Variable Response of Glaciers to Climate Change in Uttarakhand Himalaya, India

Dwarika P. Dobhal and Bhanu Pratap

Abstract The glaciers are fragile and dynamic in nature and influence the climate system (e.g. albedo feedback) and as well as key indicator of climate change. The reduction in mass, volume, area and length of glaciers are considered as clear signals of a warmer climate. Uttarakhand Himalaya contains 968 glaciers out of the total 9,575 glaciers in Indian part of the Himalaya, covering an area of 2,888.37 km^2 with 213.74 km^3 of ice volume lies between the altitudes 6,600 and 3,860 m with different dimensions. The observations made during the end of nineteenth century over the Uttarakhand Himalayan glaciers indicate that there is continuous retreat of glaciers but rate of retreat are different to different glaciers. In this study, the results of a detailed mapping campaign and ground-based measurements of terminus retreat, area vacated and mass/volume change has been carried out on few glaciers for the period between 1962 and 2010. The study shows continuous negative mass balance on Tipra, Dunagiri, Dokriani and Chorabari glaciers during last three decades. In general, Uttarakhand Himalayan glaciers are under substantial thinning (Mass loss) and reduction of length and area in the present climate conditions.

Keywords Glacier · Retreat · Mass balance · Climate change · Uttarakhand Himalaya

1 Introduction

Several future scenarios have been predicted for the climate change and future of Himalayan glaciers speculating the trends and consequences (Bajracharya et al. 2008). Change in temperature and snowfall pattern have been observed in the

D.P. Dobhal (✉) · B. Pratap
Centre for Glaciology, Wadia Institute of Himalayan Geology,
Dehradun, Uttarakhand, India
e-mail: dpdobhal@wihg.res.in

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Himalaya during last century. For instance, significant rise of 1.6 °C temperature between 1901 and 2002 has been reported in the Northwestern Himalaya (Bhutiyani et al. 2007). The seasonal mean, maximum and minimum temperatures of winter months have also been increased over the western Himalaya from 1985 to 2008 and pattern of snowfall has been decreased in winter during similar period (Shekhar et al. 2010). Variation in climatic parameters (e.g. temperature and precipitation) directly affects the glacier mass balance and its dynamic properties. Therefore, glaciers are considered to be as a sensitive indicator of climate (Dobhal et al. 2004) and good indicator of energy balance (Oerlemans 1989).

A study by Mayewski and Jeschke (1979) indicates that generally Himalayan glaciers have been receding since 1850. Several studies have also reported the increase in glacier recession rate and continuous negative mass balance in the last decades especially in the central Himalaya (Dobhal et al. 2008; Kulkarni et al. 2007; Bolch et al. 2012; Bhambri et al. 2011). Recently, a study has reported significant ice mass loss for smaller glaciers concurrently increased number of glaciers due to fragmentation of the tributary glaciers in the Bhagirathi and Alaknanda basins (Bhambri et al. 2011). In addition, Kulkarni et al. (2007) and Dobhal et al. (2013b) have described the role of debris thickness in the lower region of the glaciers that can reduce the retreat of glacier but can leads to fragmentation of the snout. Due to glaciers retreat, favorable conditions for formation of lakes have increased and generally form behind the newly exposed terminal moraine.

The rapid accumulation of water in these lakes can lead to a sudden breach of the moraine dam. The resultant rapid discharge of huge amounts of water and debris is known as a glacial lake outburst flood (GLOF) and the results can be catastrophic to the downstream (Richardson and Reynolds 2000; Dobhal et al. 2013a). One recent glacier inventory in Alaknanda and Bhagirathi suggest that ~25 % of total glacial area is covered by debris in their ablation zones (Bhambri et al. 2011). Thus, the regular monitoring of these glaciers of this region is important as water discharge from these glaciers and snow melt contributes to a significant amount to the overall river runoff of Ganga (Immerzeel et al. 2010) and provide noteworthy contribution in hydropower development in Uttarakhand state.

2 Study Area

The Indian Himalaya with various climatic zone consist 9,575 glaciers covering an area of ~40,000 km^2 with an ice volume of ~2,000 km^3 (Raina and Srivastava 2008). Himalayan glaciers in the Indian subcontinent are broadly divided into the three river basins namely the Indus, Ganga and Brahmaputra. The Indus basin has the largest number of glaciers (~7,997), whereas the Ganga basin including Brahmaputra contain about 1,578 glaciers (Raina and Srivastava 2008). Out of these, Uttarakhand Himalaya covers 968 glaciers covering 2,888 km^2 (Raina and Srivastava 2008). This show ~13.8 % glacier area of entire Indian Himalaya exists in Uttarakhand.

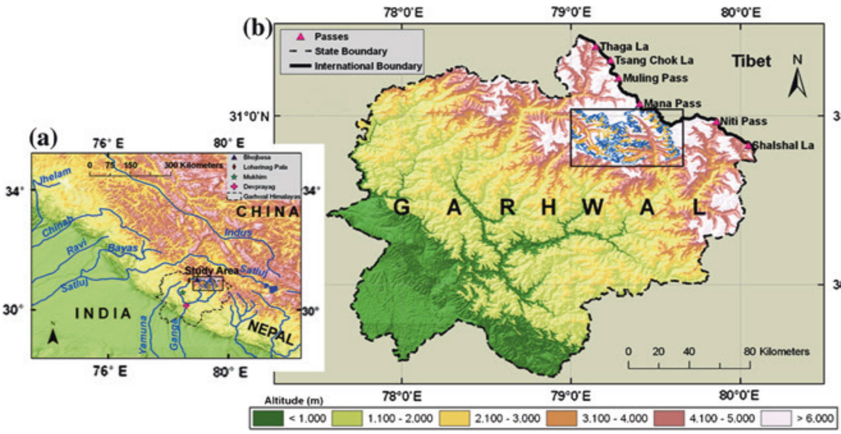

Fig. 1 Location of Uttarakhand Himalaya in India

The Uttarakhand Himalaya covers Yamuna, Bhagirathi, Alaknanda and Kali Ganga (Ghaghra) basins (Fig. 1). The Bhagirathi River is the main source stream of the Ganga River, which originates from the snout (Gaumukh; ~3,950 m a.s.l.) of Gangotri Glacier, the largest valley glacier (~30 km) in the Uttarakhand Himalaya. The headwater of the Alaknanda River originates from the snouts of Bhagirath Kharak and Satopanth glaciers. The Alaknanda basin has ~407 glaciers covering ~1,255 km^2, whereas the Bhagirathi basin contains ~238 glaciers covering ~759 km^2 (Sangewar and Shukla 2009). Uttarakhand Himalayan glaciers are fed by summer monsoon and winter snow regimes (Thayyen and Gergan 2010). However, maximum snowfall occurs from December to March, mostly due to western disturbances (Dobhal et al. 2008).

3 Glacier Variations in the Uttarakhand Himalaya

3.1 Length Changes

The Geological Survey of India (GSI) and other scientific Indian organizations have at their disposal almost 100 years of well-documented recession records of the lengths of selected Uttarakhand Himalayan glaciers, such as Gangotri (1842–2006), Meola (1912–2000) and Milam (1906–1997) glaciers. Gangotri and Dokriani glaciers have been surveyed extensively by several researchers working on mass balance, hydrological, geomorphological, isotopic and frontal recession. The cumulative length recession records of Uttarakhand Himalayan glaciers (Fig. 2) indicate that glacier retreat is irregular in extent and rate. Therefore, these records have to be used with caution owing to the different response time of the glaciers. For instance, in Bhagirathi basin, Dokriani Glacier retreated at the rate of 16.5 a^{-1} during 1962–1991, 17.8 a^{-1} from 1991 to 2000, and 15.75 m a^{-1} for the periods of 2000–2007 (Dobhal and Mehta 2008).

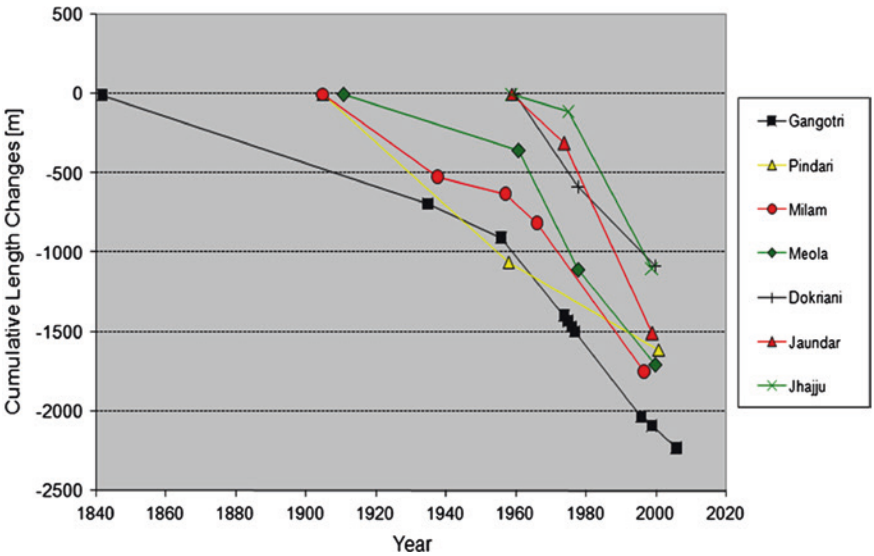

Fig. 2 Length records of selected Uttarakhand Himalayan glaciers (*Source* Bhambri and Bolch 2009 modified)

During the study period of 1996–2007 no advancement was found indicating that the glacier is receding continuously. Available fluctuation records of Indian glaciers suggest that commonly, south, southeast and southwest facing glaciers, such as Jaundhar, Jhajju and Tilku Glaciers in the Tons Valley, have receded rapidly at a rate of more than 34.18, 15.38 and 13.46 m a^{-1} respectively between 1962 and 2010 (Mehta et al. 2013). Measurement of snout positions of the Tipra and Rataban Glaciers from 2002 to 2008 indicates an enhanced annual retreat of 21.3 and 21.2 m a^{-1}, respectively (Mehta et al. 2011). These valley glaciers accumulate under the influence of the southwestern monsoon. The study suggest that glaciers longer than 15 km retreat at a rate of more than 20 m a^{-1}, except for Millam and Gangotri glaciers and furthermore, the recession of these glaciers has accelerated compared with the previous observation (Fig. 3).

However recession of Gangotri Glacier in last decade shows different behavior as compare to relatively small glaciers in Uttarakhand Himalaya. This glacier retreated 819 ± 14 m from 1965 to 2006 (Bhambri et al. 2012). On an average, Gangotri Glacier retreated at the rate of 5.9 ± 4.2 m/year from 1965 to 1968 and 26.9 ± 1.8 m/year from 1968 to 1980, and it retreated 21.0 ± 1.2 m a^{-1} between 1980 and 2001. The recession rate declined during 2001–2006 and it receded at a rate of 7.0 ± 4.0 m/year. From 2001 to 2006, the recession of Gangotri Glacier has declined compared to the previous observation during the study period. However, it does not imply that Gangotri Glacier recession has ceased as length changes show only the indirect and delayed response of a glacier to climate change, in contrast to glacier mass balance. The response time of the large debris-covered Gangotri Glacier is likely to be much longer than that of smaller

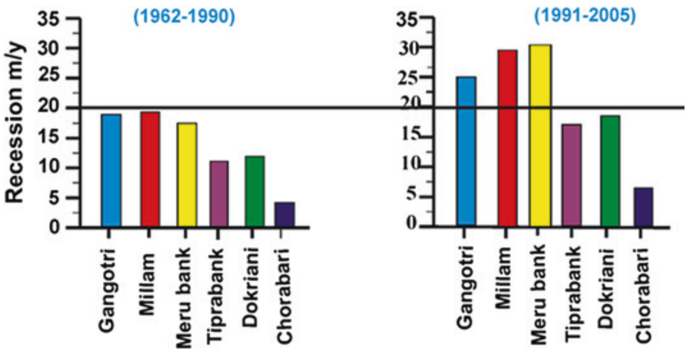

Fig. 3 Changes of Snout retreat rates of glaciers in Uttarakhand Himalaya during the last few decades

glaciers in the Uttarakhand region. Considering rate of recession of these glaciers, it has been observed that they are generally in state of recession, however rate of recession varied from 5 to 20 m/year. A study of long term monitoring glaciers in Uttarakhand Himalaya clearly show that the retreat rate has been enhance during the last few decades but there is no change in their trend (Fig. 3).

3.2 Glacier Area Changes

Glacier area change can be analyzed in terms of frontal area and entire area loss. In the Alaknanda basin, the ice-covered area of Satopanth Glacier diminished by 0.314 m^2 (1.5 %) near the snout from 1962 to 2006, whereas Bhagirathi Kharak Glacier lost an area of 0.129 m^2 (0.4 %) during a similar time period (Nainwal et al. 2008). These two glaciers are situated in the same basin and likely experienced similar climatic conditions. However, both glaciers are reported to be retreating at different recession rates. Bhagirathi Kharak and Satopanth glaciers retreated 7.4 and 22.8 m a^{-1} during 1962–2006, respectively. This might be due to uneven distribution of tributary glaciers, active cirques, drainage density and distributions of supra-glacial debris cover (Nainwal et al. 2008). One recent study reveals that Tipra and Rataban glaciers vacated their frontal area by 0.084 and 0.028 km^2 respectively between 1962 and 2002 (Mehta et al. 2011).

Bhambri et al. (2011) recently reported glacier area decreased from 600 ± 15.6 km^2 (1968) to 572.5 ± 18.0 km^2 (2006), a loss of 4.6 ± 2.8 % in Uttarakhand Himalaya. In this study, glaciers in Saraswati/Alaknanda basin and upper Bhagirathi basin lost 18.4 ± 9.0 km^2 (5.7 ± 2.7 %) and 9.0 ± 7.7 km^2 (3.3 ± 2.8 %) respectively, from 1968 to 2006 (Fig. 4). The number of glaciers in this study increased from 82 in 1968 to 88 in 2006 due to fragmentation of glaciers. In addition, smaller glaciers (<1 km^2) lost 19.4 ± 2.5 % (0.51 ± 0.07 % a^{-1}) of their ice, significantly more than for larger glaciers

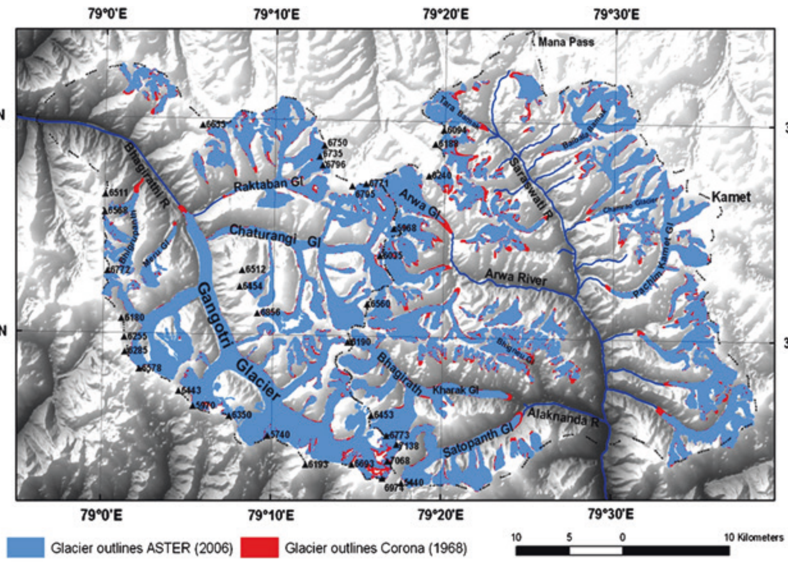

Fig. 4 Glacier change in the Uttarakhand Himalaya from 1968 to 2006 (*red* and *blue* glacier outlines derived from Corona and ASTER images respectively

(>50 km^2) which lost 2.8 ± 2.7 % (0.074 ± 0.071 % a^{-1}). From 1968 to 2006, the debris-covered glacier area increased by 17.8 ± 3.1 % (0.46 ± 0.08 % a^{-1}) in Saraswati/Alaknanda basin and 11.8 ± 3.0 % (0.31 ± 0.08 % a^{-1}) in the upper Bhagirathi basin. Individual study on Dokriani Glacier shows that this glacier lost about 9.5 % area during 1962–2007 (Dobhal and Mehta 2010).

3.3 Mass Balance Studies

Glacier mass balance is the in situ measurements of accumulation and ablation of entire glacier during a balance year that provide immediate indication of storage system (Paterson 1994). Changes in glacier mass over years reflect the behavior of the glaciers. When a large quantity of snow accumulates in winter survives and exceeds ablation, the glacier shows mass gain. Similarly, if melting is more pronounced than the accumulation, the balance shows negative response and subsequently glacier losses it's mass (Kasser et al. 2003; Dobhal et al. 2008; Cogley et al. 2011). Ideally, glacier mass balance is monitored continuously for many hydrological years to derive volume loss or gain to understand climatic fluctuations. Thus, cumulative mass balance trends of several years indicate regional climatic variability (Hodge et al. 1998; Dyurgerov and Meier 2005). In Uttarakhand Himalaya, so far only four glaciers have been considered for mass balance estimation by field based glaciological methods: Tipra Bank (1982–1989), Dunagiri

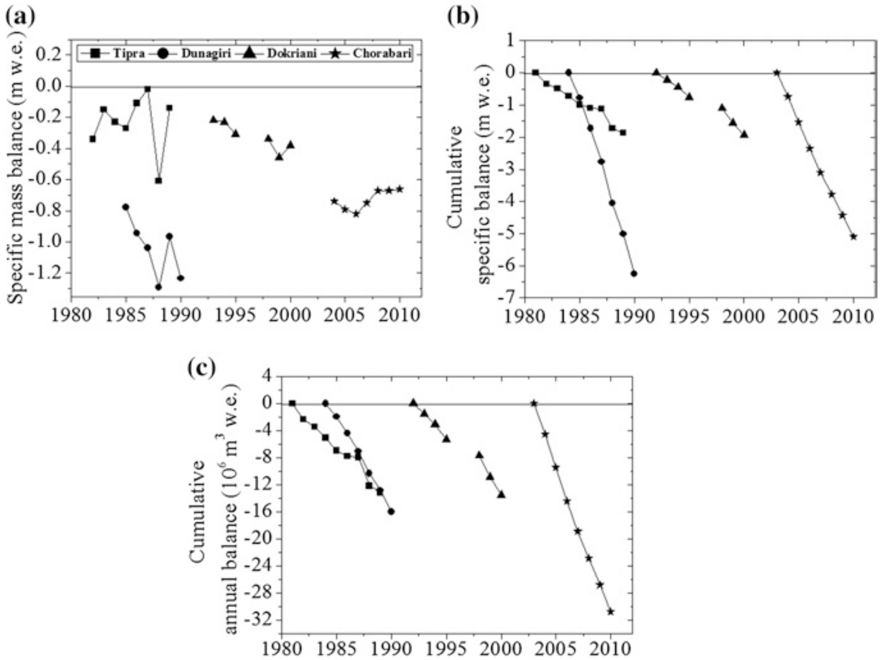

Fig. 5 **a** Annual specific mass balance, **b** cumulative specific mass balance and **c** cumulative net glacier-wide mass balance of 4 Uttarakhand Himalayan glaciers

(1985–1990), Dokriani (1993–2000) and Chorabari (2004–2010). Mass balance measurements of Tipra Bank (7 km^2) and Dunagiri (2.5 km^2) glaciers shows average thinning of −0.23 and −1.04 m a^{-1} w.e. during 1980s (Fig. 5a, b). Mass balance analyses in 1990s on Dokriani Glacier indicate continuous negative annual mass balances. From 1992/1993 to 1998/1999 the trend was increasingly negative; −0.22 to −0.44 m w.e. respectively. The cumulated mass balance reached −1.94 m w.e. from 1993 to 2000 which shows −0.32 m a^{-1} w.e. ice mass loss of the glacier. The calculated ice volume of Dokriani Glacier was 385.11×10^6 m^3 w.e. in 1962 and 315.0×10^6 m^3 w.e. in 1995 suggests a total reduction of -70.11×10^6 m^3 w.e. ice mass in 33 years.

The annual mass balance from 1995 to 2000 shows continuous negative mass balances, which tend to compute total loss of -12.0×10^6 m^3 w.e. in 5 years. Therefore, total volume change is -82.11×10^6 m^3 w.e. for Dokriani Glacier since 1962–2000. In the first decade of 21st century (2000–2010) annual mass balances was measured for Chorabari Glacier during 2004–2010 (Fig. 5a). Over these 7 years glacier showed mean annual balance of −0.73 m w.e. a^{-1}. This leads to total cumulative mass balance of −5.1 m w.e. from 2004 to 2010. The annual specific mass balance investigated during the study period is with the maximum deficit (−0.82 m w.e.) in 2005/2006 and minimum deficit of (−0.65 m w.e.) in 2009/2010. The thinning is the main component of glacier shrinkage. Therefore, during the periods of 7 year the

Chorabari Glacier has reduced its ice thickness by 6 m. Field based studies on the two glaciers (Dokriani and Chorabari) in Bhagirathi and Mandakini basins provide great insight into the heavy rainfall events during monsoon periods of 2011 and 2013 in short time span, which caused large amount of sediment transport as well as catastrophic events of debris flow and moraine dammed Lake Outburst near the glaciers snout.

4 Conclusions

Glacier variability depends on several environmental conditions such as minimum and maximum temperature, solar radiation, amount of solid precipitation and debris cover load, as well as altitude and orientation of the glaciers, which influence the mass balance so as the length change of the glaciers. Out of 968 glaciers in the Uttarakhand Himalaya only few glaciers were monitored for the long term mass balance and snout recession. Overall, studies of glacier length and area change in Uttarakhand Himalaya indicate that larger glacier has less variation rather than small glaciers. Therefore, it can be concluded that glaciers length change is largely dependent on the shape, size and thickness of the glacier. Glacier mass balance study was conducted only for four glaciers in the Uttarakhand Himalaya during 1982–2010. The result shows continuous negative mass balance trend along with variability in net annual mass balance. Maximum cumulative ice mass loss is observed in Chorabari Glacier i.e. -30.77×10^6 m^3 w.e. in 7 years (2004–2010) with -4.4×10^6 m^3 w.e. a^{-1} resulting -0.73 m w.e. y a^{-1} of specific mass balance (Fig. 5a–c). Differences in mass balance observations of individual glacier may be due to variability in the orientation and topographic regime of the region besides the climate.

As a result of negative mass balance and vacating glacierised area, field based studies on the two glaciers (Dokriani and Chorabari) during 2011 and 2013 emphasized catastrophic events of debris flow sediment transport as well as moraine dammed Lake Outburst near the glaciers snout. In general, glaciers in Uttarakhand Himalayan are under substantial ice melting in the present climate conditions. However, existing data exhibit short time series biases to make out a complete scenario of climate change impact on Himalayan glaciers. Thus, there is a need to design for long term glaciers monitoring network to understand the variability of glaciers mass changes over Himalaya.

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References

Bajracharya SR, Mool PK, Shrestha BR (2008) Global climate change and melting of Himalayan glaciers. In: Ranade PS (ed) Melting glaciers and rising sea levels: impacts and implications. ICFAI University Press, Hyderabad, pp 28–46

Bhambri R, Bolch T (2009) Glacier mapping: a review with special reference to the Indian Himalayas. Prog Phys Geogr 33(5):672–704

Bhambri R, Bolch T, Chaujar RK (2012) Frontal recession of Gangotri glacier, Uttarakhand Himalayas, from 1965–2006, measured through high resolution remote sensing data. Curr Sci 102:489–494

Bhambri R, Bolch T, Chaujar RK, Kulshreshta SC (2011) Glacier changes in the Uttarakhand Himalaya, India 1968–2006 based on remote sensing. J Glaciol 57:543–556

Bhutiyani MR, Kale VS, Pawar NJ (2007) Long term trends in maximum, minimum and mean annual temperatures across the northwestern Himalaya during the twentieth century. Clim Change 85:159–177

Bolch T, Kulkarni A, Kaab A, Huggel C, Paul F, Cogley G, Frey H, Kargel JS, Fujita K, Scheel M, Bajracharya S, Stoffel M (2012) The state and fate of Himalayan glaciers. Science 336:310–314

Cogley JG, Hock R, Rasmussen LA, Arendt AA, Bauder A, Braithwaite RJ, Jansson P, Kaser G, Möller M, Nicholson L, Zemp M (2011) Glossary of glacier mass balance and related terms, IHP-VII technical documents in hydrology No. 86, IACS contribution No. 2, UNESCO-IHP, Paris, p 114

Dobhal DP, Mehta M (2008) Snout fluctuation of Dokriani Glacier (1962–2007) vis-à-vis the impact of climate change. Himalayan Geol 29(3):23–25

Dobhal DP, Mehta M (2010) Surface morphology, elevation changes and terminus retreat of Dokriani glacier, Uttarakhand Himalaya: implication for climate change. Himalayan Geol 31(1):71–78

Dobhal DP, Gergan JT, Thayyen RJ (2008) Mass balance studies of the Dokriani glacier from 1992 to 2000, Uttarakhand Himalaya, India. Bull Glaciol Res 25:9–17

Dobhal DP, Gupta AK, Mehta M, Khandelwal DD (2013a) Kedarnath disaster: facts and plausible causes. Curr Sci 105:171–174

Dobhal DP, Mehta M, Srivastava D (2013b) Influence of debris cover on terminus retreat and volume change of Chorabari glacier, Garhwal region, central Himalaya, India. J Glaciol 59(217):961–971

Dobhal DP, Gergan JT, Thayyen RJ (2004) Recession and morphometrical change of Dokriani Glacier (1962–1995), Uttarakhand Himalaya, India. Curr Sci 86(5):692–696

Dyurgerov MD, Meier MF (2005) Glaciers and changing earth system: a 2004 snapshot. Institute of Arctic and Alpine Research, University of Colorado, Boulder, occasional paper No. 58, p 117

Hodge SM, Trabant DC, Krimmel RM, Heinrichs TA, March RS, Josberger EG (1998) Climate variations and changes in mass of three glaciers in western North America. J Clim 11(9):2161–2179

Immerzeel WW, Van Beek LPH, Bierkens MFP (2010) Climate change will affect the Asian water towers. Science 328:1382–1385

Kaser G, Fountain A, Jansson P (2003) A manual for monitoring the mass balance of mountain glaciers. IHP-VI technical documents in hydrology No. 59, UNESCO-IHP, Paris, p 106

Kulkarni AV, Bahuguna IM, Rathore BP, Singh SK, Randhawa SS, Sood RK, Dhar S (2007) Glacial retreat in Himalaya using Indian remote sensing satellite data. Curr Sci 92:69–74

Mayewski PA, Jeschke PA (1979) Himalayan and Trans Himalayan glacier fluctuations since AD 1812. Arct Antarct Alp Res 11(3):267–287

Mehta M, Dobhal DP, Bisht MPS (2011) Change of Tipra glacier in the Uttarakhand Himalaya, India, between 1962 and 2008. Prog Phys Geogr 30:1–18

Mehta M, Dobhal DP, Pratap B, Verma A, Kumar A, Srivastava D (2013) Glacier changes in upper tons river basin, Uttarakhand Himalaya, Uttarakhand, India. J Geomorphol 57(2):225–244

Nainwal HC, Negi BDS, Chaudhary M, Sajwan KS, Gaurav A (2008) Temporal changes in rate of recession: evidences from Satopanth and Bhagirath Kharak glaciers, Uttarakhand, using total station survey. Curr Sci 94:653–660

Oerlemans J (1989) A projection of future sea level. Clim Change 15:151–174

Paterson WSB (1994) The physics of glaciers, 3rd edn. Pergamon Press, Oxford

Raina VK, Srivastava D (2008) Glacier atlas of India. Geological Society of India, Bangalore 316

Richardson SD, Reynolds JM (2000) An overview of glacial hazards in the Himalayas. Quatern Int 65(66):31–47

Sangewar CV, Shukla SP (2009) Inventory of the Himalayan glaciers. Geological survey of India. Special publication No. 34

Shekhar MS, Chand H, Kumar S, Srinivasan K, Ganju A (2010) Climate change studies in the western Himalayas. Ann Glaciol 51:105–112

Thayyen RJ, Gergan JT (2010) Role of glaciers in watershed hydrology: a preliminary study of a Himalayan catchment. Cryosphere 4:115–128