Glaciological Observations during the 30th Indian Antarctic Expedition

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Abstract

Glaciological observations in Antarctica started since the beginning of the Indian Antarctic Programme and are continuing till date. The data collected at Polar Ice sheet – land interface along part of the southern margin (termed as Dakshin Gangotri glacier) of Schirmacher Oasis and the snow accumulation / ablation studies on the ice shelf are providing to be important inputs in understanding the ongoing global climate change. As part of this ongoing Dakshin Gangotri glacier and the ice shelf stakes monitoring programme, observations were made during the 30th InSEA. This glacial ice front has shown a retreat in the last 30 years of observations. It may be attributed to the global warming trend apart from other local causes. In the year 2011, DG glacier snout has receded by an average 81 cm as compared to 2010. Out of 17 observation points on western extension of DG glacier snout, data was recorded at only 16 points. Among these, 15 points were compared to the data of the previous year, which shows an annual average recession of 1.19 m. Average decadal recession was calculated to be 18.42 m from 2001 to 2011. During the last expedition, the earlier stake network was found to be buried below the ice and hence a new network of 8 stakes was fixed on the ice-shelf. The data obtained this year shows an annual average accumulation of 33.5cm on ice-shelf. A new stake network consisting of 20 stakes was fixed on the ice-shelf. For the first time, a new stake network of 16 stakes was fixed on Polar Ice sheet and the initial readings were taken.

Keywords:DG Glacier snout, Recession, Schirmacher Oasis, Accumulation, Ablation.

INTRODUCTION

The icy continent of Antarctica in the southern part of the Globe is surrounded in all sides by the Southern Ocean which has adjoining Pacific, Atlantic and Indian Oceans. The continent covers an area of about 14.2 million sq. km with exposed land surface of less than 2 percent and the rest covered under the Polar ice sheet. The average thickness of the ice cap is over 3.5 km and is maximum at the pole. Understanding of the dynamics of polar ice sheets including shelf-ice is vital for realistic evaluation of climatic models. The Ice Shelf is a continuation of polar ice sheet that is moving away from the continent and floating over the Antarctic Sea. The presence of large amount of ice shelves in the peripheral parts of Antarctica continent makes it a unique continent. The ever increasing global average temperature accelerates the melting of the glaciers and Polar ice sheet of Antarctica. This results in the global sea level rise which is a matter of concern worldwide. There is a serious disagreement regarding the mass balance of the Polar ice sheet of Antarctica. The three geographic entities of Antarctica show different mass balance scenarios. Most of the scientific data agree on the fact that Antarctic peninsula and West Antarctic ice sheet are losing mass due to negative mass balances. However, the disagreement is reported for the East Antarctic Ice sheet mass balance [Hanna et al., 2013]. The average annual precipitation is only ~15 cm (less than that in the Thar Desert of India). Though the average annual temperature is -25°C, it varies from 10°C in summer (especially on coastal regions) to – 65°C in winter. Because of this extreme cold condition it controls the world's climate to a major extent. In this regard, the glaciological observation from parts of East Antarctic ice sheet plays an important role in understanding the behaviour of Polar ice sheet with respect to the effects of increasing global temperature.

STUDY AREA

The Schirmacher Oasis is situated on the Princess Astrid Coast in Dronning Maud Land in East Antarctica with an average elevation of about 100 metres above mean sea level. It is located between 70° 43'50” and 70° 46' 40” South Latitudes and 11° 22' 40” and 11° 54' 25” East Longitudes is a group of three visible ice -free landmass separated by different lakes (Fig. 1). The main part of the oasis is separated from a small landmass in the western part by a lake (Lake Zig-zag/ Lake E-1) and an island (Nadezhdy Island / Lanka Island) to the north by a lake (Lake Ozhidaniya / Lake E-10). The epi-shelf lakes are connected to the ocean that lies beneath the ice sheet (Swain and Chaturvedi, 2011). This ice free landmass consists of rock exposures which include various types of bedrock, moraine covers, valleys displaying present and past glacier/meltwater activity, different types of lakes which are seasonally covered by a blanket of ice cover, seasonal and permanent cover of snow. All these landmasses together have been assigned the name Schirmacher Oasis having a length of 19.55 km trending ENE - WSW and maximum width of about 3.35 km covering an area of about 34 sq. Km. Schirmacher Oasis represents a naturally exhumed piece of land, reclaimed from the retreating ice cover subsequent to the Last Glacial Maximum. Many erosional landforms related to a peri-glacial environment are seen in this oasis. Roche moutonees, striations, glaciated valleys, terraces occur as glacial erosional landforms and different types of moraines occur as depositional features. Eight glacial valleys are present in this area. Six glacial valleys that run along ENE-WSW direction are structurally controlled and are sub-parallel to regional foliation. The other two relatively younger tectono-glacial valleys that trend NNE-SSW dissect the earlier described valleys at two different places. Sudden change in the width of this oasis at two places, increase in topographic slope, and change in striation-trends suggest that retreat of the ice cover over Schirmacher might have been episodic.

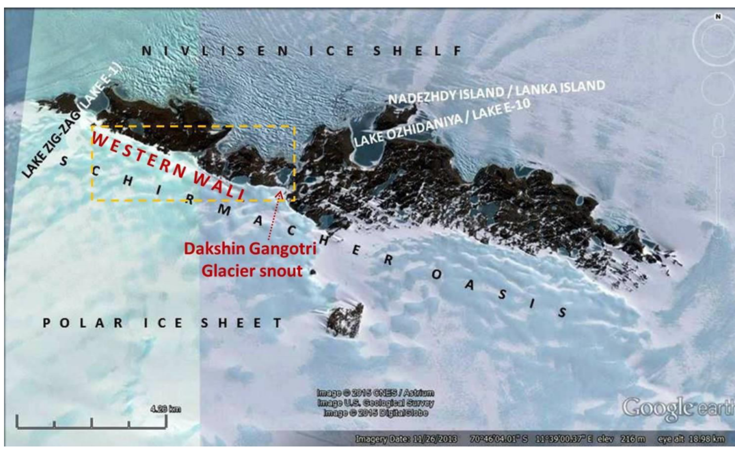

Fig. 1. Schirmacher Oasis group of exposed rocky landmass are separated into three distinct zones by different lakes (Lake Zig-zag/ Lake E-1 separates one landmass towards west and Lake Ozhidaniya / Lakek E-10 to the north separates Nadezhdy / Lanka island from the main Schirmacher Oasis). Monitoring of the Western Wall and Dakshin Gangotri Glacier snout are being done annually by Geological Survey of India. The detail of area within the yellow dashed lines is shown in Fig. 2).

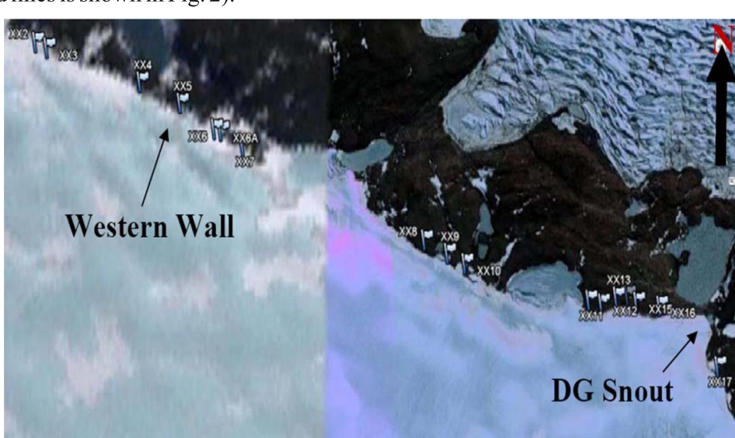

Fig. 2. Different observation points in Western Wall of Schirmacher Oasis are marked as XX2, XX3, XX4, XX5, XX6, XX7, XX8, XX9, XX10, XX11, XX12, XX13, XX14, XX15, XX16 and XX17. DG snout is also seen in the eastern end of the Figure.

Fig. 3. *Ground view of DG Glacier snout, Scirmacher Oasis, East Antarctica*

All major lakes of Schirmacher Oasis are localized along the glacial valleys. In each valley, the glaciers directly feed the southern-most pro-glacial lakes; and towards north, the successive lakes are partly fed by the seasonal snow and partly through a subsurface flow regime [Swain and Chaturvedi, 2011] manifested as patterned ground or by elementary development of surface channels. These subsurface as well as surface flow regimes eventually drain the entire valley in north on to the ice shelf, which in turn is marked by huge epi-shelf lakes.

As a part of the programme on monitoring the temporal fluctuations of continental ice margin, a prominent glacial tongue was identified in Western Schirmacher Oasis (Fig. 1 and 2) in the very beginning of Indian Antarctic Expedition and was named Dakshin Gangotri (DG) Glacier Snout (Fig. 3). An aerial view of the DG Glacier snout (Fig. 2) and its ground view (Fig. 3) shows it as a descending part of the Polar ice sheet forming lobes. The glacier snout was monitored earlier from fixed survey points using plane table method and average annual recession rates were computed using this data. The data showed a consistent recession, but there was a fluctuation in the recession rate [Asthana et al., 1996; Chaturvedi et al., 1999a, b & c, Chaturvedi et al., 2003, 2005, 2008; Singh and Jayaram, 1989; Swain and Roy, 2011]. The annual recession rates were computed to be 0.57 m from 1983 to 1995. In 1996, nineteen peripheral points were fixed along this glacier snout to enhance the details of the observations (Fig. 4). Also, the advance / retreat patterns along the periphery of the glacier were recorded every month during the austral winter of 1996-98.

This established the overall model of recession of the glacier. The glacial ice front has been observed to be retreating during the last 26 years of observations with a little advancement during polar winter. The recession may be attributed to the global warming trend apart from other local causes. The retreat of the ice front is not uniform throughout the year but shows significant seasonal fluctuations. In 2001, the monitored length of the glacial front was increased by many km. to cover the entire wall of polar continental ice margin west of DG glacier snout in Schirmacher Oasis. The western wall showed a different amount of recession compared to the glacier snout due to topographic factors and the amount of solar energy received by different stretches or segments of the cap ice front [Shrivastava et al, 2011]. The succeeding years, till date, have shown that not only the glacier snout of the glacier but the entire ice front is receding at an alarming rate. This uninterrupted observation for a period of more than last two decades is providing a valuable input for studying the impact of global warming in Antarctica.

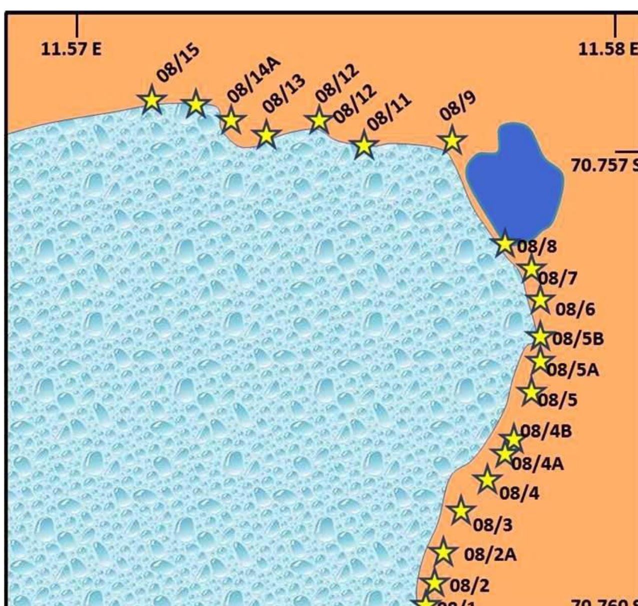

Fig. 4. *Fixed points along the periphery of DG Glacier snout.*

Another long term project initiated in the Second Expedition was to record the ablation and accumulation patterns on the ice shelf. The ice shelf surrounding the continent is very active as wind-blown snow accumulates at suitable locales constantly changing the topographic expression of the terrain. Monitoring of the accumulation/ ablation of snow/ ice on the ice shelf also form a part of the glaciological studies being done. These observations have been carried out by periodically (annual) monitoring a fixed network of 16 graduated stakes at intervals of 50 metres in a grid pattern. However, during the current expedition all the 16 stakes were found to be covered by snow. Thus a network of eight graduated stakes was fixed on the Ice Shelf. Seasonal / monthly patterns of accumulation/ablation were sporadically recorded during selected austral winters The results of these observations have quantified the rate of ablation during polar summer (November to January) and the rate of accumulation during the polar winter (February to October). The average annual net accumulation on the ice shelf has also been calculated.

Monitoring of icebergs in Antarctica as per the guidelines of the Norwegian Polar Research Institute for keeping a world-wide watch on icebergs had been a part of glaciological programme of the GSI since the beginning of Indian Antarctic Expedition. The observations include recording the location, dimensions and morphological characteristics of the icebergs observed during the cruise. As the journey to Antarctica was performed by flight, this data could not be taken up during the current expedition.

METHODOLOGY

In response to global climate change, the glaciers in Antarctica are also influenced. These glaciers respond to this change rather quickly and show direct evidence in terms of recession. The monitoring of DG glacier snout was started in 1983 from a fixed survey point. In 1993, another fixed reference point was added. Later on, in the year 1996, nineteen more observation points were added along the periphery of the snout. The projected points were measured from these fixed points along a particular direction using various electronic measuring devices and meter tapes. The position of the glacial front is measured annually at the end of peak austral summer (usually during end of January or first week of February) at these fixed points along the arrow mark at a certain angle towards the glacier snout wall painted on these locations. Since more and more new area was vacated by the glacier snout during recent years, carrying out the measurements using the old points was becoming cumbersome. To tackle this problem, additional points were fixed at selected locations during XXVII Indian Scientific Expedition to Antarctica [Swain and Roy, 2011]. These points were numbered using the old convention with a '/08' prefix to ensure continuation of the observations. In order to have a better understanding of the recession or advancement of ice sheet in this part of East Antarctica, the study was extended by fixing another 18 observation points along the margin of the polar ice sheet occurring as a wall in the western flank of the Dakshin Gangotri glacier in the year 2001 (Fig. 1 and 2) and are named as Western wall observation points. The position of the DG glacier snout and the western wall is noted every year to record the position of the continental ice sheet overriding the Schirmacher Oasis with respect to the fixed points. The arithmetic average of the advancement / recession of all the peripheral points are taken as annual average advancement /

recession for that particular year. The movement of the ice sheet has also been observed in a collaborative programme between GSI and IIG using high precision D-GPS, strategically fixed on the ice surface farther south in the vicinity of the DG glacier snout area during 2002-04 [Sunil et al., 2007].

The observation of snow accumulation or ablation with the help of a network of systematically arranged stakes on ice shelf near earlier Dakshin Gangotri station in India Bay region is also an annual programme. These observations have been carried out by periodically (annual) monitoring a fixed network of 16 graduated stakes at intervals of 50 m in a grid pattern. This observation is carried out by measuring the exposed height of the stake - network. To understand the accumulation / ablation pattern on Polar Ice sheet, a new network of 16 stakes (Fig. 5 and 6) were fixed at 4 km south of Novo Airport in a grid pattern with the distance between each stakes fixed at 50 m, thus encompassing an area of 150 X 150 sq m and the exposed height of the stake readings were taken.

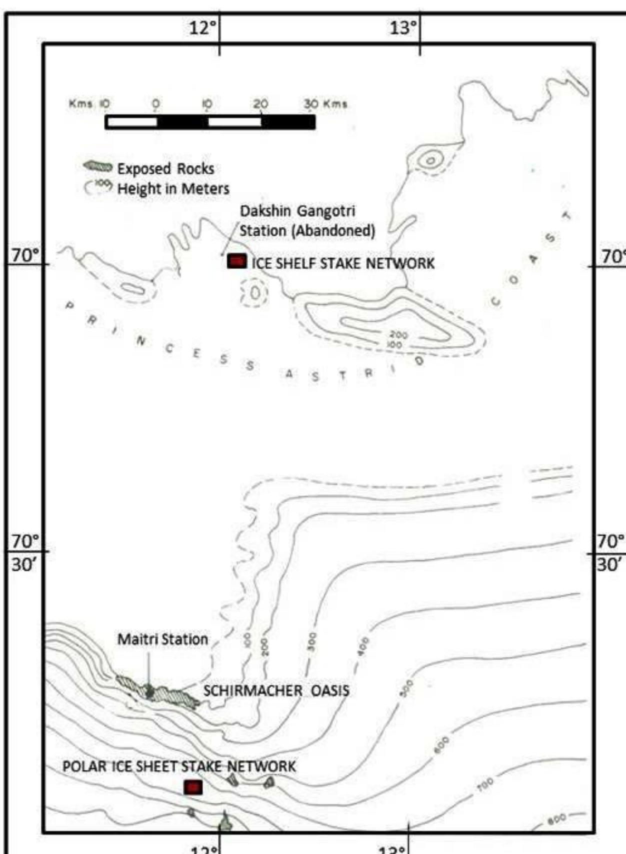

Fig. 5. *Stake Network locations on Ice shelf and Polar Ice sheet in cDML, East Antarctica.*

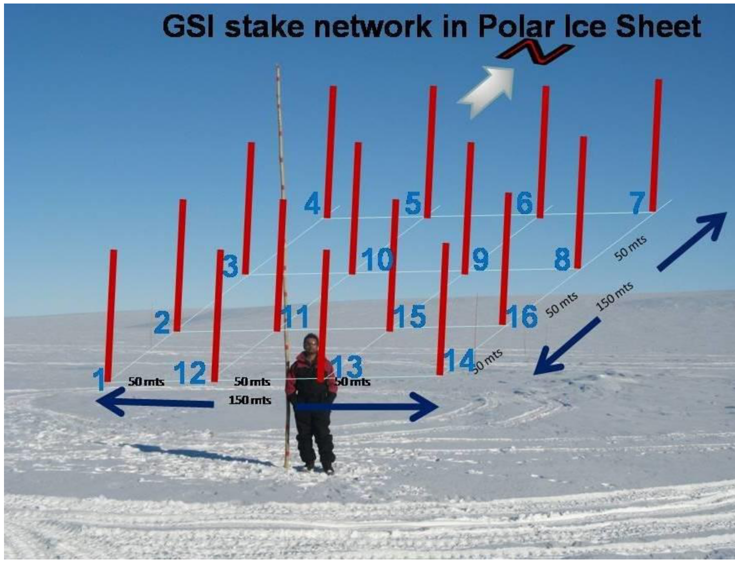

Fig. 6. *New Stake Network established on Polar Ice sheet during 2010-11.*

RESULTS AND DISCUSSIONS

Various workers [Kaul et al., 1988; Singh and Jayaram 1989; Mukerji et al., 1995; Chaturvedi et al, 1999 a,b, 2005, 2008, 2009; Ravindra and Dey, 1992; Shrivastava et al, 2011 a,b; Swain and Roy, 2011] have studied the trends followed by DG glacier snout. Chaturvedi et al. [1999a] observed that the recession of the snout is accelerated by the calving process in which the upper layers of the ice front move faster relative to the lower ones resulting in cracks along which calving occurs. Mukerji et al. [1995] have provided interesting information on the overall area vacated by the retreating glacier body in three early periods between 1983 and 1992. The advancement of southern flank between 1983 and 86 was reported by Kaul et al. [1988]. The overall recessional trend between 1996 and 2005 was explained by Chaturvedi et al. [2009]. The advancement of glacier front during the winter months was reported by Chaturvedi et al. [1999a]. Swain and Roy [2011], Shrivastava et al. [2011 b] and Swain et al. [2011] have reported the annual average recession rate as 110 cm in 2007-08, 108 cm in 2008-09 and 76 cm in 2009-10.The accumulation/ablation studies were initiated in 1983 during the second expedition [Kaul et al., 1985] but, the regular monitoring of the behaviour of the snow surface in terms of level variation due to accumulation/ablation started only during the Fifth expedition [1985-87] [Singh et al., 1988]. According to Asthana et al. [1996] and Beg et al. [1997], the average annual accumulation of snow was 18.71 gm/ sq cm between 1990 and 1994. A net yearly accumulation of 66.50 cm of snow was recorded during March 1996 to March 1997 amounting to a net rise of 2.20 cm on the shelf surface [Chaturvedi et al., 1999c]. A summary of the accumulation ablation of snow in last two decades was reported by Chaturvedi et al. [2005]. There exists a wide variation in the accumulation rates of succeeding years.

Observations during 30th ISEA

The glaciological observations carried out during 30th expedition (2010-11) are grouped under following five categories.

a) One set of measurement of the advancement / recession of Dakshin Gangotri Glacier snout.
b) One set of measurement of the advancement / recession of the ice wall in western extension of the DG glacier snout.
c) The measurement of snow accumulation / ablation on ice shelf.
d) Fixation of new stake network on ice shelf.
e) Fixation of new stake network on Polar Ice sheet.

Dakshin Gangotri (DG) Glacier snout

The current readings are taken from these new observation points. The continuous monitoring of DG glacier snout, overriding Schirmacher oasis shows continuous recession like previous years, but the intensity of recession differs at different points (Fig. 7, Table 1). The data was taken on 31 January 2011, which was the peak of the austral summer period for 2010-11. This date was chosen to see the maximum recession of the glacier snout under observation. In total there are 19 points of observation covering the whole span of the periphery of the snout and are numbered systematically from the south-eastern to north-western end, passing through the central part, in front of which a proglacial lake has formed in recent years after the glacier vacated the land. Among these 19 recorded points (Table 1) (Fig. 7), 18 points show marked

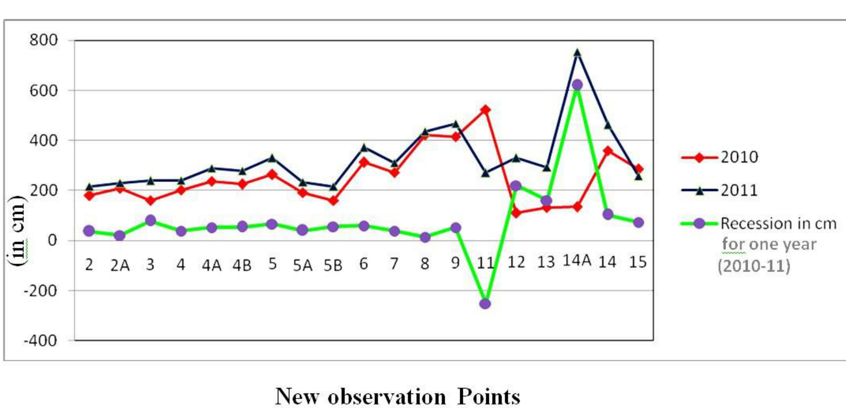

Fig. 7. *Recession in Dakshin Gangotri glacier snout.*

recession in the year 2010-11 compared to the previous years. The snout has continued to show recessionary trend as in the previous years. The data indicates that the average annual retreat of the snout during the year 2010-2011 is 0.81 m. The glacial front has advanced at point 11, situated along the northern side of the snout by 2.52 m. In the year 2009-10, this point has shown maximum recession of 3.93 m [Swain et al., 2011]. Maximum recession of 6.20 m was observed at point 14A during 2010-11.

Table 1:

New Observation Points	28-Jan-10 readings in cm	31-Jan-11 readings in cm	Recession in cm
2	180	217	37
2A	209	230	21
3	161	239	78
4	202	240	38
4A	237	289	52
4B	225	280	55
5	264	330	66
5A	193	233	40
5B	160	216	56
6	313	372	59
7	272	310	38
8	422	436	14
9	415	468	53
11	523	271	-252
12	110	330	220
13	132	293	161
14A	134	754	620
14	359	462	103
15	285	258	73
Total advance/recession from all 19 points			1532
Average annual recession = 1532/19 = 80.63 cm ~ 0.81m			

Glacier wall along Schirmacher Oasis – Polar ice sheet margin

Observations were also made along the western extension of the ice wall to see the impact of advancement / recession. Glaciological data has been collected from sixteen points (Table 2) and compared with that of the previous year (2009-10) and the baseline data of 2001. It shows that the average annual recession of the western wall is 1.19 m (Table 2). In a dataset of fifteen observed points (from where data is available for both years), seven points show advancement and eight points show recession (Fig. 8). Advancement is noticed at locations XX3, XX4, XX6, XX8, XX9, XX12 and XX15. The maximum advancement of 3.65 m is recorded at XX6 whereas the maximum recession of 12.7 m is observed at XX13. It has shown a total average recession of 18.42 m from the year 2001.

The DG glacier snout has consistently shown a retreating trend and the western wall has receded more than the DG glacier snout. The western wall has receded by an annual average of 1.19 m during 2010 - 2011, while the DG glacier snout has receded by only 0.81 m.

Table2. Location and distance record to fixed points as observed in the Western wall, Dakshin Gangotri glacier with its annual and average recession.

Fixed Points	Latitude (S)	Longitude (E)	2001 data in m	2010 data in m	2011 data in m	Recession (2010-11) in m	Recession (2001-11) in m
XX2	700 44.603’	110 26.390’	1.06	51.65	54.48	2.83	53.42
XX3	700 44.621’	110 26.529’	0.95	59.25	58.60	-0.65	57.65
XX 4	700 44.729’	110 27.660’	0.78	22.60	21.05	-1.55	20.27
XX 5	700 44.797’	110 28.147’	1.53	16.60	16.90	0.30	15.37
XX 6	700 44.879’	110 28.562’	2.67	27.85	24.20	-3.65	21.53
XX 7	700 44.932’	110 28.905’	2.53	11.87	12.20	0.33	9.67
XX 8	700 45.225’	110 31.120’	2.50	21.00	17.38	-3.62	14.88
XX 9	700 45.268’	110 31.401’	1.72	6.73	6.50	-0.23	4.78
XX 10	700 45.300’	110 31.614’	3.30	21.08	21.35	0.27	18.05
XX 11	700 45.417’	110 33.135’	1.84	10.24	10.73	0.49	8.89
XX 12	700 45.428’	110 33.289’	1.08	10.40	8.42	-1.98	7.34
XX 13	700 45.407’	110 33.478’	1.58	6.20	18.90	12.70	17.32
XX 14	700 45.403’	110 33.619’	1.02	14.85	15.92	1.07	14.90
XX 15	700 45.424’	110 33.733’	4.06	5.43	4.50	-0.93	0.44
XX 16	700 45.436’	110 34.022’	0.53	2.44	14.90	12.46	14.37
XX 17	700 45.631’	110 34.739’	0.94		16.78		15.84
XX 18			2.87				
Total recession from 15 observation points where data could be recorded in 2010 and 2011 =						17.84	
Annual average recession = 17.84 / 15 =						1.1893 ~ 1.19	
Total recession from 16 observation points where data could be recorded in 2001 and 2011 =							294.72
Annual average recession = 294.72 / 16 =							18.42

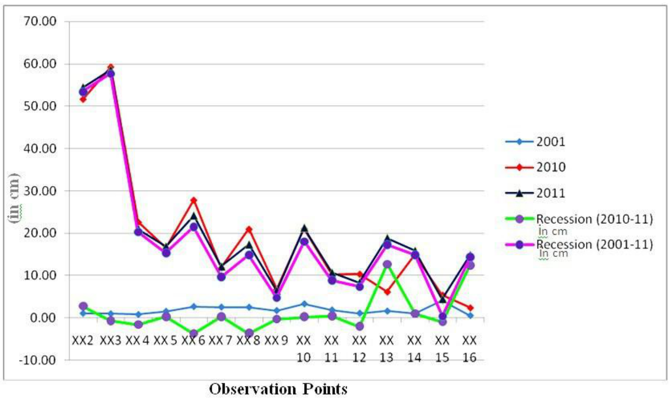

***Fig. 8.** Recession in Western wall of the Dakshin Gangotri Glacier. Table1. Annual Recession of Dakshin Gangotri Glacier Snout.*

Snow accumulation / ablation studies

Monitoring of the accumulation/ ablation of snow over the shelf in the erstwhile Dakshin Gangotri station area with the help of an array of 16 stakes evenly spread over an area of 150 x 150 m2 was carried out annually till 2008-09 period. During 2009-10, the earlier stake network got buried below the ice and a new network of 8 stakes was fixed on the ice-shelf and the initial readings were recorded [Swain et al., 2011]. In the current expedition, the data taken from this stake network on ice shelf (Table. 3) shows the net accumulation of 33.50 cm snow in one year (2010-11). A new network of 20 stakes has been fixed on ice shelf in this area and initial readings are taken to augment the area of snow accumulation / ablation studies (Table 4). These readings would be compared with the next year's observations to find the accumulation / ablation pattern. As a result, there are two stake network comprising of 8 and 20 stakes are fixed on ice shelf, from which data can be collected each year.

Table 3. Location and height record of the stake network on Ice Shelf.

Stake No.	Latitude (S)	Longitude (E)	2010 data	2011 data	Net accumula-tion (cm)
1	700 04.115’	120 01.390’	189	160	29
2	700 04.148’	120 01.377’	195	150	45
3	700 04.170’	120 01.353’	171	147	24
4	700 04.198’	120 01.333’	182	133	49
5	700 04.205’	120 01.433’	182	160	22
6	700 04.177’	120 01.428’	179	143	36
7	700 04.143’	120 01.435’	183	135	48
8	700 04.123’	120 01.443’	165	150	15
Net accumulation of 8 stakes =					268
Average annual accumulation of the stake network = 268 / 8 =					33.5

Table 4. Location and height record of the second stake Network on Ice Shelf.

S. No.	Latitude (S)	Longitude (E)	Exposed Height (cm)
1	70º 04.414’	12º 01.185’	419.1
2	70º 04.390’	12º 01.113’	429.3
3	70º 04.382’	12º 01.155’	449.6
4	70º 04.391’	12º 01.190’	439.4
5	70º 04.389’	12º 01.271’	457.2
6	70º 04.413’	12º 01.266’	457.2
7	70º 04.433’	12º 01.188’	457.2
8	70º 04.429’	12º 01.101’	454.7
9	70º 04.422’	12º 01.000’	482.6
10	70º 04.395’	12º 01.010’	464.8
11	70º 04.370’	12º 01.027’	452.1
12	70º 04.343’	12º 01.042’	462.3
13	70º 04.349’	12º 01.117’	457.2
14	70º 04.355’	12º 01.195’	452.1
15	70º 04.361’	12º 01.270’	457.2
16	70º 04.367’	12º 01.348’	457.2
17	70º 04.393’	12º 01.348’	454.7
18	70º 04.413’	12º 01.349’	452.1
19	70º 04.439’	12º 01.346’	457.2
20	70º 04.437’	12º 01.269’	449.6

To assess the snow accumulation / ablation on the Polar Ice Sheet, a new stake network was fixed, 4 km south of Novo Airport, Antarctica and initial records were taken (Table 5). These readings would be compared with the next year's observations to find the accumulation / ablation pattern. This network is only one in the Polar Ice sheet so far in addition to two similar networks of stakes on ice shelf.

Table 5. Location and height data of the New Stake Network on Polar Ice sheet.

Stake No.	Latitude in degree and Minute (S)	Long in degree and Minute (E)	Exposed Height in (cm)
1	700 50.533’	110 37.793’	529
2	700 50.507’	110 37.776’	523
3	700 50.480’	110 37.764’	521
4	700 50.452’	110 37.748’	521
5	700 50.448’	110 37.855’	519
6	700 50.449’	110 37.936’	523

Stake No.	Latitude in degree and Minute (S)	Long in degree and Minute (E)	Exposed Height in (cm)
7	700 50.446’	110 38.009’	526
8	700 50.475’	110 38.028’	520
9	700 50.479’	110 37.945’	524
10	700 50.476’	110 37.862’	527
11	700 50.504’	110 37.872’	521
12	700 50.536’	110 37.877’	521
13	700 50.537’	110 37.962’	515
14	700 50.540’	110 38.051’	515
15	700 50.509’	110 37.953’	521
16	700 50.505’	110 38.031’	520

CONCLUSIONS

The data collected at Polar Ice sheet – land interface along part of the southern margin (termed as Dakshin Gangotri glacier) of Schirmacher Oasis and the snow accumulation / ablation studies on the ice shelf are providing important information in understanding the changes in the advancement-recession of the glacier and accumulation- ablation variation on ice shelf and polar ice sheet. The arithmetic mean of the recessions at different fixed points along the ice margin during one year of observation is calculated as the average annual recession. An average annual retreat of 0.57 m was recorded during the period 1983 to 1995 [Chaturvedi et al., 2005]. The rate of recession from 1996 onwards is fluctuating [Chaturvedi et al., 2009]. Swain et al., [2011] have reported the annual average recession rates as 1.1, 1.08 and 0.76 m in 2007-08, 2008-09 and 2009-10 respectively, which are comparatively higher than that of the base line data of 1996-97. Field observations show that the factors like topography of the area, the exposure time of the different segments of the glacier snout to the solar radiation and internal dynamics of the glacier of this region are contributing to the recession of the DG snout [Shrivastava et al., 2011 a]. In the year 2011, DG glacier snout has receded by an annual average of 0.81 m as compared with the previous year. The recession varies at different points (Fig. 7).

In the peripheral part of DG glacier snout, the fixed point numbers 12, 13, 14A and 14 show greater annual recession in 2011 (more than 1 m) as compared with the previous year, whereas the glacial front shows advancement of 2.52 m at point 11 (Table 1). Probably this point attributes to a collapse of the ice wall along the periphery. The points showing greater recession are situated at the northern extremity of the DG glacier snout, getting more insolation of solar energy resulting in greater recession.

In the Western wall sector of the glacier front, seven locations at XX3, XX4, XX6, XX8, XX9, XX12 and XX15 showed annual advancement (Fig. 8; Table 2), while rest have shown recession. Annual average recession of the Western wall is calculated to be 1.19 m, whereas in one decade it has recorded by 18.42 m with 2001 as base. The greater recession of ice in the Western wall compared with the DG glacier snout, might be related to its topographic disposition as the observation points of the Western wall are situated at higher elevation compared to that of the DG glacier snout, thereby exposing to higher insolation.

A summary of the accumulation/ ablation of snow in last two decades were reported by Chaturvedi et al. [2005], which shows that there is a wide variation in accumulation trend every year from 1983 to 2003. An annual average accumulation of 5.90 cm was reported in 2007-08 [Swain and Roy, 2011] and 74.20 cm in 2008-09 [Shrivastava et al., 2011]. In the year 2010-11, the earlier stake network got buried below the ice and thus data could not be recorded [Swain et al., 2011], but in 2010-11, the average annual recession is calculated by 33.50 cm. In 2011, the area of observation is widened by fixing 20 more stakes in the existing area and a network of 16 stakes was fixed on Polar ice sheet to understand the accumulation/ ablation pattern in this zone. This fixation of a stake network on Polar ice sheet may turn out to a landmark event in glaciological studies by India at Antarctica for the mass balance calculation of the Polar ice sheet.

Acknowledgements

Authors are thankful to Director General, Geological Survey of India and Dy. Director General, Mission IV for providing opportunity to work in Schirmacher Oasis of East Antarctica. Authors are also thankful to the Director, Director (Logistics), National Centre for Antarctic and Ocean Research, Goa and the Leader as well as Expedition members of 30th Indian Scientific Expedition to Antarctica for providing logistic support during the Expedition. We are also thankful to the then Director, Antarctica Division, GSI for his constant guidance and all the officers of the Division for their overall support.

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