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The Current Stable Phase of Ladakh Himalayan Glaciers and the Climate Change Effect: An Overview of Morphology and Dynamics of Drass Glaciers

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It is a great honor and privilege to deliver the Prof. S. R. Basu Memorial lecture at IGI conference in Kolkata. I am extremely grateful to the family members of Prof. S. R. Basu and the IGI for having provided an opportunity to share my experience on Cold Geomorphological sciences with young scientists. My association with Prof. S. R. Basu dates back to 1988, when I had an opportunity of meeting Prof. Basu while I was presenting the research findings on Kashmir Himalaya at IGI Conference held at the Department of Geography, Rajasthan University, Jaipur. Since then I have had the privilege of knowing Prof. Basu intimately as a dynamic researcher and above all as a great human being. Prof. Basu was one of the top ten geomorphologists of the country with one of the sharpest minds and most prodigious output of his generation, a great researcher and above all a renowned scholar of international repute in the field of fluvial geomorphology particularly channel morphology. He envisaged the importance of empiricism and modeling techniques in field of physicalgeography. His research contributions in Physical geography had global acceptance. I have great admiration on his commitment to this society and the discipline of geography more so his humanitarian attitude towardsyoungsters. Therefore, I accepted to deliver and share data on impact of recent climate changes on the stability of Ladakh glaciers, particularly Drass basin glaciers for the benefit of young researchers.

Introduction

Ladakh is the most heavily glaciated region of India as it houses nearly 50% glaciers of India confined to protracted zones of High Himalaya-Karakorum (Zanskar, Ladakh) ranges that contain some of the world's highest peaks and largest glaciers outside the polar region. It contains nearly 5000 glaciers encompassing a glaciated area of 3187 km^2 and total ice volume of 815.62 km^3.The region is mainly influenced by the westerly air mass, particularly during the western disturbances in thewinter season that results in extension of snow cover in higher reaches and glacial melt-water production in lower reaches. This area acts as a watershed of the Indus. The Indus contributes a lot to the agrarian as well in industrial economy of northern India by providing perennial irrigation water as well generating hydroelectric power.

Glaciers are dynamic reservoirs of ice which form a part of the global hydrological system, with which they constantly exchange mass and energy by a process by which glaciers gain or lose snow and ice and establish a link between glacial mass and glacio-fluvial dynamics and climate. The glacial dynamics is related directly to the behaviour of climate. Variability of climate and its impact on glacial mass balance has been reported from the Alps and the Rocky (Fujila, 2008, Bitz and Battisti, 1999, Bowling, 1977). Conflicting signals of climate change, in terms of change in temperature, snowfall and extent snow coverage reported from the Western Himalayas (Yadav et al., 2004; Fowler and Archer, 2006; Bhutiyaniet al., 2007; Koul and Ganjoo, 2010). The studies have investigated the role of meteorological parameters in governing the snow cover extent and it has been found that annual change in glacial mass balance is largely due to winter and spring time anomalies in accumulation which in turn are mainly due to anomalies in precipitation and temperature (Kaul, 1988).

Objectives and methodology

The recent publication of the Fourth and Fifth Assessment reports of the Intergovernmental Panel on Climate Change (IPCC) generated lot of debate about the status of the Himalayan glaciers. The high relative relief causes perturbation in ambient temperature and generates katabatic winds. Thepresent study aims to understand how katabatic winds in glacial valleys affect the extent and terminus of valley glaciers. Further, our objective is also to determine if the glaciers in this valley at present behave in steady state phase and relate the same to present day climatic and other top-climatic factors generated by high relative relief.

The regional differences in extent of glaciers in Drass glacial valley in Higher Himalaya were assessed, from remotely measured changes in glacier snout and glacial area between 1965 and 2013.The detailed field-truth verification during 2011–2014 assessed theoverall behaviour of glaciers in the valley.

Regional Setting

The Kargil region forms a vast mountainous region between the Great Himalaya Range in the south-southwest and Indus valley in the northeast and occupies southern part of Ladakh. It has nearly 1796 glaciers, confined in upper Indus basin, housed in Zanskar, Suru and Drass sub-basins. Drass sub-basin has 150 glaciers encompassing an area of 152.6775 km2 with an ice volume of 62.02 km^3.

Drass sub-basin is the 5th order basin of 4th order Indus and it extends between the Gumri (close to Zoji-La) in the west to Kargil in the east. Zoji-La is the gateway to Drass, situated on National Highway 1A — the road which connects Srinagar with Kargil, and Lehi (Ladakh).The Srinagar-Kargil road remain closed to vehicular traffic during winter season due to closure of Zoj-La pass as result of heavy snowfall (Fig.1).Drass valley is encircled by ridge crests of high peaks (5,200m –6100m) of Himalaya and ridges descend precipitously. The study region is a bi-armed valley system lying between Great Himalaya and Drass mountain. The magnitude of relief and overall steepness of the slopes provide an overwhelming impression that the region has distinct climatic condition between that of Central Asia and monsoon land of South Asia.

Drass sub basin or Drass valley holds special geographical significance for study of snow cover changes in the light of climate change phenomenon, if any. The valleyhas a distinct climatic characteristic due to its location inthe rain shadow zone of the Great Himalaya having an aerodynamic link with

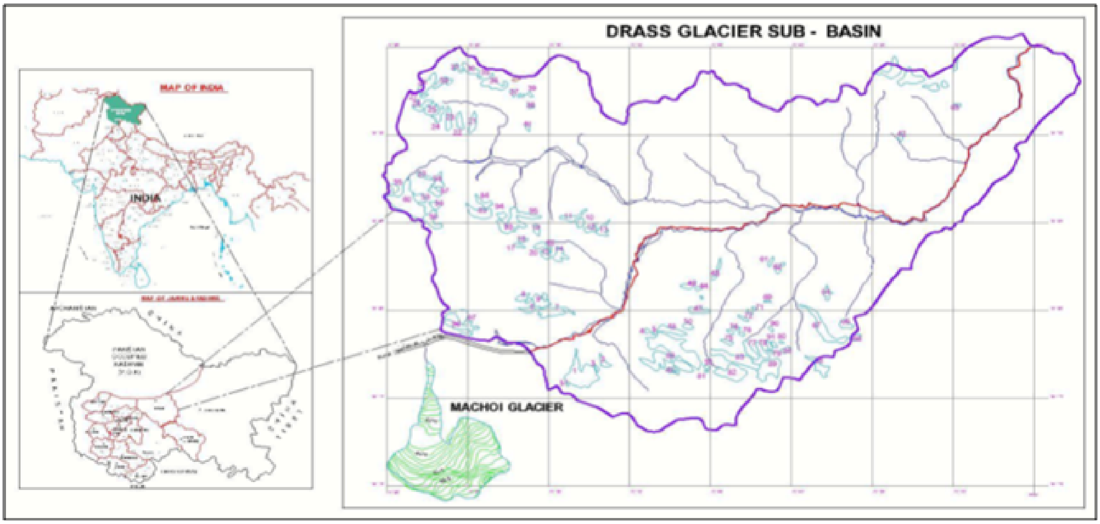

Figure 1. Location map of Drass glacier sub-basin and Machoi glacier, Kargil, Ladakh.

the air mass of westerly air flow and western disturbances, moving aloft the Pamir range. The air mass develops cold high air pressure at higher altitude that ultimately sinks to lower altitude giving rise to cold anticyclone leading to production of thermal gradient during winter season (October to May) that is responsible for anchoring the southerly jet. The study region has cold semi-arid type of climate. The winters are long and chilly (mean minimum temperature is –15°C to –35°C), lasting fromNovember to May. Summers are short (June to September) and mild (temperature varies between –8°C to 25°C).Nearly 72% of the annual precipitation is received from western disturbances that are confined to November to May which sometime prolongs to summers as well, otherwise summers get scanty rains. During the last one decade, the region is getting some precipitation during summers as well through westerly winds, showing sign of climatic shift

Methods

Most of the glaciers in Drass valley are located in remote and treacherous terrain that is inaccessible and not connected with motorable road. The monitoring of glaciers is difficult by direct field methods .Remote sensing has advantage of giving synoptic view of the region on regular basis .The IRS-IC LISS III data (October, 2001 and 2013) was provided for Drass basin by Space Application Centre (SAC) at pixel resolution of 23.5m for the detailed study. The base map of the area was prepared from Survey of India (SoI) 1965 topographic maps of 1:50000scale. Only seven topographic sheets of Drass basin were available that covered 115 glaciers out of these 81 glaciers (>0.1 km²) were selected for detailed study. All the satellite images were georeferenced using SoI boundaries were delineated using topographic maps and the area was digitised in the GIS platform. From satellite images the glaciers boundaries were delineated by visual interpretations. Standard FCC was used successfully to map various glacial features such as glacier boundary, accumulation area, ablation area, equilibrium line, moraines etc. Shape file of the basin as well the glacier boundaries delineated from the satellite images were overlain on the SoI vectors for change detection.

Machoi glacier is located at the road head and selected as a benchmark glacier in Drass basin, monitored and studied by many geologist as well glaciologist for the last

130 years. Hence it was selected for detailed mass balance studies, which was useful to assess its fluctuating character. ‘Net mass balance’ is the net change in glacial mass at the end of theablation season, relative to the previous year. The specific net ablation and net accumulation was estimated in the field through ablation stakes measurement, fixed firmly in the ablation zone of glacier by steam ice drill. Net accumulation measurement wascarried out by snow pit measurement in the accumulation zone of the glacier at the end of ablation season (generally in September). Snow densities were measured forsnow water equivalent during field season 2011–2012, 2012–2013 and 2013–2014.

The location and sources of meteorological data used in this study werechosen considering their proximity to glaciers and length of their records. The meteorological data of Drass ismonitored by the Indian Meteorology Department (IMD) and Snow and Avalanche Establishment (Government of India), adopting standard meteorological practices. The data for a period of 28 years (1987-2013) were used to assess seasonal changes, if any in monthly mean maximum, mean minimum temperature and precipitation as tool to glacierstratigraphic system. Hence, under this system length of season and duration of‘mass balance year of glacier year’ varies. The mass balance year is divided into winter (Nov–Mar), late winter (Mar–May), summer (Jun–Aug) and late summer (Sep–Oct). This is used in this study to isolate the inter-seasonal signals. The monthly mean maximum, mean minimum temperature and snowfall been analysed for each phase by fitting linear least square trend line (1988–2000, 2001–2008 and 2008–2013) to assess the impact of temperature and precipitation on the health of glaciers. The significance of the trend line is shown by probability value(P value) for significance level □=0.05.The value of $R^2$from regression is used to show correlation between glacier fluctuation and external climatic variables like temperature and precipitation (HaeberliandBeniston,1998; Kulkarni et al., 2002; Singh et al., 2005;Koul and Ganjoo, 2010).

Results

Glaciers are sensitive to climate change. The overall growth or decay of glaciers depends on the temperature of the ambient climate to a large extent and input of mass in the form of solid precipitation to a lesser extent. The studies carried in North America, show that some glaciated regions have positive correlation between temperature and snowfall and in some regions snowfall and temperature are negatively correlated (Bowling, 1977).Therefore the changes of snow cover is uncertain and much depends on meteorological parameters which require in-depth investigation. It is often argued that variability in mass balance of continental glaciers is dominated by winter season precipitation, while valley glaciers like in Drass are strongly influenced by change in temperature during summer season. The mid latitude westerly flows across the Himalaya particularly over western Himalaya during winter and cause precipitation in pre monsoon at higher reaches in the form of snow and plays very crucial role in accumulation of snow over different glaciers. Assessing the role of meteorological parameters in governing the extent of snow cover and it has been found that annual change in glacier extent is due to winter anomalies in accumulated snow and maximum temperature anomalies in summer. Twenty eight years of mean maximum and mean minimum temperature along with precipitation data has been used to assess the seasonal change in the relationship between snowfall and temperature in Drass valley.

Temperature

Time series temperature at Drass Valley

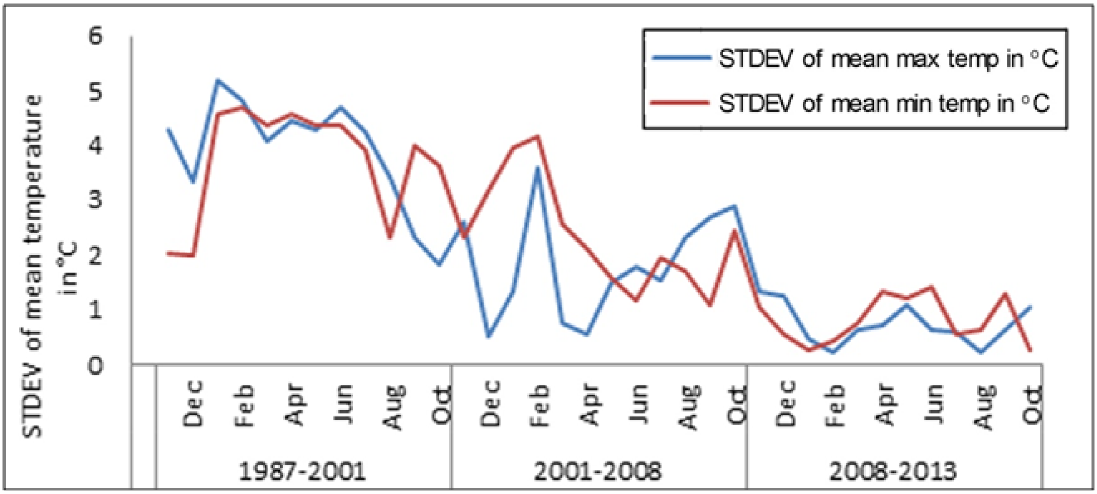

Figure 2. Mean maximum and mean minimum temperature of Drass (STDEV): 1987–2013.

Station (1987–2013) has been used to provide a regional picture of seasonal and year-to-year variation in temperature and glacial mass. Over a period of 28 years, there has been a small increase in annual mean temperature at Drass of –0.326°C decade^{-1} prior to 1995. However, since 1996 the rate of increase has accelerated to 0.175°C decade^{-1}. If individual months are further examined then large significant increase in mean temperature can be seen during the winter season, particularly from November to June— a possible indication of seasonal shift of winter to June.

The mean monthly maximum summer temperature for time series 1987–2001, 2001–2008 and 2008–2013 provide a regional picture of seasonal and year-to-year variation in temperature (Fig.2). The mean monthly maximum summer temperature from June, July, August and September is 16.2°C, 20.8°C, 17.7°C and 11.7°C respectively for the years 1987–2001, as compared to 20.6°C, 23.7°C, 23.6°C and 20.4°C for the years 2001-2008 and 14.9°C,17.22°C, 15.17°C and 10.82°C for the years 2008–2013. During summerseason, particularly in July and August highest temperature ranged between 26.2°C and 25.3°C in the years 2001–2008 and 1987–2001 respectively as compared to 12.1°C and 13.7°C during 2008-2013 respectively. The variation of standard deviation of mean maximum temperature during summer months ranged between 5.18–1.85°C, 3.6°C–0.91°C, and 1.3–0.22°C (Fig.2) during 1987–2001, 2001–2008 and 2008–2013, respectively indicating higher range of dispersion in maximum temperature during 1987–2001 in comparison to 2008–2013.

The mean minimum temperature during winter season ranged between –3.635°C to –22.45°C, –1°C to –19.33°C and –9.48°C to 1.02°C respectively for the time periods 1987 to 2001, 2001 to 2008 and 2008 to 2013 respectively, showing variation of standard deviation of 1.98°C to 4.71°C, 1.57°C to 4.17°C and 0.28°C to 1.39°C (Fig.2).The lowest minimum temperature during winter season recordedin January and February is–34°C and –27°C in 1989–2001 and 2001–2008 respectively as compared to –13.4°C and –10.7°C during the timeperiod2008–2013.

The monthly diurnal temperature range for winter and summer season (Fig. 3)shows an increasing trend during 1987–2001 and 2001–2013 and the average winter diurnal is 14.9°C, 11.3°C and summer diurnal is

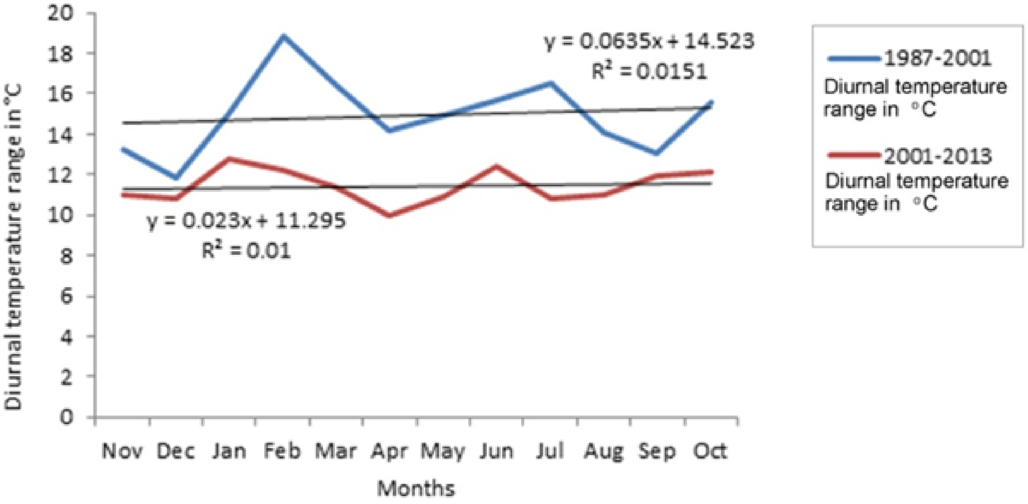

Figure 3. Diurnal temperature range in Drass (1987–2013)

14.98°C, 11.576°C respectively for the time series. The highest diurnal range in 1987–2001 and 2001–2013 during winter was inFebruary, which was 18.8°C–12.8°Cand in summer it was in July, ranging from 16.48°C to 12.04°C respectively.

Precipitation

The analysis of daily precipitation from first fortnight of November 1995 to last fortnight of October 2001 varies from 984 mm to 171.6 mm in water equivalent (WEV) in comparison 979.9 mm to 219 mm WEV during years 2001-2013 (Fig.4A and 4B). Out of total precipitation, highest contribution (above 500 mmWEV) of snowfall is 984 mm (1995–96), 979.5 mm (2010–2011), 565 mm, 562 mm, 589.1 mm, 495 mm and 587.3 mm WEV (2007-2012). Moderate snowfall recorded during the years of 2001–2007 and 2012–2014 amounted to 300-450 mm WEV. Low snowfall of less than 300 mm was recorded during 1991–95, 1997–1998, 1999–2000 and 2000–2001, respectively revealing1991 to 2001 a dry decade with exceptional anomaly during 1995–1996.

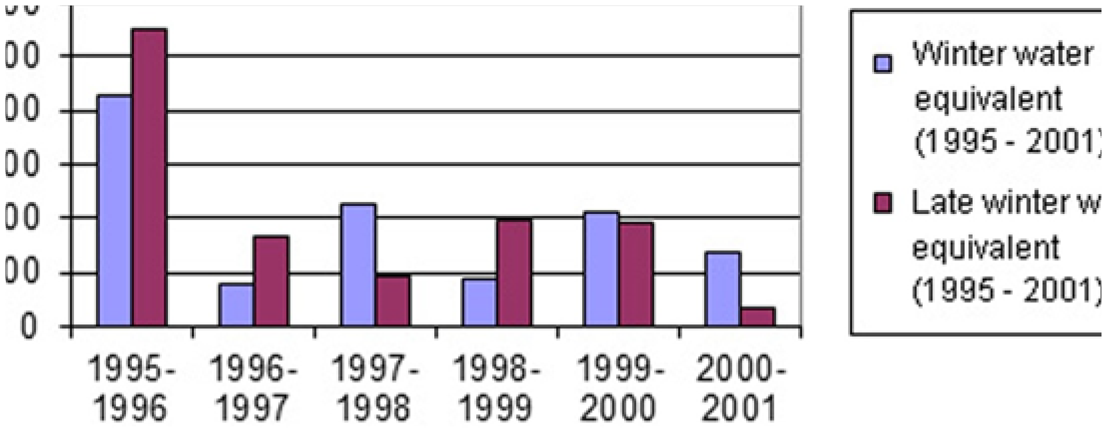

Figure 4A. Drass: winter precipitation in water-equivalent 1995–2001

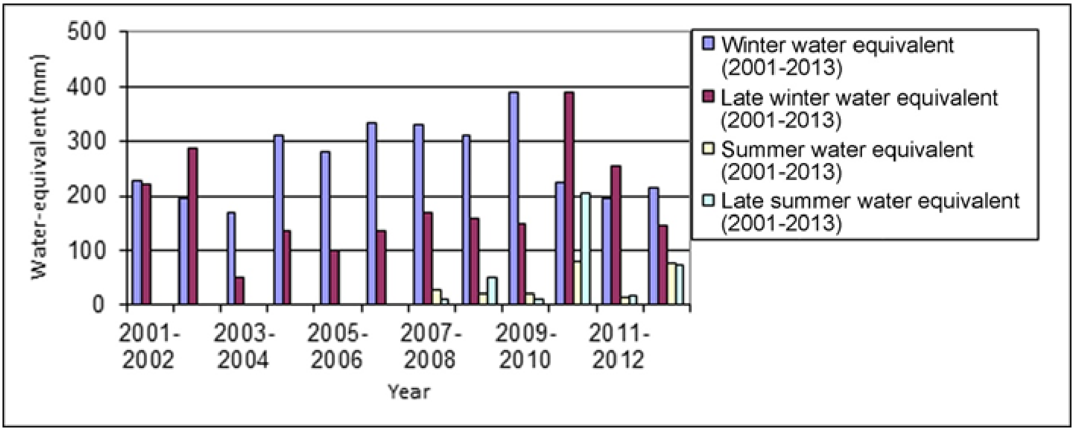

Figure 4B. Drass: Seasonal (winter and summer) precipitation in water-equivalent 2001–2013

Moderate snowfall recorded during the years of 2001–2007 and 2012–2014 amounted to 300-450 mm WEV and low snowfall of less than 300 mm was recorded during 1991–95, 1997–98,1999–2000 and 2000–2001 respectively. The pattern in annual, seasonal and monthly mean snowfall investigated for the time series 1995–2001, shows that 196 mm WEV of snow fall takes place between November and March (winter) and 206.8 mm WEV of snow between March and May (late winter), suggesting that about 52% of snowfall took place in latter part of winter. During the period 2001 to 2007—253.4 mm WEV of snowfall took place in winter and155.48 mm WEV of snowfall in late winter. This reveals that 38% snowfall took place in late winter (Fig. 5). During 2008–2013, 278 mm WEV of snowfall was in winter season, 211.67 mm WEV of snowfall in late winter and 100.71 mm WEV of precipitation in summer (June–September), suggesting that 37.5% snowfall took place in late winter and 17% precipitation in summer season (Fig. 5). Heavy snowfall in later part of winter and summer holds considerable significance in terms of health of glacier and helps in consolidating ice, reducing ambient temperature and degree-day melting that results positive impact on glacier stability and growth.

Analysis of rainfall records shows that Drass station experienced overall dry spell during the summer periods of 1995–2002. The rainfall scenario in summer period initiated a change in year 2002–03 latter as regular phenomenon since 2005–06. The total rainfall/snowfall record for the years 2011, 2012, 2013, 2014 from May to September is 42.0, 56.2, 90.1, 146.1 mm in water

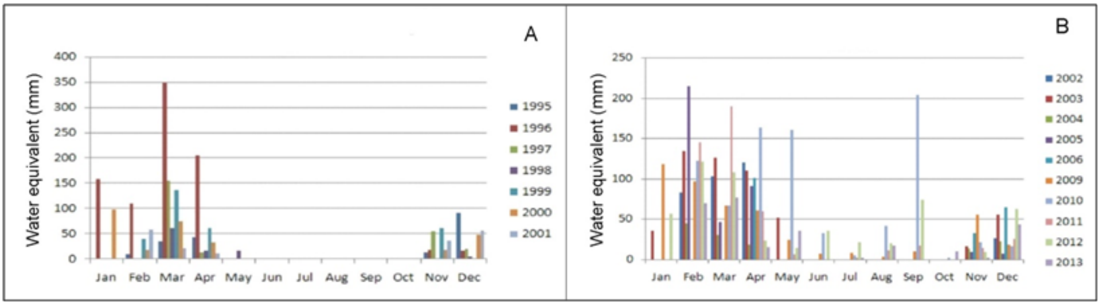

Figure 5. Drass: (A) Monthly distribution of snowfall (water equivalent) in 1995–2001 and (B) monthly distribution of snowfall (water equivalent) in 2002–2013.

equivalent respectively (Fig. 5). Whereas the analysis of precipitation recorded at the glacier, base camp and at equilibrium line reveal that rainfall occurs at lower elevation in the vicinity of glacier snout and snowfall at higher elevation (near equilibrium line of glacier).

Analysis of temporal temperature and precipitation change:

The trends in annual, seasonal and monthly mean temperature and precipitation in the form of snow fall were investigated for Drass glacier basin from 1988 to 2013.The records have been analysed by fitting linear least square trend line to assess the behaviour of temperature and precipitation. The analysis reveals that mean maximum temperature during the period 1987–2000 shows no change in trend line during winter as well as late winter (Fig.6B). In comparison, the mean minimum winter season temperatureshows marginally increasing trend in relation to late winter (Fig.6A). During 2001–2013 the mean maximum temperature trend line shows decreasing trend during summer as well as late summer season (September–October). This indicates cooling, hence reducing degree-day melting of glaciers (Fig. 6D).The trend line of mean minimum temperature however shows marginal change in itsbehaviour (Fig. 6C).

The trends in diurnal temperature change shows increasing trend in 1987–2000 and 2001–2013 in summer as well winter that substantiate that late winter warming leading to sublimation of ice from glacial body triggering the influence of precipitation during summer 2005–2013.

Snowfall pattern reveal increasing trend in

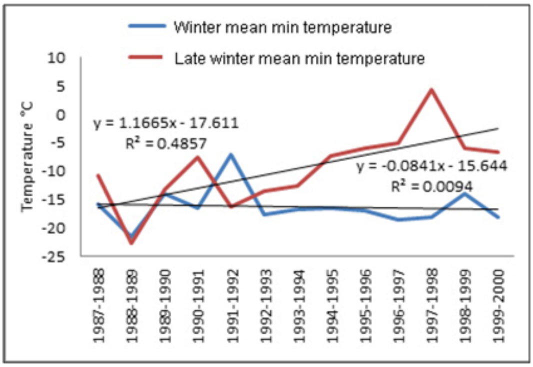

Figure 6A. Mean minimum temperature of Drass in winter season and late winter(1987–2000)

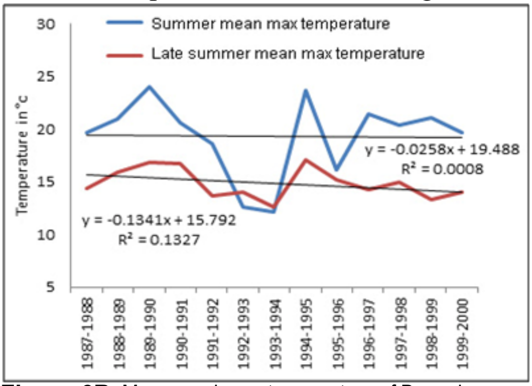

Figure 6B. Mean maximum temperature of Drass in summer season and late summer(1987–2000)1995–2001

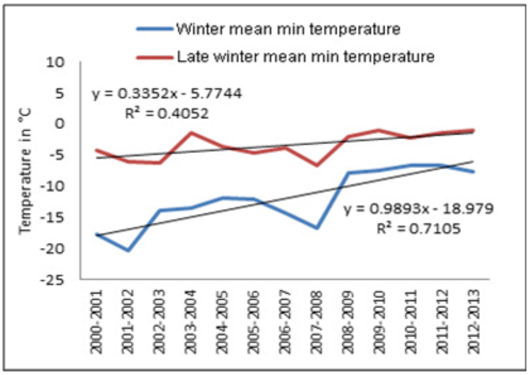

Figure 6C.Mean minimum temperature of Drass in winter season and late winter(2000–2013)

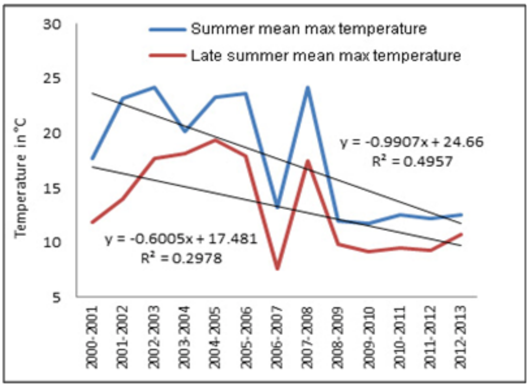

Figure 6D. Mean maximum temperature of Drass in summer season and late summer(2000–2013)

September–October, February–May and June —this helps in the growth and development of the glacier. The micro-meteorological data from 2011–2014 has served as a tool to correlate different meteorological parameters with mass balance inputs and equilibrium line altitude to assess the fluctuating record of the Machoi glacier body.

The role of temperature and precipitation have been examined in governing the extent of glacial cover in Drass valley and found that negative correlation (–0.471, –0.145) between mean minimum temperature and snowfall in 1995–2000, in comparison to weak positive correlation (0.191) during winter season of 2000–2013 time series, is insignificant as per P-values (Table 1). The analysis of temperature and precipitation and their trend shows an interesting shift of peak from summer and winter to late summer and late winter. This shift has helped the overall health of glaciers and their stabilisation process.

Glacier inventory:

The glacier inventory is prepared from the available SoI topographical sheets document nearly 115 glaciers in Drass valley basin between 3600 m to 6000 maltitude. Out of these, 81 glaciers having greater than 0.1 km² areas have been selected for detailed comparative study. Thirty seven glaciers are more than 1 km² in area.16.7% of glaciers are >3 km², 4.2% of the total glaciers are between 3 km² and 6 km², 5.8 % of the total glaciers are between 6 km² and 9 km², 1.7% of total glaciers are between 9 km²and 12 km² and 2.5% total glaciers are <12 km². The largest glacier in the basin has an area of 15.14 km². This clearly suggests that Drass basin is occupied by large number of small glaciers and niche glaciers. The glaciers in Drass basin are distributed more or less equally in all directions but they do show a preferred orientation to north, northeast, and northwest (66%). Twenty one glaciers are orientated towards northeast and 19 towards northwest, 14 towards north and 9 towards east. The total area covered by glacier was187.9 km². However, as per the satellite data of year 2001 and 2013, the total numbers of glaciers have increased to 150but the areal extent of glaciated area has decreased from 187.9 km² to 158.42 km² and 156.65 km² during the period 1965, 2001 and 2013 respectively. Satellite data have been used to assess the behaviour of the Drass glaciers during 2001–2013 and also to compare the changes from the 1965 So I topographical sheets. Detailed analysis of the satellite images helps to understand the causative factors responsible for changes in behaviour of glaciers in Drass valley.

Monitoring of current behaviour glaciers

Table 1. Correlation results of seasonal monthly temperature and precipitation of Drass (1995-2013)

Season	Correlation variables	Correlation	p-Value	Significance
	Winter mean minimum temperature and (precipitation (WEV)1995–2000 (Dec–Feb	0.18–	0.772	No
	Winter mean minimum temperature and (precipitation (WEV)2000–2013 (Dec–Feb	0.191	0.533	No
	Late winter mean minimum temperature and (precipitation (WEV)1995–2000 (Mar–May	0.474–	0.42	No
Winter	Late winter mean minimum temperature and (precipitation (WEV)2000–2013 (Mar–May	0.69–	0.822	No
Summer	Summermean maximum temperature and (precipitation (WEV)2007–2013 (June–Aug	0.145–	0.784	No

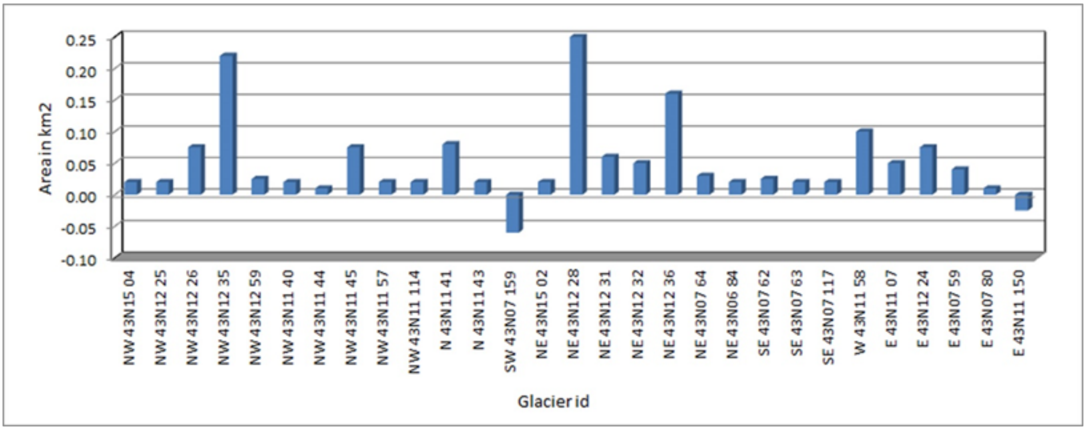

Figure 7. Change in area of the glaciers in Drass basin (2001 and 2013)

(2001 and 2013)

To assess the current behaviour of the glaciers the IRSLISS-III images of 2001 and 2013was visually interpreted to demarcate the boundaries of 150 glaciers of Drass valley. The satellite image of 2013 was analysed by applying various digital imageprocessing techniques, supplemented with ground truth data for accurate identification of snout position and to assess change in areaof all the glaciers.

SteadyState phase in glacier area and snout position

The study shows that 120 glaciers of different dimensions do not show any change in their area between the periods 2001 and 2013. Ninety eight glaciers are less than 1 km² in area, 19 glaciers have areas between 1 km²–3 km² and one glacier is more than 10 km² area The glaciers of these categories are distributed more or less in all direction with large percentage (61.2%) oriented northwards, a fair percentage is oriented towards NW(21%), N and NE(20%).

The remaining 30 glaciers show marginal change in area and length, as per satellite imageries of 2001 and 2013.Twenty eight glaciers out of 30 glaciers show reduction inarea from 2001 to 2013.The dominant orientation of these glaciers is towards northwest (41%), northeast and north (18.75%).

Eighteen glaciers have lost less than 0.05 km² area, 6 glaciers 0.05 km²–0.1 km², 2 glaciers 0.1 km²–0.2 km² and 2 glaciers lost above 0.2 km² area.

Interestingly, the glaciers No.43N07139 and 43N11150 show gain in area by 30% and 40% respectively from 2001 to 2013. The snouts of the glaciers are confined in northwest and eastern direction (Table 2).

Table 2. Glaciers showing gain in area (2001–2013)

Glaciers Id	Orientation	Area 2001 (km²)	Area 2013 (km²)	Change in area
43N07139	SW	0.2	0.26	+0.06
43N11150	E	0.05	0.07	+0.02

The constant shift in the altitudinal

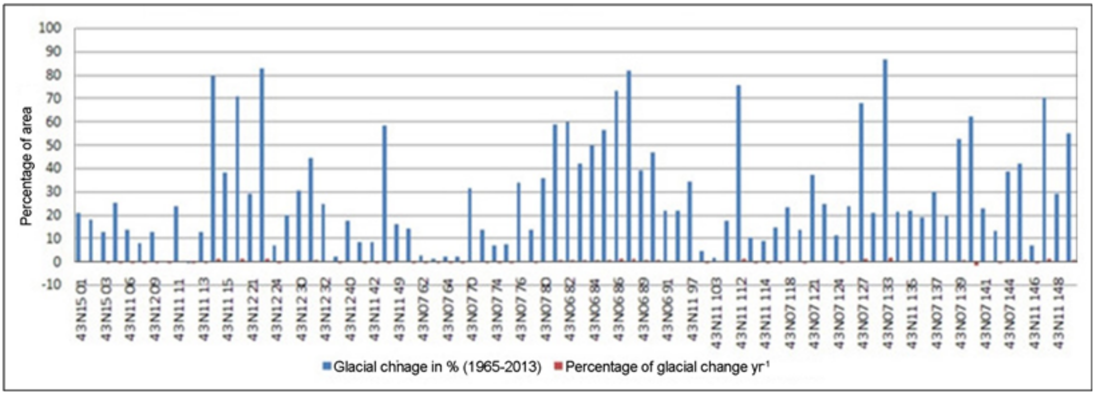

Figure 8A. Percentage of changes in glacier area from 1965–2013.

position of three main classes of glaciers based on area 0 to 2 km^2, 2 to 5 km^2 and greater than 5 km^2, show that larger glaciers with above 5 km^2 area have vacated smaller area (0.64% to 2.64%) in comparison to small glaciers ranging between 2 km^2 to 5 km^2 in area (1.68% to 9%) during 12 years period. This indicates that glaciers of Drass valley in general retreat at slowpace (Fig.7).

Long term monitoring of glaciers between 1965 and 2001

Eighty one glaciers of Drass valley have beenidentifiedfor long term monitoring for the period 1965–2001 and 2001–2013. Inhomogeneity in glacial area change shows that 10 glaciers experienced gain in area, 13 glaciers a loss of more than 50% and 18 glaciers lost 25–50% of glacier area. The remaining glaciers lost marginal area during the last 50 years (Fig. 8A). Due to in-homogeneity in observation period, we evaluated the changes in glacial area on yearly basis. Five glaciers vacated at the rate of more than 10,000m^2yr^{-1}, 5 glaciers experienced loss of5000–10,000m^2yr^{-1}, 9 glaciers vacated 2500–5000m^2yr^{-1} and remaining glaciers lost 15–1500m^2yr^{-1}. This indicates that majority of glaciers in Drass basin are small and niche ones confined in higher altitude affected by solar radiation melting. The yearly change in area ofeach glacier ranges 0.12% to 1.7% of glacier area (Fig.8B).

Ten glaciers out of 81 show gain in area during the last three and half decades (Table3). Majority of these glaciers are oriented towards northwest and northeast (30% each) followed by southeast (20%), southwest and east (10% each).The snout of the glaciers oriented towards northwest show increase in length (26.5%) as well as

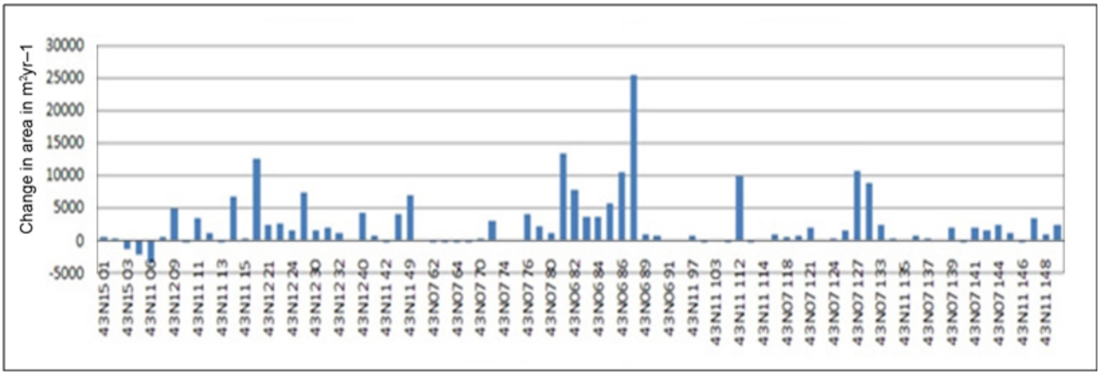

Figure 8B. Change in glacier area in m^2yr^{-1} from 1965–2013.

Table 3. Glaciers showing gain in area (1965-2001)

Glaciers id	Orientation	Area 2001 (km²)	Area 1965 (km²)	Change in Area
43N1503	NW	3.83	3.33	+0.5
43N1504	NW	1.96	1.55	+0.41
43N11 13	N	0.23	0.2	+0.03
43N1142	NE	0.23	0.21	+0.02
43N0762	SE	0.7	0.68	+0.02
43N0763	SE	1.56	1.54	+0.02
43N0764	NE	4.01	3.68	+0.33
43N11102	NE	0.42	0.4	+0.02
43N11113	E	0.19	0.17	+0.02
43N07140	SW	0.17	0.16	+0.01

area (15%). The glacier id Nos. 43 N15-03 (0.5 km²), 43N15-04 (0.41 km²) and 43N11-13(0.03 km²)— all show increase in area of the glaciers. The glaciers in northeast direction show increase in area by 9.5% such as glacier id No. 43N1142, 43N0764 and 43N11102 (Fig.7 and Fig. 8A and 8B).

Out of the ten glaciers, four glaciers with id. Nos. 43N15-04, 43 N07-62, 63 and 64, show gain in area during 1965 to 2001but loss in area from 2001 to 2013 and remaining six glaciers show gain in area from 1965 to 2001and no change in their area between 2001 and 2013 (Table2 and Table 3)

Relative change of snout position of large glaciers from 1965 to 2001

Eleven large glaciers show considerable shift of their snout positions during the period 1965 and 2001 thereby showing decrease in length as well the area of glaciers. Four glaciers such as id No.43N1228, 43N1240, 43N1149 and 43N07132 show considerable deformations in glaciers that lead to vacation of large area, to the extent of above 15–21% of glacier area loss. Similarly, in case four glaciers id No 43N1504, 43N1209,43N0772 and 43N0777 the relative position of snout shifts uphill showing decrease in the length of glacier and moderate decrease in area(10% to 15%)as well.However three glaciers id No.43N1224, 43N1236 and 43N1141 show very small shift in glacial snout as well in glacier area(less than 10%).

The overall vacation of area of 11 large glaciers from 1965 to 2001 show that one glacier shrunk in area at the rate of 25,000m²yr–1, 4 glaciers vacated the area at the rate of 10,023 m²yr–1, 3 glaciers vacated area at the rate of 3920m² yr–1 and 3 at a rate of 1478 m²yr–1 (Fig.6andTable4). Further 13 large glaciers of different dimensions have fragmented to nearly 30 glaciers during 1965 to 2001 but do not show any appreciable change in reduction of area as well as maximum length.

Morphology and glacier dynamics

Drass valley has a complex environmental condition of cold, arid and permafrost in the accumulation zone (4200m–5500m) and sub-arid condition in the ablation zone. The high glaciated valleys having characteristic morphology of cirques, scoured bed rocks,U-shaped valleys, drumlins, whale backs, rôchemoutonnée and prominent terminal and lateral morainic ridges.The area is a zone of sporadic and discontinuous permafrost. Drass mountain complex is composed of crystalline rock overlain by thick bed of sedimentary rocks designated as “Phe” formation of upper Proterozoic age. These comprise of silt stone, black carbonaceous shale with limestone. The Volcanic formations are overlaid by group of rocks comprising of dark shale, limestone of Permian-Triassic age. Over the limestone group one can find Cretaceous volcanics known as Drass Volcanic. The region has low temperature below freezing (–10˚C to –35˚C) during prolonged winter seasonleading to permafrost condition along the ice margin of Higher Himalaya and Drass uplands to foothill valley margins, leading to production of ice wedges and rock glaciers. Solifluction is observed within basin slope and patterned ground with pingos in valley floor along the meadows. Due to recent climatic change, temperature and precipitation are changing rapidly during late winter and summer season in the area. The change is rapid than the adjoining north-western Himalayan average. This results in highly dynamic environmental processes, making the Drass a potential area to understand the interrelations between geomorphology and permafrost, as influenced by climate change. Due to its marginal nature, permafrost degradation is rapid in the vicinity of 3500–3850m, and related geomorphological processes such as landslides and mudslides are accelerating.

Geomorphological time–depth (2010-2014) analysis is being done by thermistors focusing on permafrost indicators such as rock glaciers, solifluction, permafrost creep, and polygonal patterned ground and thermokarst. Mapping the present day situation is based on detailed fieldwork, existing maps, satellite imagery and DEM Models. A specific geomorphological map representing the (peri) glacial geomorphology has been prepared based on the SoI topographic map of 1965. In addition, 3D-photomodelling of rock glaciers andsolifluction lobes has been done to understand the short-term geomorphic dynamics of the area. To understand the permafrost dynamics ofthe last fifty years (1965–2014), shape files of the basin as well the glacier boundaries delineated from the satellite images weresuperimposed on digitised topographic sheets using GIS techniques. This is being furthervalidated with geomorphological and climatological field data using the regional permafrost probability maps. Quantifying the magnitude of greenhouse gas emissions (CO_2 and CH_4) from thawing, permafrost areas have been delineated for understanding the geomorphological sensitivity of cold climate to degradation. The total permafrost area evaluated fromSoI topographic map (1965) is 99.62 km² and as per satellite data of 2001 and 2013 and field observation, the permafrost area reduced to 84.24 km²and 81.76 km² respectively.The permafrost line has also shifted from 3245m altitude to 3280m from 1965 to 2001 as the average annualchange in temperature has also shot up from –0.426ºC to +0.371˚C. Further permafrost degradation at lower altitude has reducedthe thickness of the active layer (1–2m) which is thawing in summer and refreezing in winter leading to warm permafrost conditions since year 2001 particularly from 2005–2006.Fragmentation of permafrost line has been observed between 3217m and 3334m along an aerial distance of 20 km. The mass movement areas are confined to parts of Higher Himalayan flanks and Drass uplands on slopes composed oflimestone, shale and volcanic rocks, devoid of ice bodies. During winter season snowfall on the bare slopes is sometimes drifted to interior areas otherwise subjected to extreme freezing due to very low temperature (–40˚C) for long duration during the winter. The freezing leads to increase in pressure and stress condition on valley walls and solifluction and navé-fluctionis seen onbasin floors and valleys. This leads to formation of cracks and hummocks. During summer season thawing produces more water than retained and develops frost thrusting along valley walls due to differential heaving. Along the valley walls there is mass wasting caused by super-saturated permafrost that moves down slopes and produces screed cones and rock glaciers, covering an area of 290.63km^2.

Dynamics of Machoi (benchmark)glacier

The reconnaissance of Machoi valley from the altitude 4600m, down to Machoi stream, at an altitude of 3400m near the confluence with Gumri river, reveal abundant drift material in the form of moraines.High lateral moraine ridges extend along the flanks of the glacier from the equilibrium line of the glacier up to V-shaped notch at an altitude of 3700m near the snout of the glacier. The lateral moraine ridges stretch further northwards up to Gumri Nala in a slight arcuate fashion covering a distance of nearly one kilometre This clearly reveals that Machoi glacier in the early Holocene was broad footed glacier and was massive in nature with embankment of moraines between 60m and 100 m high from the valley bed having slope 15°to 35°. Three series of medium lateral moraine stretches are found between 3400m and 3700 m along either side of Machoi Nala (stream) in the lower section, where as in higher section, a subdued morainic stretch between 3700m and 4100m is observed which coalesce with high lateral moraine ridges at 25° angle.

In the lower section, the medium high(30–60m) lateral moraines have lobate form. The form and texture of sediment indicate their origin to reworked medial moraines that were deposited when Machoi glacier extended to 3420m altitude. Later the glacier retreated leaving behind three sets of medial moraines. After thinning of the glacier, the medial moraines turned into three lateral moraines. Subsequently the glacier again advanced and reworked the deposits of lateral moraines in the vicinity of 3580m and 3750m to produce kettle moraines. The sediment of the kettle moraine gives the overview of genesis from medium lateral moraines. The observations of terminal moraines at three field sitesat 3440m, 3665m and 3760m further authenticate that Machoi glacier in the past extended up to 3440m to join Gumri. Since then the glacier has been retreating at a slow rate and advancing as well as observed from the scars of terminal moraine from multi-temporal satellite data (LISS III 2001, 2013) and the data retrieved from SoI topographic sheet (1965).Presently the snout of the glacier is confined below the V-shaped notch protruding in tongue like form.

The glacier had net positive balance of $+0.960392\times10$□m^3 in the year 2011–2012, $+0.719603\times10$□m^3 in the year2012–2013 and $+1.002060\times10$□m^3 in the year2013–2014 (Table 4) .The increase in net positive balance during the year 2013–2014 than year 2012–2013 is due to cool and moist summer. In comparison, during 2011–2012 the accumulation as well ablation was more. There is consistently low temperature from June to September leading to less summer melting than the earlier reporting years. The fluctuation in net balance values is also attributed to variability in meteorological parameters particularly with respect to pattern of snowfall, amount of solar radiation and duration of sunshine hours during summer. The residual snow measurements carried out during the field trips from 2011 to 2014 ranged between 1.5 to 2.5 m. The average snow density in the accumulation zone was 0.49 gm3 in late summers. The accumulation zone encompasses nearly 65% of the total area out of which two altitudinal zones ranging between 4500 to 4800 meters, and 4800 to 5000 meters accounted for nearly 79% of the net accumulation area of the glacier. These accumulation zones are mainly cirque floors separated by stairs that encompasses near the 74% of the accumulation area.

Discussion and conclusion

The monitoring of 150 glaciers in Drass sub basin suggest that 120 glaciers do not show any change in their area,2 glaciers show gain in area and 28 glaciers loss in glacier area. The snouts of majority of the large glaciers are facing northeast, northwest and east(67% of 30 glaciers). The long term monitoring of Drass glaciers shows decrease in area from 187.9 km^2(1965) to 158.42 km^2(2001) and further to 156.65 km^2(2013). The glaciers have vacated maximum area (28.48 km^2) between 1965 and 2001 in comparison to 1.77 km^2 between 2001and 2013. Thus overall glacial area loss in Drass basin per year is 0.813 km^2 (1965–2001).For 11 individual large glaciers in the basin, the loss is between 5423m^2 and 1473m^2. Snouts of the glaciers facing N and NW do not show any change in area between 1965 and 2001. During 2001–2013, these glaciers vacated about 0.136 $km^2yr^{-1}$and 80% glaciers are in stable mode, showingno change in area.

Over a record period of 28 years, there has been a small increase in annual mean temperature at Drass prior to year 1995. However, since 1996 the rate of increase has accelerated to 0.375°C decade–1.The analysis of mean monthly temperature (maximum and minimum) trend line for a period of 28 years shows lack of fit during 1988–2000 as compared to 2001–2013. This can be attributed to phase transition threshold. It indicates that winter is cooler, late winter warm and humid and summer cool and wet during time series 2001–2013 in comparison to cold winters, mild late winter and warm and dry summer during 1988–2000. Further, the decrease in mean maximum as well as mean minimum temperature during 2004–2013 is associated with El Nino and Southern Oscillation events that resulted in lower ablation season temperature particularly during summers of 2004–2014(Yasunari 1987, Fig. 3 and Fig.4). This is further substantiated by decreasing trend in diurnal temperature during 2004–2013. These trends in weather conditions have undoubtedly leaded a favourable environment for decelerated retreat to or 'no-change' in 80% (120 glaciers) from 2004–2013 (Hewit, 2005; Mayer et al., 2006). The remaining 30 glaciers, including Machoi glacier where detailed field study was conducted (2011–2014), reveal slow retreat of permafrost line and glacial snout with marginal loss in glacier area. Hence substantiating that Drass sub-basin glaciers are passing through a stabilising stage. Prior to 2001, the maximum and minimum temperature was low during winter andsummerwas dry leading to dry condition and the glaciers of Drass valley were under climatic stress resulting in fragmentation of large glaciers (Bahuguna, et al.2014, Bolch, et al. 2008, Fujila, 2008).

Machoi glacier valley was selected as benchmark glacier in Drass basin, been monitored and studied by many geologists and glaciologist for past 130 years. A photograph of the glacier published in the book "Valley of Kashmir" by Lawrence shows the extension of Machhoi glacier up to a rock cliff (Lawrence, 1895) closely in contact with the base of lateral moraine ridge. The glacier was relatively thicker than at present and narrow in lateral valley. R.D. Oldham of the Geological Survey of India visited the glacier (Oldham, 1904). According to him the glacier was about half a mile from the road head and extended almost down to where the road now runs and is shown by heaps of morainic material. His observation was also confirmed by Latouchi (1910). The geomorphological evidences document that Machoi glacier earlier extended up to the altitude of 3410 m and joined main Gumri valley glacier.

The scars of Machoi glacier deposits observed on the side of Gumri River in the form of remnant moraines breached at several places. The research team of university of

Figure 9. Snout position of Machoi glacier (2012–2014)

Jammu extensively monitored the glacier from the snout to an altitude of 4800m (accumulation zone) by GPS and carried continuous field mass balance measurements during 2011 to 2014. The glacier has a positive net balance with cumulative specific balance of 0.16m WEVkm–1yr–1. This has resulted in shifting of equilibrium line from 4540m asl in the year 2011–2012 to 4509m aslin 2013–2014 (Table 4) and the glacier snout to advance 4m in central part (3656m to 3652m), but along the sides there has been deformation squeezing and retreat of 1.56m (Fig.9).

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Table 4. Summary of Net Mass Balance estimates of Machoi glacier (2011-2014)

Year	Ablation area (km^2)	Accumulation area (km^2)	Net ablation (km^3)	Net accumulation (km^3)	Net balance (km^3)	Accumulation Area Ratio (AAR)	Equilibrium-Line Altitude (ELA) Balance (m km^{-2} yr^{-1})
2011–12	2.219	3.54	-2.748	3.709	+0.960	0.615	0.174540
2012–13	2.100	3.62	-2.585	3.261	+0.675	0.636	0.124520
2013–14	1.933	3.83	-2.263	3. 265	+1.002	0.65	0.18 4509

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