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In view of climate change, Himalayan glaciers are losing its mass. In present study we analyzed 7 year long field based data series of surface mass-balance measurements performed between 2011/12 and 2017/18 at Naradu glacier, western Himalaya. The average specific mass balance for the studied period was 0.83 m w.e. with a highest melting of 1.15 m w.e. The analysis of topographic features showed that south and southeast aspect along with the presence of debris cover area and the slope between 18 to 36 degree are the major factors which causes highest melting from a particular zone. For better understanding of SMB variability and its causes, multiple linear regression analyses (MLRA) was performed by taking temperature and precipitation as predictors. The temperature and precipitation records were taken from NASA GIOVANNI website. The MLRA shows that 71% of the variance of observed SMB can be explained by temperature and precipitation. The MLRA shows the importance of summer half-year temperature. This variable alone explains the 64% variance of observed SMB. The seasonal period analysis showed that with two predictor variables most of the SMB variability is described by summer temperature and winter precipitation. All monthly combinations show that SMB variance is best described by June temperature and September precipitation.

The importance of glaciers cannot be overlooked as they are the key indicators of climate change apart from providing the fresh water to the downstream population. Worldwide, an increased global average temperature by 1.5 ˚C is causing the enhanced melting of glaciers [1]. Rapid glacier mass loss may further cause changes in the landscape of mountains and Polar Regions that affects the global albedo and gives positive feedback to the warming phenomenon. It also has a very real impact on local hazards, regional water cycles, and global sea levels [2-6].

For more than a century, World Glacier Monitoring Service (WGMS) along with its antecedent organizations is collecting and publishing glacier fluctuation data obtained from its forty-one scientific collaboration countries. This effort has been taken to gather long-term glacier observations which would further give insight into processes of climatic change such as the formation of ice ages [7]. The key work focus of WGMS is to collect standardized observations on changes in mass, volume, area, and length of glaciers with time. Also, they are deeply indulged in providing statistical information about the distribution of perennial surface ice.

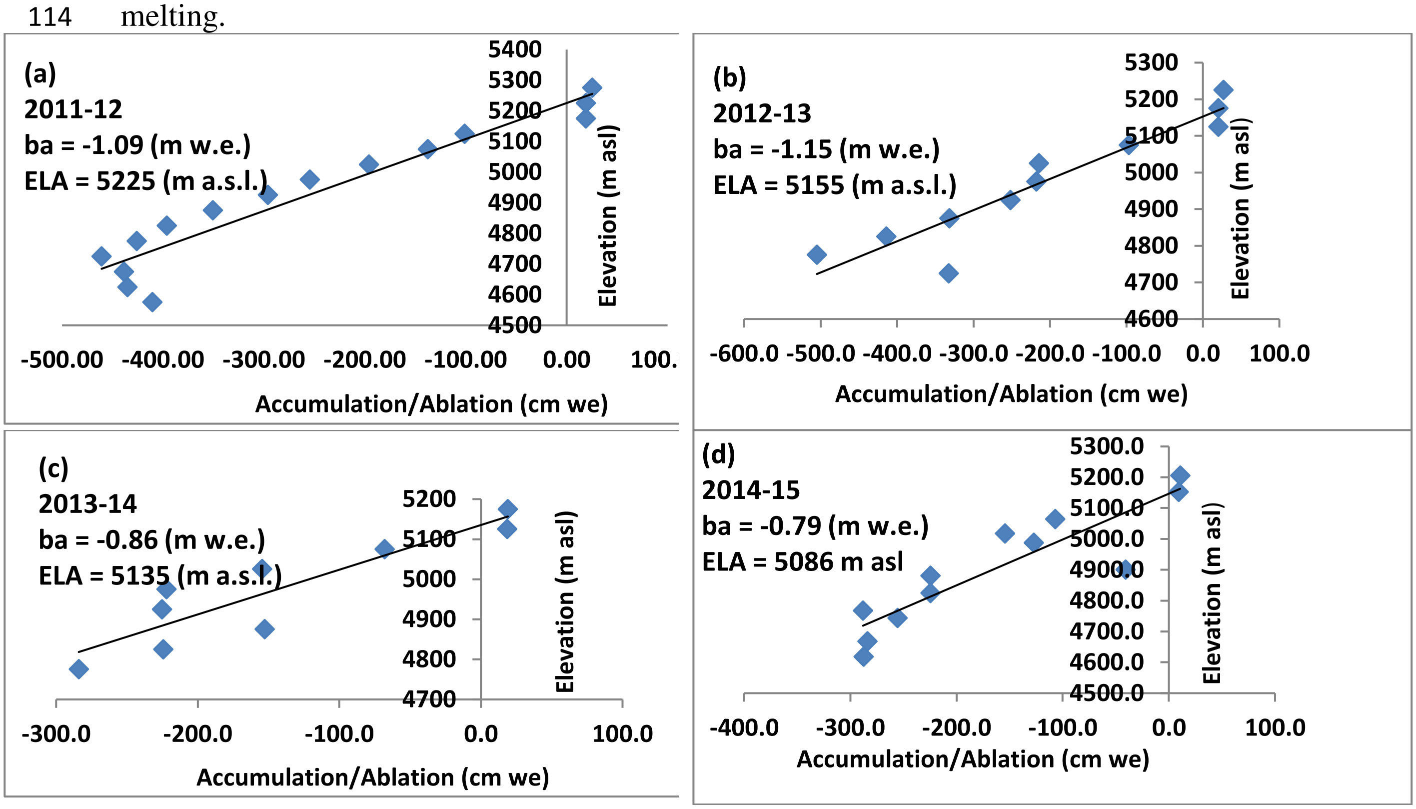
Glacier mass balance shows the most direct relationship between climate and glacier dynamics and consequently between climate and mountain hydrology [8,9]. It is a measurable unit and can be defined as the sum of glacial mass gain and loss [10]. In present, mass balance studies are of great concern as they are useful in determining global climate change and explaining rising sea levels [11-15]. Several glaciological parameters are being used to detail glacial response against climate change but unfortunately, they are indirect and delayed [16]. In opposite, glacier mass balance is a direct and un-delayed process to make out the effect of climate change on the glaciers [17-22]. To make glaciers as a good indicator of climate variability, it is necessary to have an extensive and regular glacier mass balance study [23]. The international research community views the study of glacier mass balance as important research now-a-days as it is of an extensive belief that glaciers are in the state losing mass [24-29] due to global warming. In addition to this, understanding the behavior of glaciers against climate change is of enormous significance when one is assessing future water availability [30-33]. Apart from the role of glacier mass balance in stooling about the climate, they also help us to improve our understanding about the processes involved in Earth-atmosphere mass and energy fluxes. Mass balance studies are also useful to estimate the contribution of glaciers to runoff and sea level changes, and make possible the development of numerical models to analyze climate-glacier relationships [34].

The Himalayan region comprises of the largest glacier mass outside the polar areas and this region is often referred to as the "water tower of Asia". The role of Himalayan originated rivers in providing fresh water to the downstream population is very important, especially, in the nonrainy [35, 36] season. Unfortunately, less (when compared with the importance) mass balance studies (ground and remote sensing-based) have been done [37-39] over different parts of the Himalaya. This discouragement is not only been reported in the Himalayan region but also the entire world. In most parts of the world, glaciers have been studied for less than 50 years and hence studies related to glaciers are limited [40]. The main objective of this study is to estimate the mass balance of Naradu glacier, Western Himalaya. For the same, the trendy glaciological method was used. The glaciological mass balance of the Naradu glacier has been calculated for seven continuous years to understand its considerable contribution to Baspa River as well as to study glacier sensitivity with changing climate.

Results & Discussion

Accumulation and Ablation analysis. The mass balance study on Naradu glacier has started long back by [38] under the DST funded project and studied the glacier for the period of 2000/01-2002/03. The second series of mass balance has been performed under the DST funded project No. SR/ DGH/HP-1/2009 dated 09.09.2010 for the year 2011/12-2013/14 followed by the extension of the activities for another four years (2014/15 - 2016/17) under the project SB/DGH-92/2014 dated 19/02/2015 funded by DST. In addition one more year (2017/18) fieldwork has been performed to the Naradu glacier to collect the data. The continuation of the past mass balance studies held on Naradu glacier may provide an opportunity to take the glacier as a benchmark glacier which will be useful to improve the understanding about the response of glacier against the climate change. This study uses the glaciological method, the most accurate and trendy method to calculate the mass balance [41]of the Naradu glacier for seven (2011/12 - 2017/18) consecutive years. The estimation has been done by taking a total of 115 annual SMB measurements at different locations during the study period. The specific ablation with elevation in different years has been shown in **Figure 1 (a - g).** All measurements show a negative mass balance.

During the period of 2011/12, melting was measured through a network of 13 stakes distributed between 4590 to 5136 m a.s.l. with an average of 5 stakes (each 1.5 m) at a specific location on the central line of the glacier whereas four pits at the elevation between 5152 to 5289 m a.s.l. have been dug in the accumulation zone to obtain the annual specific accumulation. During the year 2012/13, total numbers of 15 stakes observations were used to calculate the melting and accumulation observations were based on the 4 snow pits at the elevation range of 5132-5249 m a.s.l. The mass balance for the year 2013/14 is based on the observations of 10 new stakes distributed between 4773 to 5017 m a.s.l. and earlier stakes which continued standing in this year while the accumulation observations were based on two snow pits at an elevation of 5123 and 5170 m a.s.l. The mass balance of the year 2014/15 has been calculated by using 12 stakes (4618 – 5064 m a.s.l.) and two pits (5128 & 5183 m a.s.l.). To estimate the ablation of the year 2015/16, 10 new stakes were installed in the ablation zone and the previous year's stakes enhanced the network while two pits have been dug at the elevation of 5156 and 5222m asl. The network of 10 stakes (with some old stakes) has been used for 2016/17 and 2017/18 mass balance estimation. During the seven years of analysis, the variation between lowest and highest melting was -0.04 m w.e. to -5.07 m w.e. The highest melting zone for four years (2012/13, 2013/14, 2014/15 and 2017/18) was at the elevation range of 4750 – 4850 masl. The topographic characteristics which play an important role in glacier melting are glacier hypsometry, slope and aspect [42]. In view of this, we tried to study all the possible topographic factor for Naradu glacier which may affect the melting and found that south and southeast aspect along with the presence of debris cover area and the slope between 18 to 36 degree are the major factors which make this zone the highest melting zone for four discussed years. The detailed map showing the aspect, debris area and slope of Naradu glacier has been presented through **Figure 2 (a-c)**. During seven years of analysis it was found that the year 2012/13 showed the highest melting of -1.15 m w.e. and detailed analysis of the reason behind indicates about comparatively high temperature during the same period. Along with temperature, net radiation, latent heat flux and other topographical characteristics also played important role in this highest melting.



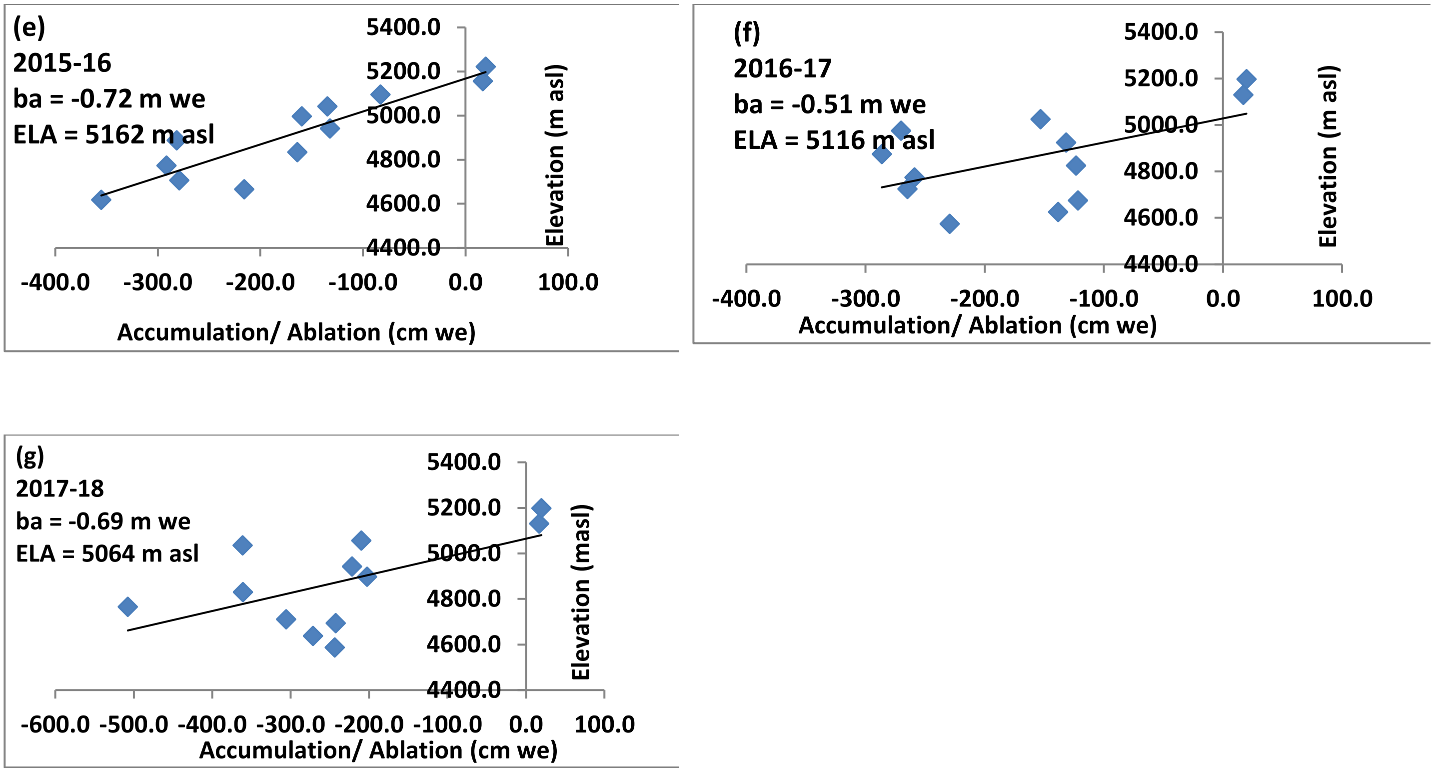


Figure 1: Specific ablation with elevation during the year (a) 2011-12/ (b) 2012/13/ (c) 2013/14, (d) 2014/15, (e) 2015/16, (f) 2016/17 and (g) 2017/18

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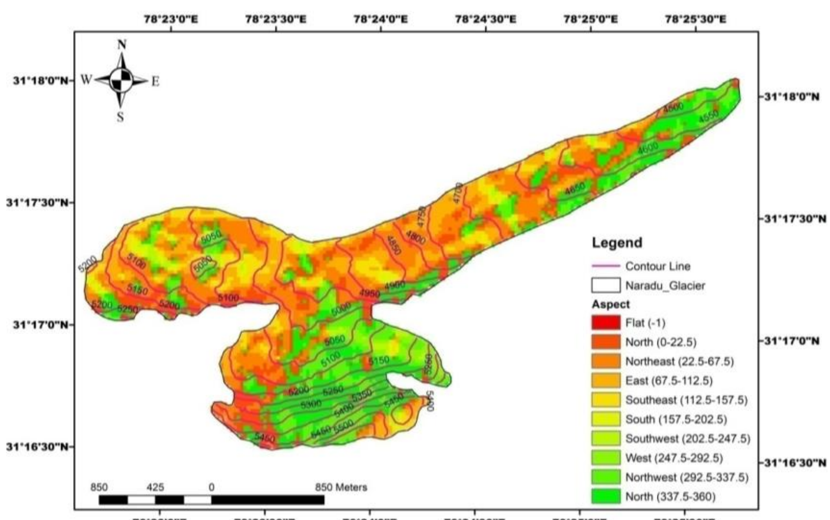


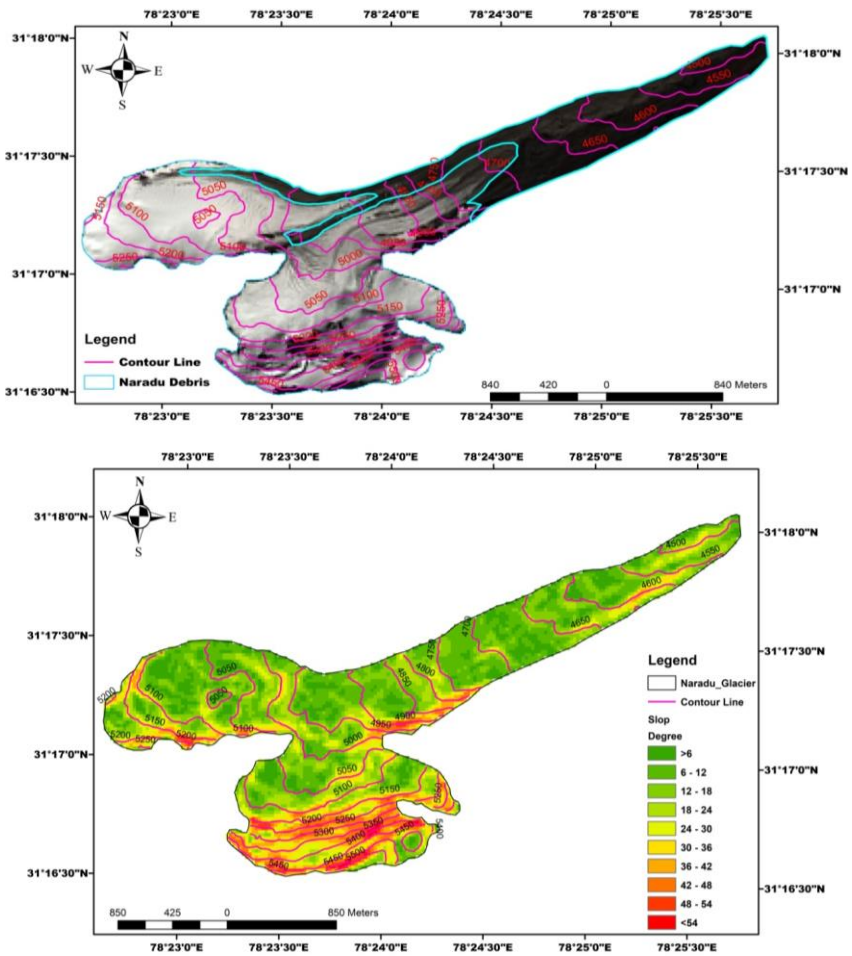


Figure 2: Naradu glacier map showing a) aspect, b) debris covered area and c) slope of different elevation zone.

Uncertainties of the measurements. Worldwide, most the mass balance calculations were done only for a few years and large numbers of results are reported without uncertainties [21]. Globally, longer series of mass balance (more than 40 years) have been reported only for 33 glaciers [43] hence for these types of long mass balance series data, quality is of great interest. Various previous studies with discussion of errors in mass balance calculated by the glaciological method are in the record. Many authors estimated error between ±0.2 and ±0.4 m w.e. [44-47]. [48] indicated errors between ± 0.1 and ± 0.34 m w.e. for balances determined by the glaciological method. [49] calculated an error of ± 0.19 m w.e. for ablation measured with stakes whereas ± 0.3 m w.e. of error was reported by [50]. [51] calculated the winter and summer balance and found an error of ±0.10 m w.e. for ablation measured in ice and between -0.25 and +0.4 m w.e. for ablation measured in firn. Error estimation in mass balance studies by using the glaciological method is a very important issue so while visiting Naradu glacier different possible causes of the error have been taken care. The error due to the movement of ice is negligible because of the very low flow of ice. Errors linked to the mechanical play like joint of stakes and inaccurate surface at the bottom of the stakes have been taken seriously. To avoid errors occurred while the spatial averaging of the results over the entire glacier more numbers of stakes were installed. In most of the mass balance studies glacier area has been taken to be invariant whereas it changes with time in real practice ultimately contributes to the overall error in the mass balance result [37, 52]. To solve the issue of change in glacier area in different year most recent images were used to calculate the SMB for a single year. Further, the uncertainty related to the stake height determination, depth of snow in the ablation zone, snow/ice density have been considered to calculate overall uncertainty in the calculation of SMB of Naradu glacier. Uncertainty in SMB calculation of Naradu glacier has been estimated by the equation suggested by [53] and mentioned in Table 1.

Table 1: Mass balance results for the period 2011/12 to 2017-18

Year	Net balance (km^3)	ELA (m a.s.l.)	Sp. Bal. (m w.e.)	Uncertainty (%)
2011/12	-3.5	5225	-1.09	2.6%
2012/13	-3.7	5152	-1.15	2.3%
2013/14	-2.7	5135	-0.86	1.3%
2014/15	-2.5	5086	-0.79	3.42%
2015/16	-2.3	5162	-0.72	1.86%
2016/17	-1.6	5116	-0.51	2.72%
2017/18	-2.2	5064	-0.69	2.05%
Average	**-2.64**	**5134**	**-0.83**	**2.32%**

Statistical Analysis. The MLRA was conducted by taking a total of 21 SMB measurements. These 21 SMBs are based on 3 stakes observations which cover the whole 7 years period. All three stakes were in the ablation zone. The ablation zone of Naradu glacier is a highly debris covered area (refer to **Figure 4b**) and may have a major impact on the melting of ice/snow depending on its thickness [54]. MLRA does not include those SMB measurements which are from the stakes that were not able to survive for the whole study period. The involvement of these kinds of measurements will surely raise the biases due to the gap in their dada record [55].

The stakes elevation change with time due to glacier flow and changes in local ice thickness [55-57] During 7 years period, elevation change was around 253 m at the location of stake 1, 210 m at the location of stake 2 and 183 m at the location of stake 3. To analyze the effect of elevation change on SMB, all stakes were anticipated back to their initial elevation (i.e. 2011/12) by using equation 1. The observed and modelled SMB analysis shows a moderate correlation ($r^2 = 0.53$). The corrected annual SMB shows a melting of 248 cm a^{-1} which does not show a significant difference with real observed melting 234 cm a^{-1}.

The individual stake measurement is shown through **Figure 3 a & b**. The annual SMB was more than 500 cm w.e. for all the balance year except 2014/15 which showed a slightly lower value. Modelled SMB values clearly show a significant increasing trend over 7 years as the p value of F-test is much lower than $\alpha = 0.01$. The standard deviation in SMB per stake per year varied between 0.2 - 11.8 cm w.e. a^{-1} and does not show correlation with elevation (as $R^2 = 0.07$) (**Figure 4**).

For analysis, the modelled SMB measurements for each stake were converted to perturbations by taking a 7-year stake's mean. The SMB perturbation has been shown through **Figure 5**. During analysis, we found a perfect correlation between SMB perturbation and elevation for all three stakes. Further, no link has been found between meteorological parameters (i.e. temperature and

precipitation) and annual SMB elevation gradient. This "no linkage" is a prerequisite condition for our analysis and is in the line with many other studies like [49] and related studies [58-61].
To find the relation between meteorological data and SMB perturbation, the MLRA approach has been used [55, 62] by considering below equation 2. This correlation analysis required the abandon of the effect of measurement of different meteorological parameters in different units (here, the temperature in degree C and precipitation in mm w.e.) and hence these parameters have been standardised by converting the data to z-score.

$$y = a_1x_1 + a_2x_2 + \cdots \ldots \ldots \ldots \ldots a_nx_n + b \qquad (2)$$

Where y = dependent/response variable and will indicate SMB perturbation in the present study. 'a' and 'b' are the regression coefficients and $x_1, x_2, \ldots\ldots\ldots x_n$ are the independent/predictor variables. Here, x_1 *and* x_2 will be represented by the z-score of the meteorological parameters i.e. temperature and precipitation. The used monthly temperature and precipitation data showed a week correlation ($r^2 = 0.3$) and this non-dependency is a common approach for MLRA performed on SMB series (e.g. [55, 63, 64]. The regression coefficients "$a_1, a_2 \ldots\ldots$" show the climatic variability of meteorological parameters due to the conversion of these data to a z-score. Further, it has been assumed that the regression coefficients of both the parameters are uncorrelated and indicate the importance of both for SMB. The intercept of the regression analysis i.e. 'b' is equal to zero as it shows a value of y when all of the independent variables are equal to zero. The error in a degree of freedom in the different products of the total number of years (i.e. 7 in this analysis) and the number of the independent variable used in the analysis (here temperature and precipitation). The outcome of MLRA has been expressed in terms of R^2 and p-value of F-test. The factor R^2 shows the variability of the response variable. The F-test performs a significant linear regression relationship between the response variable and the predictor variables. The p-value of F-test is the probability of obtaining a linear correlation if the null hypothesis is true. The lower p-value at a higher significance level results in the rejection of the null hypothesis. For analysis, we opted a null hypothesis that there is no linear correlation between the response variable and the predictor variable.

Meteorological Data MLRA

The goal of the study is to describe the observed SMB (through MLRA) by using temperature and precipitation as predictors. The additional predictors can be added but it increases the fraction of SMB variation, consequently reduces the degree of freedom. The p value of F-test should be as low as possible, to justify the addition of predictors. The analysis is only based on continuous periods.

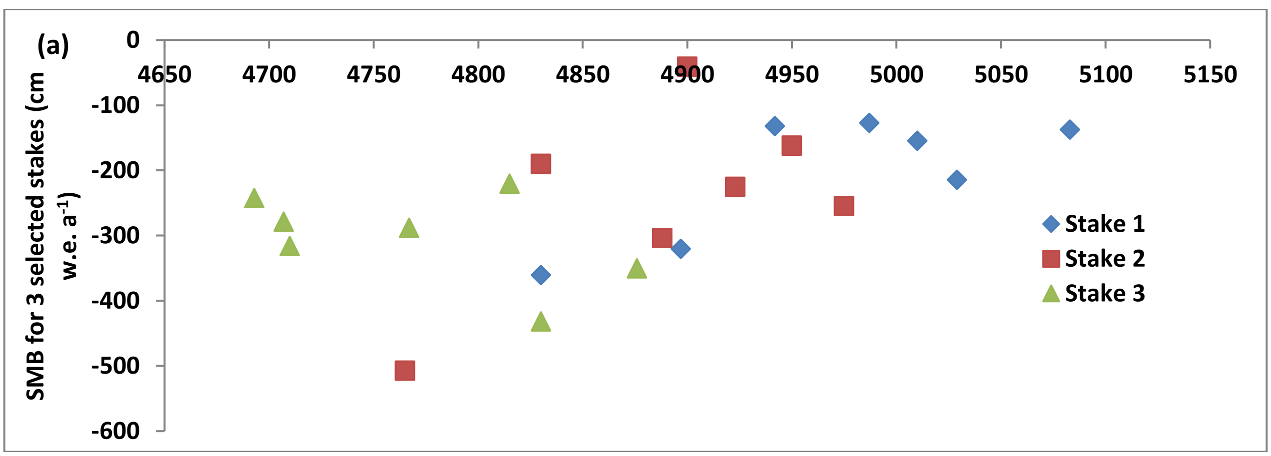
Firstly, the annual average temperature (T_{ann}) and total annual precipitation (P_{ann}) have been used to explain the observed SMB variation (MLRA with 5 degree of freedom). An MLRA shows that 71% of the variance of observed SMB can be explained by these two predictors. The lower p value of F-test (0.07) describing the strong significance of the model. The negative sign of Tann shows negative correlation between temperature and SMB and the positive sign of Pann shows a positive correlation between precipitation and SMB (refer to **Figure 6a** and Table 2).

Secondly, the year is sub-divided into two categories i.e. winter half-year (WHY) and summer half-year (SHY). The first category i.e. WHY consists of fall (OND: October, November, December) and winter (JFM: January, February, March). The second category consists of spring (AMJ: April, May, June) and summer (JAS: July, August, September). The chosen monthly combination does not agree with meteorological seasons. They are chosen according to the glaciological season so that the fall season (OND) should start just after field measurement.

The MLRA shows the importance of SHY temperature. This variable alone explains the 64% variance of observed SMB (R^2 = 64%; p-values F-test = 0.02). In the absence of this variable no SMB variance can be explained in MLRA with two predictor variables (For example R^2 = 58%; p-values F-test = 0.17) (Table 2). The summer temperature and winter precipitation account for 80% of the observed SMB variance (with p-value of F-test 0.03), hence the null hypothesis, no linear correlation has been rejected. The larger absolute regression coefficient T_{SHY} (-73) compared with P_{WHY} (-11) indicates relatively higher importance of the SHY temperature (**Figure 6b**).

Thirdly, the predictors were split into seasonal components i.e. spring (AMJ), summer (JAS), autumn (OND) and winter (JFM). This allows us to do analysis for 36 possible combinations for MLRAs by using a temperature and precipitation as a predictor variable. In the seasonal analysis we found that with two predictor variables most of the SMB variability is described by summer temperature and winter precipitation (R^2 = 82%; p-values F-test = 0.032) (refer to Table 2).

Depth analysis of all monthly combinations was also done and the results show that the SMB variance is best described by the June temperature and September precipitation. This MLRA is statistically significant as it has much lower p-values F-test = 0.0031 and R^2 = 94%. The individual monthly equation (refer Table 2 and **Figure 6c**) clearly indicates the dominance of temperature (regression coefficient of -50.51) compared with the September precipitation (regression coefficient of -36.45).



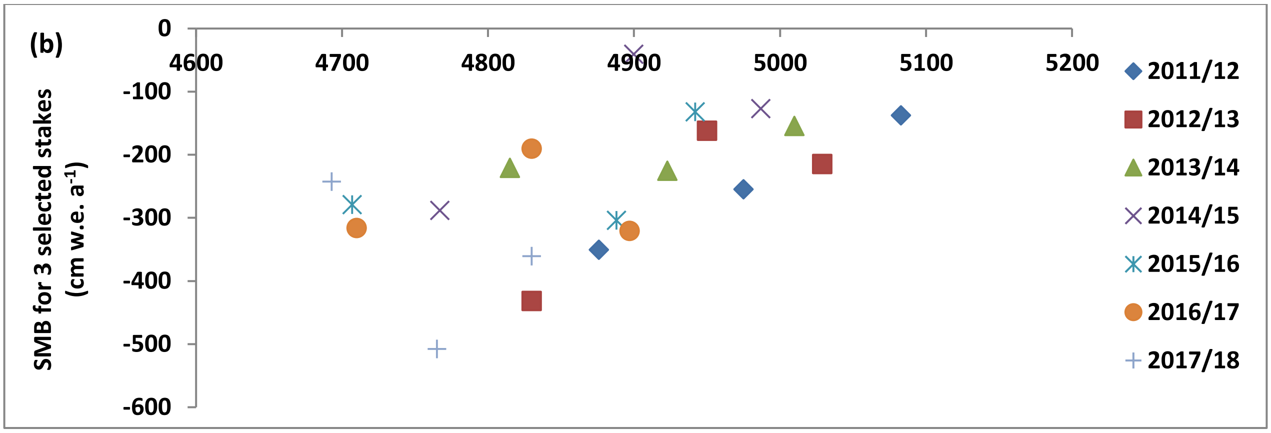


Figure 3: a) SMB against elevation for different years for three selected stakes (before projection to initial elevation); **b)** SMB against elevation for different years for three selected stakes (before projection to initial elevation).

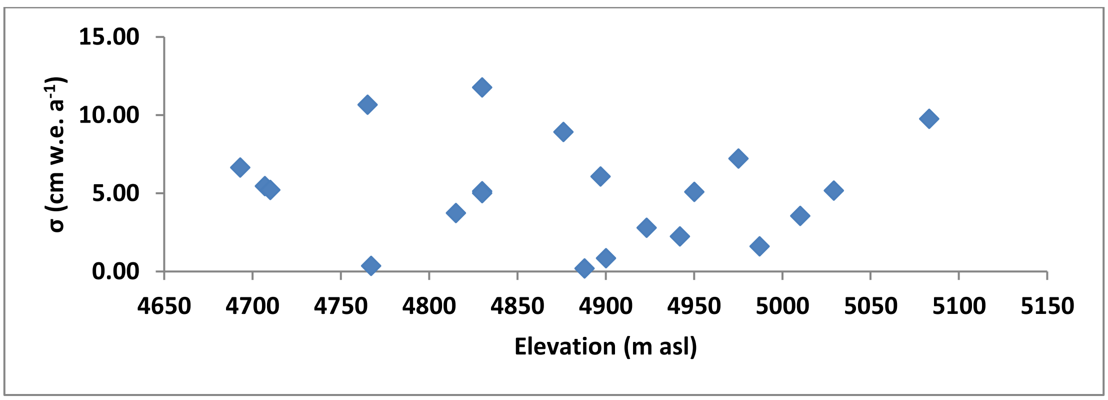


Figure 4: Standard Deviation of individual stake during 7 years period

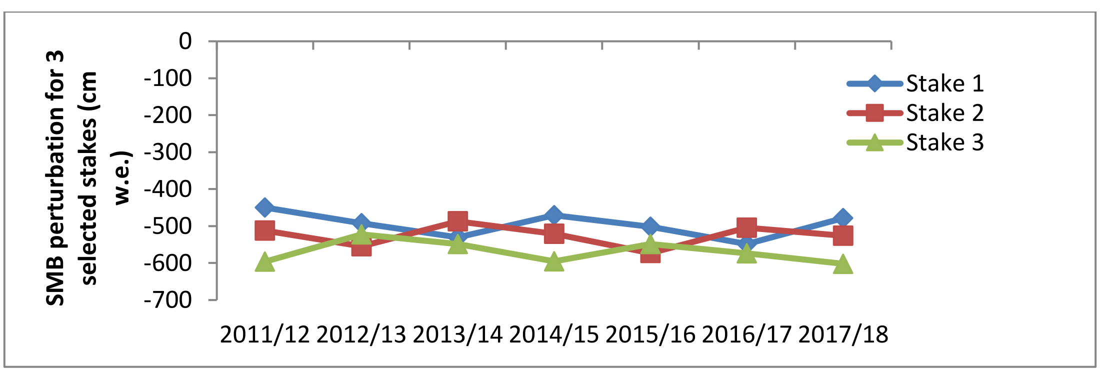


Figure 5: SMB perturbation for 3 selected stakes

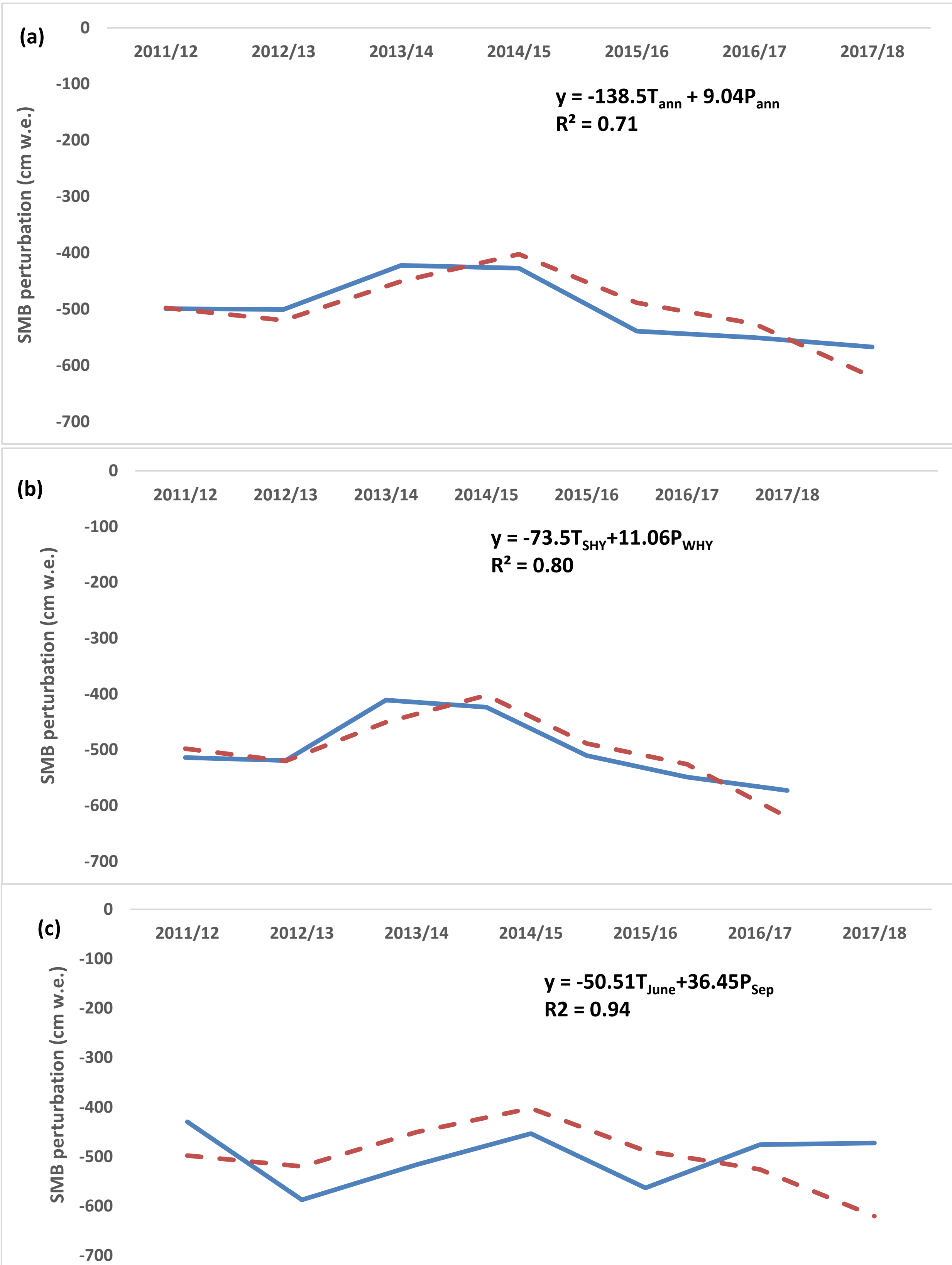


Figure 6: Observed SMB Perturbation and modelled SMB perturbation based on MLRA using two predictors **(a)** annual temperature and annual precipitation, **(b)** Summer half-year temperature and winter half-year temperature, **(c)** June temperature and September precipitation. The round cap red dash line is the observed SMB, the round cap solid blue line is the calculated SMB signal resulting from the MLRA.

Table 2: Multiple regression analysis (MLRA) between z-score standardized meteorological variables and observed SMB perturbations for three selected stakes covering the period 2011/12 – 2017/18

Time period	Best-fit multilinear correlation	R^2	p-value F-test
Annual	$SMB = -138*T_{ann} + 9.04*P_{ann}$	0.71	0.07
Half-year	$SMB = -59*T_{SHY} -7*P_{SHY}$	0.68	0.09
	$SMB = -80*T_{WHY} + 9.04*P_{WHY}$	0.60	0.15
	$SMB = -73*T_{SHY} -11*P_{WHY}$	0.80	0.03
	$SMB = 2*T_{WHY} -17*P_{SHY}$	0.56	0.19
Spring	$SMB = -51.97*T_{spr} + 0.49*P_{Spr}$	0.34	0.4
	$SMB = -37.9*T_{spr} -19.06*P_{Summ}$	0.68	0.09
	$SMB = -49.7*T_{spr} +19*P_{Aut}$	0.55	0.19
	$SMB = -58.3*T_{spr} + 23.12*P_{Win}$	0.64	0.12
	$SMB = -20.14*T_{spr} -14.19*P_{SHY}$	0.59	0.16
	$SMB =-55.17*T_{spr} + 17.34*P_{WHY}$	0.76	0.05
Summer	$SMB = -103.1*T_{summ} – 3.57*P_{Spr}$	0.82	0.034
	$SMB = -95.3*T_{summ} -1.07*P_{Summ}$	0.81	0.035
	$SMB = -104.72*T_{summ} -4.16*P_{Aut}$	0.82	0.033
	$SMB = -93.43*T_{summ} +4.45*P_{Win}$	0.82	0.032
	$SMB = -106*T_{summ}+2.04P_{SHY}$	0.81	0.035
	$SMB =-96.1*T_{summ}+0.77*P_{WHY}$	0.81	0.036
Autum	$SMB = -15.42*T_{Aut} -15.28*P_{Spr}$	0.20	0.63
	$SMB = -9.2*T_{Aut} -21.6*P_{Summ}$	0.51	0.23
	$SMB = -0.90*T_{Aut}+19.78P_{Aut}$	0.22	0.59
	$SMB = -7.2*T_{Aut} +17.2*P_{Win}$	0.21	0.62
	$SMB =1.3*T_{Aut} -17.4*P_{SHY}$	0.56	0.19
	$SMB =28.9*T_{Aut} +22.18*P_{WHY}$	0.40	0.35
Winter	$SMB = -26.3*T_{win} -10.8*P_{Spr}$	0.24	0.56
	$SMB = 16.4*T_{win} -20.1*P_{Summ}$	0.53	0.21
	$SMB = -60.69*T_{win} +30.67*P_{Aut}$	0.66	0.11
	$SMB = -44.9*T_{win} +22.2*P_{Win}$	0.47	0.27
	$SMB = -0.90*T_{win} -17.1*P_{SHY}$	0.56	0.19
	$SMB =-61.4*T_{win} +22.4*P_{WHY}$	0.28	0.03
SHY	$SMB = -107.6*T_{SHY} +12.3*P_{Spr}$	0.68	0.09
	$SMB = -62.9*T_{SHY} -12.5*P_{Summ}$	0.75	0.05
	$SMB = -77.1*T_{SHY} +10.4*P_{Aut}$	0.69	0.09
	$SMB = -81.2*T_{SHY} +15.5*P_{Win}$	0.78	0.04
	$SMB = -59.2*T_{SHY} – 7.3*P_{SHY}$	0.68	0.09
	$SMB =-73.5*T_{SHY} +11.0*P_{WHY}$	0.80	0.03
WHY	$SMB = -135*T_{WHY} +11.24 *P_{Spr}$	0.45	0.29
	$SMB = -54.8*T_{WHY} -15.86*P_{Summ}$	0.58	0.17

	$SMB = -91.7*T_{WHY} +15.7*P_{Aut}$	0.56	0.19
	$SMB = -88.61*T_{WHY} +11.75*P_{Win}$	0.49	0.25
	$SMB = 2.43*T_{WHY} -17.6*P_{SHY}$	0.56	0.19
	$SMB =-80.7*T_{WHY} +11.8*P_{WHY}$	0.60	0.15
Individual monthly combination	$SMB =-50.51*T_{June} +36.45*P_{Sep}$	0.94	0.003

Temperature Dominance. The analysis shows that the observed SMB and temperature are strongly correlated. The same findings have been reported by [38], in which they have assessed the impact of inter and intra annual meteorological parameters variation on Naradu glacier mass balance. Koul and Ganjoo estimated that the rate of melting of the Naradu glacier is positively proportional to the temperature which is a function of solar radiation that reaches the glacier body. [65]found that the turbulent heat flux has a significant impact on the SMB of Chhota Shigri Glacier and is so closely correlated with the temperature. The lack of such kind of studies for nearby glaciers, which analyses the SMB variability and its causes related to the meteorological parameters, restricts us to present more evidence in favor of the findings. The energy balance study of Naradu glacier under the above mentioned financial assistance has been done for five non continuous years (2012 - 2014 and 2015 - 2018). During the analysis we found that the specific energy balance of the glacier is significantly driven by radiation mechanisms and sensible heat flux. The finding of this study that temperature explains a large fraction of the observed SMB comes from the fact that temperature is the representative index for solar radiation and sensible heat flux [66, 67] . The deep analysis of surface energy balance and its relation with meteorological parameters will be discussed in the coming publication.

The Naradu glacier starts losing its mass from April and the process continues till September or May extend till mid-October. In these months, along with the high temperature, the absence/reduction of the snow cover also plays an important role in glacier melting. In these months, the snow cover, which protects the glacier by reflecting the radiation shrinks and the glacier ice area is now widely exposed to melt. The MLR analysis shows the temperature and precipitation conditions of April to September months have a significant effect on SMB variability. Among all the month's combination, the variability is best described by June temperature and September precipitation (kindly refer sec, 5.3.1.4). The precipitation during these months occurs as rain which further enhances the melting along with the high temperature.

Comparison of mass balance of Naradu glacier with the glaciers of Baspa basin and glaciers of other parts of the Indian Himalayan Region. The mass balance study on Naradu glacier has been done by using the most accurate glaciological method. Very few glaciological mass balance studies have been reported in the Himalayan region [20, 22, 68] and further they are more limited in Baspa basin. The available field based glacier mass balance data from different Indian Himalayan region and also from Baspa basin is presented through **Figure 7**. In Indian Himalayan, the Geological Survey of India (GSI) has started the detailed mass balance study by using the glaciological method in 1974. The study was undertaken on Gara glacier, Himachal Pradesh to understand the importance of mass balance study as they provide the direct and undelayed response against climate change and are also helpful to understand the local and regional hydrological system. The Gara glacier has been studied between the period of 1974/75 - 1981/82 [69, 70] . During the study period it showed the positive mass balance for the years 1974/75, 1975/76 and 1981/82 and rest five years showed the negative mass balance. These positive mass balance results are dissimilar with most of the analysis done in the basin. The publication i.e. [69] did not give any scientific view which details out the specific reason behind this behaviour of the glacier. Likewise the Nehnar, Kashmir Himalaya glacier have been studied continuously 8 years between the period of 1975/76 - 1983/84. The study is one among many glaciers that has the longest glaciological mass balance record in the region. The scientific team involved in the study reported the negative mass balance for the entire study period which ranges from -0.4 to -0.7 mw.e. [71]. The Shaune Garang glacier has the longest study series (10 years or more) in the Baspa basin showed positive mass balance only for two years and rest eight years showed significant mass loss [72,73] . Later on, the reconstruction of mass balance on the same glacier has been done by [74] for the 2001/02 to 2007/08. In this reconstruction analysis, Kumar and others showed a negative mass balance for five years whereas the glacier gained the mass in 2001/02 and 2004/05. On average, the results of Shaune Garang glacier shows more mass loss compared to Naradu glacier. This high melting at Shaune Garang glacier may be linked with the high temperature and fewer precipitation conditions at Shaune Garang glacier [75]. Another glacier which has the longest study series outside the Baspa basin is the Chhota Shigri glacier [76]. This glacier is well-studied in many aspects. The glacier has been studied for mass balance, energy balance along with the reconstruction of the mass balance for over 43 years (1969-2012). The mass balance reconstruction for over 43 years was done to get the larger perspective of glacier-climate relationship. The reconstruction study of the glacier shows that the ablation was more for most of the study years when compared with the positive value. Likewise, the results of the mass balance of the glacier by using the glaciological method show a negative mass balance for most of the study period. The positive values were reported for the years 2004/2005; 2008/2009 and 2009/2010 with a marginal positive balance [65]. Very petite duration mass balance studies have been reported from and glaciers like Rulung, Kolahoi II, Shishram. The one year study of these glaciers shows the negative mass balance [20] but since they are for a very short duration hence do not help to understand the impact of climate change.

The Gor Garang, another important glacier of Baspa basin have been studied for nine long and continuous year showed negative mass balance for seven years and positive mass balance only for two years [20, 70] The Dunagiri and Chorabari glaciers of Uttarakhand Himalaya have been studied for 6 and more years and have been negatively reported by [77-79] respectively. The mass balance of Dokriyani glacier for a period of 6 years [78] showed a negative trend. The observed reported reason was the less winter precipitation causes longer period exposure of the glacier surface ice for melting. The less precipitation during the winter season leads to less input to the accumulation zone of the glacier. Hamtah and Naradu glacier of the western Himalayan region has been studied for 11 and 3 years respectively. Both the glaciers show negative mass balance [38, 80, 81]

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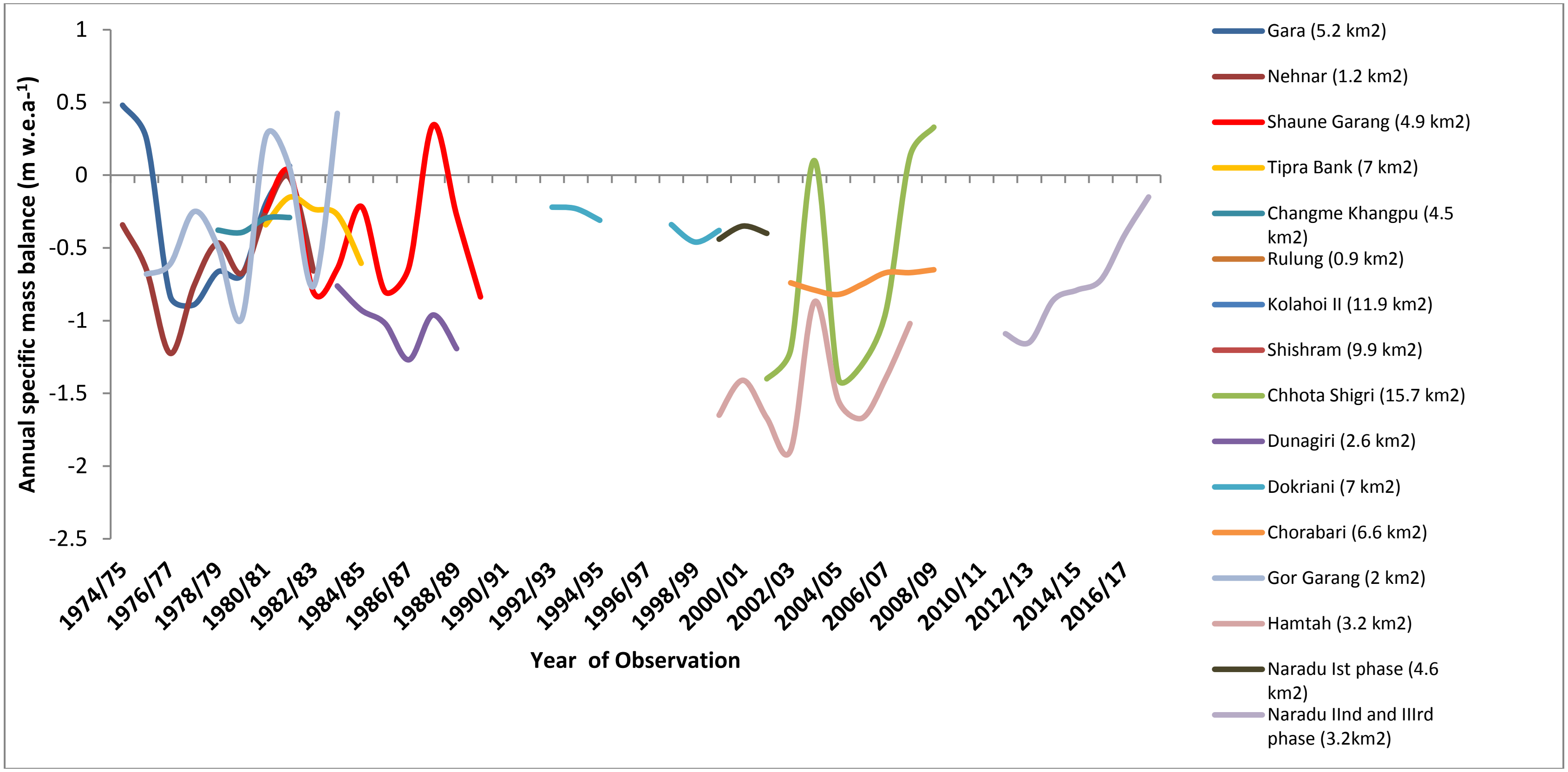


330 **Figure 7:** Annual specific glacier mass balance available in Indian Himalayan Region [82] with the present study.

Other MLRA studies. Similar studies are limited in western Himalaya and this limitation is extended throughout the Himalayan region [83]. The studies, analyzing the effect of temperature and precipitation on SMB variation found that SMB is more sensitive to temperature rather than precipitation [55, 84] but the scenario may change depending on the spatial position of a glacier [82] resulting in the change in the magnitude of various meteorological parameters. The same findings have been reported by [85]. This study was done on Glacier AXOIO in the Nepalese Himalaya by taking three predictors namely; air temperature, precipitation, and relative humidity. The results of the study showed that mass balance is more sensitive to air temperature as apart from melting it also controls the phase of precipitation (snow or rain). In 2017, [75] have done the same study by taking 4 glaciers of the western Himalaya (3 glaciers of the Baspa basin and 1 glacier from Gara Khad basin). They reported that during the ablation season the temperature perturbations were higher whereas precipitation perturbations were higher during accumulation season. The findings are the same in our analysis also but there may be a difference in the magnitude of melting as the above study includes October month in the ablation period (in this study months from April to September defines the ablation season). In a recent study conducted at 45 glaciers of the Tianshan Mountains and Central Himalaya Mountains, done by [86], found a linear increase in mass balance with the increase in precipitation perturbation. This study also confirms our results as the quantity and form of precipitation totally depends on temperature.

[87] analysed four glaciers of Norway using the sensitivity formula given by [88]. In this analysis, Engelhardt found that at a higher temperature, SMB sensitivity to temperature increases whereas SMB sensitivity to precipitation decreases. This shows the sensitivity of SMB also depends on the magnitude of temperature and precipitation, for example, higher temperature causes the reduction in the accumulation period and consequently reduces the amount of precipitation to be fallen as snow. Our continuous monthly time period analysis shows a higher correlation compared with other studies [55]. This may happen because their analysis was based on many variables i.e. May-June-July temperature and winter precipitation (here we took June temperature and September precipitation). Apart from variation in no. of variables, the results also depend on the authenticity of the data source (here we took meteorological data from NASA GIOVANNI and field based SMB data) and it's processing before use like a validation of the satellite data with field data and checking of the homogeneity.

Conclusions. This study uses the most accurate glaciological method to estimate the mass balance of one among 89 glaciers of the Baspa basin for continuous and long seven years. Annual SMB of Naradu glacier for the period of 2011/12 to 2017/18 showed a negative trend with the maximum deficit of -1.15 m w.e. in the year 2012/13. The direct melting proportionality with the temperature makes this glacier witness of the higher sensitivity to temperature change. The study of SMB of the glaciers of the Indian Himalaya started in 1974 and since then many glaciers of the region have been studied. Almost all the glaciers showed a negative trend except for one or two with the marginal positive values (e.g. Gara glacier) which is the indication that the entire basin along with the whole Indian Himalaya is experiencing the glacier mass loss. Although in recent decades the interest of the research community has increased to explore the glaciers of the Indian Himalayan Region (IHR) yet the present study suggests more attention to the glaciological study as they are very few in numbers and hence the understanding is weak in spatial and temporal aspect compared to other world's mountain glaciers. This study also describes the SMB variation through MLRA by taking temperature and precipitation variables. The authors did not add other meteorological parameters (such as solar radiation, relative humidity, etc.) in the analysis as temperature and precipitation alone describe 71% of the variance of observed SMB. The analysis shows SMB variation can be better described by summer temperature rather than precipitation. The summer temperature is an important variable explaining 64% variance of observed SMB with p-values F-test = 0.02 which is quite satisfactory. The seasonal analysis shows that with two predictor variables most of the SMB variability is described by summer temperature and winter precipitation (R^2 = 82%; p-values F-test = 0.032). The monthly analysis indicates that high temperatures and low precipitation in the month of June causes most of the snow to be melted out and exposed old ice surface is rooting poor albedo. Further, the type of precipitation (rain/snow) also influences the SMB over the Naradu glacier.

Study Area. Naradu glacier is one among 89 glaciers of the Baspa basin, western Himalaya [89]. The basin contributes its water to the Baspa River, a tributary of Satluj River. Baspa River joins Satluj River on its left bank near Karchham at an elevation of about 1770 meter above sea level (m asl). Naradu Garang is a 3rd order stream of Sutluj and joins Baspa River on its left bank opposite to Chitkul village at an elevation of about 3450 m asl. The glacier ranges between 78˚25' 06.17" to 78˚25' 34.07" E and 31˚17' 27.1" to 31˚ 18' 18.9" N and covers an area of 3.8 km^2 [89]. Naradu is a southwest-northeast facing glacier and falls in the SOI toposheet No. 53I/07. The location of Naradu glacier in the Baspa Basin has been shown through **Figure 8**.

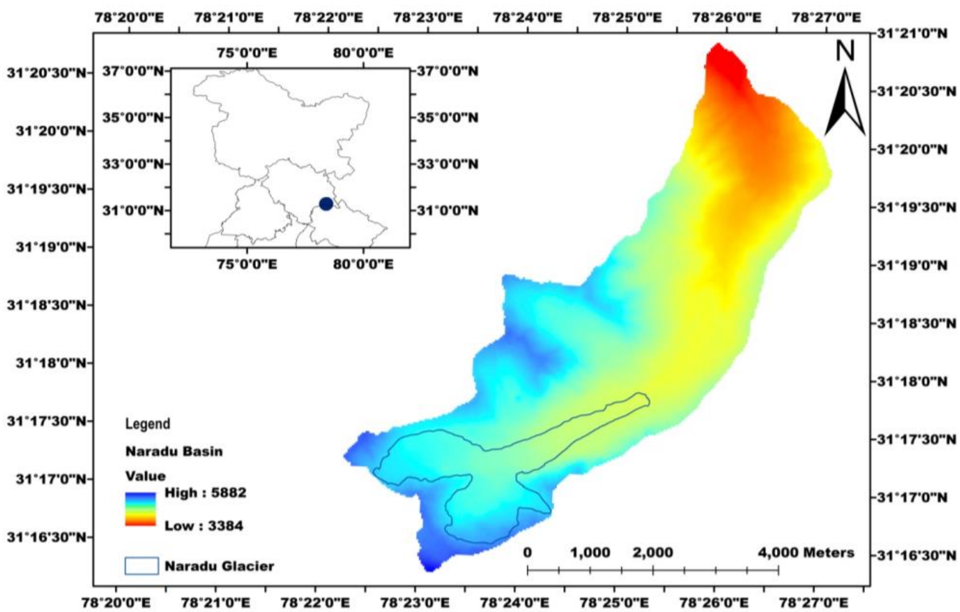


Figure 8: Location map of Naradu glacier in the Naradu catchment area

Climate dynamics of the valley. The hydrological cycle of the Himalayan region mainly depends on two circulation systems, Summer Monsoon and Western Disturbance (WD) [90-96]. Glaciers of western Himalaya have their accumulation through WD mainly in January and February while the glaciers of eastern and central Himalayas are accumulated through summer monsoon [66]. Western disturbance is the non-monsoonal precipitation driven by westerly which brings sudden winter rain. The moisture of the western disturbance originates over the Mediterranean Sea [97]. In winter months, western disturbance use to go to their lowest latitudes, and during their way they cross north and central parts of India in a phased manner from west to east, disturbing normal features of circulation pattern [98] and causes snowfall in higher elevations of NW India and winter rainfall in plains of northern and central India. Baspa Basin falls in the western Himalayan Range and hence receives its precipitation during winter months due to westerly disturbances (WD). The study region receives nearly 70% of annual precipitation in winter and springs in the form of snowfall, and only 30% as rainfall near snout and as dry snow in higher-up regions [38]. The meteorological analysis shows that the average monthly temperature of the glacier between 2011/12 to 2017/18 ranges from -18.7˚C to 6.31 ˚C. The region's temperature trend analysis during the period of 1979-80 to 2012-13 showed an increase of 0.9 ˚C in mean air temperature whereas precipitation shows a decrease of 14.38 cm [89].

Data Description and Methodology. The most precise method for mass balance measurement is the glaciological method. To assess the melting, this method uses observations of differential exposure of installed stakes in the ablation zone and pits measurement in the accumulation zone to assess accumulation. To have observations of ablation and accumulation, field visits have been done in the last week of September or the beginning of October every year. The 1.5m long bamboo stakes were installed by using a portable steam drill [99] in the ablation zone to measure the mass loss. The change in the mass between the two different dates of a particular year is measured at several positions at the glacier surface. The resultant mass gives the mass balance of that particular point when multiplied with the surface density. Density values for ice are assumed constant at 900 kg m^{-3} while the snow density was calculated at the different depths of the snow pit.

The variation between the beginning and the end of a hydrologic year represents the mass balance change for that year [100-103]. In order to know the ablation of Naradu glacier in a particular year, the surface area was divided into different altitudinal zones - generally covering a range of 50 m, and the average ablation in each zone was calculated from the point values. In the ablation area, local net ablation was estimated using a network of ablation stakes 4 to 6 m bamboo stakes fixed into the glacier at various altitudes.

For net yearly ablation measurement, the length of stakes above the glacier surface was measured at two successive dates (t_1 and t_2). The depth of snow (D) over the ice surface was also measured. The difference between stake lengths buried in ice (L) and snow depths at t_1 and t_2 dates gives the specific ablation (ΔS) at this point. Exposed stake lengths and snow depths were measured at each stake. The net ablation at a specific point was calculated by using the formula given below:

$$\Delta S = D_i[L(t_2) - L(t_1)] + D_s[D(t_2) - D(t_1)]$$

Where;

ΔS= Specific ablation

t_1 = Year of Initial Measurement

t_2 = Year of subsequent Measurement

L =Length of stakes buried in ice

D =Depth of snow

D_i= Density of ice

D_s = Density of snow

The length of the stakes above the glacier surface was measured every year from September 2014 to September 2018 together with ice/snow density and the emergence difference gives the annual ablation at that point.

The pits have been dug at several altitudes in the accumulation zone to measure the density of snow. The pit location on the glacier is presented through a map. The previous year's surface was identified from the dirty ice of the last year. The mass of the sampled snow was estimated through a weighing machine. Snow density (ρ) at specific depth intervals was calculated by using the below formula:

$$\rho = \frac{M}{V}$$

Where, M is the mass of snow collected in a known volume, V

The ablation and accumulation values have been integrated over the glacier to calculate the mass balance. The overall mass balance, B_i is calculated according to:

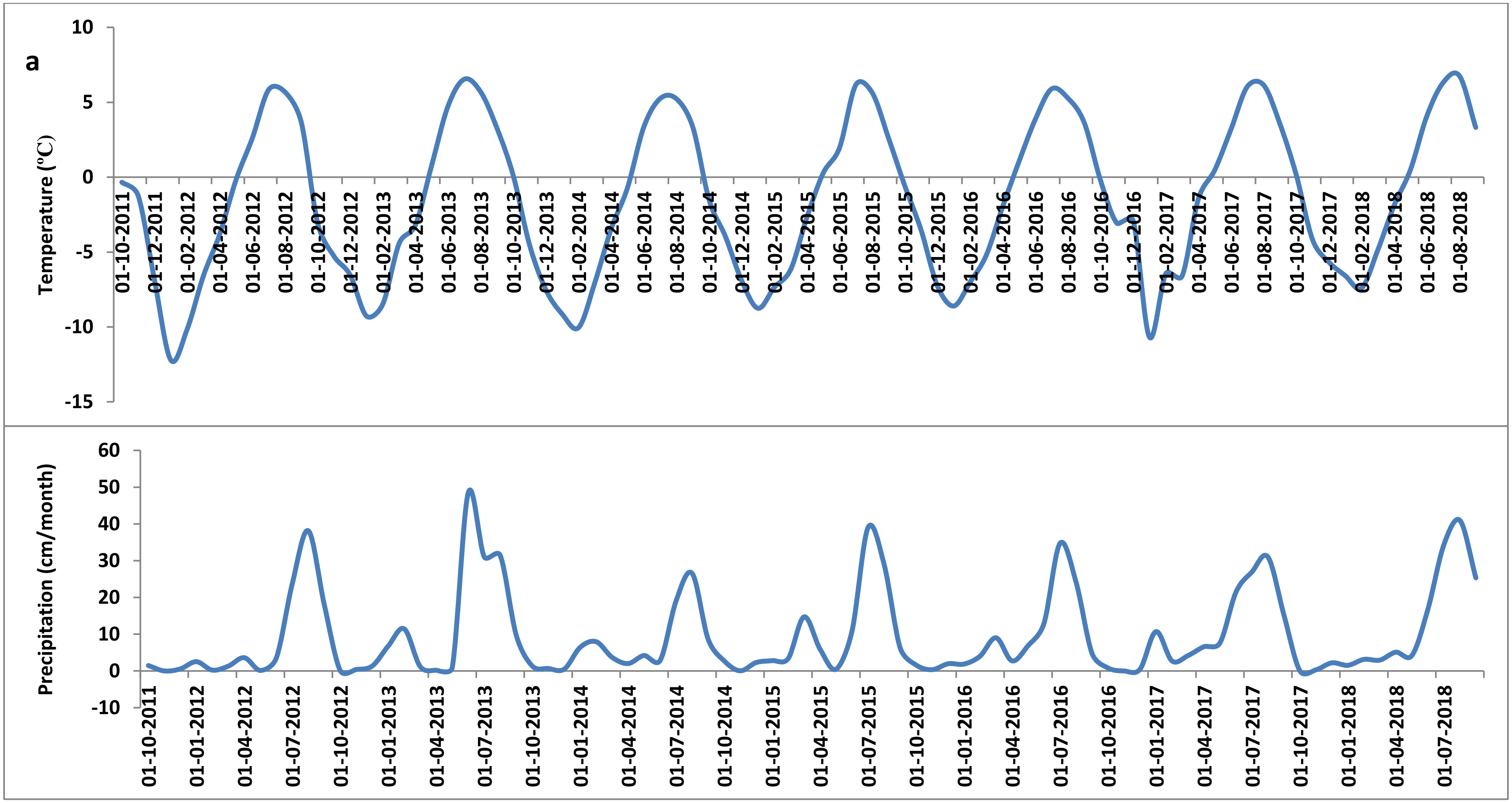
$$B_i = S \sum b_i \,(si\,)$$

Where b_i is the mass balance of the altitudinal range, *i,* of area s_i and *S* is the total glacier area. For each altitudinal range, b_i is obtained from the corresponding stake readings or net accumulation measurements.

Meteorological data. For a better understanding of the causes of glacier surface mass balance (SMB) variability, multiple linear regression analysis (MLRA) is performed with temperature and precipitation series. For the analysis, monthly temperature and precipitation data have been downloaded from the website of NASA GIOVANNI (**Figure 9a**). GIOVANNI is the acronyms of Geospatial Interactive Online Visualization And aNalysis Infrastructure (Goddard Earth Sciences Data Information Services Center). It is an online (Web) environment for the display and analysis of geophysical parameters. Data for both the parameters have been downloaded by selecting coordinates 31˚06'-31˚30'N and 78˚12'-78˚37'E with a grid size of 0.5˚ x 0.625˚ in the "selected region". Checking the homogeneity of data series, prior to use for research, is an important step, and hence GIOVANNI data has been carefully analysed for homogeneity. ANOVA test has been used to check the inhomogeneity in temperature data whereas due to non-availability of real annual precipitation data, we were unable to apply the same on precipitation data. ANOVA test has been applied by considering the field observations (through AWS) of annual temperature data for years 2012/13-2013/14 and 2015/16 to 2017/18. The test does not show any inhomogeneity as the calculated value is less than the table value of "F" at 5% level. Further, it has been assumed that GIOVANNI data for precipitation is homogeneous in nature. The data shows a lower winter temperature (**Figure 9b**). This may be the consequence of stronger winter inversion in the valley. An attempt has also been made to model the elevation against SMB. For the same, a best fit linear equation (1) has been estimated considering all stakes.

$$\text{SMB} = 0.39\ (\pm 0.073) * \text{Elevation} - 2167\ (\pm 355) \qquad (1)$$

Where SMB is the annual specific mass balance (m w.e.), elevation represents the stake elevation (m asl) and the uncertainties correspond to the 95% confidence level. Based on this simple linear fit approach, the average ELA for the period of 2011/12 – 2017/18 is expected to occur at 5523 masl. Which is slightly over estimated compared to real observations.


a
Temperature (ºC)
10
5
0
-5
-10
-15
01-10-2011
01-12-2011
01-02-2012
01-04-2012
01-06-2012
01-08-2012
01-10-2012
01-12-2012
01-02-2013
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01-04-2017
01-06-2017
01-08-2017
01-10-2017
01-12-2017
01-02-2018
01-04-2018
01-06-2018
01-08-2018
Precipitation (cm/month)
60
50
40
30
20
10
0
-10
01-10-2011
01-01-2012
01-04-2012
01-07-2012
01-10-2012
01-01-2013
01-04-2013
01-07-2013
01-10-2013
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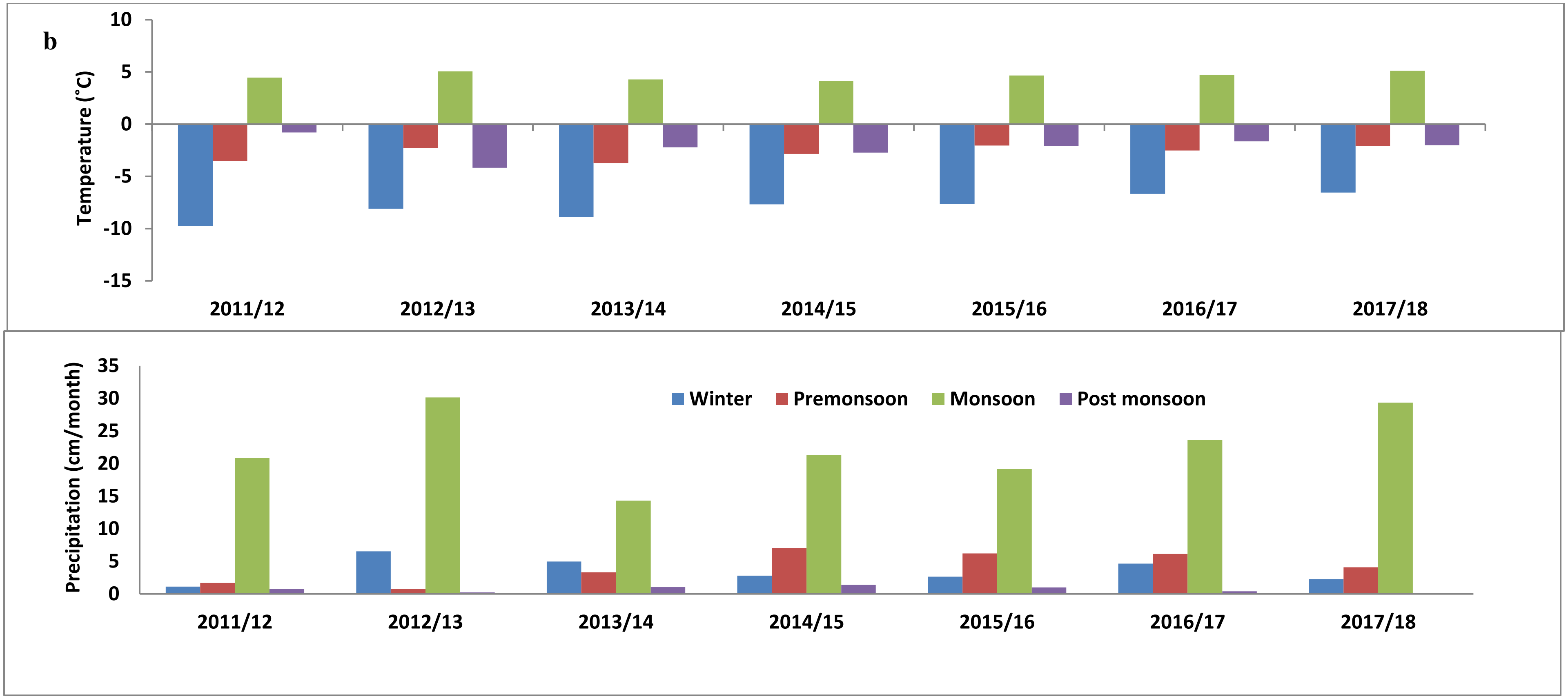

Figure 9. (a) Monthly temperature and precipitation at Naradu basin; **(b)** Seasonal temperature and precipitation at Naradu basin

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Author Contributions

Rajesh Kumar: The field based data used in this research has been generated under the projects (grant no. SR/ DGH/HP-1/2009 dated 09.09.2010 and SB/DGH-92/2014 dated 19/02/2015) sanctioned to Dr. Rajesh Kumar, He also conceptulised and designed the research, supervise, review & edit the manuscript
Shruti Singh conceptulised and designed the research, wrote the manuscript with the inputs from Rajesh Kumar and Surjeet Singh Randhawa, review & edit the manuscript
Ramesh Kumar: Data curation
Atar Singh: Data curation
Saktiman Singh: Data curation
Surjeet Singh Randhawa: review & edit the manuscript

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Figures

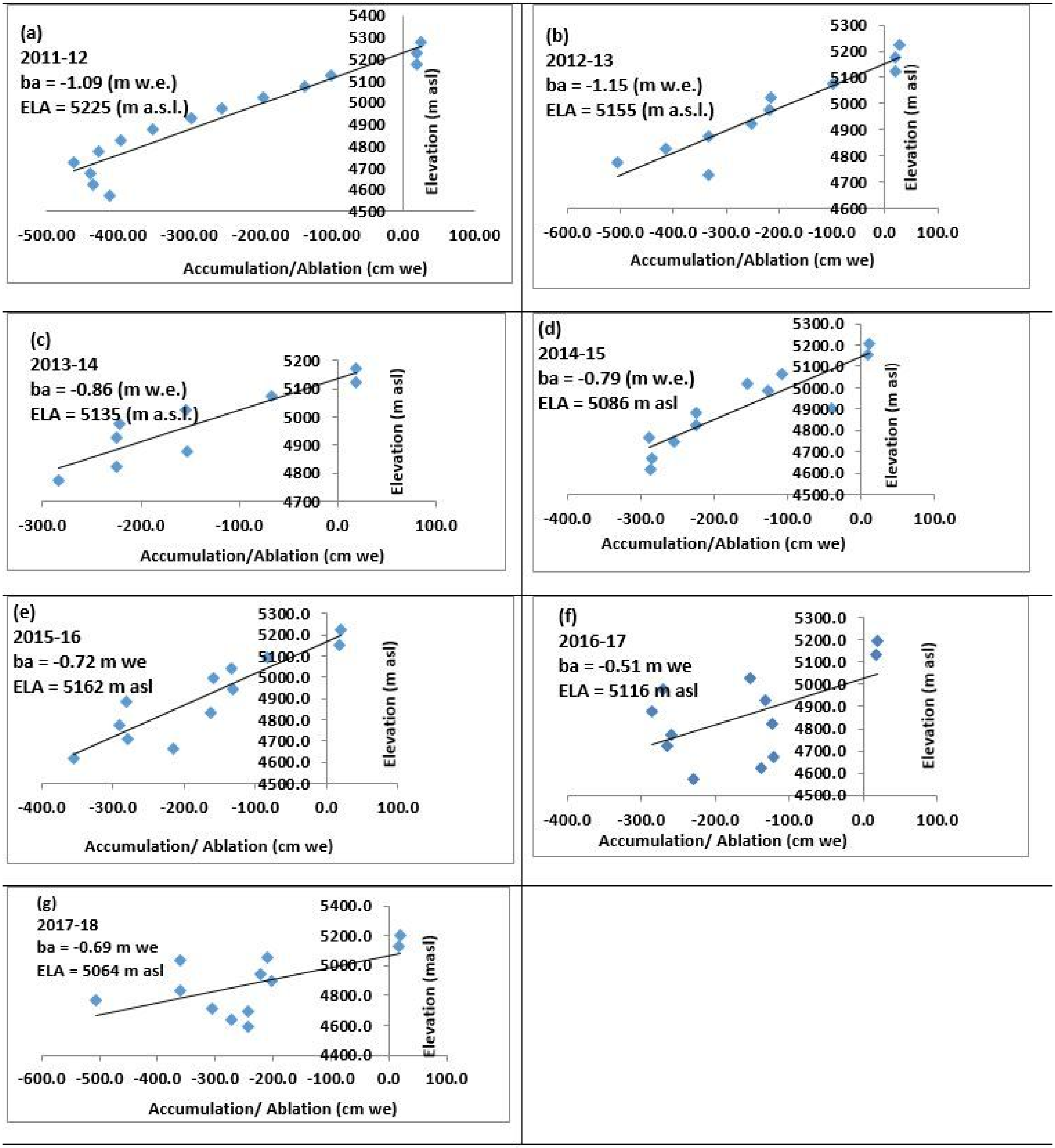

Figure 1

Specific ablation with elevation during the year (a) 2011-12/ (b) 2012/13/ (c) 2013/14, (d) 2014/15, (e) 2015/16, (f) 2016/17 and (g) 2017/18

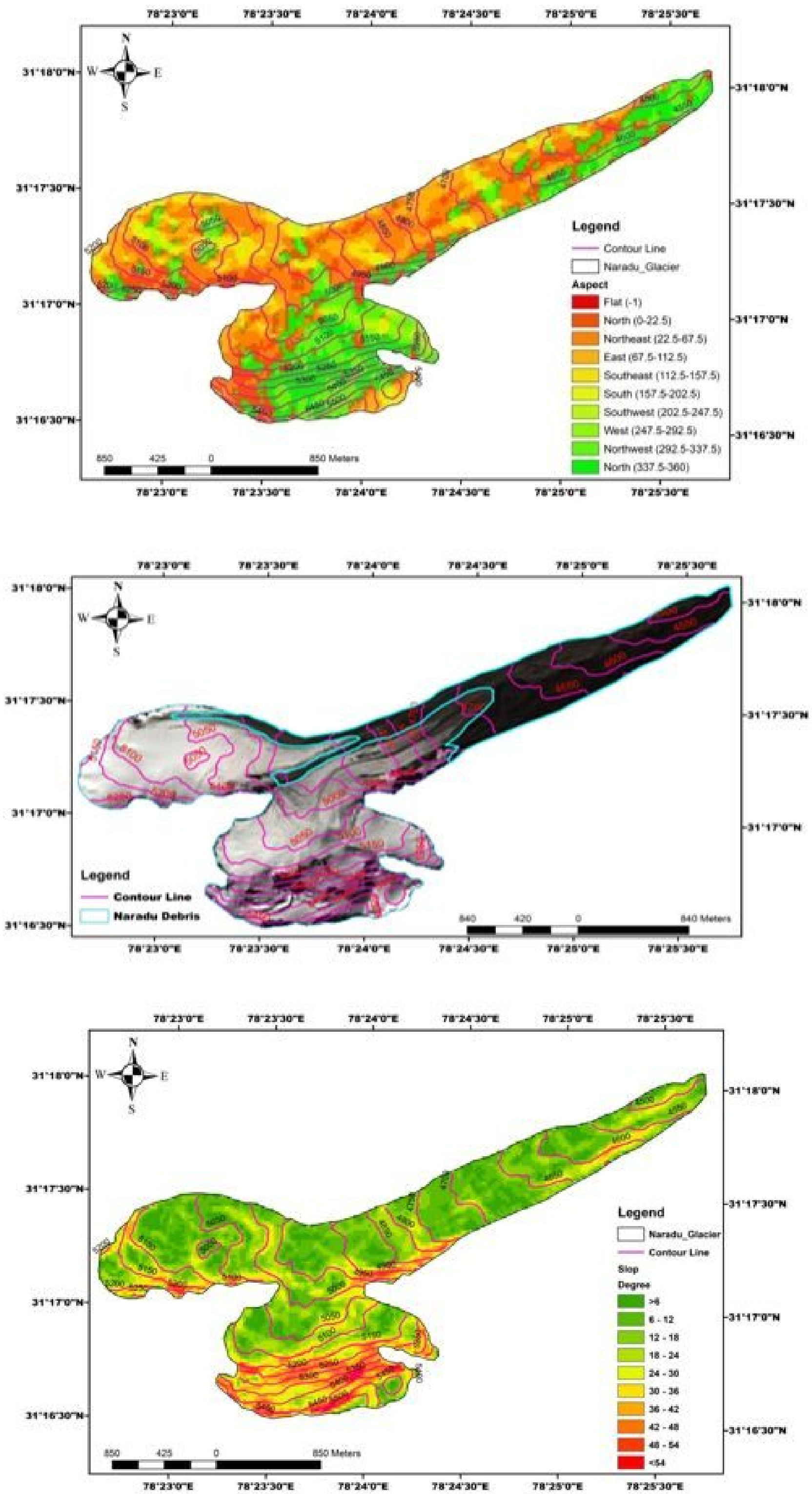

Figure 2

Naradu glacier map showing a) aspect, b) debris covered area and c) slope of different elevation zone.

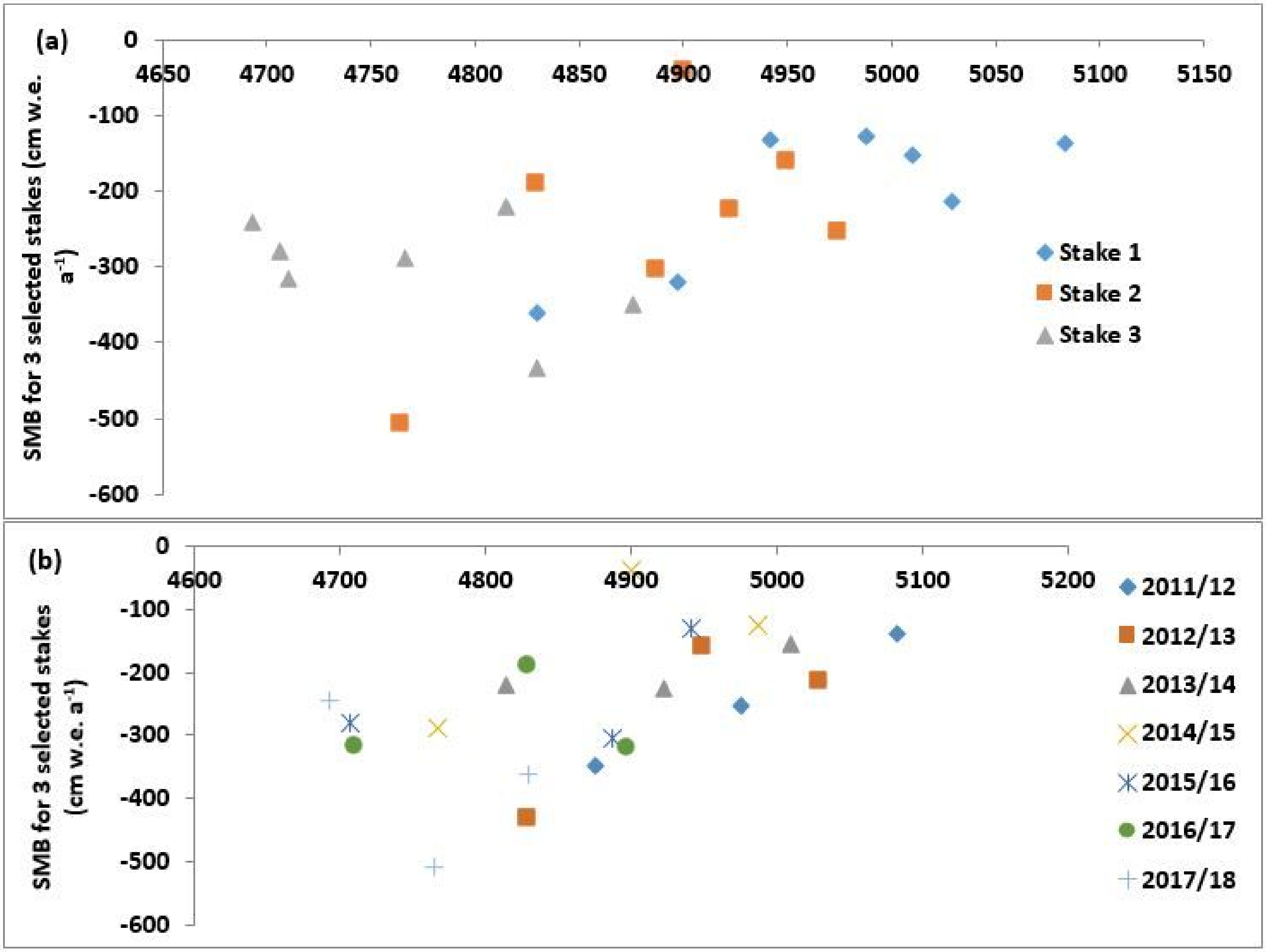

Figure 3

a) SMB against elevation for different years for three selected stakes (before projection to initial elevation); b) SMB against elevation for different years for three selected stakes (before projection to initial elevation).

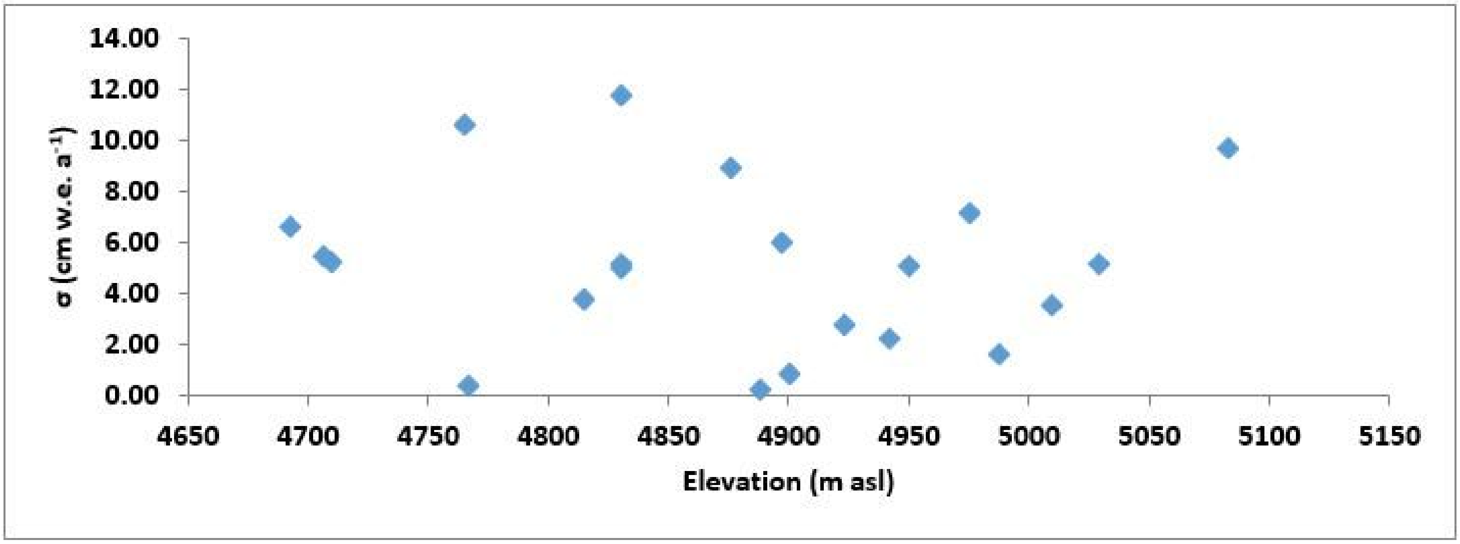

Figure 4

Standard Deviation of individual stake during 7 years period

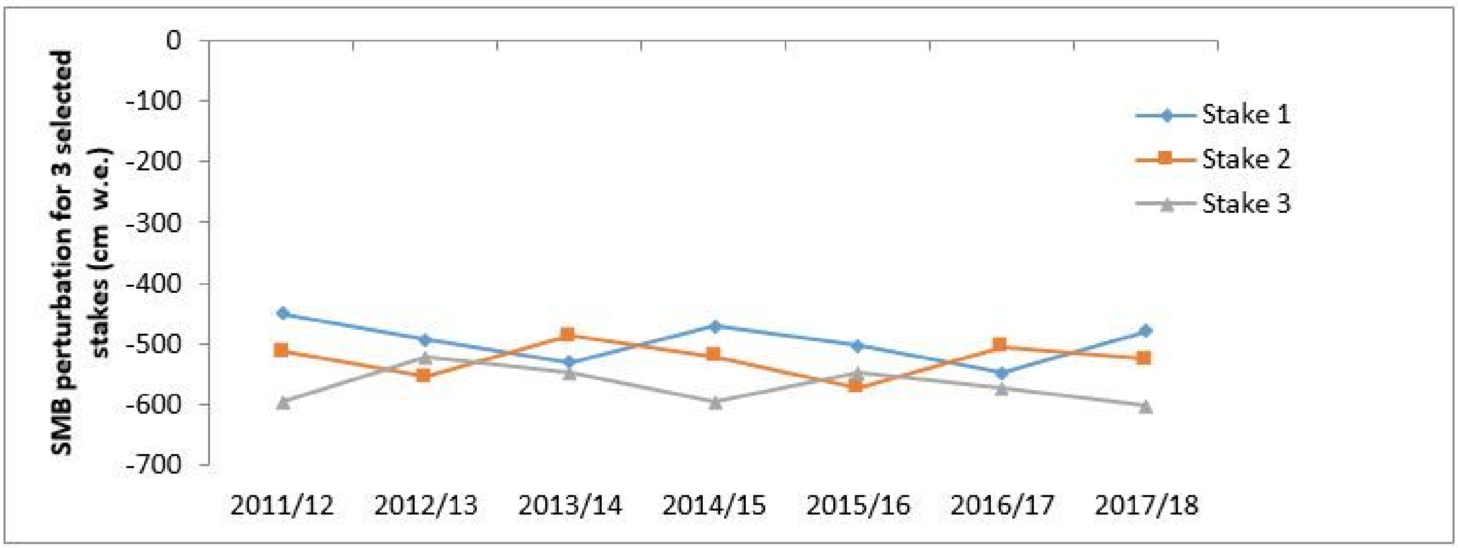

Figure 5

SMB perturbation for 3 selected stakes

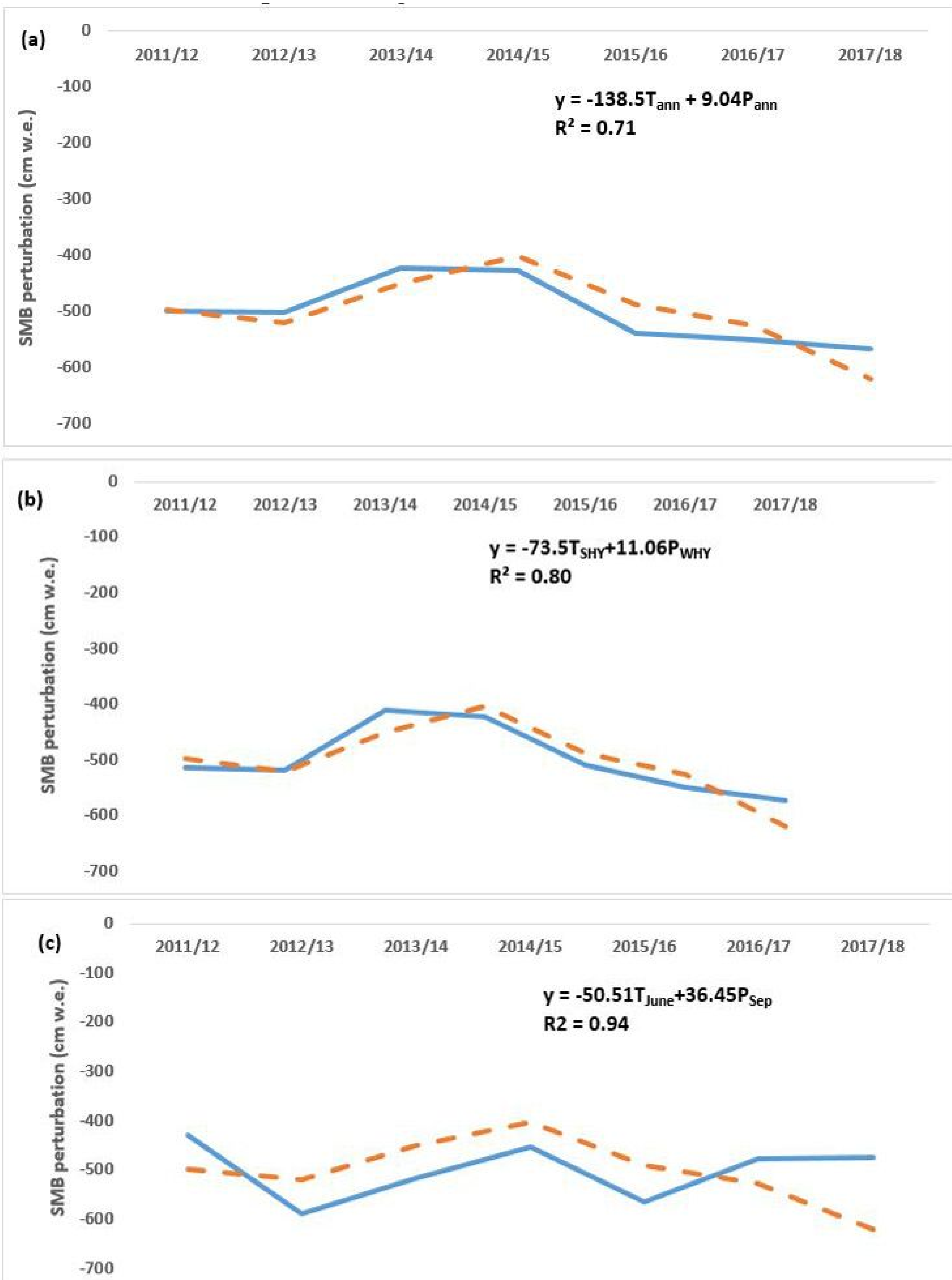

Figure 6

Observed SMB Perturbation and modelled SMB perturbation based on MLRA using two predictors (a) annual temperature and annual precipitation, (b) Summer half-year temperature and winter half-year temperature, (c) June temperature and September precipitation. The round cap red dash line is the observed SMB, the round cap solid blue line is the calculated SMB signal resulting from the MLRA.

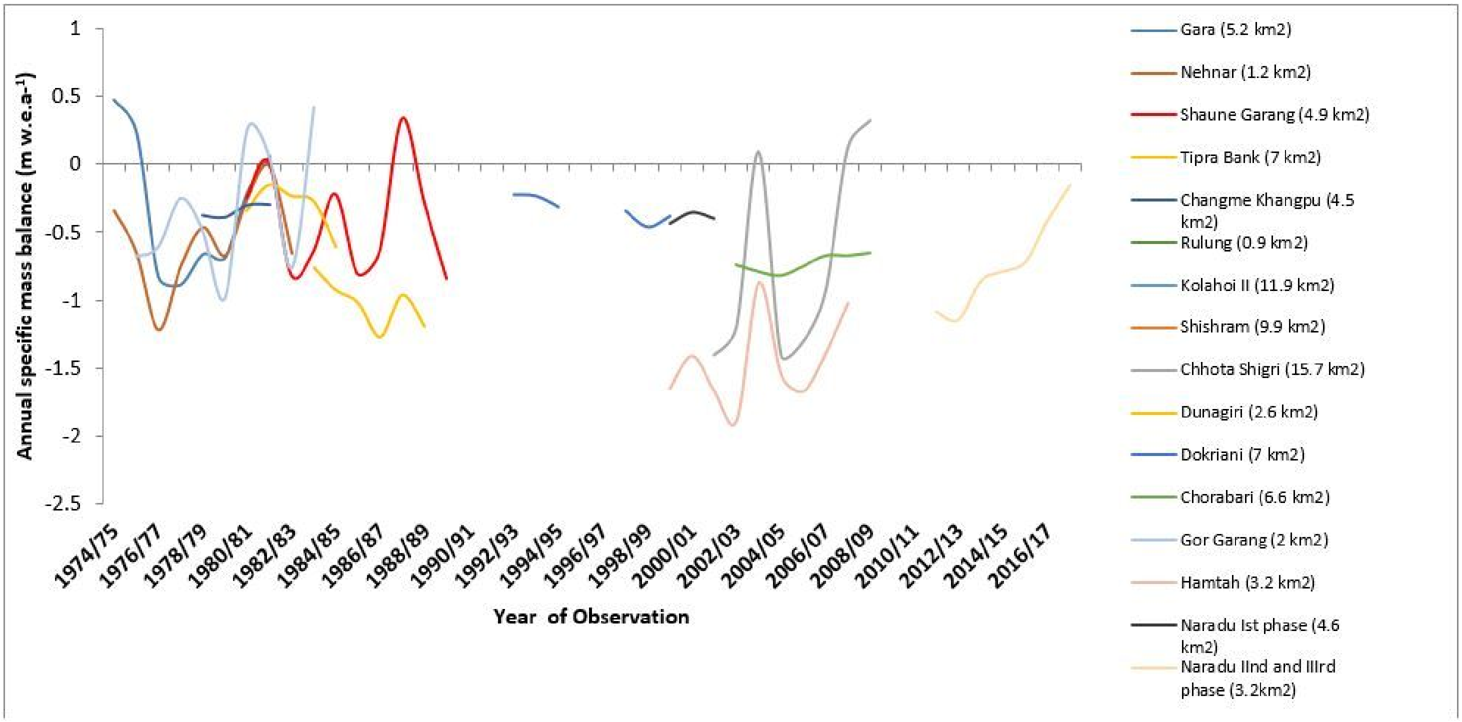

Figure 7

Annual specific glacier mass balance available in Indian Himalayan Region (Singh et al., 2018) with the present study.

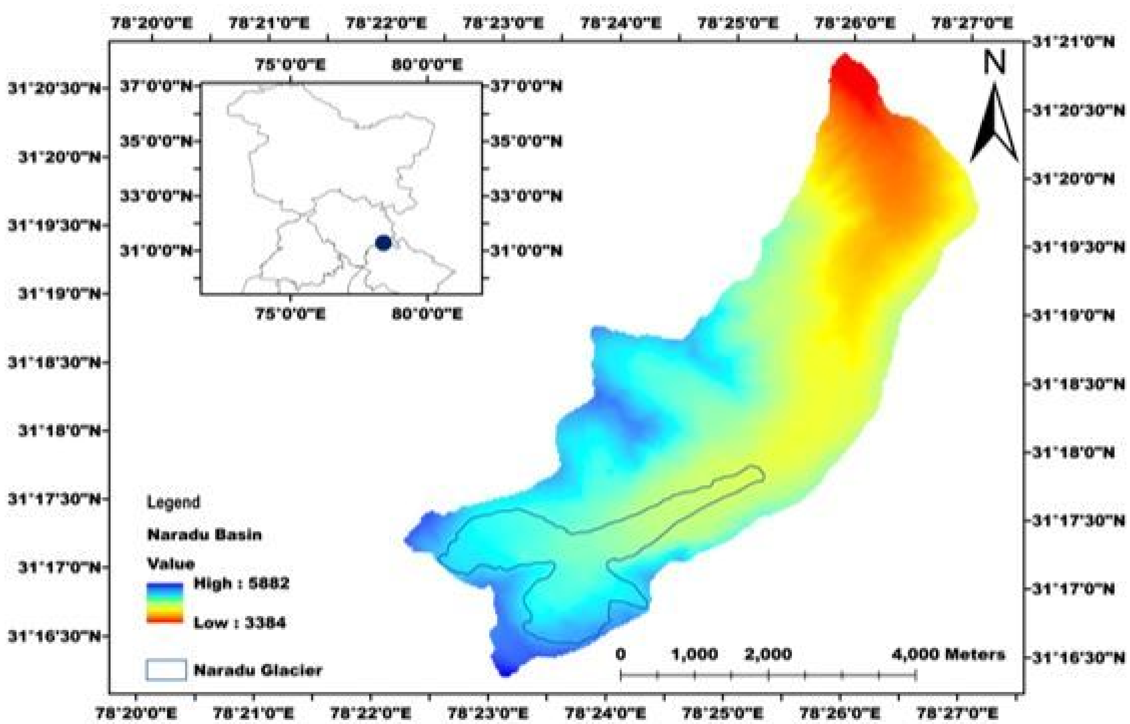

Figure 8

Location map of Naradu glacier in the Naradu catchment area

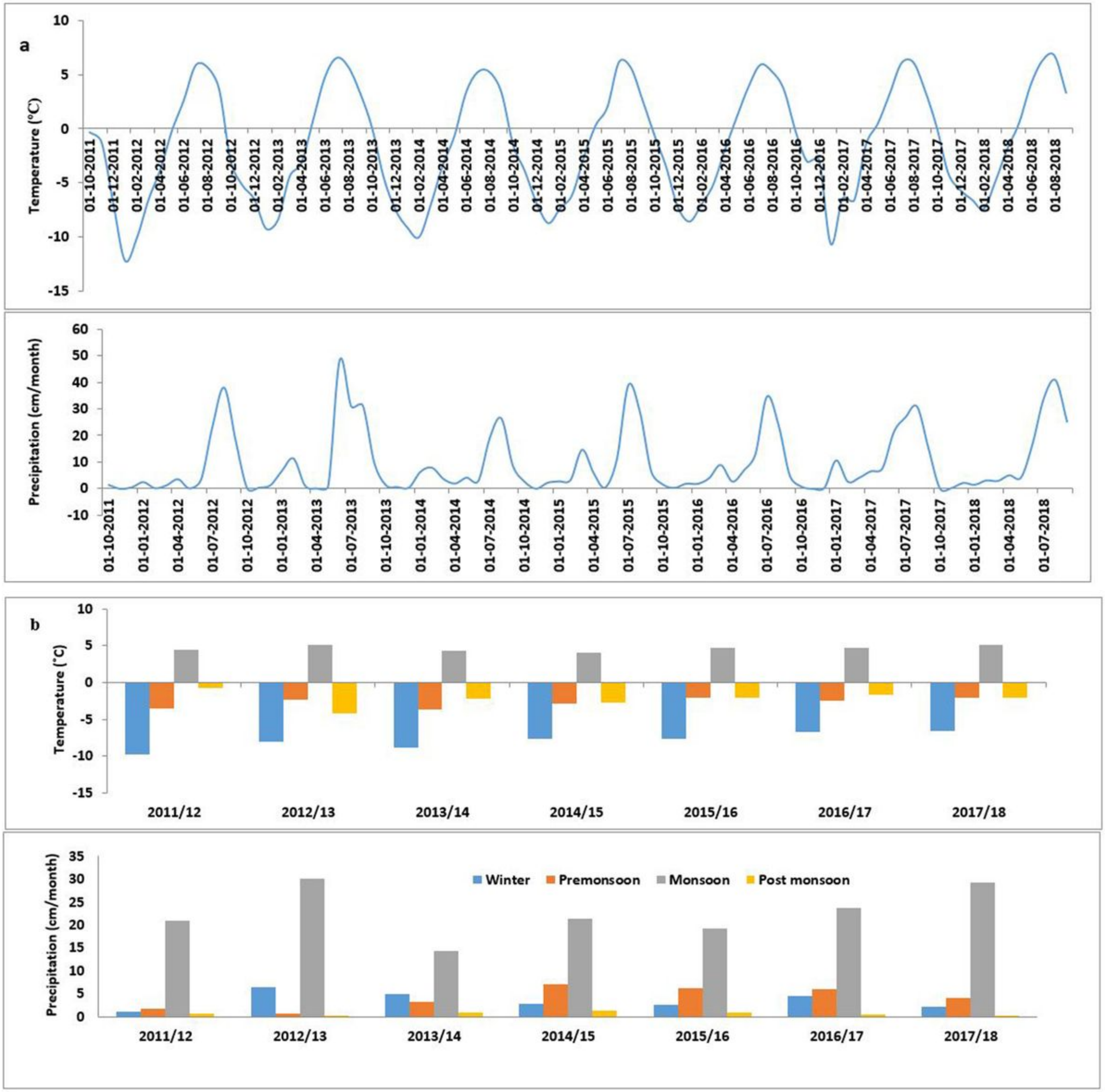

Figure 9

(a) Monthly temperature and precipitation at Naradu basin; (b) Seasonal temperature and precipitation at Naradu basin