacier surface, covering more glacierized catchments/watersheds in the IHR. Data sharing policies among the agencies and nodal centre would be a positive step to understanding the meteorological applications in all aspects. This would be helpful to develop large-scale futuristic models for glacier-climate interaction and runoff evolution with good confidence.

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Declarations

Competing interests The authors declare no competing interests.

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