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Impact of inter- and intra-annual variation in weather parameters on mass balance and equilibrium line altitude of Naradu Glacier (Himachal Pradesh), NW Himalaya, India

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Abstract Glaciers in Himalaya have been studied with respect to their mass balance to assess their response, if any, to global warming. Naradu glacier in the Baspa Valley of Himachal Pradesh is one such glacier that has been studied in the backdrop of the impact of inter- and intra-annual variation in weather parameters on the health of glaciers. The trends in seasonal and monthly mean temperatures from 1994 to 2003 show an interesting shift of peak summer (late August–September) and winter seasons (February–March). The data also suggest night warming during summer (June, August, and September) and winter (November, January, April), and cooling during peak summer seasons (July) and very cold during winter (December, February, March). The fluctuation in ELA, snout position and surface ablation of Naradu glacier is attributed to variation in albedo of rock debris and valley walls from season to season and year to year.

1 Introduction

The equilibrium-line altitudes (ELAs) mark and the position where accumulation of snow over a period of one year is balanced by ablation reflecting a very close relationship between ELA and local climate, particularly the precipitation (snowfall) and air temperature (Benn and Lehmkuhl 2000). In response to decrease in snowfall

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and/or increase in air temperature, the ELA rises and vice-versa is also true. Fluctuation in ELA, therefore, is an indicator of glacier response to climate change. Relationship between temperature, solar radiation and precipitation at glacier ELAs have been established using statistical and analytical methods (Kuhn 1984; Ohmura et al. 1992; Shi et al. 1992; Seltzer 1994). Regional variation in ELA of glacier is used to determine precipitation gradient and also in reconstructing moisture sources and atmospheric circulation (Miller et al. 1975; Burbank and Kang 1991; Lehmkuhl et al. 1998). Furthermore, reconstructed glacier ELA is a mean to correlate moraines with glacier volume (Maisch 1982; Lehmkuhl 1997). Knowledge of glacier ELAs, therefore, is a source to proxy palaeoclimate data in mountain regions and allows to predict response of glacier to future climate change (Maisch 1982). Avalanche and debris cover on glaciers, however, complicate the relationship between climate and glacier distribution. The terrain characteristics also develop complexities in morphology and mass balance of a glacier. The present study is to understand the relationship between the local climate, glacier mass balance and ELA of Naradu glacier situated in the high mountain region of NW Himalaya.

2 Study area

Himalayan glaciers are confined to protracted zones of High Himalaya having high relative relief that is a cause for perturbations in ambient temperature generating katabatic winds in the glacier valley. The orography serves an important factor to affect the parameters of climate, such as albedo, sunlight duration, solar radiation, adiabatic lapse rate, etc., causing significant variation in degree-day melting of glacier and precipitation regime of the glacier valley.

Naradu glacier (Fig. 1), in the High Himalaya of District Kinnaur, Himachal Pradesh, is located near village Chitkul on Hindustan-Tibet Highway No. 22 (Shimla-Reckong Peo Road). The glacier is located in the upper reaches of Naradu Garang (valley) enclosed by high mountain peaks, namely Khimsung (5,600 m), Khomsung (5,700 m) and Khimloga (5,400 m), in south and southeast of the valley. The south boundary of the valley is a water divide between the Sutlej and the Ganga basins that also happens to be the major divide of the first order basins of the Indus and the Ganga in India. The glacier is one among the 89 glaciers of Baspa basin that forms the fifth order basin of Sutlej river.

Naradu glacier is 5.15 km in length and covers an area of 4.56 km^2. It originates from an altitude of 5,400 masl in the vicinity of Khimloga Pass. The NE–SW oriented glacier terminates at an altitude of 4,395 masl (snout). The irregular outline of snout is covered with supra-glacial material. The glacier is distributed in four treads punctuated by steps. The first tread extends from snout to an altitude of 4,520 masl and has a gentle gradient covering an area of 19.6% of the glacier. A raised stairway lies between 4,520 and 4,560 masl covering an area of 2.76%. The second tread extends between an altitude of 4,560 and 4,920 masl and covers an area of 27.84% of the glacier. From the equilibrium line at 4,920 masl to an altitude of 5,080 masl there is another tread of moderate gradient covering an area of 26.50% of the glacier. The fourth and last tread, with moderate gradient, extends between the altitude of 5,080 and 5,200 masl and covers an area of 12.6% of the glacier. Above 5,200 masl lies a deep trough with serrated ridges that covers an area of 9.7% of the glacier.

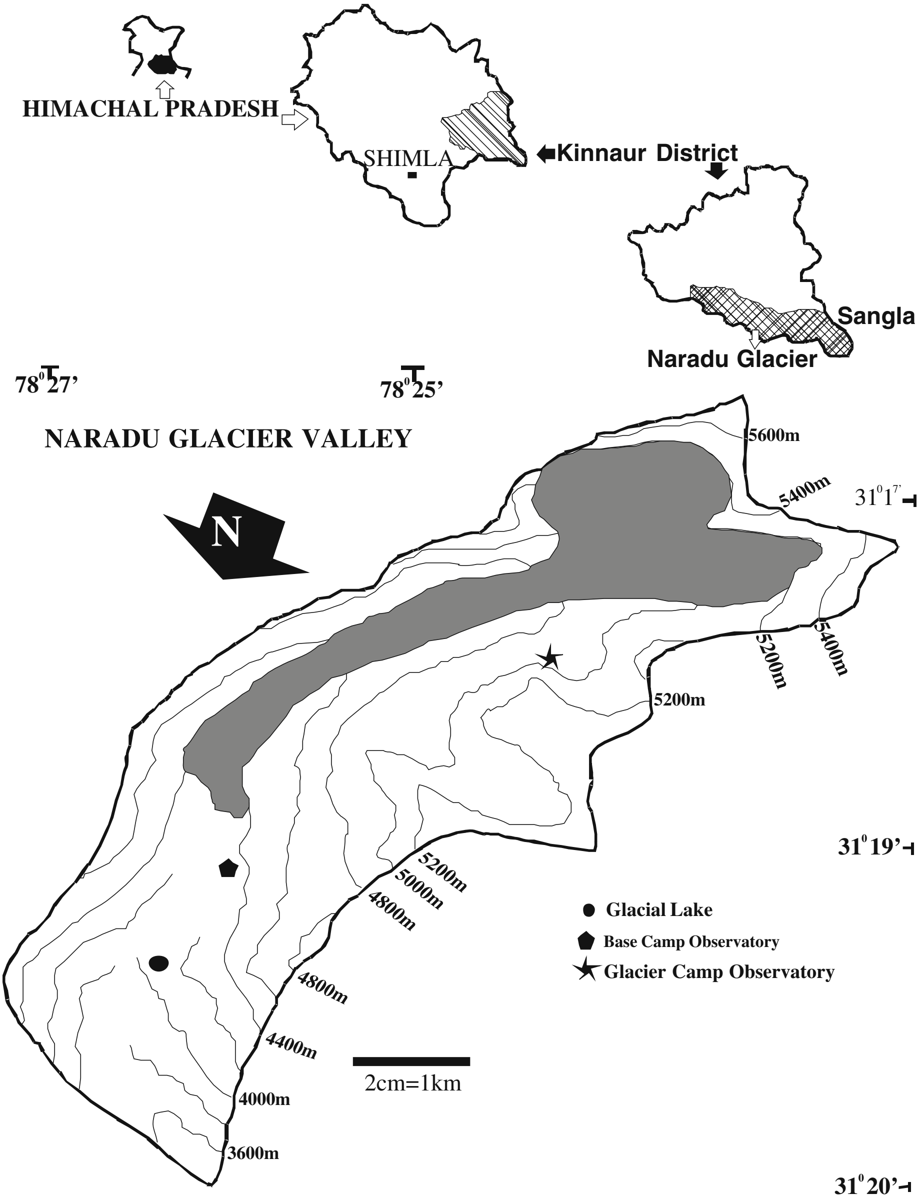


Fig. 1 Location map of Naradu glacier, District Kinnaur, Himachal Pradesh (India) with location of observatories marked

3 Methodology

A few studies have been carried out on the mass balance of Himalayan glaciers (Raina and Kaul 1977; Kumar and Dobhal 1994; Srivastava and Swaroop 1996; Gergan et al. 1999; Srivastava et al. 2001; Dobhal et al. 2004; Kulkarni et al. 2005).

Mass balance study of Naradu glacier emphasizes an annual mass estimation through residual accumulation and ablation techniques. The mass balance of Naradu glacier is estimated for the years 2000 to 2003 by monitoring the ablation stakes (bamboo sticks with aluminum pointed base) fixed on glacier body at the end of ablation season (October). Forty-six ablation stakes were fixed on the glacier body during August–September 2000 after drilling holes in the ice with the help of portable ice auger so as to fix the stakes firmly in ablation zone from snout (4,395 m) to accumulation zone (5,000 m). Additional eight stakes were fixed on the glacier body during the ablation season of 2001 between the altitudes of 4,400 to 4,700 masl along the debris covered zone to assess the impact of debris on rate of melting. The ablation stakes fixed on Naradu glacier were monitored on a regular fortnightly basis from the months of May to October for the years 2001 to 2003. At the end of each ablation season (October), net accumulation and net ablation is measured from the thickness, density and water equivalent of residual snow, by opening pits in the snow/ice of accumulation zone.

To assess the annual variation in weather parameters and its impact on glacier dynamics and geomorphology of Naradu Garang, two meteorological observatories were set up—one near the glacier snout and second at glacier firn line. An automatic weather system (AWS, Model DT 50—Earth and Atmospheric Sciences, USA) with its sensor package operating on solar batteries, mounted on galvanized steel tower fitted with A-50 data logger and other accessories (a set of 12 V batteries operated on solar system) and housed in weather proof enclosures was installed at an altitude of 4,100 masl during 1994 field season, and the site was designated as base camp observatory. The sensors comprise air temperature, humidity, speed and direction of wind, cloud, precipitation (snowfall and rainfall), solar radiation, sunshine hours and albedo. The weather station has a resolution of 0.1°C and with an accuracy of ±1% of full scale, and has been monitoring the data on daily basis between 1994 and 2003. A manual observatory was setup in the year 2000 at an altitude of 4,950 masl in the vicinity of firn line to study the general weather condition near accumulation zone particularly to monitor minimum and maximum temperature, solid precipitation (snowfall), and speed and direction of wind. The observatory designated as glacier camp observatory was in use during the periods of visit to the glacier site for a short duration of ablation season (May to October).

Number of statistical techniques is used to understand the relationship between mass balance and meteorological variables particularly the correlation between glacier fluctuation and external climate variables (Dobhal et al. 2004; Haeberli and Beniston 1998; Haeberli and Heolzle 2000; Kulkarni et al. 2002; Naithani et al. 2001; Oerlemans 2000; Singh et al. 2005).

4 Meteorological observations

Naradu glacier has a distinct climatic characteristic owing to its location in higher altitude and it being enclosed on three sides by mountains. The study region has alpine to sub-Mediterranean type of climate and receives nearly 70% of annual precipitation in winter and springs in the form of snowfall, and only 30% in the form of rainfall near snout and in the form of dry snow in higher-up regions.

The meteorological data of Naradu Garang for a record length of 10 years (1994–2004) is useful to assess seasonal change, if any, in mean maximum and minimum temperature of glacier basin. Short term records of different parameters, particularly temperature (maximum, minimum), precipitation (rainfall, snowfall), solar radiation, sunshine hours and direction of wind, are useful tools for the computation of mass balance. Glaciers are the dynamic reservoirs of constantly exchanging mass with parts of global hydrological system, processes by which glaciers gain or loose snow and ice and establish a link between climate, glacier mass balance and glacial fluvial dynamics. Variability of climate and its impact on mass balance have been reported from Alps and Rockies (Bowling 1977; Brinkman and Barry 1962). However, conflicting signals of change in climate, in terms of change in temperature, snowfall and snow extent is reported from west Himalaya (Fowler and Archer 2006; Yadav et al. 2004; Bhutiyani et al. 2007). 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 are largely due to winter time anomalies in accumulation which in turn are mainly due to anomalies in precipitation and temperature (Letreguilly 1988).

4.1 Temperature

The mean monthly maximum summer temperature from June, July, August and September is 14.7°C, 15.6°C, 13.8°C and 12.5°C, respectively for the years 2000 and 2001 as compared to 13.6°C, 13.5°C, 12.7°C and 9.9°C for the years of 2002 and 2003. During summer season, particularly, in July and August highest maximum temperature ranged between 18.9°C and 21.8°C in the years 2000 and 2001, respectively as compared to 17.6°C and 19.9°C during 2002 and 2003, respectively. The degree variation of standard deviation of mean maximum temperature during the summer months ranged between 2.34–1.92°C, 2.59–1.5°C, 2.56–1.15°C and 2.34–1.36°C (Fig. 2) during 2000,2001, 2002, and 2003, respectively indicating higher range of dispersion in maximum temperature during 2000–2001 in comparison to 2002–2003.

The mean minimum temperature during the winter season (November, December, January, February, March and April) ranged between −5.2°C and −16.9°C for the years 2000 and 2001, and between −6.1°C and −18.6°C for the years 2002 and 2003, showing a degree variance of standard deviation of 1.24–2.04°C, 0.67–2.56°C and 1.19–2.63°C (Fig. 2) with the maximum dispersion in December and February.

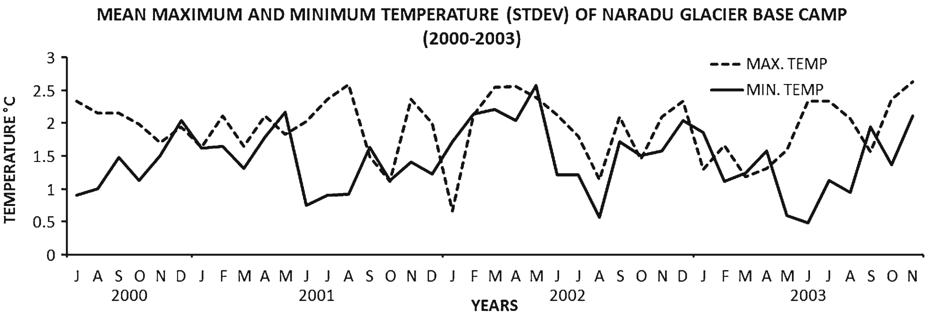
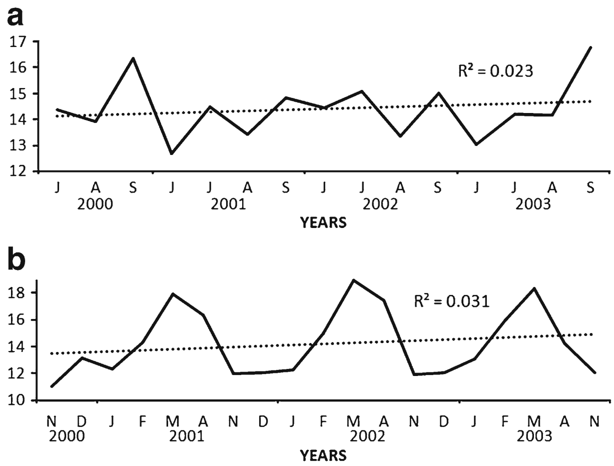


Fig. 2 Mean maximum and minimum temperature (standard deviation) from 2000 to 2003 of Naradu glacier base camp

Fig. 3 **a** Diurnal range of temperature (summer). **b** Diurnal range of temperature (winter)



The monthly diurnal temperature range during summer (Fig. 3a) and winter (Fig. 3b) season show an increasing trend. The average diurnal range of summer season is 15.2°C and of winter is 14°C. The highest diurnal range is in March (18.4°C) and September (16.4°C).

The mean maximum temperature varies from 9.7°C to −6.3°C in accumulation zone of glacier near ELA (4,950 m, vicinity of glacier camp observatory), and from 16.3°C to 5.4°C near snout (base camp observatory) during summer season (Table 1).

The comparative analysis of monthly diurnal range during summer season as shown in Table 1 shows mean range of temperature at glacier surface is lower by 2.3°C. The small difference in range at two sites is possibly due to short period of observation during the stipulated summer season. The average mean summer

Table 1 Comparative statement of temperature range at snout and equilibrium line of Naradu glacier

Year	2000	2001	2002	2003
Temperature range near equilibrium line (4,950 m)				
Highest max. temp.	8.9 (September 5)	9.8 (July 11)	10.2 (July 17)	7.8 (August 31)
Lowest min. temp.	−8.2 (September 17)	−5.0 (July 25)	−5.8 (July 28)	−6.3 (August 21)
Range	17.1	14.6	16	14.1
Mean = 15.5				
Mean diurnal range	13.8	11.7	13.2	9.4
Mean = 12.02				
Temperature range near glacier snout (4,395 m)				
Highest max. temp.	18.9 (July 4)	21.8 (July 17)	19.9 (July 11)	19.6 (August 5)
Lowest min. temp.	7.6 (July 22)	9.5 (July 28)	5.8 (July 13)	5.4 (August 19)
Range	11.3	13.3	14.1	14.2
Mean = 13.2				
Mean diurnal range	14.8	13.8	14.2	14.5
Mean = 14.3				

temperature for 2000 and 2001 is 10.9°C whereas for the years 2002 and 2003 it is 8.8°C.

4.2 Solar radiation

The mean maximum solar radiation follows the seasonal trend higher during the summer season (435 to 510 W/m^2) and least during the winter season (219 to 278 W/m^2). The highest maximum solar radiation is received during the month of July and August (952 W/m^2) and the lowest minimum in January and February (163 W/m^2). The mean monthly maximum solar radiation from June to September is 504, 590, 565, 490 W/m^2 respectively for the years 2000 and 2001 as compared to 500, 504, 538 and 454 W/m^2 for the years 2002–2003 (Fig. 4), with a standard deviation variation of 202, 262, 245, 175 and 242, 245, 258 and 196 W/m^2, respectively. It reveals more or less similar dispersion of solar radiation data during the summer seasons. The average solar radiation during the winter season (November to April) for the years 2001 and 2002 is 250 W/m^2, whereas for the years 2000 and 2003 it is 280 W/m^2.

4.3 Sunshine hours

Sunshine hours is an indicator to assess degree-day melting of a glacier. It ranges between 6.80 and 9.40 h/day for the months of May to October. Peak sunshine (8.23 to 9.40 h/day) is from June to August (Fig. 4). The sunshine received in the years 2000 and 2001 is higher than the sunshine received in the years 2002 and 2003 (Fig. 3). The average sunshine hours are longer (8.3 h/day) in summer (May to October) for the years 2000, 2001 and 2003, as compared to the year 2002 (7.9 h/day). The mean sunshine hour during the winter season (November to April) for the years 2000–2001, 2001–2002 and 2002–2003 is 3.3, 2.8 and 3.8 h/day, respectively. The winter of 2000–2001 and 2001–2002 is relatively cool. A lag of 1 to 2 h is observed between the solar radiation and mean maximum temperature.

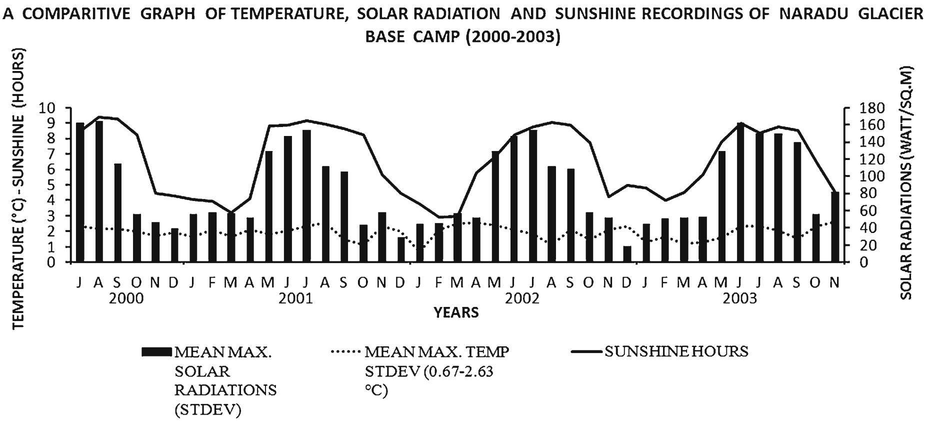


Fig. 4 Comparative graph of sunshiner, standard deviation of temperaure and solar radiation

4.4 Precipitation

Naradu glacier valley receives precipitation in the form of solid snowfall during the winter season due to western disturbances and liquid precipitation in the form of rainfall during summer season due to southwest monsoon. Most of the precipitation in higher reaches above snout is received in the form of solid precipitation both during summer and winter seasons.

An average daily precipitation from first fortnight of July 2000 to last fortnight of November 2003 varies from 2,202.5 to 1,815.2 mm. The average highest precipitation for the year 2000 is 767.2 mm, for the year 2001 is 2,082.7 mm, for the year 2002 is 2,202.5 mm, and for the year 2003 is 1,815.2 mm. The solid precipitation in the form of snowfall is converted into rain by water equivalent (w.e.v.) method. Out of total precipitation, contribution of snowfall is 277.7 mm (35.93 mm w.e.v.), 1,538.5 mm (199.02 mm w.e.v.), 1,562.2 mm (202.6 mm w.e.v.) and 1,273.7 mm(186.88 w.e.v.) for the years 2000, 2001, 2002 and 2003, respectively, revealing 66% to 75% of total precipitation in the form of snow. The pattern of snowfall varies on monthly and yearly basis (Fig. 5). 1,105.7 mm (142.55 w.e.v.) of snowfall took place between the months of January and May and rest (427.7–55.97 mm w.e.v.) between the months of October and December of the year 2001 suggesting that about 28% of snowfall took place in later part of the winter. Similarly, 1,374.14 mm (174.92 mm w.e.v.) of snowfall took place between the months of January and May, and 213.16 mm (27.12 mm w.e.v.) between the months of October and December of the year 2002 revealing that about 15% of snowfall took place in later part of the winter. In the year 2003, 1,132.33 mm (144.15 mm w.e.v.) of snowfall was between the months of January and May, and 159.2 mm between the months of October and November suggesting that only 12.5% of snowfall took place in the later part of winter of 2003. Heavy snowfall in later part of winter holds a considerable significance in terms of the health of glacier and helps in consolidating the ice, reducing the ambient temperature and degree-day melting that results in a positive impact on mass balance of Naradu glacier.

The rainfall pattern in Naradu glacier valley shows variation through the years from 2000 to 2003. The total rainfall for the years 2000 (July–December), 2001, 2002 and 2003 is 489.5, 544.2, 640.3 and 541.5 mm, respectively (Fig. 5). The rainfall takes place between July and September, with highest in August. Relative humidity varies from 51% to 99% in summer and 27% to 70% in winter. The rainfall is a cause for high discharge in Naradu Garang (tributary of Baspa river that is a tributary of

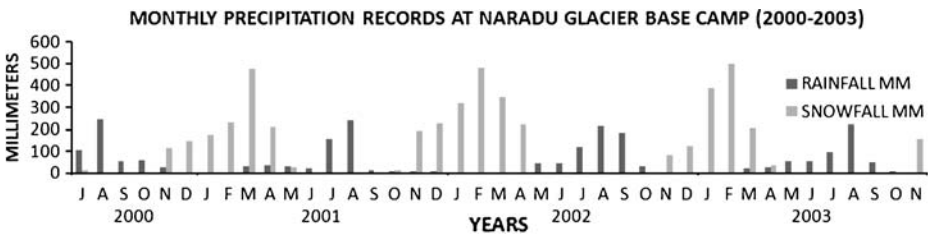
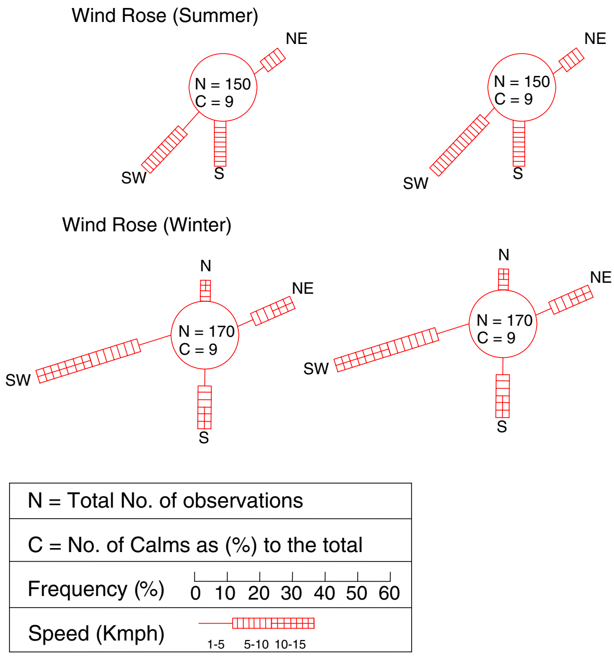


Fig. 5 Monthly precipitation at Naradu glacier base camp (4,395 m)

Fig. 6 Wind rose diagram of Naradu glacier valley



Sutlej) that results in erosion and transportation of debris from mountain slopes to valley and finally to the trunk river.

Based on the variation in precipitation and insulation, Naradu glacier valley is divided into three sub-zones—(1) ablation zone—from 4,470 to 4,980 masl with maximum yield in the form of water, (2) rain and snow zone—between 4,700 and 3,650 masl, and (3) watershed—area above 4,980 masl that receives precipitation in the form of snow.

4.5 Wind

The wind flows down the slope from Khimloga and Khomsung pass to Baspa valley in southwest and southeast directions at a speed between 3 and 10 km during summer season and between 5 and 15 km during winter season, with occasional change in direction to north and northwest. Wind is calm in the morning and gains momentum by noon and afternoon. Winds turn calm in the evening during the summer season, but in the winter, winds gain momentum during the night (Fig. 6).

5 Analysis of temporal temperature change

The assessment of inter- and intra-annual variability in weather conditions of Naradu glacier basin, on the basis of temperature data from 1994 to 2003, suggest a marked seasonality in weather with winter seasons (November–April) long, summer seasons (June–September) short, and spring and autumn of 1 month each duration. The micro-meteorological data from 2000 to 2004 has served a tool to correlate different meteorological parameters with mass balance inputs and equilibrium line altitude to assess the fluctuation records on glacier body.

Trends in annual, seasonal and monthly mean temperature were investigated for Naradu glacier from 1994 to 2003. The records have been analyzed by fitting linear least square trend line to assess the behavior of temperature during a period of 10 years. The analyses of seasonal mean maximum (Fig. 7a, b) and minimum (Fig. 8a, b) temperatures of each months of summer and winter season shows that

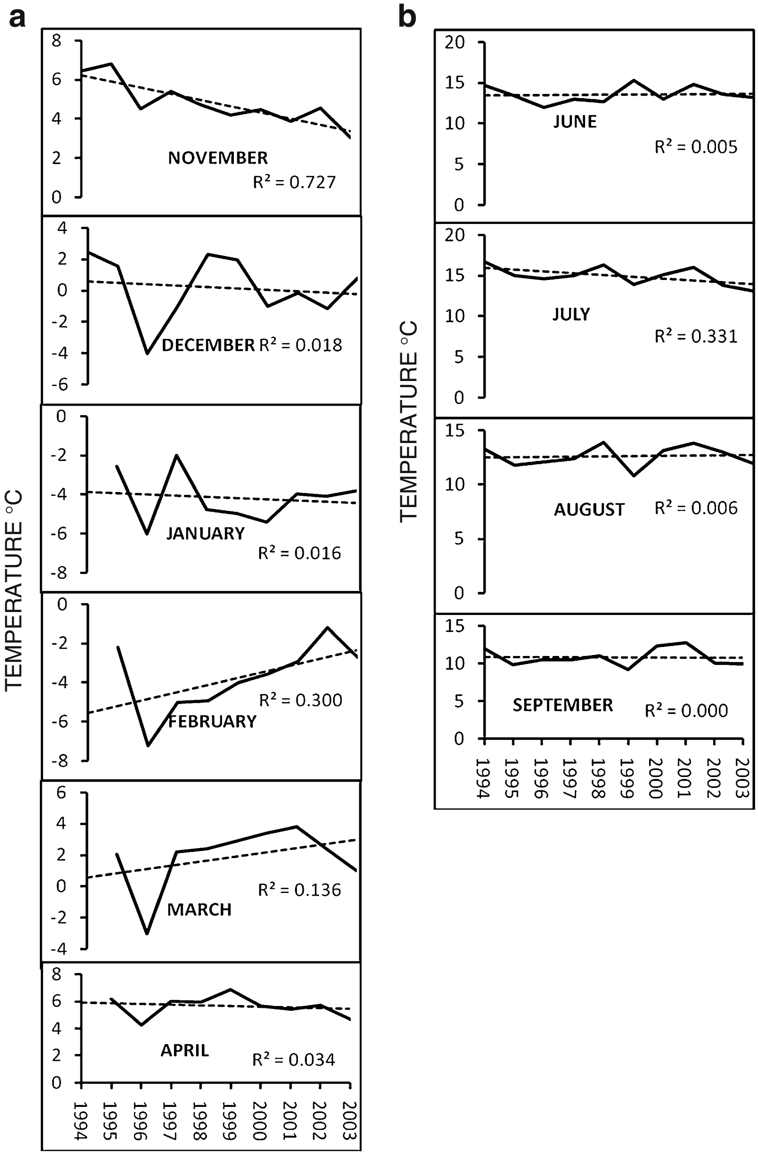


Fig. 7 **a** Mean monthly maximum temperature of winter at snout of Naradu glacier between 1994 and 2003. **b** Mean monthly maximum temperature of summer at snout of Naradu glacier between 1994 and 2003

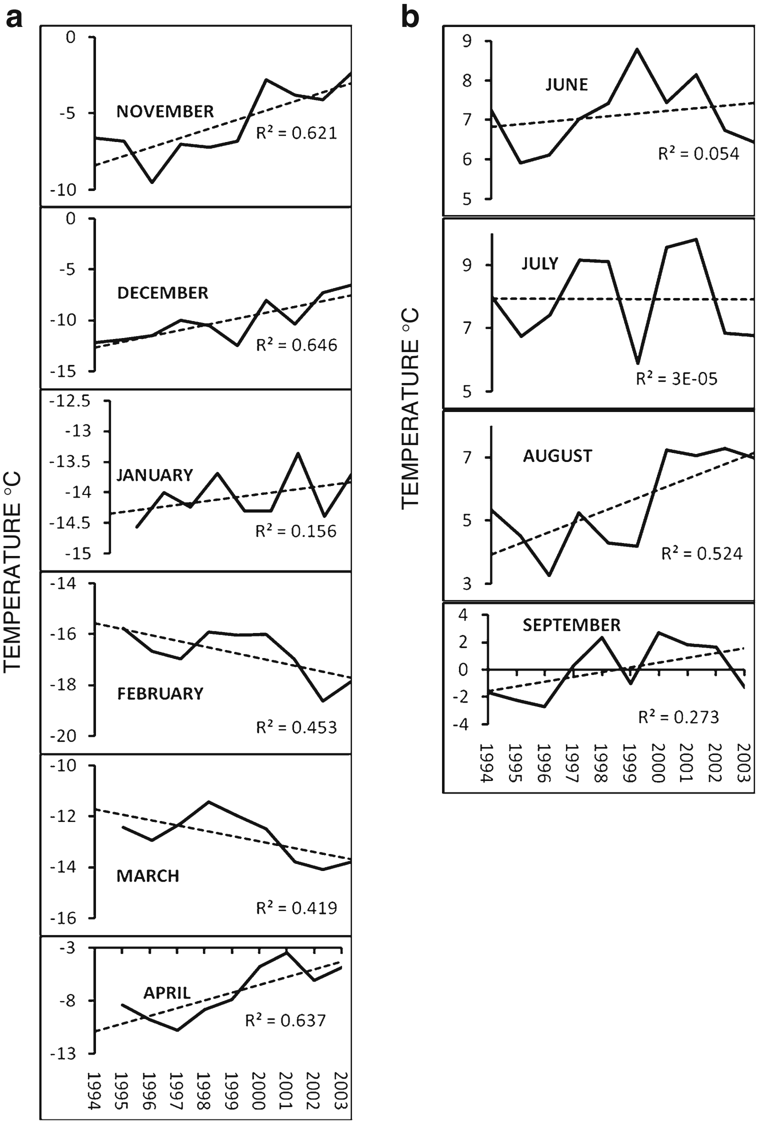


Fig. 8 **a** Mean monthly minimum temperature of winter at snout of Naradu glacier between 1994 and 2003. **b** Mean monthly minimum temperature of summer at snout of Naradu glacier between 1994 and 2003

mean maximum temperature during 1994–2003 had a decreasing trend during the peak summer and late winter season, thereby indicating cooling particularly during the months of June and July (summer) and February and March (winter). Observational records and reconstructions from tree rings reflect pre-monsoon temperature cooling in the western Himalaya during the later part of the twentieth century (Yadav et al. 2004).

During 1994, 1998 and 2001, the mean maximum temperature during June and July has shot up to 15°C and 16°C with rest of the summers comparatively cool. On the other hand, mean minimum temperature show increase in trend during 1997, 1998 and 2001, thereby indicating warming of nights during June, August, September (summer) and November, January, April (winter). Overall nights are cool in peak summer (July) and cold in December, January, March (late winter). The years 1996 and 2002 were the coldest years in the decade. The temperature analysis and their trend line shows an interesting shift of peak summer and winter seasons till late summer (August, September) and late winter (February to April).

6 The ELA and glacier mass balance

The steady-state ELA (the ELA values associated with zero annual mass balance for the whole glacier is known as steady-state ELA) for modern glacier should ideally be based on observations of glacier mass balance over several years. The ablation record of Naradu glacier is based on the observations made for three consecutive years from 2000 to 2003. Based on the observations the ablation is of two forms—surface and basal ablation.

6.1 Surface ablation pattern

The ablation data for 3 years (2001, 2002 and 2003) show that degree-day melting reaches 5.46 cm/day in peak melting season, i.e. July and August. The rate of ablation varies, both, with respect to altitude and onset of summer. The melting of glacier, in ablation zone, commences from the second fortnight of May (3.5 cm/day) and attains peak in July/August (5.4 cm/day). It declines to 4.5 cm/day in later part of August that corresponds to gradual decrease in summer temperature. The gradual decrease in the melting of glacier is from the month of September till it reaches as low as 0.5 cm/day in the month of October. The peak surface ablation of the area between equilibrium line and snout of the glacier is from the months of July to mid-August. The degree-day melting of Naradu glacier is high (3.5 to 5.4 cm/day) for the years 2000 and 2001as compared to the years 2002 and 2003 when the degree-day melting is between 3.5 and 4.5 cm/day (Fig. 9). The rate of melting in summers of the years 2001–2003 reaches as high as 5.46 cm/day in the ablation zone (4,600 and 4,720 masl). The melting retards in ablation zone from August (3.5 cm/day) and reaches to its lowest (0.5 cm/day) in October. The melting of glacier is appreciably low (0.1 cm/day) between the altitude of 4,720 and 4,920 masl for the same period of the year. The melting of glacier between the altitude of 4,600 m and the snout (4,395 masl) decreases from 2.5 to 1.4 cm/day for the summer period. The low rate of melting in this zone is primarily due to thick cover (almost 2 m) of supra-glacial material. The supra-glacial cover thins down to 0.5 m beyond the altitude of 4,720 masl. Variable rate of melting of Naradu glacier is dependent on the amount of solar radiation that reaches the glacier body which in turn depends on the thickness of supra-glacial material present at various altitudinal levels. High rate of ablation in summer is due to highest maximum temperature (19.9–22°C) and solar radiation. Solar radiation varies from 554 to 508 W/m^2 in the summers of years 2001 to 2003. High rate of melting of east part of snout is due to the fact that the part is free

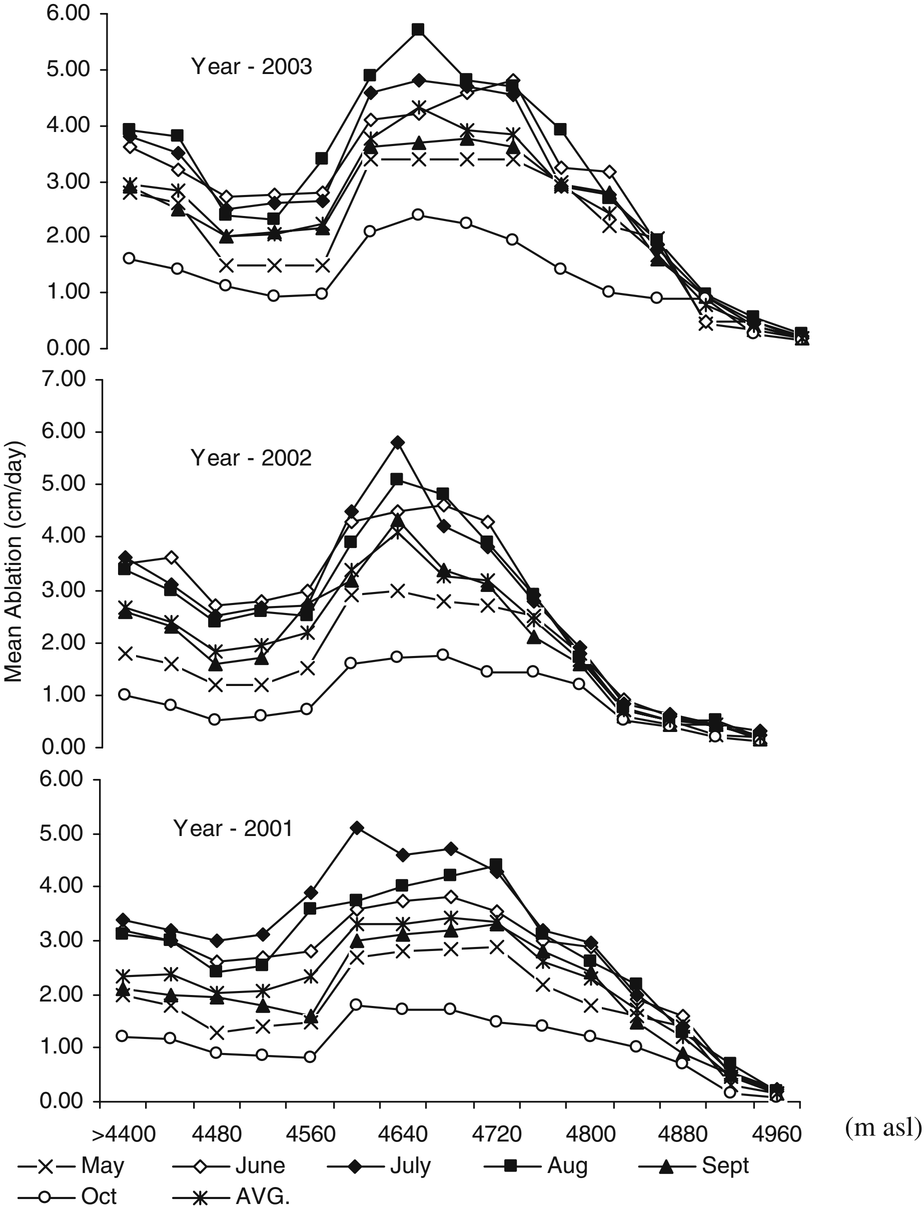


Fig. 9 Mean monthly ablation vs elevation

of debris cover. The west part of snout, on the other hand, is covered with 1.5 m thick debris that prevents incoming solar radiation from affecting the glacier surface and results in negligible melting. Variable rate of melting of snout has led to the development of an irregular outline of snout. Presence of transverse crevasses in the snout further adds to the variable rate of melting that leads to an irregular outline of the snout.

Surface melt estimation for the years 2001 to 2003 suggest a pattern that correspond to three altitudinal zones—4,395 to 4,600 masl, 4,600 to 4,760 masl, and 4,760 masl to equilibrium line. The net ablation of 24% to 26.38%, 53.8% to 66% and 7.2% to 16.6%, correspond to the three altitudinal zones, respectively. The three altitudinal zones encompass 53.8%, 49.8%, and 53.6% of the glacier area (Fig. 10a, b) respectively. The high accumulation and ablation in the years 2001–2002 resulted for low net balance causing decline in equilibrium line from an altitude of 4,900 to 4,880 masl. The altitudinal range lying between 4,600 and 4,760 masl account for 35.7% of net ablation and covers 22% of the total glacier area. The area between an altitude of 4,395 masl (snout) and 4,600 masl contribute 24% to 26.5% to net ablation and encompass 41% of ablation area. An altitudinal area between 4,760 m and equilibrium line contribute 7% to 16% to net ablation and encompass 16% of

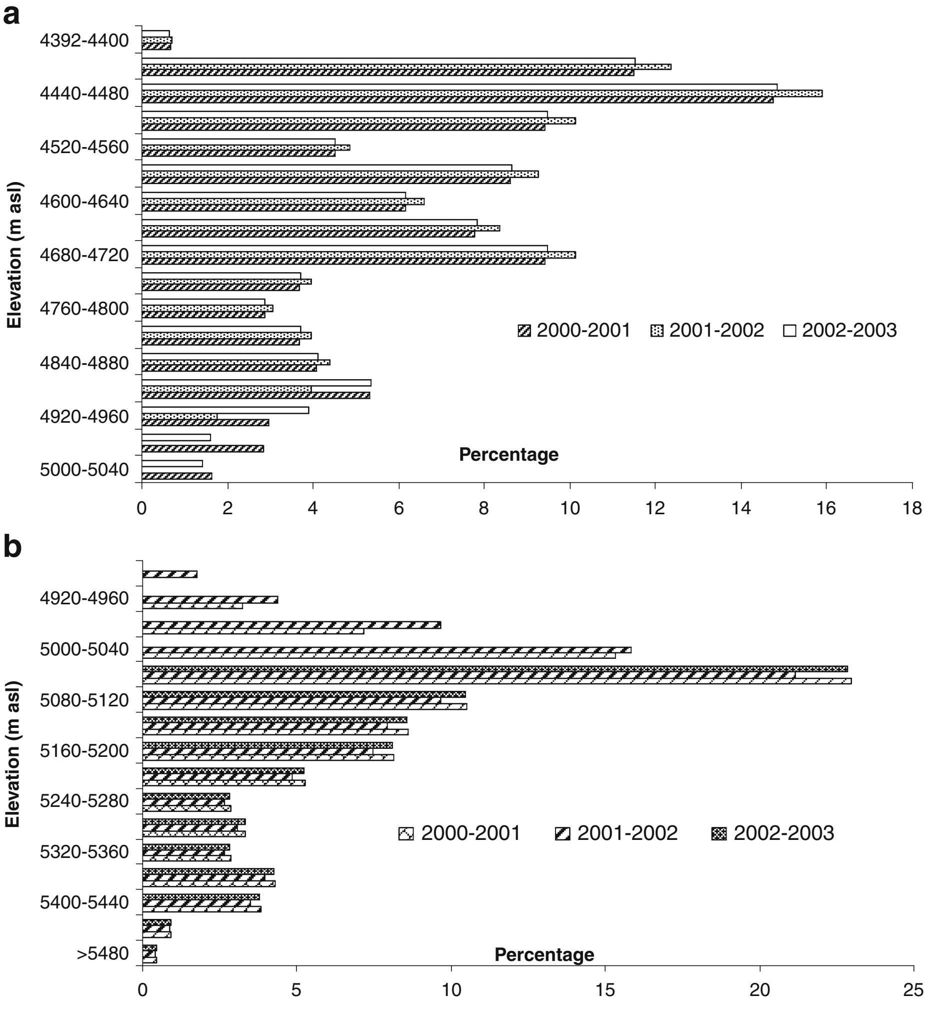


Fig. 10 **a** Elevation vs ablation area. **b** Elevation vs accumulation area

ablation area. The ablation for the years 2000–2001 and 2002–2003 show more or less similar pattern with a contribution of nearly one and half times for the year 2002 compared to the years 2001 and 2003.

6.2 Basal ablation

The horizontal movement of ice in the lower part of Naradu glacier is about 10 cm/day that gradually increases to 13.4 cm/day at equilibrium line. This has caused shift in the equilibrium line from an altitude of 4,900 masl in the years 2000–2001 to an altitude of 4,880 masl in the years 2001–2002 and further up to an altitude of 4,910 masl in the years 2002–2003. Movement of Naradu glacier is consistent (8.5 cm/day) in accumulation zone. The horizontal movement of glacier is fast in ablation zone but slow in snout zone. The slow rate of movement of Naradu glacier in snout zone is attributed to thick cover of debris that reduces the melt of glacier and thins ice in this zone.

7 Accumulation patterns

The growth and fluctuation in glacier body is related to the extent and nature of snowfall. Change in the timing of snowfall and period of snow accumulation season from year to year in Naradu glacier valley has affected the position of equilibrium line.

Net accumulation measured for the years 2001 and 2003 varied between 50 and 150 cm in water equivalent whereas in the years 2001–2002, the net accumulation amounted to 200 cm in water equivalent. The altitudinal zone between 4,880 and 4,960 masl acts as a transition zone between accumulation and ablation zones with least accumulation and ablation. The altitudinal zone between 5,000 and 5,200 masl accounts for 63% to 73% of net accumulation of snow and encompasses 58% of accumulation area (Fig. 6b).

8 Net balance

Naradu glacier, a warm glacier, reveals greater ablation rates. The net ablation and net accumulation volume for the years 2000–2001, 2001–2002 and 2002–2003 is given in Table 2 and in Fig. 11a, b. Naradu glacier has a net balance of -1.28×10^6 m^3 for the years 2000–2001, -0.334×10^6 m^3 for the years 2001–2002, and -1.181×10^6 m^3

Table 2 Mass balance estimates, AAR and ELAs of Naradu glacier

Year	Net ablation (km^3)	Net accumulation (km^3)	Net balance (km^3)	Ablation (km^2)	Accumulation (km^2)	Specific balance	AAR	ELA (masl)
2000–2001	−2.23	0.94	−1.28	2.43	2.09	−0.44	0.46	4,900
2001–2002	−2.57	2.24	−0.33	2.25	2.27	−0.35	0.50	4,880
2002–2003	−2.28	1.1	−1.18	2.4	2.12	−0.40	0.47	4,910

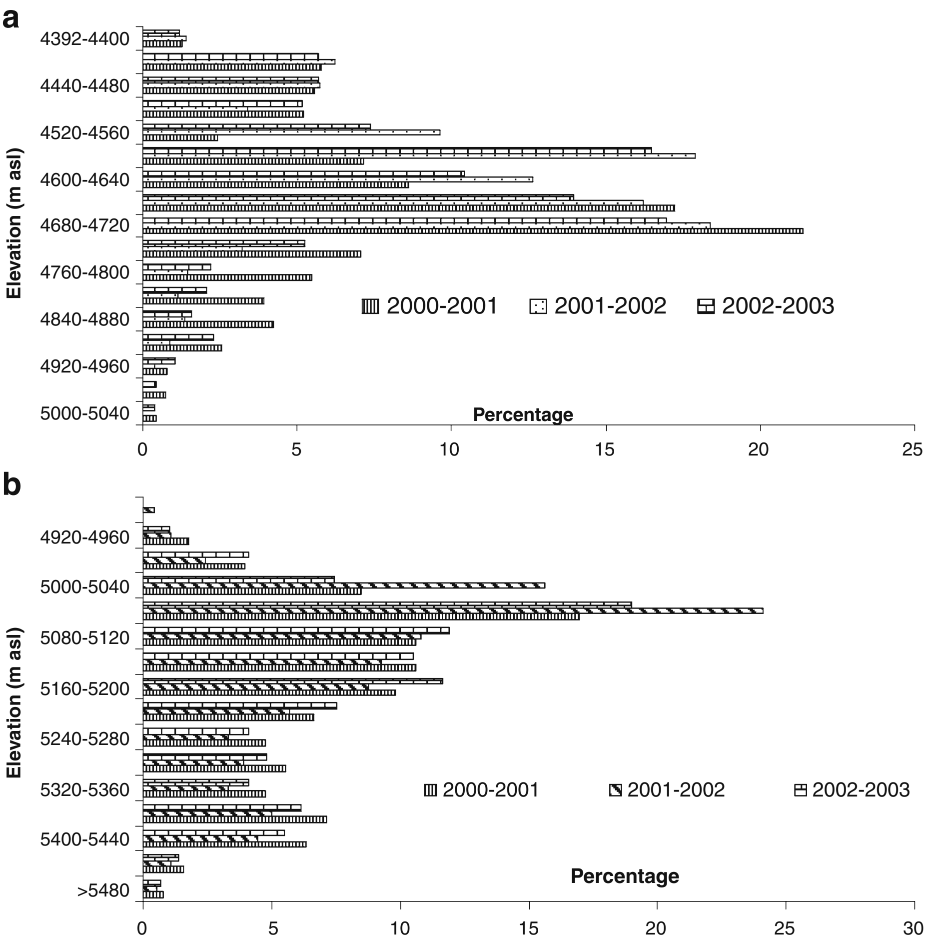


Fig. 11 **a** Elevation vs ablation volume. **b** Elevation vs accumulation volume

for the years 2002–2003 (Fig. 12). The specific balance for the years 2000–2001, 2001–2002 and 2002–2003 is given in Table 2 and Fig. 13. High ablation and accumulation of snow in the years 2001–2002, almost one-and-a-half times more than that of the years of 2000–2001 and 2002–2003, is a cause for low net balance rate.

The negative value of net balance is attributed to the inter-annual fluctuation in meteorological parameters, particularly the change in the pattern of snowfall, solar radiation and sunshine hours during summers. The rate of retreat and area vacated are documented below:

Year	Snout position (masl)	Lateral retreat (m)	Area vacated (m^3)
2001	4,393.30	4.3	663
2002	4,394.00	2.9	307
2003	4,395.10	3.9	586

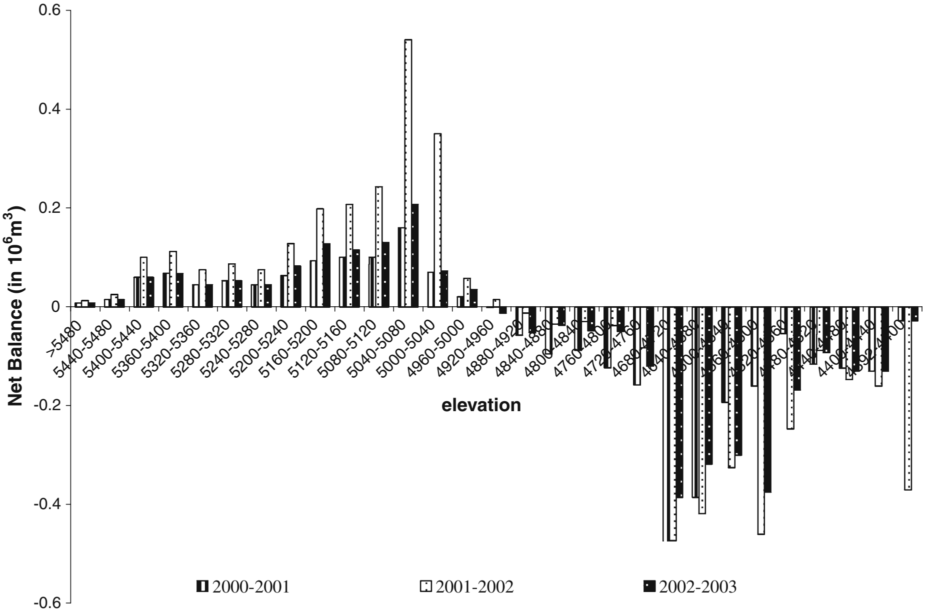


Fig. 12 Net balance vs elevation

9 Equilibrium line elevations

In the year 2002, the equilibrium line shifted to an elevation of 4,880 masl from its position of 4,900 masl in the years 2000–2001 and further up to 4,910 masl in the years 2002–2003. The equilibrium line descends in the east part of glacier body and ascends in west showing an irregular pattern.

10 Discussion

Thermally induced pressure differences between land and ocean coupled with dynamics of upper air flow including jet stream are some of the factors that control

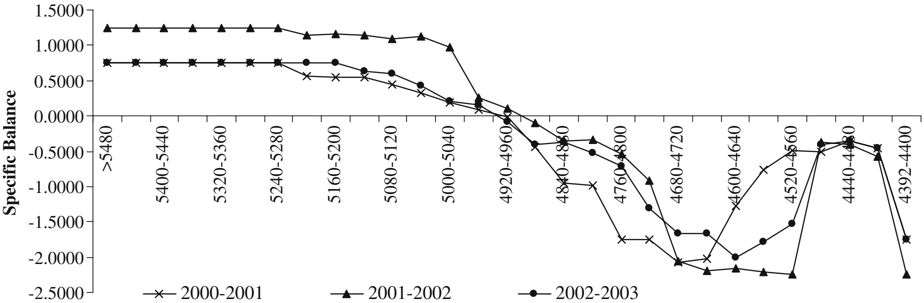


Fig. 13 Specific balance vs elevation

the change in the pattern of divergence on inter-annual and inter-decadal scale (Mayewski et al. 1980).

The solar radiation data of Naradu glacier for the ablation period (May to October) varies between 400 and 592 W/m^2 for the years 2000 to 2003, with maximum sunshine hours in the months of July and August (Table 3). The mean maximum daily solar radiation in summer months is 470 W/m^2 for the year 2001, 436 W/m^2 in 2002, and 472 W/m^2 in 2003. The longest period of sunshine hours (9.15 h) is in the months of July 2001, in August 2000 is 9.4 h and in August 2002 is 9.05 h in comparison to June 2003 (8.98 h) (Table 3). The average sunshine hours in the summer months are 8.3 h/day for the years 2001 and 2003, and 7.9 h/day for the year 2002. The degree-day ablation for the years 2000 to 2003 reveal highest average degree-day ablation of 2.5 cm/day during the years 2001 and 2003 in comparison to 2.37 cm/day for the year 2002. This is further corroborated with high average in summer temperature in the year 2001 (10.9°C) in comparison to 8.8°C for the years 2002 and 2003 (Table 3). The sharp decrease of average summer temperature of 2002 and 2003 by 2°C resulted in slow and steady retreat of ELA and snout. The mean daily minimum temperature for summer season ranged between 9.8°C and 13.2°C during the years 2000 and 2001,

Table 3 Standard deviation of maximum and minimum temperatures and sunshine hours of Naradu glacier from 2000 to 2003

A	B	C	D	E	F	G	H	I	J
2000	July	15.1	2.3	589	163	9.6	0.9	12.4	8.5
	August	13.8	2.2	620	165	8.2	1.0	11	9.4
	September	12.3	2.2	512	115	3.7	1.5	7.98	9.3
	October	11.1	2.0	320	55.5	−3	1.1	3.86	8.2
	Mean	13.1	2.2	510	125	4.5	1.1	8.8	8.9
2001	May	10.1	1.8	420	129	2.2	2.2	6.15	8.8
	June	14.7	2.0	504	147	8.2	0.8	11.5	8.9
	July	16.1	2.4	592	154	9.8	0.9	13	9.2
	August	13.8	2.6	510	112	11	0.9	10.4	8.9
	September	12.7	1.5	408	106	2.8	1.6	7.75	8.7
	October	8.37	1.1	390	43.3	−4	1.1	2.35	8.2
	Mean	12.6	1.9	471	115	5	1.3	8.51	8.8
2002	May	10.2	2.4	412	129	1.7	2.6	5.93	6.8
	June	13.8	2.1	505	147	6.8	1.2	10.3	8.2
	July	13.9	1.8	528	154	7.9	1.2	10.4	8.8
	August	11.0	1.2	500	112	7.3	1.0	9.14	9.0
	September	10.1	2.1	410	109	1.7	1.7	5.88	8.9
	October	7.49	1.5	260	58.2	−3	1.5	2.3	7.7
	Mean	11.1	1.8	436	118	3.7	1.5	7.31	8.2
2003	May	9.97	1.6	480	129	3.3	0.6	6.65	7.7
	June	13.4	2.3	494	163	6.4	0.5	9.92	8.9
	July	13.1	2.3	491	150	6.8	1.1	9.94	9.4
	August	14.4	2.1	576	150	7.0	1.0	10.7	8.7
	September	9.9	1.6	408	140	−1	2.0	4.31	8.5
	October	7.56	2.4	400	55.8	−4	1.4	1.85	6.5
	Mean	11.4	2.0	475	131	3.1	1.1	7.23	8.3

A year, *B* month, *C* maximum temperature, *D* standard deviation of maximum temperature, *E* maximum solar radiation, *F* standard deviation of solar radiation, *G* minimum temperature, *H* standard deviation of minimum temperature, *I* average temperature, *J* sunshine hours whereas it ranged between 6.8°C and 11.9°C during the years 2002 and 2003. The mean maximum and mean minimum records during the winter season and summer season reveal a decreasing trend in mean monthly minimum during winter season (February–March) and descending trend in mean maximum temperature during summer season (June–July) has resulted in cooling in peak summer season followed by chilly winters that had the positive trend to increase the precipitation in winter period to cement accumulation zone.

The rise and fall in diurnal temperature is not always in correspondence with the rise and fall in solar radiation. The critical evaluation of temperature curve suggests that non-periodic variation in the temperature is a result of atmospheric disturbance occurring at irregular intervals and not controlled by sun alone. Based on the observations, solar radiation recorded in the year 2003 (May to August) is higher as compared to the year 2001 and that led to maximum volume of ablation of Naradu glacier during the mass balance year 2003.

The snow accumulation record show that the years 2001–2002 is the wettest year during which 2,430 mm of precipitation is recorded out of which 1,818 mm is received in the form of snowfall. It is one and a half times more than the snow accumulation of the years 2000–2001 (1,384 mm) and 2002–2003 (1,325 mm). This pattern led to low negative net balance of $-0.33\times 10^6 m^3$ for the years 2001–2002. In the years 2000–2001 and 2002–2003, the amount of snowfall received in the winter is 1,384 and 1,325 mm, respectively out of which 82.4% and 95.5% of snowfall is received during early winters (November to May) and rest in late winters. This resulted in low negative balance $-1.18\times 10^6 m^3$ in the years 2002–2003 as compared to the negative balance of $-1.28\times 10^6 m^3$ for the years 2000–2001, even though the snowfall in the years 2000–2001 is more than the years 2002–2003. The fluctuation in net negative balance has played an important role in shifting the mass balance profile in terms of shift of ELA from 4,900 masl in the years 2000–2001 to 4,880 masl in the years 2001–2002 and then pushing it further up to 4,910 masl in the years 2002–2003.

11 Conclusions

Naradu glacier is a dirty glacier and confined to narrow cirque valley that has a high relative relief. A major part of the ablation zone is covered by debris, and snout is criss-crossed by transverse and longitudinal crevasses. All these factors contribute to change in geothermal heat flux. The mass balance of the glacier is closely linked to kinematic response to seasonal and climatic change. The change is triggered due to the effect of local topography particularly the high relative relief that induces change in micro-meteorological parameters, e.g. change in accumulation of glacier mass at the surface of the glacier, change of energy input from atmosphere (particularly sunshine hours and maximum temperature curve rather than minimum temperature curve), and change of geothermal heat flux. The surface melt water of glacier is attributed to short wave radiation compounded with long wave terrestrial radiation caused by debris cover that is produced by mechanical weathering of walls of the glacier valley. The degree-day melting on the glacier body is far less up to the altitude of 4,700 m because of thick debris cover. The thick (1.5 to 2 m) debris cover of dark coloured phyllites and light coloured granite covering the glacier body from snout to an altitude of 4,700 m acts as an insulating body to reduce the melting of glacier appreciably in comparison to the part of glacier covered by thin debris above 4,700 m. As a consequence of low albedo of dark coloured debris and high albedo of light coloured debris, the resultant temperature is much higher than the free air temperature causing variable rate of melting of glacier. The slow rate of melting of glacier as a consequence of thick debris cover has resulted in the fluctuation of equilibrium line down the slope.

During 2002–2003 the appreciable decrease in temperature followed by high solid precipitation (snowfall) has led to low specific balance (−0.35) and accumulation area ratio (AAR) (0.50) in comparison to 2000–2001 (specific balance −0.44 and AAR 0.46) and 2002–2003 (specific balance −0.40 and AAR 0.47).

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