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Climate Change from Himalayan Glaciers' Perspective—Case Studies from India

Mohd Soheb, AL. Ramanathan*, Pratima Pandey and Arindan Mandal
School of Environmental Sciences, Jawaharlal Nehru University, New Delhi
✉ alrjnu@gmail.com

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Abstract: Glaciers are the most visible indicator of climatic change and are the store houses of fresh water as well as hydropower energy. The study of glaciers is important to understand climate change and the societal impacts of glacier response to climate change in terms of water resource management. Mass balance, length, area, equilibrium line altitude (ELA) and accumulation area ratio (AAR) are some of the parameters, which are directly or indirectly related to climatic conditions. This study attempts to infer the climatic conditions of Indian Himalaya (west to east) by analysing the glacier responses. Available mass balance, snout positions and ELA/AAR of three glaciers viz. Chhota Shigri, Dokriani and Changme Khangpu glaciers have been considered as representatives of the three parts of Himalaya i.e. Western, Central and Eastern Himalaya respectively.

Keywords: Climate change; Himalayan glaciers; Glacier mass balance; ELA; AAR.

Introduction

The fundamental goal of glaciology is to infer climatic signals and understanding fluctuations in water regimes due to climatic variability. Glacier mass balance, snout movement and equilibrium line altitudes (ELA) are the most visible glacier parameters, which are directly or indirectly related to prevailing and/or past climate. Himalaya is the youngest and highest mountain chain of the world and is abode to many large and small glaciers, and so is known as the Water Tower of Asia (Immerzeel et al., 2010). It is important to study the status of Himalayan glaciers to understand the trend of prevailing climate and to predict future scenarios. The Himalayan region is fed by two major weather systems viz. the Indian Summer Monsoon (ISM) and the mid-latitude westerlies (Benn and Owen, 1998). The eastern part of Himalaya experiences substantial amount of summer precipitation from ISM which declines northwestward. The mid-latitude westerlies brings winter precipitation maximum at the extreme west of the Himalaya, Trans-Himalaya and Tibet, as a consequence of moisture being advected from the Mediterranean, Black and Caspian Seas (Benn and Owen, 1998). Hence the southern and eastern glaciers are summer accumulation type and the glaciers present in the extreme west of the Himalaya, Trans-Himalaya and Tibet are winter accumulation type whereas glaciers in central Himalayas are both summer as well as winter accumulation type. In this paper, we attempt to review the impact of climate change on the three different climatic regimes of Himalaya by studying glacier behaviour and response of glaciers from these regimes.

It is a well known fact that glaciers are one of the primary indicators of change in climate. Therefore to understand climate change in the Himalayan region, literature in public domain has been reviewed and three most studied and representative glaciers from each one of these three different regimes have been selected for review. According to the published observations and

*Corresponding Author

results by different researchers, an attempt was made to link up the changes in these glaciers with climate change.

Study Area

To carry out the study, three representative glaciers from the three different precipitation regimes were selected extending from Western to Eastern Indian Himalaya (Figure 1) i.e. Chhota Shigri glacier (Western Himalaya), Dokriani glacier (Central Himalaya) and Changme Khangpu glacier (Eastern Himalaya).

Chhota Shigri glacier (32°11′-32°17′ N and 77°29′-77°33′ E, GSI Inventory 2009: Identification No. IN5Q21212159), a very well-studied glacier of Western Himalayas lies in the Chandra river basin on the northern ridge of Pir Panjal range in the Lahaul-Spiti valley of Himachal Pradesh, India. It seems to be a winter accumulation type glacier, mostly fed during the winter season by mid latitude westerlies (Azam et al., 2014b). Chhota Shigri has a very well defined snout at about 4050 m amsl and maximum elevation reaches up to 6263 m amsl. The mean orientation of the glacier is north with 9 km and 15.7 km^2 glacier length and area respectively. Around 3.4% of its area falling in the lower most ablation zone is covered by highly heterogeneous debris layer ranging from millimetres to several metres (Vincent et al., 2013) and ELA lies close to around 4900 m amsl (Azam et al., 2014).

Dokriani glacier (30°50′ N and 78°47′ E) is a valley type glacier which lies in Garhwal region and one of the well-studied glaciers of Central Himalayas. The snout of the glacier lies at an elevation of 3890 m amsl and the maximum elevation of the glacier is about 5990 m amsl (Dobhal et al., 2008). One third of the glacier area is covered with thick layer of supra glacial debris (Pratap et al., 2015). The glacier is fed mainly from the ISM in summer (June to September) and also affected significantly from mid latitude westerlies during winter. Thus the glacier is influenced by both the circulations.

The Changme Khangpu glacier (27°58′ N and 88°41′ E) is located in Tista river basin, in Sebu valley of north-east Sikkim of Eastern Himalayas. It is a transverse valley glacier with a glacier orientation of south and has an area of 5.60 km^2. It is also one of the well-studied glaciers of Eastern Himalayas and has an altitude range

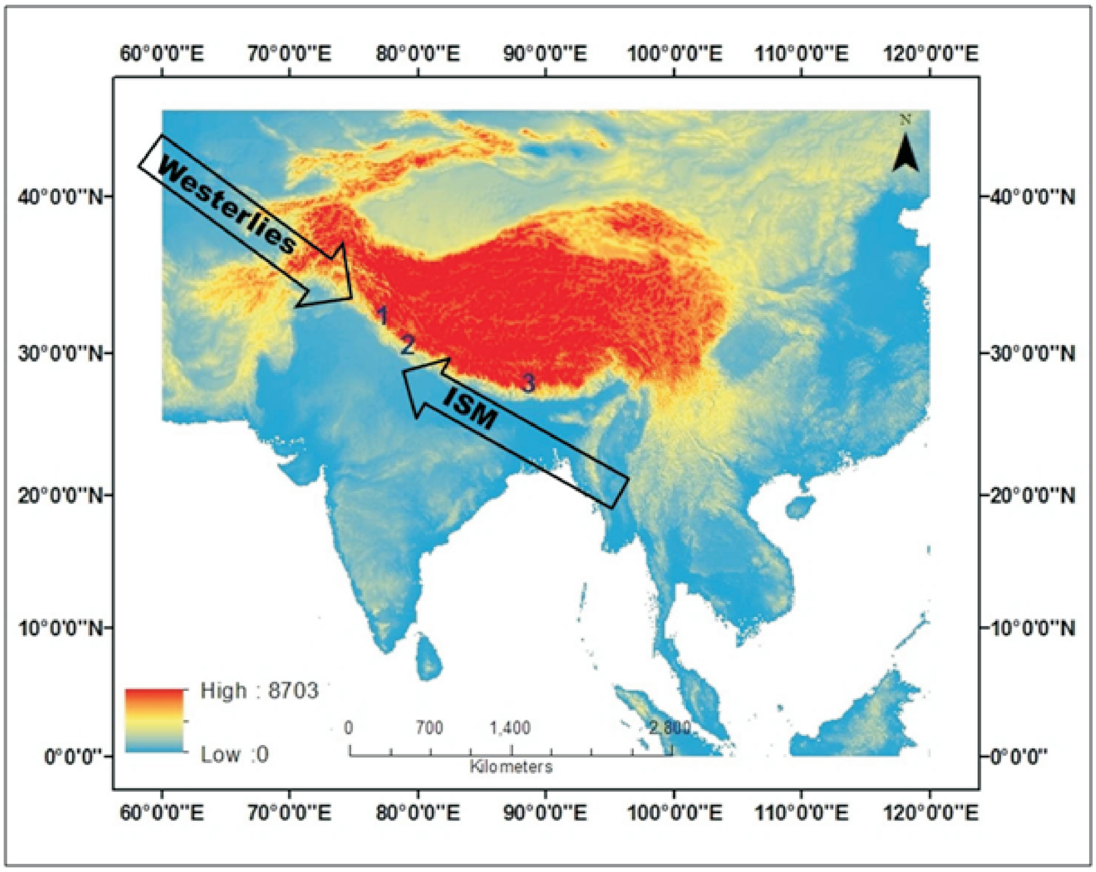

Figure 1: Schematic of influence of Indian summer monsoon (ISM) during summer and westerlies during winter on the study area. In the picture, 1, 2 and 3 represent Chhota Shigri, Dokriani and Changme Khangpu glaciers respectively.

of 800 metres, the snout lies at 4850 m amsl and has a maximum elevation of 5650 m amsl. Almost entire ablation zone of the glacier is under supra-glacial debris. The terminal part of the glacier is completely buried under moraine. The lowest part of the snout is exposed at an elevation of 4850 m amsl. It receives majority of the precipitation from Indian summer monsoon which makes it a summer accumulation type glacier.

Data Used

Due to the difficulties involved with the direct monitoring of glaciers, only a few Himalayan glaciers have been studied in the end of the past century by in-situ method. Since Himalayan glaciological studies were limited, little was known about the glacier response, trends, their importance and contribution towards the local and regional water supply, until the controversial statement by Intergovernmental Panel on Climate Change (IPCC, 2007) fourth assessment report came into limelight, which suggested the possibility of disappearance of Himalayan glaciers by 2035 or perhaps sooner to be very high, if the earth keeps warming at the current rate. Even now, data is very sparse and discontinuous for the region.

As far as Indian Himalayan glaciers are concerned, Chhota Shigri is one of the well-studied glaciers in every aspect and has the longest available mass balance data sets (Wagnon et al., 2007; Vincent et al., 2013; Azam et al., 2012; 2014a). After Chhota Shigri, Dokriani glacier has relatively longer period data but most of the data are either not published or in the form of diagrammatic representations. The Changme Khangpu glacier is not studied well; so data for only a few years were available for this glacier. Although the mass balance data is not very long but it is the only glacier in eastern Himalayas for which the mass balance data is available. Therefore to understand the dynamics of these glaciers with changing climate regime, an attempt has been made with the available limited data sets. Table 1 lists the mass balance values of the Chhota Shigri, Dokriani and Changme Khangpu glaciers.

Discussion

Mass Balance

In-situ long-term mass balance data of Indian Himalayan glaciers are few and sporadic due to the harshness of weather and difficult terrain of the Himalaya. Therefore it is difficult to get a cohesive picture about the state of glaciers in Indian Himalayas. Studies carried out by the Jawaharlal Nehru University in collaboration with Department of Science and Technology on Chhota Shigri glacier carries the longest series of mass balance in Indian Himalayas (Ramanathan, 2011). The study found most of its annual mass balances to be negative. One of the major finding on Chhota Shigri glacier was the observation of a differential mass balance pattern over glacier surface, which shows that melting in the lowest part of the ablation area (<4400 m a.s.l.) is reduced by ~1 m w.e. a^{-1} irrespective of its altitude (Azam et al., 2012). Mass balance is strongly dependent on debris cover as thick debris insulates the solar radiation and protects the glacier. This suggests that solar radiation has an important role to play in glaciers mass balance (Wagnon et al., 2007).

The presence of debris also complicates the climate-mass balance relationship. Average annual mass balance of Chhota Shigri glacier was negative during 2003 to 2013 -0.59 ± 0.40 m w.e. a^{-1} revealing unsteady-state conditions over this period (Vincent et al., 2013; Azam et al., 2014a). Investigations of geodetic mass balance, surface mass balance and volume change of Chhota Shigri glacier have been carried out between 1988 and 2010 using in-situ geodetic, glaciological and remote sensing measurements (Vincent et al., 2013). As the surface mass balance study and compilation indicates over the whole period 1988-2010, the cumulative mass balance of Chhota Shigri Glacier was -3.8 ± 1.8 m w.e., corresponding to a moderate mass loss rate of -0.17 ± 0.08 m w.e. yr^{-1}. In fact, initially the glacier experienced a slightly positive or near-zero cumulative mass balance between 1988 and 1999 followed by a period of ice wastage, confirming the presumption (Azam et al., 2012). Study by Azam et al. (2014b) has suggested that even though Chhota Shigri is a winter accumulation type glacier, the role of snowfall that happened during Indian summer monsoon on albedo and in turn on melting is equally important.

Dokriani glacier is the second most important glacier in the Himalaya in terms of presence of data. The glacier is being monitored by the team from Centre for Glaciology, Wadia Institute of Himalayan Geology (WIHG), Dehradun. Although the glacier is located at the transition of central and western Himalaya, we have considered this glacier as a representative for the central Himalaya as the feeding mechanism of the glacier is similar to those of glaciers in the Central Himalaya, i.e. the glacier is mainly fed from the Indian summer monsoon, but is also greatly affected from the westerlies during the winter. Dobhal et al. (2008) have reported the annual mass balance of the Dokriani glacier in Gangotri area of Garhwal Himalaya from 1992 to 2000 (except two hydrological years i.e. 1995-96 and 1996-97). The study was conducted using glaciological method and results for six years of annual mass balance show negative trend with the maximum deficit of –3.19 × 10^6 m^3 w.e. in 1998-99 with an annual mass balance of –2.25 × 10^6 m^3 w.e. for the period of six years (1992-93 to 1999-00) and average mass balance of –2.25 m w.e. A long-term annual mass balance average, i.e. 0.43 m w.e. y^{-1}, in accumulation area was derived from radio-isotopic (^{137}Cs) concentration variation in shallow ice core from the accumulation area of Dokriani glacier. The study found almost steady mass balance in accumulation area (0.45-0.55 m w.e. y^{-1}) but varied annual mass balances in the ablation area where the mass balance decreases with increase in altitude ranging from –3 to –4 m w.e. y^{-1} and –2 to –3 m w.e. y^{-1} in the lower and higher ablation area respectively. A recent study by Pratap et al. (2014) on the influence of debris cover on Dokriani glacier has reported that the ablation of the glacier was maximum under debris thickness of 1-6 cm and minimum under 40 cm. The findings of the study revealed the importance and control of debris on the glacier mass balance.

Mass balance records in the eastern part of Indian Himalayas are very sparse. Changme Khangpu glacier has one of the old records of mass balance series of six hydrological years from 1980-1981 to 1985-1986 (Dyurgerov and Meier, 2005). Mass balances over these years are all negative ranging from –0.072 to –0.392 m w.e. y^{-1} with an average value of –0.24 m w.e.

Although direct comparisons of mass balance of these three glaciers are not recommended as they lie in different climatic regimes, and have data records available for different periods with no overlapping years (Table 1), but the trend of their mass budget can give an insight to infer the climatic conditions and changes in the respective climate regimes (Figure 2). During the respective studied periods, the mass balance of Changme Khangpu glacier showed a small increasing trend. The Chhota Shigri glacier experienced positive mass balance, 0.1, 0.13 and 0.33 m w.e. in the year 2004-2005, 2008-2009 and 2009-2010 respectively, following a good amount of snowfall reported in those years, with a negative mass balance (–0.15, –1.4, –1.2, –1.4, –1.3 and –0.93 w.e.) in the remaining years (1987-88, 2002-03, 2003-04, 2005-06, 2006-07 and 2007-08) but showing increasing trend (Figure 2). On the other hand, Dokriani glacier has experienced a negative trend in the mass balance from 1992 to 2000 (Table 1 and Figure 2).

Snout Retreat

Snout retreat data in literature are only available for Chhota Shigri (Table 2 (A)) and Dokriani glaciers (Table 2 (B)). Climate drives changes in glaciers and glacier topography controls the impact of climate on a particular glacier. Due to variations in temperature and precipitation, glaciers gain or lose mass, which is transported and distributed through glacier flow. The subsequent gain or loss in glacier mass ultimately reflects in the glacier length, area and snout position. The snout fluctuation is thus the long-term and indirect effect of climate change but the easiest glaciological parameter to study. The most famous method of monitoring snout is from remote sensing through multi temporal data. The snout fluctuations of Chhota Shigri glacier is available from multiple sources (both field and remote sensing based observations) from 1962 to 2013. Kulkarni et al. (2007) and Shruti et al. (2008) have reported a significant rate of retreat of Chhota Shigri glacier (–53.3 m/y and –25m/y respectively) between 1962 and 2006. However, recent studies by remote sensing as well as field monitoring have reported a rate of about 7 m/y between 1962 and 2010 (Ramanathan, 2011; Azam et al., 2012; Pandey and Venkataraman, 2013).

Dobhal et al. (2008) have reported the snout retreat of Dokriani glacier ranging from 15.75 to 17.8 m/y between 1962 and 2007. The average retreat of Dokriani glacier was found to be about 16.68 m/y, which is about twice of the Chhota Shigri glacier. The rate of retreat of Chhota Shigri and Dokriani glaciers are in agreement with their mass balance records. The average mass balance of Chhota Shigri glacier is about –0.64 m w.e. (using available data from 1987-1988 and 2002-2010 (Table 1)); whereas that of Dokriani glacier is –2.25 m w.e. (using data from 1992-2000 excluding 1995-96 and 1996-97 which is not available). The more loss of glacier mass of Dokriani glacier has possibly resulted in higher retreat rate of the glacier. The lesser retreat rate of Chhota Shigri glacier as mentioned in the recent studies (Azam et al., 2012) can be attributed to the lesser loss of glacier mass as compared to Dokriani glacier. If Chhota Shigri and Dokriani glaciers are taken as representative of western and central Himalaya respectively, it may

Table 1: The mass balance values of Chhota Shigri, Dokriani and Changme Khangpu glaciers

	Chhota Shigri glacier (mw.e. a^{-1})	*Dokriani glacier (mw.e. a^{-1})*	*Changme Khangpu glacier (mw.e. a^{-1})*
1980-1981	-	-	-0.39
1981-1982	-	-	-0.29
1982-1983	-	-	-0.29
1983-1984	-	-	-0.15
1984-1985	-	-	-0.24
1985-1986	-	-	-0.07
1986-1987	-	-	-
1987-1988	-0.154	-	-
1992-1993	-	-1.54	-
1993-1994	-	-1.58	-
1994-1995	-	-2.17	-
1995-1996	-	-	-
1996-1997	-	-	-
1997-1998	-	-2.41	-
1998-1999	-	-3.19	-
1999-2000	-	-2.65	-
2000-2001	-	-	-
2001-2002	-	-	-
2002-2003	-1.4	-	-
2003-2004	-1.2	-	-
2004-2005	0.1	-	-
2005-2006	-1.4	-	-
2006-2007	-1.3	-	-
2007-2008	-0.93	-	-
2008-2009	0.13	-	-
2009-2010	0.33	-	-

(Dash (-) represents data not available)

Table 2: Fluctuations of snout of Chhota Shigri (A) and Dokriani (B)

(A) Year	*Chhota Shigri Snout retreat (m/y)*
1988-2003 (Kulkarni et al., 2007)	-53.3
1972-2006 (Shruti et al., 2008)	-25
1962-1984 (Ramanathan, 2011)	-7.6
1988-2010 (Azam et al., 2012)	-7
1980-2010 (Pandey and Venkataraman, 2013)	-7.1
(B) Year	*Dokriani glacier Snout retreat (m/y)*
1962-1991 (Dhobal et al., 2008)	-16.5
1991-2000 (Dhobal et al., 2008)	-17.8
2000-2007 (Dhobal et al., 2008)	-15.75

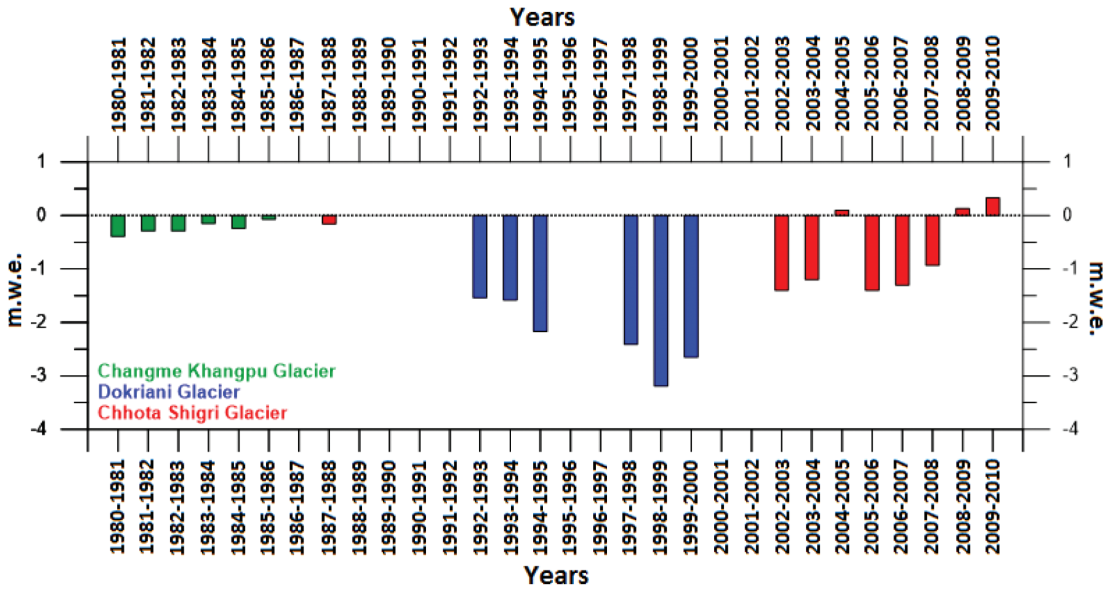

Figure 2: Mass balance record of the three studied glaciers during the available years.

be due to the favourable climatic condition in the western Himalaya for glacier stability than that of Central Himalaya as evident from the results of snout fluctuations and mass balance records of Chhota Shigri and Dokriani glaciers (Table 2 and Figure 3).

Equilibrium Line Altitude and Accumulation Area Ratio (ELA and AAR)

ELA is the boundary between the accumulation and ablation zone of the glacier. It is a theoretical line, which is irregularly distributed on the glacier and the mass balance is zero at the equilibrium line. If the glacier is in equilibrium with climate (net balance equals to zero), the ELA is termed as the steady state equilibrium line (Vorren, 1973). A clear relationship exists between its position and the annual mass balance (Meier and Post, 1962; Ostrem, 1975). In addition to mass balance, the ELA and AAR are the two other glacier parameters which are directly related to climate. The ELA of a glacier respond linearly to the precipitation and temperature and the movement of ELA reflect the variability of climatic parameters (temperature and precipitation). By monitoring the ELA movement, the climatic fluctuations can be monitored.

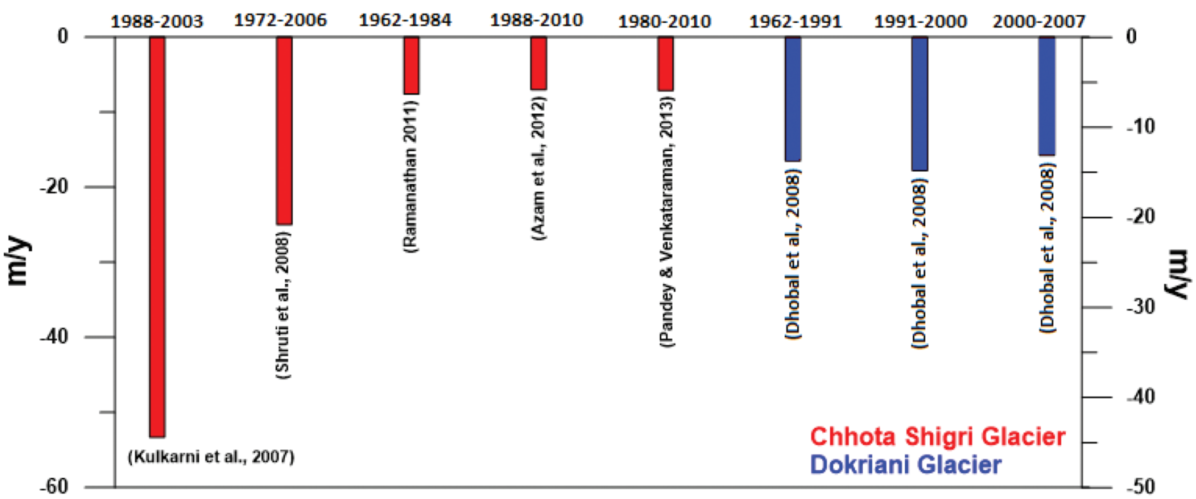

Figure 3: Rate of retreat of Chhota Shigri and Dokriani glaciers between 1962-2010 and 1962-2007 respectively, from various sources.

The accumulation area ratio (AAR) of a glacier is the ratio of accumulation area and the total glacier area. Azam et al. (2014a) have shown that a direct linear relation exists between AAR and the mass balance of a glacier. The AAR can be taken as the proxy of mass balance. Kulkarni (1992) has shown that a relationship between AAR and specific mass balance established from field data can be used to predict the mass balance for further years. The ELA modifies the AAR of a glacier. Any small change in ELA can significantly modify the relative size of ablation and accumulation area and hence the mass balance of the glacier. This will result in the retreat or advance of glaciers (Sudan and John, 1976). It was found that mean ELA of Chhota Shigri glacier is at around 4900 m amsl (Azam et al., 2014a), and mean ELA of Dokriani glacier is about 5065 m amsl (Dobhal et al., 2008) between 1992 and 2002. Table 3 illustrates the values of ELA and AAR of the two glaciers.

It was observed from the trend analysis of Chhota Shigri and Dokriani glaciers (Figure 4) that the ELA of Chhota Shigri has risen up with years during 1986 to 1989 resulting in lower AAR (Table 3 and Figure 4). If AAR is taken as the proxy for mass balance, it can be argued that during these years the mass balance of Chhota Shigri glacier had been considerably negative. This might also be the possible reason for the greater rate of retreat of the glacier as reported by Shruti et al. (2008) and Kulkarni et al. (2007). However, this might only be a possibility as we still have less understanding of the response time of the Chhota Shigri glacier. During the later periods (2002-2010) the ELA of Chhota Shigri glacier had shown a decrease in trend (Table 3 and Figure 4). On the other hand ELA of Dokriani glacier has risen over the studied period reducing AAR of the glacier. In accordance to the rise of ELA, the AAR of both glaciers have decreased in their respective years of study. The ELA of Chhota Shigri have shown variation in movement keeping a rising trend whereas the rise of ELA of Dokriani glacier was more gradual and uniform than that of Chhota Shigri glacier (Table 3 and Figure 4).

Table 3: Records of ELA and AAR of Chhota Shigri and Dokriani glaciers

Year	*Chhota Shigri glacier*		*Dokriani glacier*	
	ELA (m amsl)	**AAR (%)**	**ELA (m amsl)**	**AAR (%)**
1986-87	4650	73	-	-
1987-88	4700	59	-	-
1988-89	4840	65	-	-
1990-91	-	-	-	-
1991-92	-	-	-	-
1992-93	-	-	5030	70
1993-94	-	-	5040	69
1994-95	-	-	5050	68
1995-96	-	-	-	-
1996-97	-	-	-	-
1997-98	-	-	5080	67
1998-99	-	-	5100	66
1999-00	-	-	5095	67
2000-01	-	-	-	-
2001-02	-	-	-	-
2002-03	5170	31	-	-
2003-04	5165	31	-	-
2004-05	4855	74	-	-
2005-06	5185	29	-	-
2006-07	5130	36	-	-
2007-08	5120	37	-	-
2008-09	4890	63	-	-
2009-10	4930	70	-	-

(Dhobal et al., 1992), (Wagnon et al., 2007; JNU-SAC., 2008; JNU-IFCPAR., 2009, 2010; JNU-DST., 2011) (Dhobal et al., 2008). (Dash (-) represents data not available)

Conclusion

Three glaciers from different climatic regimes have been analysed by inferring their mass balance, snout fluctuations and ELA/AAR variations. The investigation of mass balance indicated that Changme Khangpu glacier has shown a relatively lesser mass loss in the past. Still there is debate on the role of ISM and westerlies in influencing the glaciers of Central and Eastern Himalaya. The short-term and relatively older data of Changme Khangpu glacier could not help in drawing any interpretation of climatic status and change in the Eastern Himalaya. However, the mass balance, snout retreat and ELA/AAR variation of Chhota Shigri and Dokriani glaciers have provided us opportunities to analyse the climatic conditions of western and central Himalaya. Considering the Chhota Shigri and Dokriani glaciers as the representatives for western and central Himalaya, it was observed that the climate regime of western Himalaya is favourable for glacier stability than

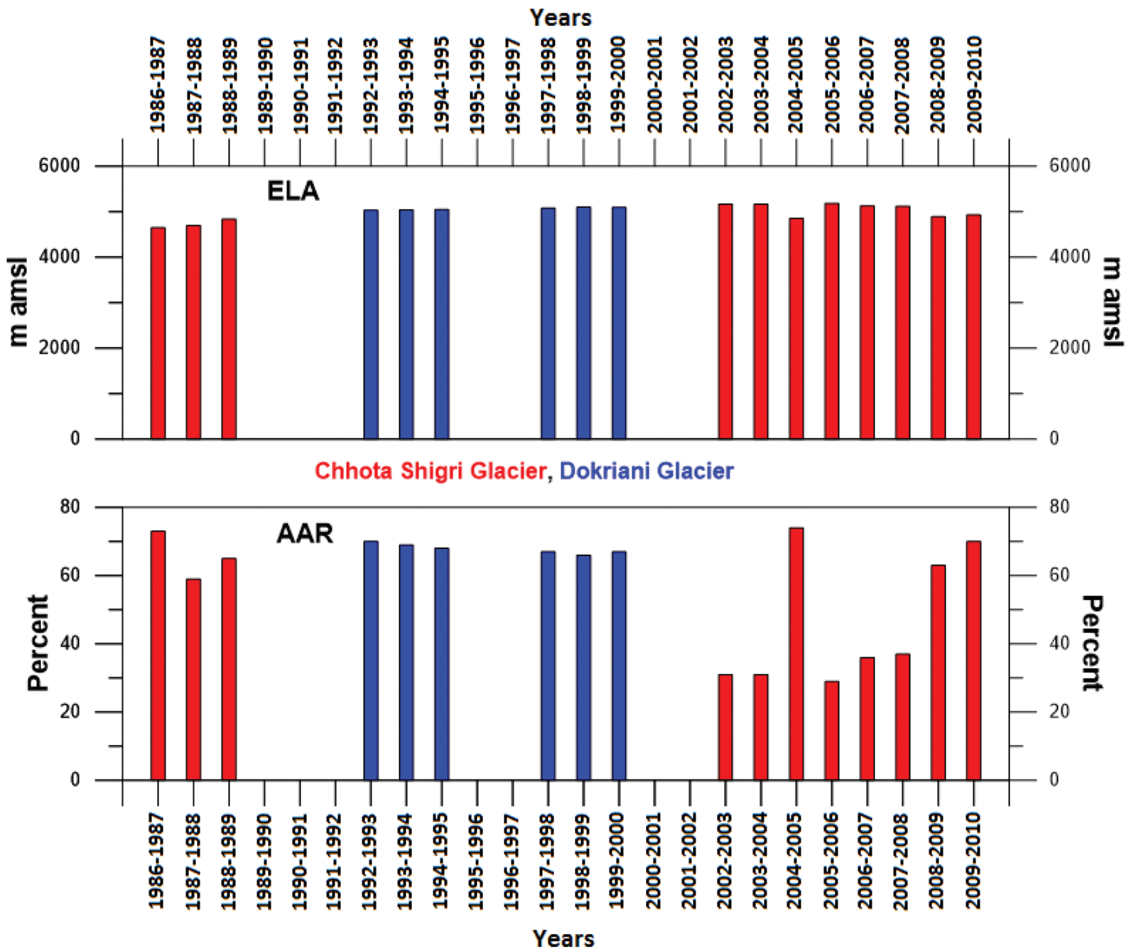

Figure 4: Fluctuations of ELA and AAR of Chhota Shigri and Dokriani glaciers.

the climate of central Himalaya. The analysis of trends in glacier parameters indicated that though the climate change is evident in western and central Himalaya, but the changes have lesser impact in the western Himalayas than the central Himalaya as observed from the available records.

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