Journal of Climate Change, Vol. 7, No. 1 (2021), pp. 79-88.
DOI 10.3233/JCC210007

Estimation of Deglaciation through Remote Sensing Techniques in Chandra-Bhaga Basin, Western Himalaya

Shruti Dutta[1]* and AL. Ramanathan[2]

[1]School of Earth & Environmental Sciences, Amity University Haryana, Gurugram, India
[2]School of Environmental Sciences, JNU, New Delhi, India
✉ shrutidutta2020@gmail.com

Received September 3, 2020; revised and accepted October 6, 2020

Abstract: Glaciers act as natural indicators of climate response and natural buffers of the hydrological cycle. Hence, continuous monitoring of glaciers is very crucial for which remote sensing techniques have emerged as a powerful tool to understand the micro-level variation and dynamics of glaciers. Unfortunately, a database involving complete basin-level approach and an extensive temporal range is not available for the entire Chandra-Bhaga (CB) sub-basin. Thus, the present investigation attempts to account for the extent of deglaciation in the CB basin showing that 16.7 percent of the glaciated area has been lost during 1989-2019. Moreover, the last three decades have witnessed a rapid rate of loss for small and medium-sized glaciers as compared to larger glaciers. Adding to it, the basin has also shown an upwards shift of mean elevation in this period. Over the last decade, an increasing temperature in the western Himalayas and Hindu Kush regions, as asserted by previous studies, have led to spatio-temporal changes in the glaciated area. The extent of deglaciation alongwith the glacier-climate behaviour and response can also provide a link to measure the topographical parameters.

Keywords: Glaciers; Deglaciation; Himalaya; Remote Sensing; Chandra-Bhaga; Spatial-temporal change.

Introduction

The intricate balance of the global climate system and its dependence on the cryosphere is well established. Glaciers are natural temperature indicators or "thermometers" and natural buffers of the hydrological cycle. A micro-level variation in glaciers, reflected through its dynamics, i.e. spatial characteristics, mass balance, velocity etc. is perceived as a sensitive indicator of climate change and can be used as a proxy indicator for climatic variations (Kaser et al., 2005). The glaciers recharge the aquifers which are fed by rivers as they release meltwater during summers and early autumn. Thus, they are highly significant as a water resource downstream influencing runoff (Bolch et al., 2012). Therefore, an understanding of glacier characteristics and dynamics becomes immensely important which can be exercised through consistent monitoring of the glaciers.

The recent IPCC Special Report on the Ocean and Cryosphere (SROCC, 2019) and the previous IPCC reports alongwith several other sources have regularly emphasised the notable status of glaciers across the globe, manifested through the glacial retreat, loss of area and volume, especially in Himalayan glaciers (Bajracharya and Mool, 2009; Bolch et al., 2012). The IPCC report predicts a rise of 1.5°C between 2030 and 2052 and SROCC (2019) predicts the shrinking of glaciers feeding 10 rivers dramatically with the current rate of emissions.

The Himalayan cryospheric region is situated at the periphery of diverse climatic zone towards its north

*Corresponding Author

and south (Pandey et al., 2013), witnessing a contrast of factors influencing the state of the climate. The north-western Himalayan precipitation is dominated by westerlies whereas the south-eastern region is influenced by summer monsoon rainfall (Bolch et al., 2012). The vast extent of the Himalayan region encompasses about 9575 glaciers (Raina and Srivastava, 2008; Sangewar and Shukla, 2009) covering an area of approximately 37,466 km^2. It works as a lifeline to millions of people. Regular and updated monitoring of glaciers thus becomes inevitable. However, field studies are scarce and difficult to carry because of the harsh terrains, inaccessibility and logistics in the adverse environmental conditions. In this scenario, the role of remote sensing techniques involving multi-temporal and multispectral satellite images, especially with the latest advancements becomes a very important tool to understand the dynamics and characteristics of microclimate at regional levels. The satellite data and their applications are now widely accepted as a potential investigation tool for cryospheric studies as compared to the conventional field-based method. However, the spectral signatures pose a limitation in the mapping of the glaciers because of similar signals from debris and the adjoining bedrock. Hence, manual delineation and semi-automated methods, although time-consuming and cumbersome, are widely employed for mapping the glaciers.

Several studies have been conducted in the Himalayan region using remote sensing methods (Berthier et al., 2007; Kulkarni et al., 2007, 2011; Wagnon et al., 2007; Bhambri et al., 2011; Technical Report, SAC 2011, 2016). Hence, in the Himalayan region, the Chandra-Bhaga (CB) sub-basin, situated in the monsoon arid transition zone, can be considered as an indicator of the monsoonal strength of the northern belt (Pandey et al., 2013). The south Asian monsoon and westerlies act as an important factor in the summer and winters, respectively, subsequently identifying the sub-basin as an appropriate region to understand the glacier climate response.

A change detection analysis for 169 glaciers in Chandra basin, Western Himalaya in India, during 1971–2016 (Sahu et al., 2020) has been done, which showed an areal loss from 639.4 ± 5.8 km^2 (in the year 1971) to 608.1 ± 10.3 km^2 (in the year 2016). Another study was conducted on Chhota Shigri and Hamtah glaciers in Chandra basin to look into the characteristics of morphometric parameters, topography and hypsometry for insights on the melt pattern and glacier-climate response, hence, evaluating the feasibility of representative glaciers amongst these two glaciers (Pandey et al., 2016). The Area Altitude ratio for these two glaciers was estimated whereas a relationship of AAR vs Mass balance has been derived and validated with field studies. An analysis of 48 representative glaciers in the Bhaga basin during 1979 and 2017 reveal deglaciation from 238 km^2 to 230.8 km^2, respectively (Kaushik et al., 2018). Another attempt to create a glacier inventory in the Bhaga basin for the selected 231 glaciers using high-resolution images reveals that they had a glaciated area of 391.56 km^2 and 385 km^2 for the year 2011 and 2001, respectively (Birajdar et al., 2014). An attempt to study the Equilibrium Line Altitude (ELA) through satellite images (1980-2007) for 19 selected glaciers in the CB basin estimates an increase of mean Snow Line Altitude and was found to be in good correlation with reported temperature measurements during summer and winters in the last century (Pandey et al., 2013). A unique study has been done to assess the spatial and temporal distributions of glacier velocity for the sub-basin CB using Advanced Land Observing Satellite-2/Phased Array type L-band Synthetic Aperture Radar-2 (ALOS-2/PALSAR-2) differential interferometry pair images (Singh et al., 2020). The study indicates a greater flow rate for Chandra basin as compared to Bhaga, mostly attributed to factors like slope and thickness.

A database involving the glacier studies at a complete basin-level approach and extensive temporal range studies is scarce in the literature for the CB basin. Moreover, the studies conducted so far have undertaken selective representative glaciers for this sub-basin, which are done at a small temporal scale. Therefore, the present study is an attempt to fill the existing gap in the database and estimate the spatial and temporal changes in the glacier-covered areas of Chandra-Bhaga basin for a period of three decades (1989-2019) and assessing the climate-glacier response.

Area of Study

The Chandra-Bhaga sub-basin is situated in Lahaul Spiti district, Himachal Pradesh, designated as a sub-basin of Chenab and located on Pir Panjal range (Kaushik et al., 2018). The predominantly debris-covered region shows a characteristic elevation range of 3900-6000 m and lies in the monsoon arid transition zone (Sahu et al., 2020) influencing monsoonal winds and westerlies in the summer and winter, respectively. Therefore, they can be considered as representative areas to monitor climatic responses. The Chandra and Bhaga rivers originate from

Chandra Taal lake and Surya Taal lake, situated east and west of Bara Lacha La pass, respectively, it confluences near Tandi, Keylong, flowing as river Chenab, thereafter. In the present study, about 227 glaciers comprising an area of about 3327 km^2, encompassing 135 and 92 glaciers of Chandra (UNESCO/TTS number 5Q21212) and Bhaga (5Q21211) basin, respectively, have been undertaken for an estimation of the changes (Figure 1).

Dataset and Methodology

Source of Database

The present work has been carried out using various satellite imageries downloaded from freely available portals. Landsat (Thematic Mapper TM, Enhanced Thematic Mapper ETM+) images (1989 and 2001) was downloaded from the USGS Earth Explorer data portal (https://earthexplorer.usgs.gov/). The IRS LISS III images (2001 and 2006) were obtained from Space Application Centre, ISRO, Ahmedabad and sentinel data was acquired from the freely available website https://scihub.copernicus.eu/ for the year 2019. The selection of the year of study is based on the notion of looking into the state of glaciers before and after the pre-industrialisation era on a decadal basis. The freely available Cartosat 1 DEM was downloaded (http://bhuvan.nrsc.gov.in/) to derive the slope and aspect. From July to September, the glaciers are fully exposed and therefore, this is considered the most suitable time for their mapping. The selection of year has also been made based on freely available satellite images for these specific months for the respective year. The details of the database have been summarised in Table 1. The images acquired are extended at a temporal range of about three decades and thus a variation in the spatial resolution of the images is evident. However, since we aspire to assess the change detection over a widespread area, this limitation and its influence on the accuracy is inevitable.

Rectification of the Satellite Images

Field surveys were conducted at Chhota Shigri (Chandra basin), Panchi-Nala glacier (Bhaga basin) and Patsio glacier (Bhaga basin) to validate the ground control points through the DGPS survey (Spectra Precision EPOCH 10) and subsequently, all the images were

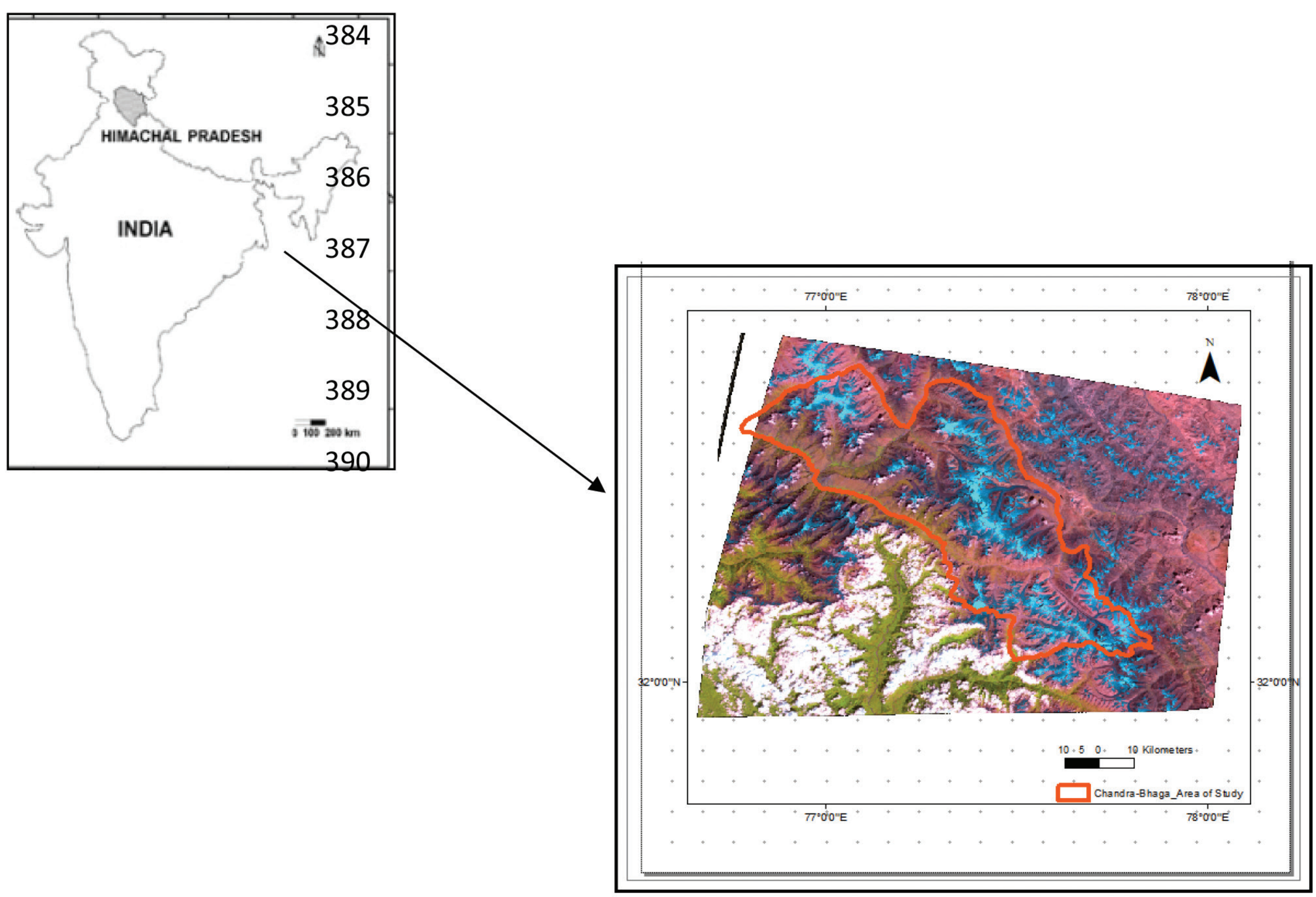


Figure 1: Area of study illustrating Chandra-Bhaga basin on IRS LISS III image 2001 (modified after Singh et al., 2020).

Table 1: Details of satellite data used in the analysis

Year	*Sensor*	*Spatial resolution(m)*	*Date of acquisition*	*Ground swath (km)*
2019	Randolph glacier inventory (https://www.glims.org/RGI/rgi60_dl.html)			
2005-14	CartoDEM Version 3 R1	30	C1_DEM_16b_V3R1	
2019	Sentinel 2-A	10	07 September2019	290
2006	IRS 1-C LISS III	23.5	15 August 2006	141
2001	IRS 1-C LISS III	23.5	15 Sept 2001	141
2001	Landsat ETM+Panchromatic	15	15 Oct 2001	185
	Landsat ETM+ Multispectral	30		
1989	Landsat TM	30	09 Oct 1989	185

rectified using the IRS LISS III image as the master image. Using an image to image co-registration, these images were geo-referenced with respect to the master image and resampled to 24-pixel size for consistency in the dataset. The Sentinel dataset (10 m resolution) was not required to be resampled and hence it was not involved in the resampling. The satellite images were reprojected and assigned Geographic Lat./Long. and WGS 84 as the projection and datum in this study, respectively.

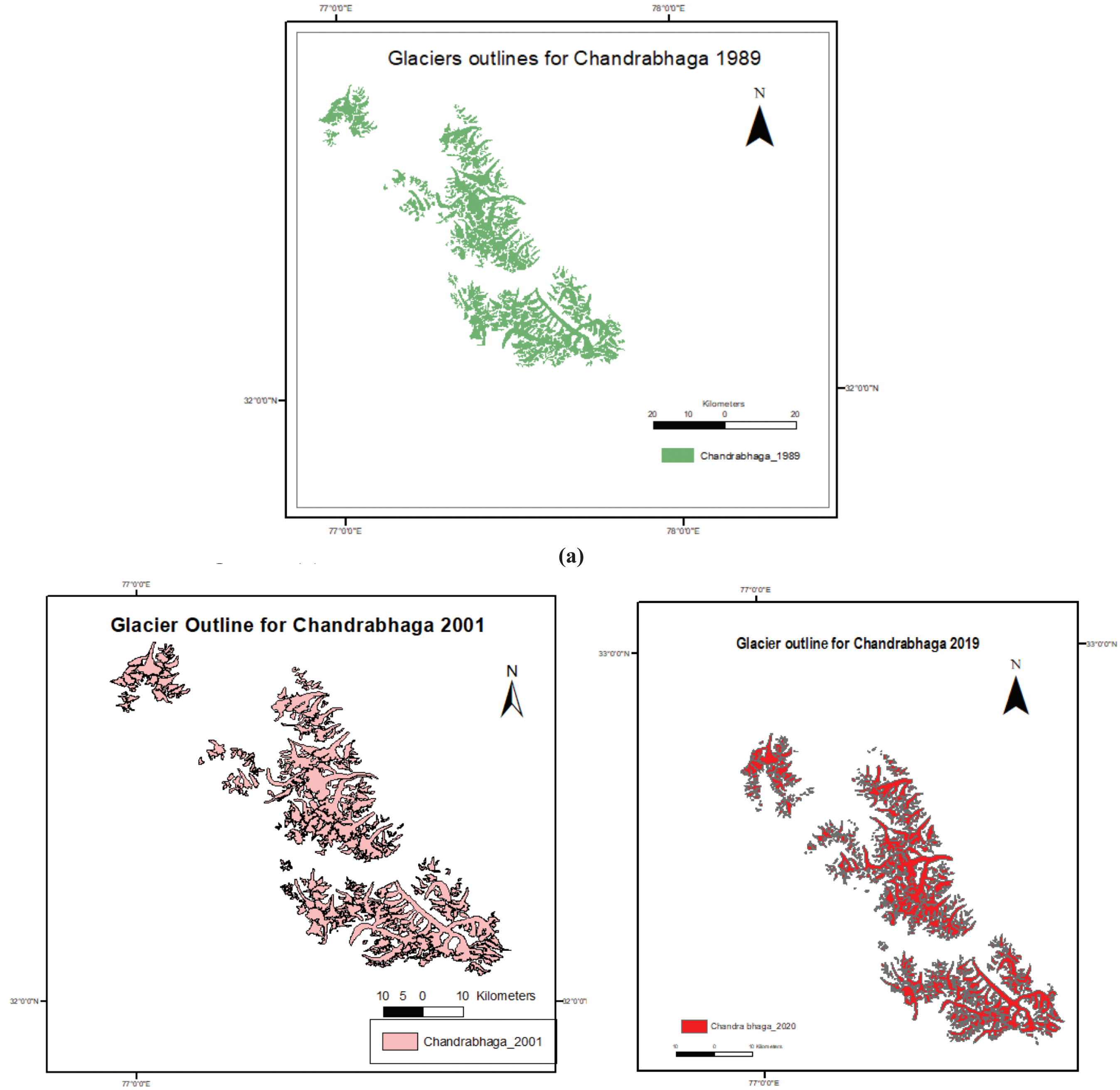
Delineation of the Glacier Boundaries

The demarcation of the glacier boundaries was done by identifying the snout and various geomorphological features e.g., moraines, etc present around the glacier body at a scale of 1:50000. There is a spectral difference between the bedrock and debris-covered ice (Andreassen et al., 2008; Bolch et al., 2010), therefore, manual digitisation was preferred over automated classification (Figure 2). The application of false colour composite resemblance and various algorithms were used to distinguish and identify glacier boundaries. Band ratioing, addition, subtraction and other algorithms gave enhanced clarity for visual interpretation and outline of the glaciers. The glacier boundaries were marked using PCI Geomatica 9.1 using the widely accepted band combination of near-infra red, green and red bands (Dutta et al., 2012; Granshaw, 2001) for the Landsat and IRS images. The glacier boundaries of 2019 were delineated from the Sentinel-2A images using the bands 8b, 4, 3 and 2 (NIR, Red, Green and band, respectively) using PCI Geomatica 9.1 (Kumar et al., 2019). The images were also compared with the Randolph Glacier Inventory database for the year 2018. Henceforth, the areal change was estimated for the period 1989-2019 and the results were compared in open source software QGIS 3.14.16. Further classification was made based on dividing the glaciated area into subcategories of 0.5-2 km^2, 2-5 km^2, 5-10 km^2, >10 km^2 (Table 2) for better spatio-temporal correlation. The delineated vector layers were reprojected into the UTM zone 43 WGS 84 projection to estimate the area of the glaciers. The slope and aspect of the area of study was calculated using the Cartosat 1 DEM

The source of satellite consists of multiple sources and therefore, may be subjected to error. A preliminary field truth was done to validate the mapping. The error encountered with the manual delineation was authenticated from the book 'Inventory of the Himalayan Glaciers' published by GSI (Sangewar and Shukla, 2009). A qualitative assessment was carried out

Table 2: Estimation of glacier covered area in Chandra-Bhaga basin during the period and pattern in sub categories

Year	*No of glaciers*	*Area of glaciers (km^2)*	*0.5-2 km^2*		*2-5 km^2*		*5-10 km^2*		*>10 km^2*	
			Area (km^2)	*No.*	*Area (km^2)*	*No.*	*Area (km^2)*	*No.*	*Area (km^2)*	*No.*
1989	227	1055.36	125.73	120	166.39	54	221.84	32	541.4	20
2001	217	1034.88	125.69	122	162.37	48	215.74	30	531.08	19
2006	222	1024.18	126.84	122	160.24	49	207.44	31	529.66	19
2019	197	887.295	122.95	127	95.61	31	147.07	19	521.65	20



(b) (c)

Figure 2: Delineation of glacier boundary on satellite images for Chandra-Bhaga for the year (a) 1989, (b) 2001 and (c) 2019.

through an overlay of outlines from multiple sources for more precision (Paul et al., 2017).

Results and Discussion

The present investigation deals with the spatial and temporal changes in the glaciated region of the CB sub-basin during the period 1989-2019. The manual delineation of the glacier boundaries was carried out for the years 1989, 2001, 2006, 2019 and the glaciated area was divided into various categories 0.5-2 km^2, 2-5 km^2, 5-10 km^2, >10 km^2. Deglaciation during the small period 2001-2006 does not show much significant change as evident from Table 2; thus, the changes in this period have not been discussed in detail. The study has been broadly divided into two periods: 1989-2001 and 2001-2019. The area estimation carried out reveals that the CB region has witnessed a loss of glacier cover from 1055 km^2 to 887 km^2 in three decades, thus showing deglaciation of about 168 km^2 which is about 16.7 percent of the total glaciated cover of the entire CB basin. The basin has vacated an area of about 85.24 km^2 for the study period 1989-2006 (17 years) and about 82.83 km^2 during the period 2006-2019 (13 years) which is about 8.15 and 8.53 percent of the glaciated area, respectively (Figure 3). The fluctuation and glacier loss is depicted in Table 2.

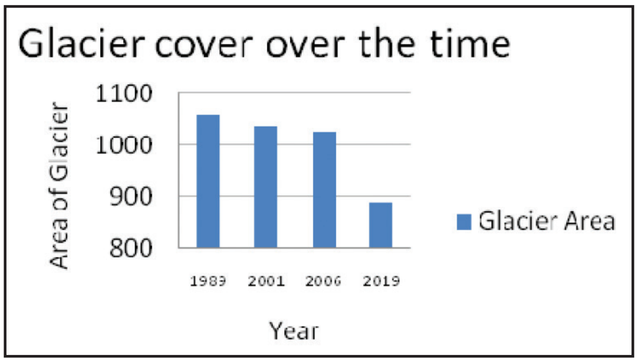


Figure 3: A graphical representation of the areal changes in Chandra-Bhaga basin (1989-2019).

A closer look within the area subcategories gives some varied and interesting results. It is seen that the glaciers incorporated within the 2-5 km^2 have been receding at the highest intensity showing a retreat of more than 40 percent in the last thirty years. However, the larger (>10 km^2) and smaller (0.5-2 km^2) glaciers have not revealed much prominent change and have remained more or less stable (Table 3). Under the aegis of the Ministry of Earth Sciences, Govt of India, six representative glaciers in the Chandra basin viz., Sutri Dhaka, Batal, Bara Shigri, Samudra Tapu, Gepang Gath and Kunzum have been studied and they have been showing retreat at varied scale (13-33 mm per year). The basin witnesses a high retreat rate for large glaciers like Samudra Tapu due to the debris-free surface of the glacier and broad valley. Moreover, it is a lake terminating glacier dominating the calving process. Therefore, all these factors contribute to a very high retreat. However, the Bara Shigri glacier, in spite of being one of the largest glaciers in the Himalayan region has shown a reduction of 15.10 km^2 in a span of 37 years (Rai et al., 2017). A comparative lesser retreat for Bara Shigri is attributed to its heavy debris cover in the lower reaches of the glacier, which has a remarkable influence on the rate of ablation. It is well established that the rate of retreat is decelerated for a glacier with thicker debris cover (Nicholson et al., 2018). A recent study by Sharma et al. (2016) also validated the fact that the distribution and thickness of debris cover over the glacier surface has a remarkable influence on the ablation. Another significant observation about exorbitantly large glaciers is that the higher elevations possess a large accumulation area and receive higher precipitation. Since the tongue of the glacier is at a lower elevation, the retreat is predominant in the lower ablation zone as compared to the high accumulation in the upper reaches. A graphical representation of spatio-temporal changes in areal coverage in CB basin during 1989-2006 and 2006-2019 and its deglaciation pattern in various area classes are summarised in Figure 4.

An assessment of the fluctuation in the number of glaciers shows that the basin has decreased in total glaciers from 226 to 197 during 1989-2006. However, the glaciers included in the 0.5-2 km^2 category have shown the highest tendency towards fragmentations as the number has increased (Table 2). The fragmentation has been more prominent in the category of glaciers whose area range 0.5-2 km^2. Glaciers larger than this class have shown a continuous reduction in the numbers. This might indicate that the majority of the small glaciers are gradually turning into glaciers less than 0.5 km^2 or ice patches.

Using the SRTM DEM datasets, contours were generated for the entire basin, the minimum, maximum and average elevation for the entire basin has been depicted in Table 4. The mean elevation has been estimated as 5189m, 5266m and 5374m for the years 1989, 2001 and 2019, respectively. The slope and aspect for the basin were estimated which showed

Table 3: A comparative account of spatio-temporal change in areal coverage in Chandra-Bhaga basin during 1989-2006 and 2006-2019

	Glaciated area vacated (km^2)	*Deglaciation (%)*	*0.5-2 km^2*	*2-5 km^2*	*5-10 km^2*	*>10 km^2*
1989-2006	85.24	8.15	0.95	3.73	6.60	2.17
2006-2019	82.83	8.54	3.07	40.33	29.10	1.51

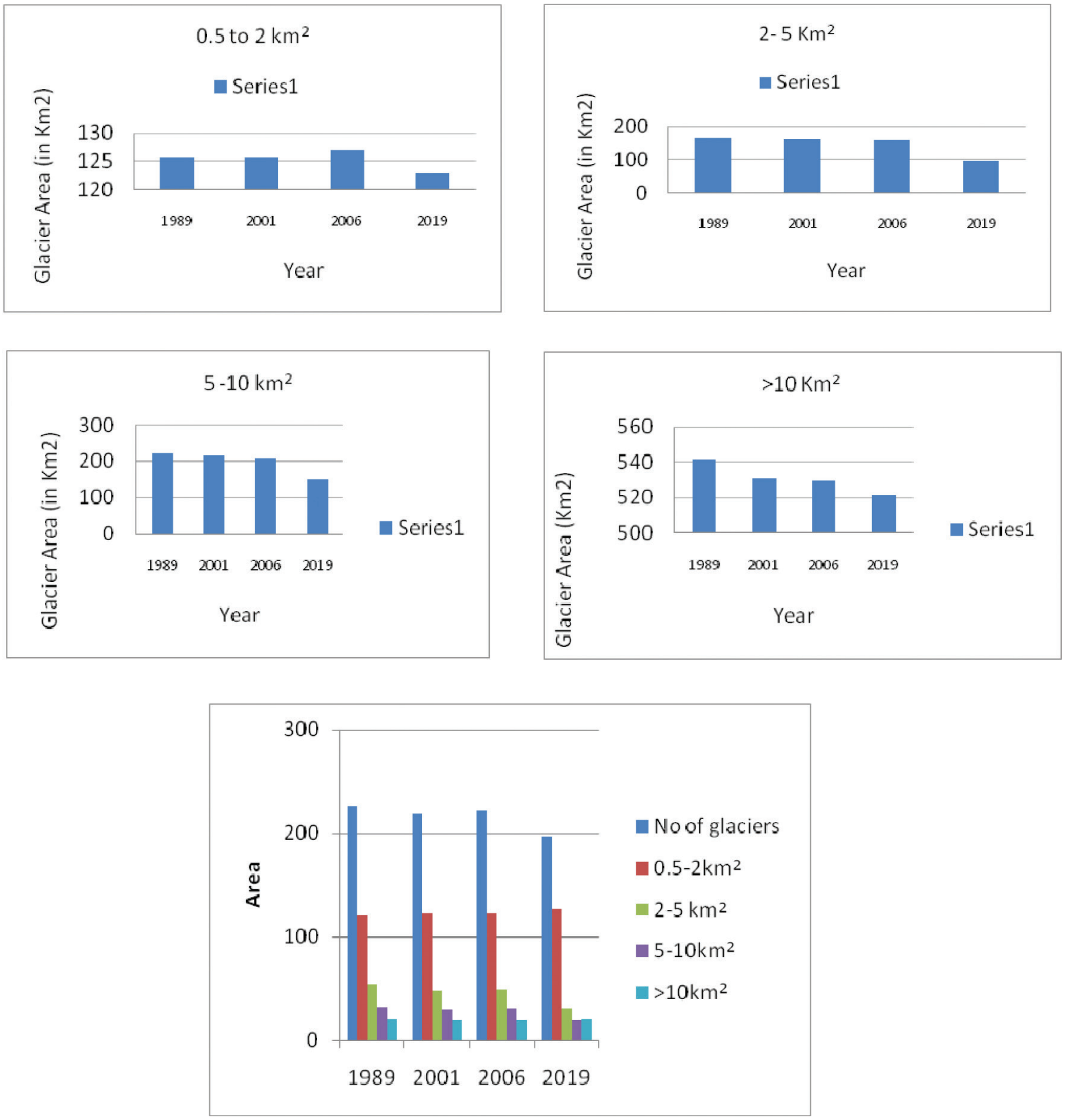


Figure 4: A graphical representation of the deglaciation pattern in Chandra-Bhaga basin.

Table 4: A change in the minimum, maximum and mean elevation in the period 1989-2019

Year	*Minimum elevation (m)*	*Maximum elevation (m)*	*Mean average (m)*
1989	4830	5505	5189
2001	4936	5553	5266
2006	4944	5580	5262
2019	5021	5727	5374

that the majority of glaciers in the Chandra basin are North facing while the Bhaga basin shows South facing glaciers (Figure 5). The orientation of the glaciers is relevant when monitoring the glacier area. It has been established that the south-facing glaciers experience longer hours of insolation, thus, enhancing the rate of retreat comparative to north-facing glaciers which are exposed to a shorter duration of sun radiation. Therefore, the glaciers of the Bhaga region experience a higher rate of deglaciation since they are debris-free and south facing orientation as compared to higher debris covered north facing glaciers.

In context with the current environmental scenario, the above-mentioned results are significant for the examination of glacier behaviour and health. Various studies have reported an increase in the air temperature

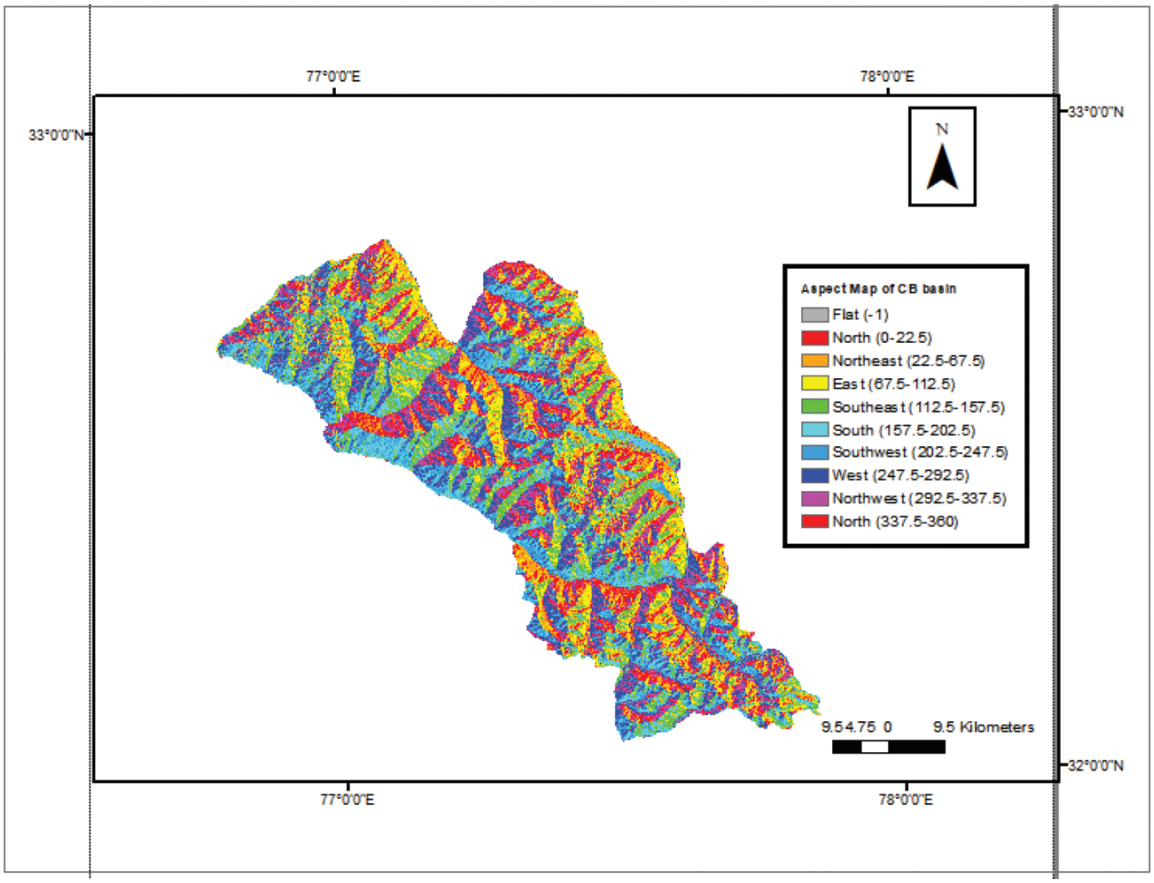


Figure 5: Aspect Map of Chandra-Bhaga basin showing glacier orientation.

in the western Himalayan region during the last decade (Kang et al., 2010; You et al., 2013, 2016). An enhancement of about 0.16°C of mean temperature per decade in the temperature was recorded for the period 1955-1996 (Liu and Chen, 2000), whereas a remarkable contrasting assessment of 0.32°C per decade (1961–2012), almost twice was reported by Yan and Liu (2014). An increase of about 2°C has been reported in the western Himalayan region for the time period 1984-85 to 2007-08 (Shekhar et al., 2010). An analysis of climatic indices based on wintertime data (1975-2006) suggests an increase in the surface air temperature and a subsequent high percentage of warm days across the western Himalayan region (Dimri and Dash, 2012). A long term (1991– 2015) and short-term (1991–2000 and 2001–2015) observation over the north-western Himalayan region gives a rising trend of temperature manifested by an increase of 0.9°C, 0.19°C and 0.65°C for the maximum, minimum and mean temperatures, respectively (Negi et al., 2018). This climatic variation over the NWH region is crucial in the interpretation of the deglaciation pattern in the Himalayan region. A recent study indicates a remarkable pattern of temperature fluctuation in the Hindu kush Himalayan region over more than a century. With a mean temperature increase of about 0.10°C, the study reveals a drastic warming trend after the 1970s (Ren et al., 2017). The consistent increase in the air temperature has a remarkable influence on the microclimate of the glaciated terrains of Western Himalayan, thus witnessing a loss of glacier cover in the last three decades.

The maximum deglaciation has been found in the small and medium-sized glaciers, thus the response time of glaciers to climate change (Kulkarni et al., 2007) is variable for different areal extent. A significant study suggests that thicker glaciers have higher response times (Johannesson et al., 1989; Chaohai and Sharma, 1988) making the smaller glaciers more vulnerable to climatic warming. Therefore, the smaller and medium-sized glaciers, i.e. 2-5 km^2 and 5-10 km^2, respectively, have witnessed more deglaciation in the Chandra-Bhaga sub-basin. The areal loss has its implications on the upward shift of the mean elevation which can be a consequence of the continuous movement of the snow line, reflecting thinning and retreat of glaciers and hence negative mass balance.

The results have been compared with the database of GSI (Sangewar and Shukla, 2009) and SAC (2011, 2016). The glacier monitoring by SAC (2016) reveals that the Chandra and Bhaga basin have vacated 17.93 percent of glacierised area in the Chandra basin (1980-2001) and the Bhaga basin has shown deglaciation of 30 percent (SAC, 2011) during 1961-2001. These reports are comparable and bear resemblances with the current findings of 16.69 percent deglaciation for the period 1989-2019.

Conclusion

Climate change is a global concern, which is being well-established by the increasing trend in air temperature and also manifested in the microclimate of the region. The Chandra-Bhaga sub-basin has witnessed deglaciation of 16.7 percent of the total glacier area during the period 1989-2019. Glaciers are showing a higher rate of area loss comprising of an areal extent between 2-5 km^2 and 5-10 km^2, which may cause higher threats to small and medium glaciers. The mean elevation has also witnessed an upward shift which can be a reflection of the shift in ELA and negative mass balance medium. Therefore, the role of climatic factors like temperature and precipitation along with topographical influences is significant and critical in the advance or retreat of glaciers. Seventeen percent deglaciation was observed during 1989-2019. Regular monitoring using the geospatial techniques and subsequent validation through field methods is suggested to develop an integrated approach that may have long term advantages in deciphering the intricate of glacier dynamics with water resource management.

Acknowledgements

The authors are thankful to Space Application Centre, ISRO, Ahmedabad for providing the satellite imageries of 2001 and 2006.

References

Andreassen, L.M., Paul, F., Kaab A. and Hausberg J.E., 2008. The new Landsat-derived glacier inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s. *The Cryosphere*, **2(2):** 131–145.

Bajracharya, S.R. and Mool, P., 2009. Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal. *Annals of Glaciology*, **50(53):** 81 86. doi:10.3189/172756410790595895

Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P. and Chevallier, P., 2007. Remote sensing estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India). *Remote Sensing and Environment*, **108:** 327–338.

Bhambri, R., Bolch, T., Chaujar, R.K. and Kulshreshtha, S.C., 2011. Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing. *Journal of Glaciology*, **57(203):** 543–556. doi:10.3189/002214311796905604

Birajdara, F.S., Venkataramana, G., Bahuguna, I.M. and Samant, H.P., 2014. A Revised Glacier Inventory of Bhaga Basin Himachal Pradesh, India, Current Status and Recent Glacier Variations, ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume II-8, 2014 ISPRS Technical Commission VIII Symposium, 09 – 12 December 2014, Hyderabad, India.

Bolch, T., Menounos, B. and Wheate, R., 2010. Landsat-based inventory of glaciers in western Canada, 1985–2005. *Remote Sensing and Environment*, **114:** 127–137.

Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J.G. and Stoffel, M., 2012. The state and fate of Himalayan glaciers. *Science*, **336(6079):** 310–314. doi:10.1126/science.1215828

Chaohai, L. and Sharma, C.K., 1988. Report on first expedition to glaciers in the Pumqu (Arun) and Poiqu (Bhote-Sun Kosi) river basins, Xizang (Tibet), China, Science Press, Beijing, p. 192.

Dimri, A.P. and Dash, S.K., 2011. Wintertime climatic trends in the western Himalayas. *Climatic Change*, **111(3-4):** 775–800. doi:10.1007/s10584-011-0201-y

Dutta, S., Ramanathan, AL. and Linda, A., 2012: Shrinking Glaciers in the Beas Basin observed through Remote Sensing techniques, 1972 – 2006, Himachal Pradesh, India. *Journal of Earth System Sciences,* **121(5):** 1105–1112. 0253-4126

Granshaw, F.D., 2001. Glacier change in the North Cascades National Park Complex, Washington State, USA, 1958 to 1998; Thesis submitted for the Master of Science in Geology, Portland State University, 2002.

IPCC, 2013a. Climate Change 2013: The physical science basic. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.

Johannesson, T., Raymond, C.F. and Waddington, E.D., 1989. Timescale for adjustment of glaciers to changes in mass balance. *Journal of Glaciology*, **35:** 355–369.

Kang, S.C., Xu, Y.W., You, Q.L., Flugel, W.A., Pepin, N. and Yao, T.D., 2010. Review of climate and cryospheric change in the Tibetan Plateau. *Environmental Research Letters*, **5(1):** 015101.

Kaser, G., Georges, C., Juen, I. and Mölg, T., 2005. Low latitude glaciers: Unique global climate indicators and essential contributors to regional fresh water supply. A conceptual approach. *In:* Huber U.M., Bugmann H.K.M., Reasoner M.A. (eds) Global Change and Mountain Regions. Advances in Global Change Research, vol 23. Springer, Dordrecht. https://doi.org/10.1007/1-4020-3508-X_19

Kaushik, S., Dharpure, J.K., Joshi, P.K., Ramanathan, AL. and Singh, T., 2018. Climate change drives glacier retreat in Bhaga basin located in Himachal Pradesh, India, Geocarto International, DOI: 10.1080/10106049.2018.1557260

Kulkarni, A.V., Bahuguna, I.M., Rathore, B.P., Singh, S.K., Randhawa, S.S., Sood, R.K. and Dhar, S., 2007. Glacial retreat in Himalaya using Indian remote sensing satellite data. *Current Sciences,* **92(1):** 69–74.

Kulkarni, A.A.V., Rathore, B.P., Singh, S.K. and Bahuguna, I.M., 2011. Understanding changes in the Himalayan cryosphere using remote sensing techniques. *International Journal of Remote Sensing*. **32(3):** 601-615. DOI: 10.1080/01431161.2010.517802

Kumar, R., Bahuguna, I.M., Ali, S.N. and Singh, R., 2019. Lake Inventory and Evolution of Glacial Lakes in the Nubra-Shyok Basin of Karakoram Range. *Earth System Environment*, **4:** 57–70 (2020). https://doi.org/10.1007/s41748-019-00129-6

Liu, X. and Chen, B., 2000. Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology*, **413(20):** 1729-1742.

Negi, H.S., Kanda, N., Shekhar, M.S. and Ganju, A., 2018. Recent wintertime climatic variability over the North West Himalayan cryosphere. Special Section: Himalayan Cryology. *Current Science*, **114(4):** 760-770.

Nicholson, L., McCarthy, M., Pritchard, H. and Willis, I., 2018. Supraglacial debris thickness variability: Impact on ablation and relation to terrain properties. *The Cryosphere*, **12:** 3719–3734.

Pandey, P., Kulkarni, A.V. and Venkataraman, G., 2013. Remote sensing study of snowline altitude at the end of melting season, Chandra-Bhaga basin, Himachal Pradesh, 1980–2007. *Geocarto International*, **28(4):** 311-322, DOI: 10.1080/10106049.2012.705336

Pandey, P., Ali, S.N., Ramanathan, AL., Champati Ray, P.K. and Venkataraman, G., 2016. Regional representation of glaciers in Chandra Basin region, western Himalaya, India, Geoscience Frontiers, Geoscience Frontiers xxx (2016) 1-10, http://dx.doi.org/10.1016/j.gsf.2016.06.006

Paul, F., Bolch, T., Briggs, K., Kääb, A., McMillan, M., McNabb, R. and Wuite, J., 2017. Error sources and guidelines for quality assessment of glacier area, elevation change, and velocity products derived from satellite data in the Glaciers_cci project. *Remote Sensing of Environment*, **203:** 256–275. doi:10.1016/j.rse.2017.08.038

Rai, P.K., Mishra, V.N., Singh, S., Prasad, R. and Nathawat, M.S., 2017. Remote sensing-based study for evaluating the changes in glacial area: A case study from Himachal Pradesh, India. *Earth Systems and Environments*, 1, 1. https://doi.org/10.1007/s41748-017-0001-2

Raina, V.K. and Srivastava, D. 2008. Glacier Atlas of India; Bangalore Geological Society of India, 316p.

Ren, Y.Y., Ren, G.Y., Sun, X.B., Shrestha, A.B., You, Q.L., Zhan, Y.J. and Wen, K.M., 2017. Observed changes in surface air temperature and precipitation in the Hindu Kush Himalayan region over the last 100-plus years. *Advances in Climate Change Research*, **8(3):** 148–156. doi:10.1016/j.accre.2017.08.001

SAC, 2016. Monitoring Snow and Glaciers of Himalayan Region, Space Applications Centre, ISRO, Ahmedabad, India, 413 pages, ISBN: 978–93–82760–24–5

Sahu, R. and Gupta, R.D., 2020. Glacier mapping and change analysis in Chandra basin, Western Himalaya, India during 1971–2016. *International Journal of Remote Sensing*, **41 (18):** 6914-6945, DOI: 10.1080/01431161.2020.1752412

Sangewar, C.V. and Shukla, S.P., 2009. Inventory of the Himalayan Glaciers; Spec. Publ. No. 34, Geological Survey of India.

Sharma, P., Patel, L.K., Ravindra, R., Singh, A., Mahalinganathan, K. and Thamban, M., 2016. Role of debris cover to control specific ablation of adjoining Batal and Sutri Dhaka glaciers in Chandra Basin (Himachal Pradesh) during peak ablation season. *Journal Earth System Sciences,* **125:** 459–473.

Shekhar, M.S., Chand, H., Kumar, S., Srinivasan, K. and Ganju, A., 2010. Climate-change studies in the western Himalaya. *Annals of Glaciology,* **51(54):** 105–112.

Singh, G., Nela, B.R., Bandyopadhyay, D., Mohanty, S. and Kulkarni, A.V., 2020. Discovering anomalous dynamics and disintegrating behaviour in glaciers of Chandra-Bhaga sub-basins, part of Western Himalaya using DInSAR. *Remote Sensing of Environment*, **246:** 111685. https://doi.org/10.1016/j.rse.2020.111885.

Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). IPCC (Report). September 25, 2019.

Technical Report on Snow and Glaciers of Himalaya, 2011. SAC, ISRO, Ahmedabad, India, Report No. SAC/RESA/MESA/SGP/TR/59/2011.

Wagnon, P., Linda, A., Arnaud, Y., Kumar, R., Sharma, P., Vincent, C., Pottakkal, J.G., Berthier, E., Ramanathan, AL., Hasnain, S.I. and Chevallier, P., 2007. Four years of mass balance on Chhota Shigri Glacier, Himachal Pradesh, India, A New Benchmark Glacier in the Western Himalaya. *Journal of Glaciology*, **53(183):** 603–611.

Yan, L.B. and Liu, X.D., 2014. Has climatic warming over the Tibetan Plateau paused or continued in recent 455 years? *Journal of Earth, Ocean and Atmospheric Sciences*, **1:** 13-28.

You, Q.L., Fraedrich, K., Ren, G., Pepin, N. and Kang, S., 2013. Variability of temperature in the Tibetan Plateau based on 473 homogenized surface stations and reanalysis data. *International Journal of Climatology*, **33:** 1337-1347.

You, Q.L., Min, J. and Kang, S., 2016. Rapid warming in the Tibetan Plateau from observations and CMIP5 469 models in recent decades. *International Journal of Climatology*, **36:** 2660-2670.