B. TECH. PROJECT REPORT

On

Long term reconstruction of annual and seasonal mass balances on Dokriani Glacier, Garhwal Himalaya

BY

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DISCIPLINE OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

November 2019

Long term reconstruction of annual and seasonal mass balances on Dokriani Glacier, Garhwal Himalaya

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

CIVIL ENGINEERING

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November 2019

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Long term reconstruction of annual and seasonal mass balances on Dokriani Glacier, Garhwal Himalaya"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Civil Engineering' completed under the supervision of **Mohd. Farooq Azam, Assistant Professor, Discipline of Civil Engineering,** IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student with date

CERTIFICATE by BTP Guide

It is certified that the above statement made by the student is correct to the best of my knowledge.

Signature of BTP Guide with dates and their designation

Preface

This report on "**Long term reconstruction of annual and seasonal mass balances on Dokriani Glacier, Garhwal Himalaya"** is prepared under the guidance of Mohd. Farooq Azam.

Through this report, I have tried to give a detailed overview of what is mass balance and why its estimation is important for any glacier. I have tried my best to explain everything in the simplest manner and provide content which has the least error.

Sudhish Kumar Mishra

B.Tech. IV Year

Discipline of Civil Engineering

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Acknowledgement

I wish to thank Mohd. Farooq Azam for his kind support and valuable guidance. It is because of his help and support, due to which I was able to complete the design and technical report. Also, I would like to thank Ms. Smriti Srivastava who is a research scholar in IIT Indore, without their support this report would not have been possible.

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Abstract

This study uses the ERA5 dataset to estimate the mass balance of Dokriani Glacier. Mass balance (MB) is an important characteristic property of a glacier as it reflects how a glacier is responding to changing weather conditions. Most of the glaciers in the world are retreating means they are losing mass which in turn implies that they have a negative MB. In this study, we have used some of the observed in situ meteorological parameters to calibrate and bias correct the ERA5 meteorological variables. Dokriani glacier receives precipitation mainly from Indian Summer Monsoon (ISM) and is also influenced by westerly disturbances. Precipitation and temperature are the key factors and using their variation we can derive relationships to minimize the error between observed and modeled mass balance profiles. Continuous negative MB trend is observed for the glacier and which is much more pronounced in the summer season. The mean glacier degradation from 1980 to 2018 is found out to be -0.53 m w.e. a^{-1} indicating that Dokriani glacier is retreating. MB values ranging from -2.05 m w.e. a^{-1} to +0.56 m w.e. a^{-1} are obtained using the modeled ERA5 dataset. There is a significant correlation between long term annual MB and annual precipitation which can be observed in the most negative MB values during 1981-85 and most positive MB of +0.56 m w.e. a^{-1} in 2010. Seasonal MB offers a better insight into the climate-glacier interaction and annual summer MB mostly follows the trend of annual MB for the current decade (2011-18). The results indicate that the Dokriani glacier has been in a mass degradation phase for the last 39 years.

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List of Abbreviations

MB	Mass Balance
ISM	Indian Summer Monsoon
ELA	Equilibrium Line Altitude
PMB	Point Mass Balance
AWS	Automatic Weather Station
OD	Observed Data
MD	Modelled Data
SEB	Surface Energy Balance
SR	Shortwave Radiation
LR	Longwave Radiation
BC	Base Camp
LS	Linear Scaling
PG	Precipitation Gradient
SBE	Stefan Boltzmann's equation

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Chapter 1

Introduction

1. Mass Balance

Mass Balance (MB) in simple words can be defined as the difference between mass gain and mass lost during a particular period of time. It is widely used as a key parameter for characterizing any glacier and it gives us information that as to what amount glacier's volume has changed. So if a glacier has negative MB then it will recede since it has lost mass and if positive MB then it will advance. It is also possible that the amount of mass gain and loss is the same approximately, then a glacier is said to be in equilibrium. The technical term for mass lost is 'Ablation' and mass gain is 'Accumulation'. Surface Accumulation processes mainly include precipitation (snow and ice mainly), avalanching and driven snow from external sources. While Surface Ablation processes include surface melting and runoff, sublimation and calving (somewhat rare but possible). Other than this there is also non-surface phenomenon like melting within the ice, rainwater percolation, etc.

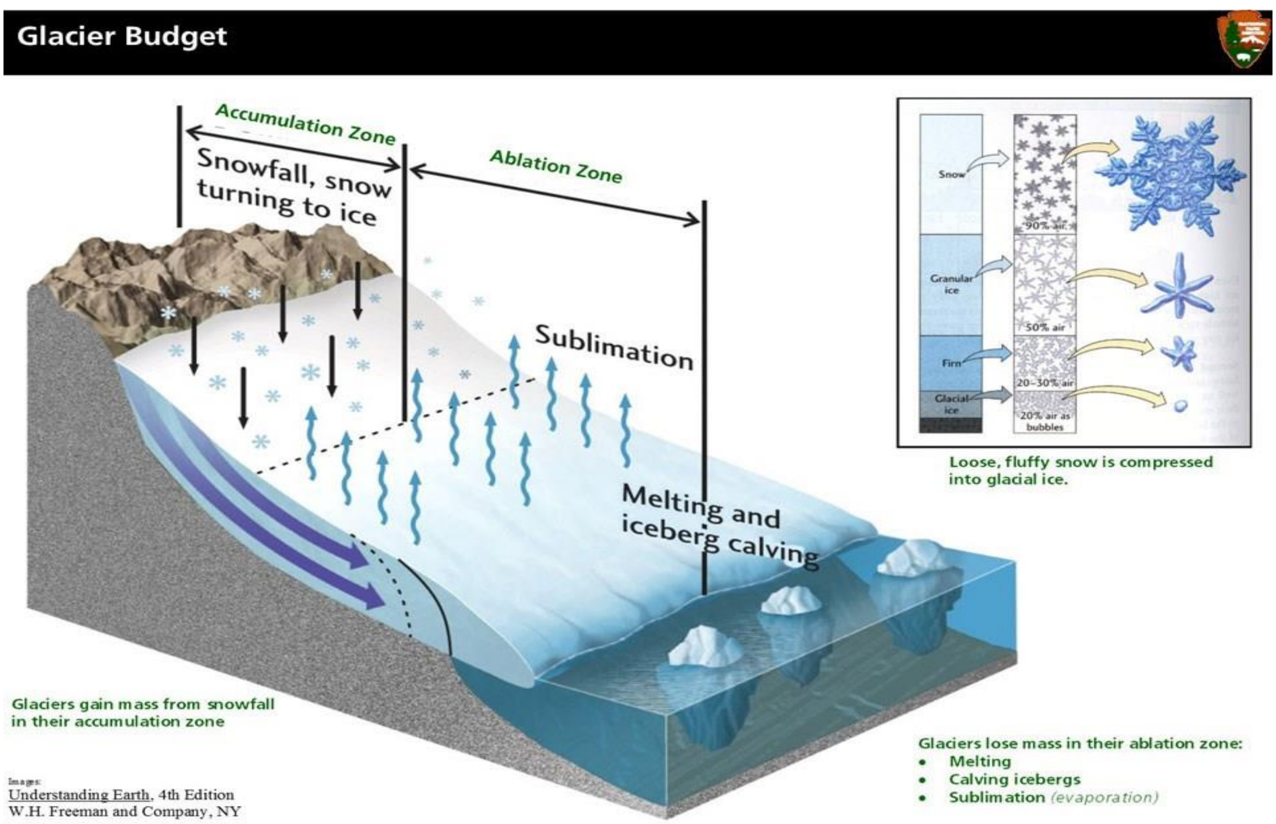


Figure 1: Schematic diagram showing glacier processes

2. Accumulation and Ablation

Usually, accumulation and ablation occur over the entire glacier but its net effect depends on altitude. At lower altitudes ablation is predominant and it is called ‘ablation zone’ while the higher altitude part where there is net mass gain is called ‘accumulation zone’. Somewhere midway along the glacier ablation is equal to accumulation and it is called **Equilibrium Line Altitude (ELA).** ELA also changes depending on the past like if ELA position moves up then that glacier must have undergone melting in the past years.

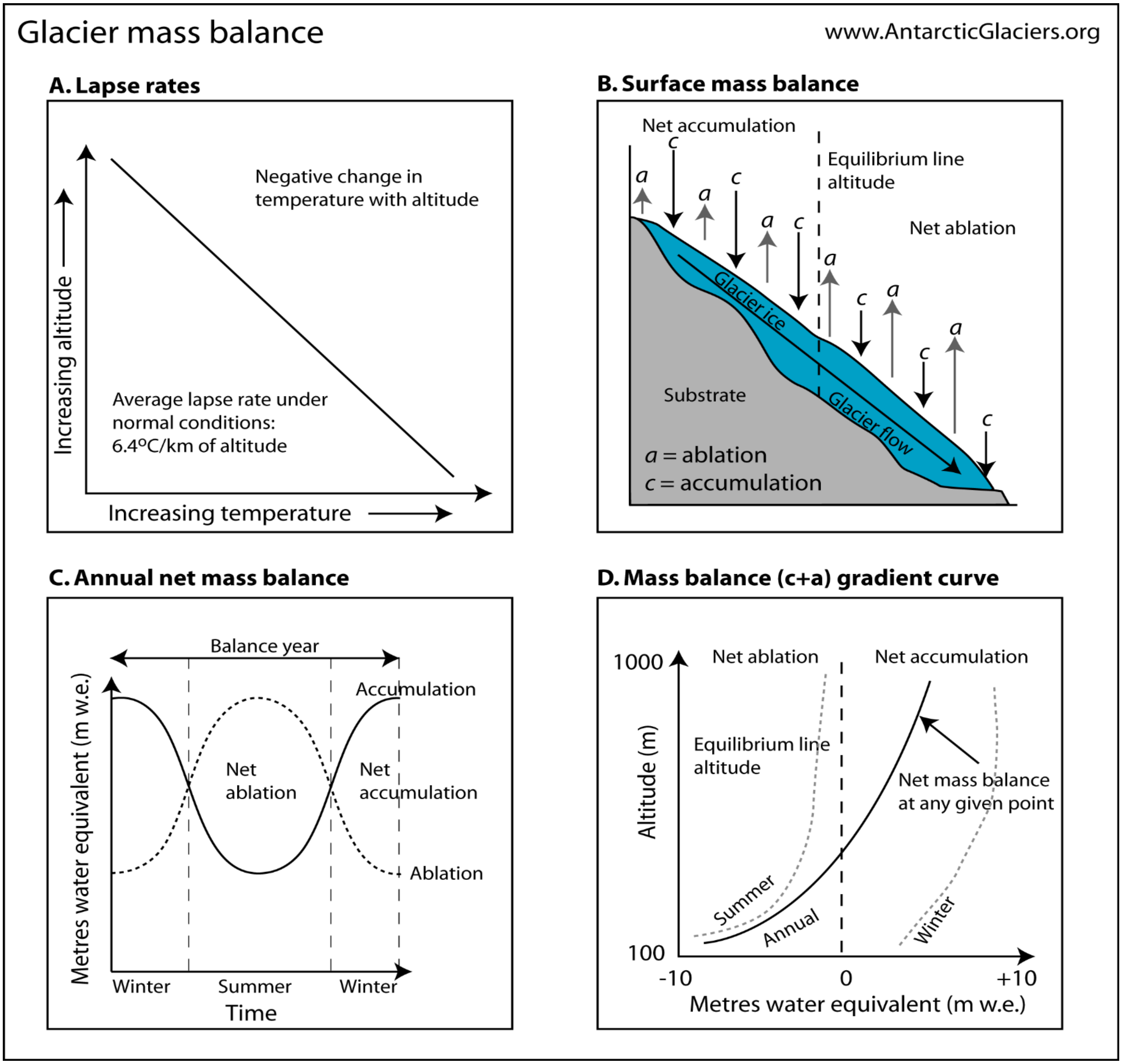


Figure 2: ELA line and mass balance variability (season and altitude wise)

We know that as we move up from the surface, air temperature decreases and so does the pressure. The whole glacier surface is much complicated due to factors like non-uniform composition, orographic effects, adverse and sudden changing weather conditions, etc. The sum of accumulation and ablation accounts for the glacier mass balance and it is usually expressed in meter water equivalent (m w.e.). So during winter accumulation is much higher due to snowfall and hence MB is positive while the summer season promotes melting and sublimation due to which MB is negative. Altitude wise also at higher altitudes there is more snow hence positive MB while at lower altitudes due to more temperature relatively, precipitation falls as rainfall leading to less positive or negative MB. The glacier net mass balance describes the amount of mass change it has undergone over the entire ‘hydrological year’. The hydrological year for any glacier starts from 1st October and ends on 30th September of next year.

3. Mass Balance measurement methods

3.1 Glaciological Method (Stake Measurement)

In situ measurements are more common but at the same time much more tedious and time-consuming. For this, stakes are used and installed over the entire glacier and after some time they provide us with data of accumulation and ablation rates for a single point and this is called **Point Mass Balance (PMB).**

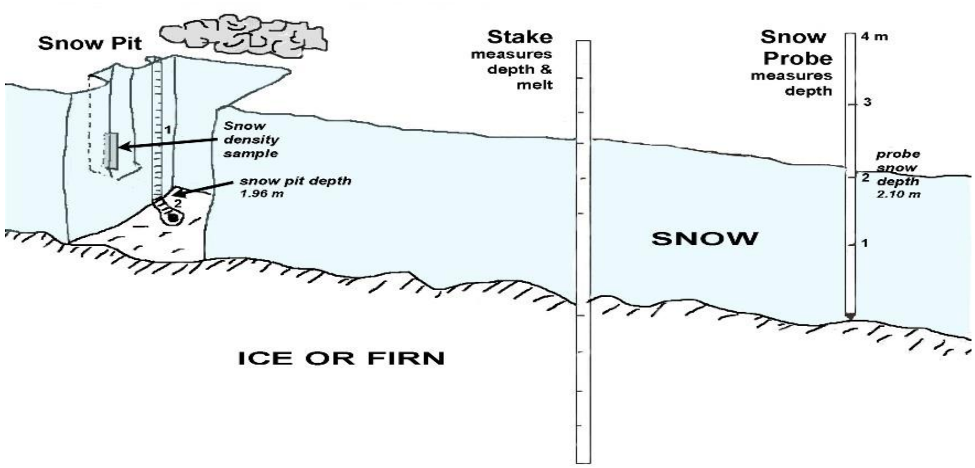


Figure 3: Stake measurement technique

GPS is used to fix each stakes position and its depth inside the glacier is recorded. **Automatic Weather Stations (AWS)** on the glacier surface measures energy fluxes and other meteorological variables like

Temperature, Precipitation, Relative Humidity, Wind Speed, etc. But this method is challenging due to adverse weather conditions on the glacier and also stakes will need to be visited several times to calculate the annual mass balance.

3.2 Remote Sensing Method

This is a widely used approach and also a better alternative as this provides us with a facility to calculate each and every variable using desk-based studies. However, this also comes at a cost that the variables calculated need to be calibrated and corrected according to the field-based AWS data. So field-based data is also equally important as it serves as a reference for other variables.

The basic methodology applied is that we have some **Observed Data (OD)** for a particular period of time from the AWS and then we have acquired **Modelled Data (MD)** from a given dataset. We will calibrate MD using the OD and bias correct it also using different methods. Finally, we will vary some key meteorological parameters to minimize the RMSE (Root Mean Square Error) between these two datasets. Mass balance can be calculated using different methods like using water balance equation, ELA/AAR (Accumulation Area Ratio) equation, Geodetic Method, **Surface Energy Balance (SEB)** method, etc. Here we have used the SEB method to calculate the annual and seasonal MB.

4. Surface Energy Balance Model

It is basically an energy balance applied on the surface of a glacier. The approach is shown in the figure below where SWI stands for incoming **shortwave radiation(SR)**, SWO for outgoing shortwave radiation, LWI for incoming **longwave radiation(LR)**, LWO for outgoing longwave radiation, SW_{sub} for shortwave radiation penetrating in the ice, G is the conductive heat flux in snow or ice, H and LE are the sensible and latent heat fluxes due to turbulence respectively.

4.1 Radiation

The main source of radiation is the Sun. Visible light, UV and Infrared all are examples of radiation and Sun emits a lot of radiation in the form of shortwave and it has a higher amount of energy than LR. So solar radiation is the incoming SR when this radiation reaches the Earth surface some of it is absorbed and some part of it is reflected back. The part of the SR that is reflected back is called SWO and it depends on the surface properties. The Infrared rays mainly contribute to the LR and after entering Earth’s atmosphere, clouds and surface absorb the solar energy. The surface heats up and re-emits energy in the form of LWO. The incoming radiation (directed towards the surface) is assumed to be positive and outgoing to be negative. SW_{sub} is the amount of shortwave energy that penetrates into the ice/snow surface and gets trapped inside undergoing multiple reflections.

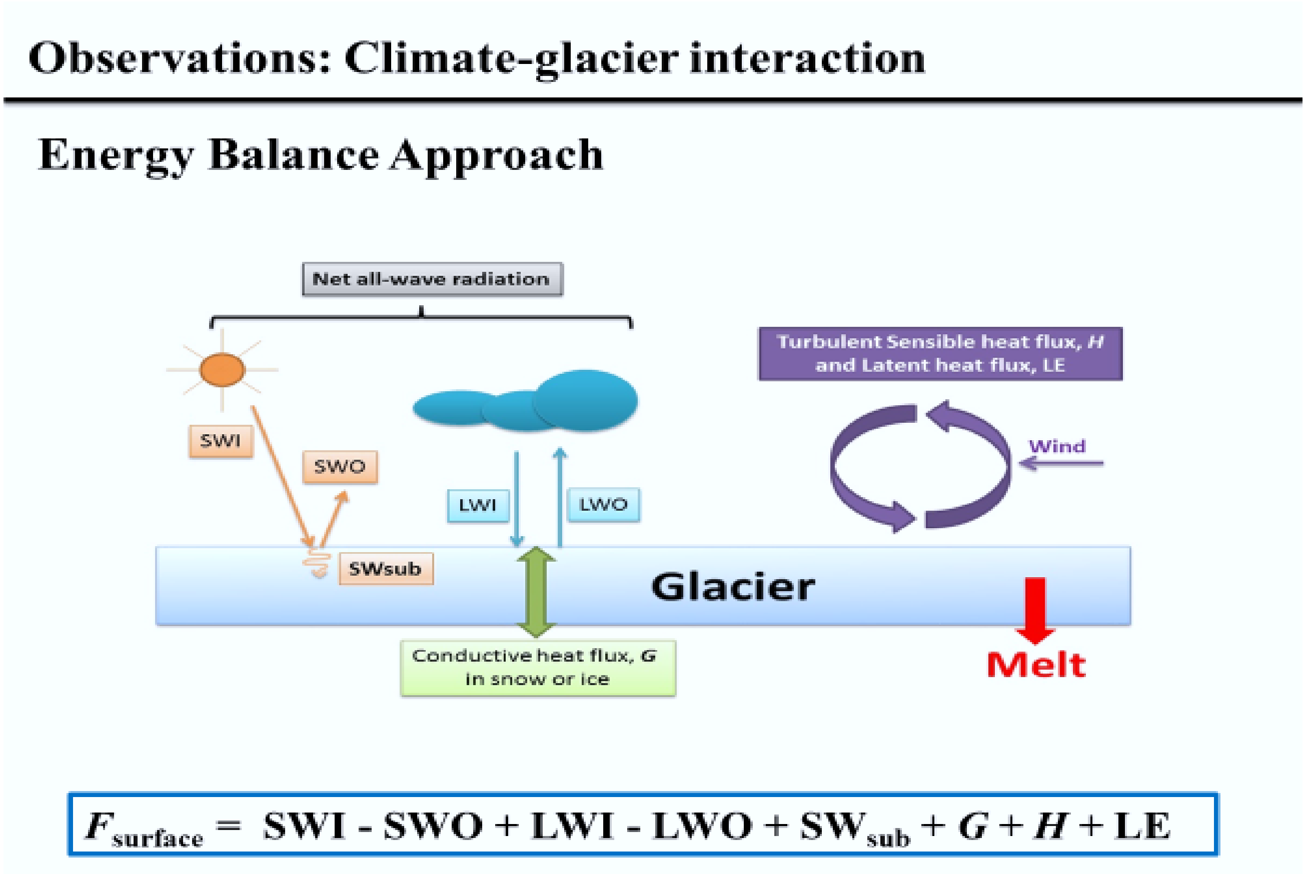


Figure 4: SEB method

4.2 Turbulent Fluxes

Latent and Sensible heat are collectively called Turbulent heat fluxes. While latent heat is related to changes in the phase of a substance between solid, liquid and gas, sensible heat is related to changes in temperature. Latent heat is the energy released or absorbed from a substance during its phase change. Sensible heat is the energy required to change the temperature of a substance.

Conduction into the ice/snow is very less but can be taken into account for the conservation of energy. Finally, $F_{surface}$ is the amount of energy available at the surface.

Chapter 2

Study Area

The Himalaya has the largest number of glaciers and these glaciers are very sensitive to climate changes, so they give us great insight into the change in regional weather conditions. Dokriani Glacier is one of the medium-sized glaciers and it is situated at the Garhwal Himalaya, to the southwest of the Gangotri Glacier System. It has an NNW orientation and lies around 30º 50' to 30º 52'N and 78º 47' to 78º 50'E [5]. The glacier occupies an area of 7 km^2 out of the total catchment area of 15 km^2. It is formed by two cirques, one on the northern slope of Draupadi Ka Danda (6000m a.s.l) and second on the western slope of Jaonli (6632m a.s.l) which confluence at 4800m a.s.l [5]. In the higher region, the general flow is NNW for 3 km and for lower 2.5 km it is WNW [5]. The stream originates from the Dokriani Glacier and is known as the Din Gad stream. For the collection of meteorological data, a permanent AWS was installed at Dokriani Glacier base camp (3774 m a.s.l) [3].

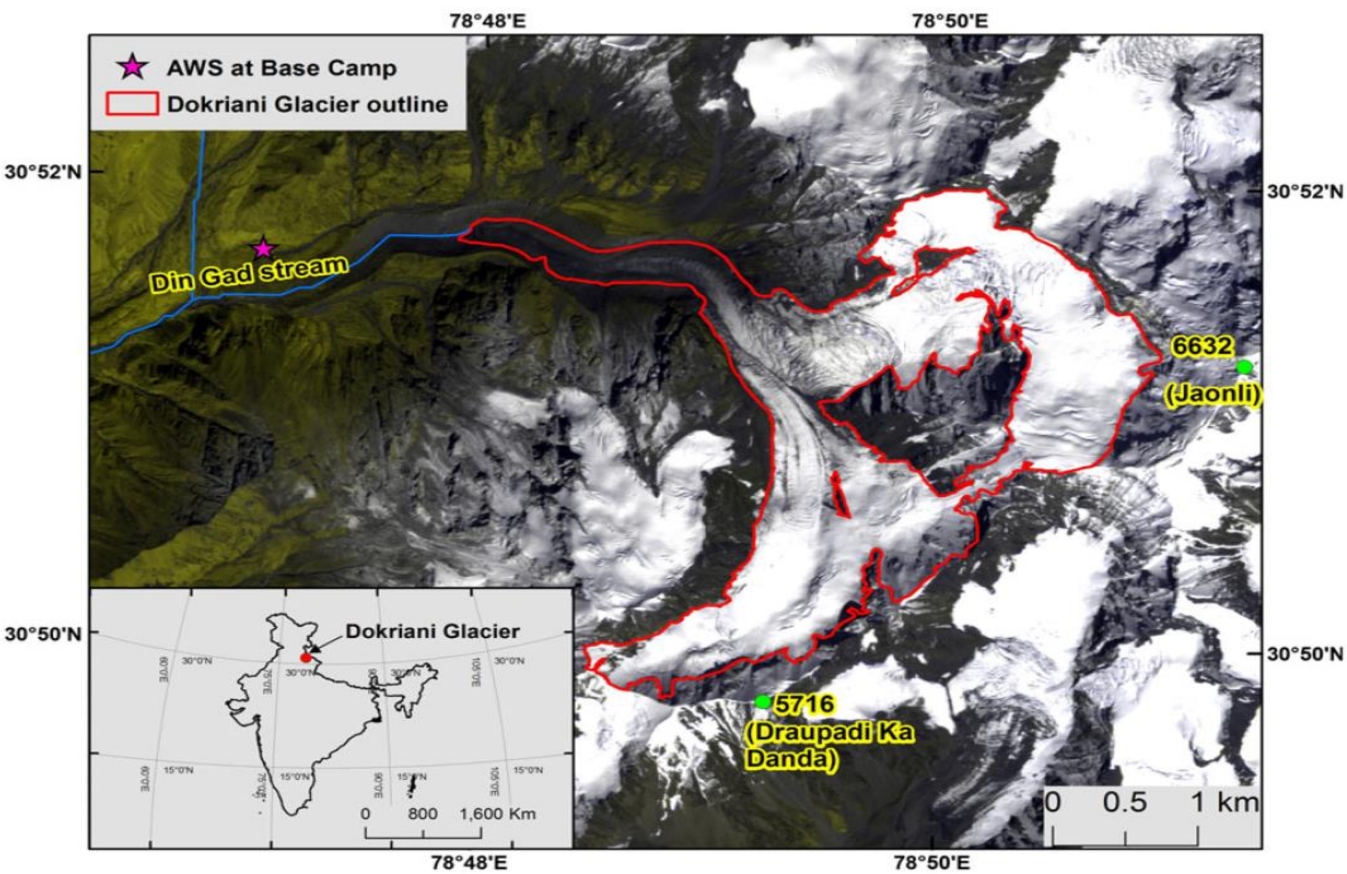


Figure 5: Outline of Dokriani glacier showing the location of BC with AWS installed, Verma et. al. [3]

The lower part of the glacier is resting over a thick subglacial till layer. Well-developed lateral moraines are the prominent glacial features in the valley that demonstrate the past extent of the glacier [5]. The average gradient is 12º and approximately one-third of the ablation area is covered with debris [5]. Marginal and transverse crevasses are well developed in the ablation area. Avalanches occur very frequently in the upper ablation area (4600 to 4900 m a.s.l) where the valley is narrow and bounded by steep rock faces. The present position of the glacier snout is at 3890 m a.s.l [5]. The Figure below shows the contour map for Dokriani Glacier.

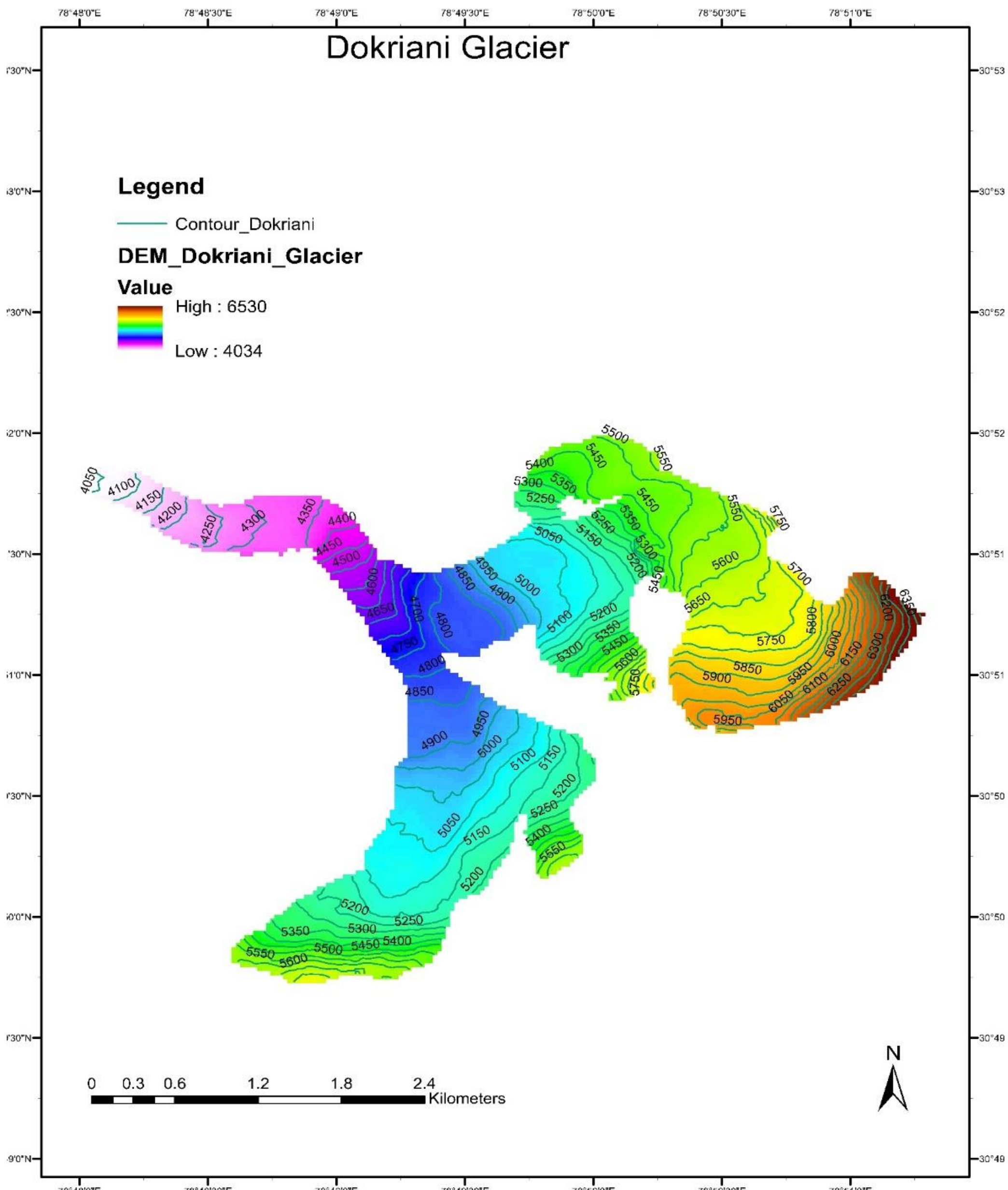


Figure 6: Contour map for Dokriani glacier

The climate of the area is humid temperate during the summer season and cold during the winter season. Precipitation occurs as rainfall mainly during the summer season and winter precipitation mainly occurs between December and March [5]. The maximum thickness of glacial ice is 120 m in accumulation zone and minimum thickness is 25 m near the snout area as measured by ground-penetrating radar [5].

The figure given below shows the hypsometry of Dokriani glacier where at each 50 m elevation band its area distribution is shown.

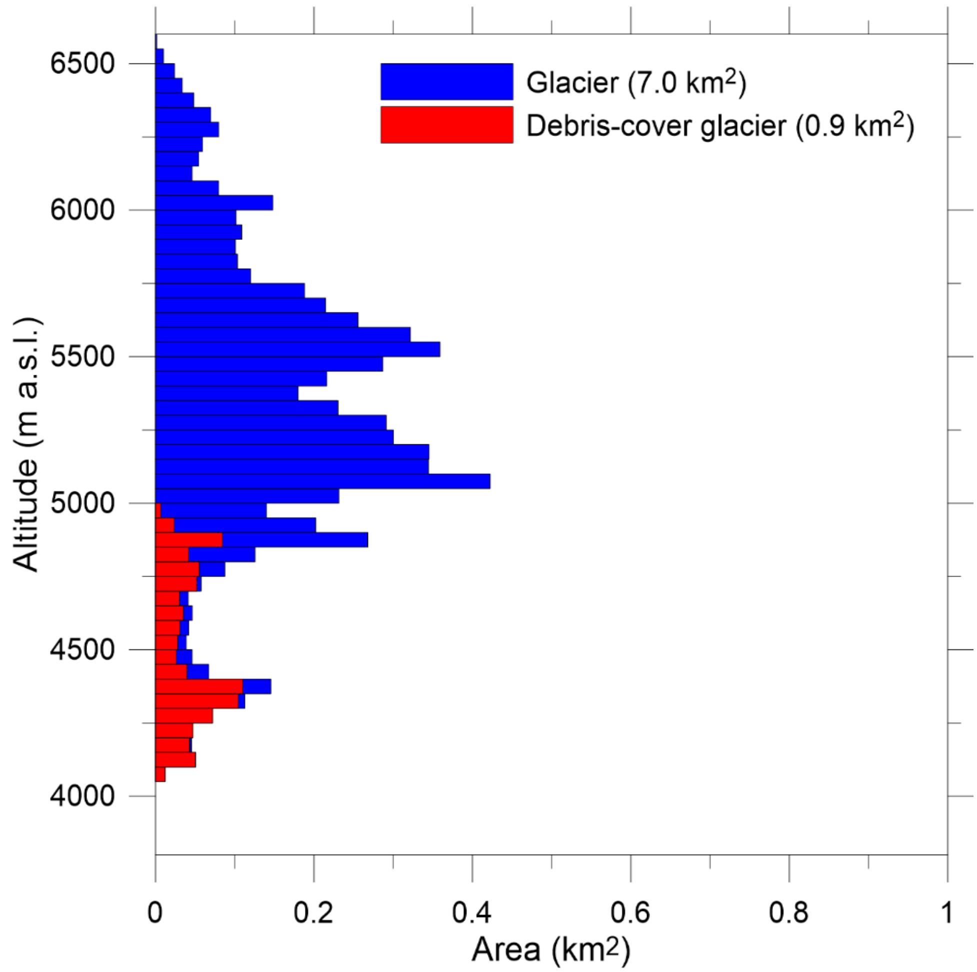


Figure 7: Hypsometry of Dokriani Glacier

Chapter 3

Approach

1. Dataset

To calculate each variable we have used the ERA5 dataset which is the fifth generation ECMWF atmospheric reanalysis of the global climate. At present it provides us with data from January 1979 to October 2019, We have used hourly data on single levels as well as pressure levels to calculate variables at required points. It has a 0.25º x 0.25º resolution gridded dataset and given the location of **base camp (BC)** we have downloaded data for the nearest four grid points and then applied inverse distance method to calculate it at the required BC location. Additionally, for pressure level variables like Temperature, Relative Humidity, etc. linear interpolation is applied corresponding to the BC pressure (in hPa).

The BC pressure at 3774 m a.s.l is 634.77 hPa. The Dokriani glacier extends from 4050 m (612.40 hPa) to 6550 m (437.3 hPa). The formula below is the inverse distance weighting method to calculate Z_p using distance (d) and corresponding Z for the i_{th} points.

$$z_p = \frac{\sum_{i=1}^{n} \left(\frac{z_i}{d_i^p} \right)}{\sum_{i=1}^{n} \left(\frac{1}{d_i^p} \right)}$$

2. Bias Correction

Correction is needed as the ERA5 data is neither calibrated nor compared with the actual data. Due to the fluctuating weather conditions, instrumental error, etc. bias correction is applied to minimize the error between the meteorological variables. Proper correction factors are applied depending on the type of a variable and the best-suited bias method for it.

2.1 Linear Scaling (LS) method

In this method, a constant correction factor is applied that is estimated from the difference between modeled values and the observed values for each calendar month. Precipitation is adjusted with a multiplier and temperature is corrected by the additive term [4].

$$P^{cor}_{hst,m,d} = P_{hst,m,d} \times [\frac{\mu(P_{obs,m})}{\mu(P_{hst,m})}]$$

$$T^{cor}_{hst,m,d} = T_{hst,m,d} + [\mu(T_{obs,m}) - \mu(T_{hst,m})]$$

Where P^{cor} and T^{cor} denote the corrected precipitation and temperature on the d-th day of the m-th month, respectively; P^{hst} and T^{hst} respectively denote the precipitation and temperature from modeled outputs during the relevant period; the subscripts d and m are specific days and months, respectively; and μ denotes the mean value [4].

2.2 Variance Scaling Method

It is a three-step method mainly used for correcting temperature. It is best used when we have to correct both the mean and variance of temperature. It is an extended version of the LS approach. After getting the corrected data from LS approach we calculate T_{hst}

$$T_{hst,m,d} = T_{LS,hst,m,d} - \mu(T_{LS,hst,m})$$

Then standard deviation (sigma) is calculated for this new temperature and observed temperature for the normalized time series [4]

$$\sigma_{hst,m,d} = T_{hst,m,d} * \frac{\sigma_m(T_{obs,m,d})}{\sigma_m(T_{hst,m,d})}$$

Finally, the corrected temperature is calculated using the formula given below [4]

$$T^{cor}_{hst,m,d} = \sigma_{hst,m,d} + \mu(T_{LS,hst,m})$$

Other than these two, Quantile Mapping Method and Delta Bias approach are also used but they did not produce the best results as compared to the above-described methods.

As will be discussed later these two methods have been widely used in this study to correct most of the meteorological variables.

3. Meteorological Variables

SR and LR are directly available from the ERA5 dataset and are used in the SEB equation.

3.1 Air Temperature (T_a)

This is calculated at the BC location and bias-corrected using the LS method. Observed data is used from Verma et. al. 2018 [3] in which we have AWS data from 2011-2014 for different parameters. Monthly mean data is provided for 4 years which is used as a reference for correcting the ERA5 data. For calculating T_a over the entire glacier, the lapse rate (ºC/km) provided by Thayyen et. al. 2005 [9] is used.

3.2 Wind Speed (U)

For this, we have downloaded the u and v component of wind from 400 hPa to 650 hPa. After applying inverse distance we have applied linear interpolation to calculate both components at each band (using pressure level of each 50 m elevation band). Then we have calculated the resultant velocity at each band and applied the LS method for bias correction.

3.3 Precipitation (P)

We have used single-level hourly data to calculate precipitation at BC and then used **precipitation gradient (PG)** for the entire glacier. LS method is used where a monthly multiplier factor is found to be best for bias correction.

3.4 Relative Humidity (RH)

This is a pressure level variable so inverse distance, linear interpolation and then bias correction is applied in the respective order. The variance scaling method is used for bias correction.

3.5 Sensible Heat Flux (H) and Latent Heat Flux (LE)

These are calculated using the empirical equation from Fujita and Ageta, 2000 [2].

$$H_{\mathrm{s}} = c_{\mathrm{a}}\rho_{\mathrm{a}}CU(T_{\mathrm{a}} - T_{\mathrm{s}})$$

c_a=Specific heat of air (1006 J $kg^{-1}K^{-1}$)
ρ_a= Density of air (kg m^{-3})
C=Bulk coefficient for sensible and latent heat (0.002)
U=Wind speed (m s^{-1})
T_a=Temperatures of air
T_s= Temperatures of Surface

$$H_{\mathrm{l}} = l_{\mathrm{e}}\rho_{\mathrm{a}}CU[\mathrm{rh}q(T_{\mathrm{a}}) - q(T_{\mathrm{s}})]$$

l_e=Latent heat for evaporation (2.50×10^6)
ρ_a= Density of air (kg m^{-3})
C=Bulk coefficient for sensible and latent heat (0.002)
U=Wind speed (m s^{-1})
rh= Relative Humidity
q=Saturated specific humidity
T_a=Temperatures of air
T_s= Temperatures of Surface

The density of air is calculated using the ideal gas equation:

$$\rho = \frac{P}{RT}$$

Here R = 287.04 J/Kg-K, T is the absolute temperature and P is absolute pressure.

Here all terms are the same as mentioned and calculated except for q. q here is the saturated specific humidity at temperature T and it is defined as:

$$q(T) = \frac{0.622e'}{P}$$

$$e' = 0.611\exp\left[\frac{17.37T}{T + 237.3}\right]$$

e' is the saturation vapor pressure in KPa, P is the pressure level of that band in KPa and T is air temperature in ºC. $q(T_s)$ is a specific humidity at surface temperature. Since all the variables used in this equation are bias-corrected, hence there is no need to bias correct heat fluxes separately.

3.6 Surface Temperature (T_s)

This is calculated at the BC using Stefan Boltzmann’s equation (SBE) given by:

$$LWO = \varepsilon\sigma T^4$$

ε is assumed to be 1 for snow and ice surface, σ is Stefan Boltzmann constant ($5.67\text{x}10^{-8}$ W m^{-2} K^{-4}) and T is the absolute temperature in Kelvin.

For other bands iterative equation is used:

$$T_s = \frac{(1-\alpha)R_s + \epsilon R_l - \epsilon\sigma(T_a+273.2)^4 - l_e\rho_a CU(1-\mathrm{rh})q(T_a) + H_g}{4\epsilon\sigma(T_a+273.2)^3 + \left(\frac{\mathrm{d}q}{\mathrm{d}T_a} l_e + c_a\right)\rho_a CU} + T_a$$

R_s is net shortwave radiation (incoming – outgoing) and R_l is incoming longwave radiation. α is the albedo value which tells us the amount of energy any surface reflects back. For bias correction, SBE results and iterative equation results are compared and a correction factor is generated using variance scaling approach and that factor is applied on all bands.

3.7 HEAT FOR MELT (Q_M)

Combining all the terms, the SEB equation gives us the energy which is available at the surface [1]:

$$Q_M = SWN + LWI - \varepsilon\sigma(\mathrm{T_S} + 273.15)^4 + \mathrm{H} + \mathrm{LE}$$

Q_M = Energy available at surface

SWN = Net Shortwave radiation

LWI = Longwave Incoming

ε = emissivity (assumed to be 1 for ice and snow)

σ = Stefan's constant (5.67×10^{-8} W m^{-2} K^{-4})

T_s = surface temperature

H = Sensible heat

LE = Latent heat

This energy available at the surface combined with evaporation and precipitation serves as the basis for mass balance calculation. If the surface temperature is more than 0 ºC then melting will occur but if T_s is less than 0 ºC then Q_M will not account for melting and it will be consumed in raising the surface temperature.

So the surface temperature threshold is set at 0 ºC.

Chapter 4

Mass Balance Measurements

1. Point Mass Balance (PMB)

It is defined as the sum of accumulation and ablation as described previously. Accumulation includes solid precipitation (P_s), sublimation re-sublimation (E_v) and refreeze rate (R_f). Solid precipitation is described as the precipitation which falls as snow, ice pellets, mixed ice, and snow, etc. To calculate this we have applied temperature constraint on precipitation (P) values.

$$Ps = P \quad if\ Tair < 1°C$$

$$Ps = 0 \quad if\ Tair > 1°C$$

The reason to take T_{air} < 1 ºC threshold other than 0 ºC is because on Dokriani glacier snowfall occurs during winter (December – April mostly) and the monthly mean temperature of April is around 1.78 ºC, so it is done to take into account April's snowfall which is considerable.

Refreeze rate is calculated using the empirical equation [8]:

$$Rf = -0.69T + 0.0096$$

Here T is the annual mean air temperature and R_f comes in cm w.e.

Now ablation accounts for the melting glacier undergo in a certain period of time and this depends on the energy available at the surface (Q_M). This energy divided by the latent heat of fusion of ice contributes to melting. The surface temperature threshold is set to be 0 ºC below which Q_M will not play any role in melting. Finally, the PMB (in m w.e) is given by Sunako et. al 2019 [1]:

$$b_z = \left(P_s - \frac{Q_M}{l_m} + E_v + R_F\right)/\rho_w,$$

P_s is in mm w.e. d^{-1}, l_m is the latent heat of fusion of ice (3.33 x 10^5 J Kg^{-1}), E_v is the sublimation and re-sublimation rate in mm w.e. d^{-1}, R_f is the refreeze rate in mm w.e. d^{-1} and ρ_w is the density of water (1000 Kg m^{-2}).

Evaporation term (E_v) in the mass balance equation is calculated using latent heat flux which takes into account sublimation and re-sublimation.

$$Ev = \frac{LE}{lv}$$

LE is the latent energy and l_v is latent heat of sublimation (2838 KJ/Kg), this value divided by the density of water gives sublimation (positive) and re-sublimation (negative) in m w.e.

Combining all these, PMB is calculated for each band and its daily value is recorded.

2. Glacier wide MB

Now after calculating PMB for each band we calculate the area factor for each band and multiply it with the corresponding PMB. Summing this up for the hydrological year gives us the annual hydrological MB. For calculating area factor, hypsometry is used and glacier wide MB is given by Sunako et. al 2019 [1]:

$$B = \frac{\sum_z A_z b_z}{\sum_z A_z}$$

A_z and b_z are calculated for each 50 m elevation band for Dokriani glacier extending from 4050 m to 6550 m.

Chapter 5

Results and Discussions

1. Bias correction results

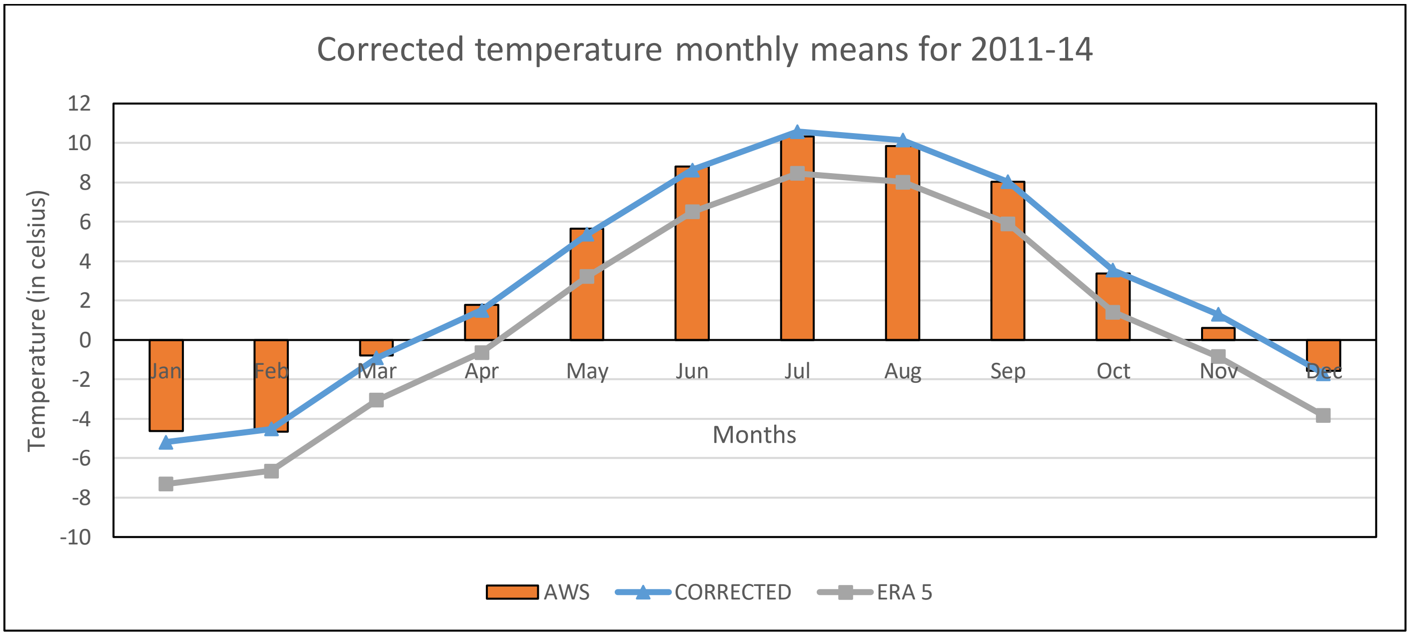


Figure 8: Bias corrected temperature for 2011-14 using the LS method

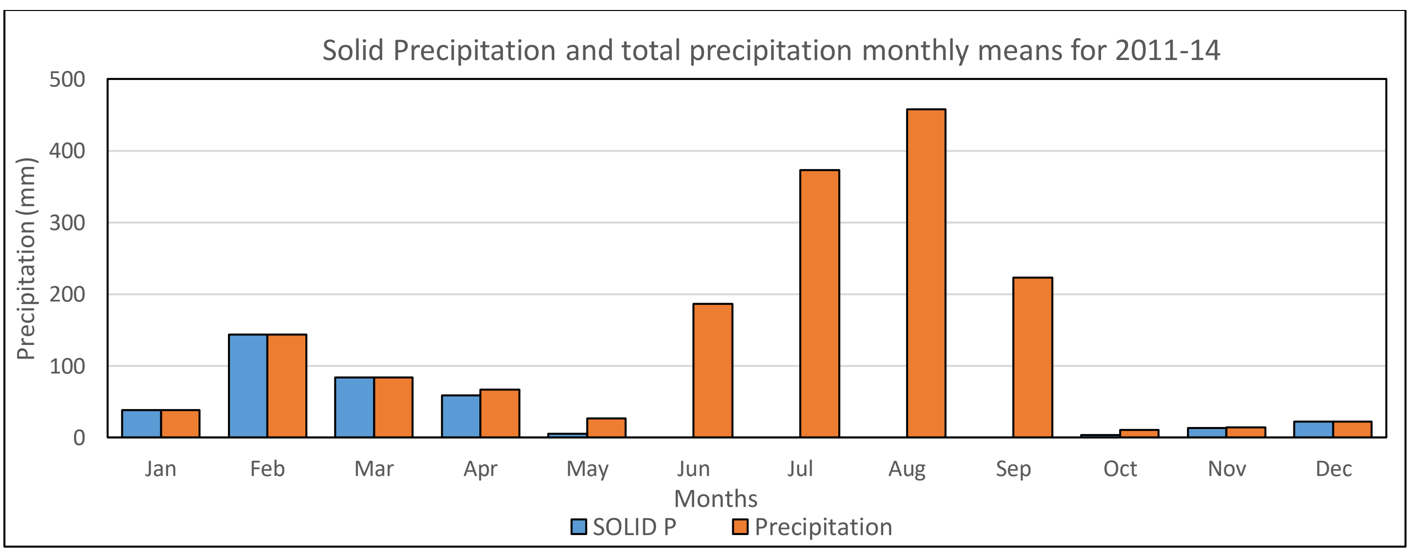


Figure 9: Bias corrected precipitation (solid and total) for 2011-14 using multiplier approach of the LS method

Figure 9 shows that August is the month with maximum precipitation (as rainfall) followed by July and September. Hence, Dokriani glacier closely resembles the Indian Summer Monsoon. Also, most of the solid precipitation (mainly snowfall) occurs between December – April. May and November are the transition months. The average total rainfall during the summer (May- September) is 1266 mm, whereas the average snowfall during the winter is 367 mm snow water equivalent [3].

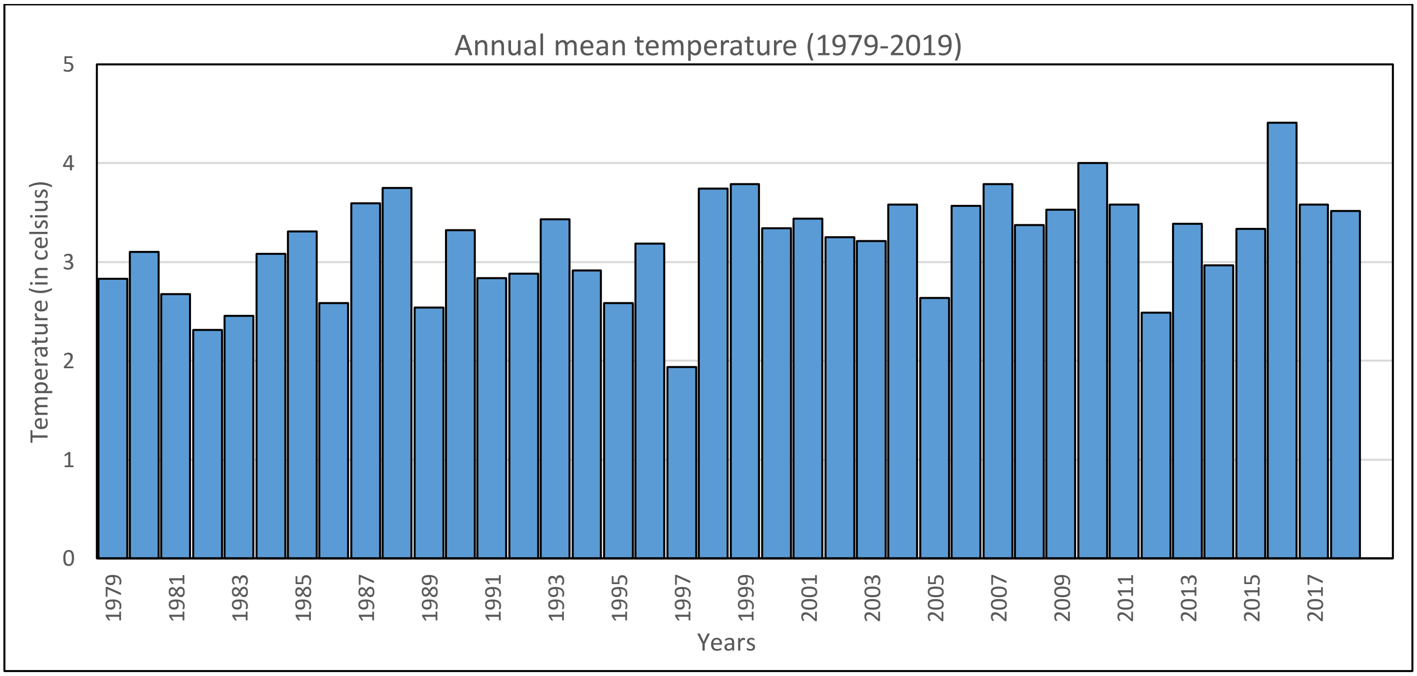


Figure 10: Bias corrected annual temperature from 1979-2018

Figure 8 shows that the hottest month at the glacier is July and the average annual temperature of the glacier is at least 2 °C (except 1997) as shown in Figure 10.

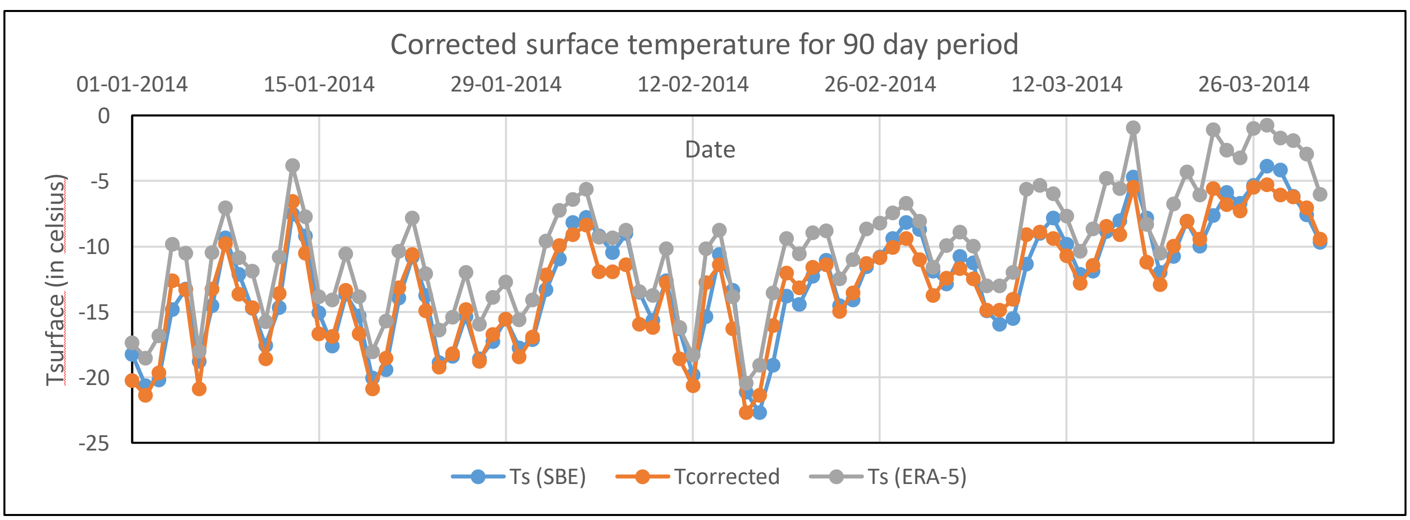


Figure 11: Bias corrected surface temperature using the variance scaling method. Here, the values are from 1st Jan 2014 to 31st March 2014 (90 days)

Figure 11 shows the bias-corrected results (60 days period) of the surface temperature using variance scaling between the surface temperature calculated using SBE and the surface temperature calculated using the iterative equation.

Figure 12 shows the LS method application for correcting wind speed data for 2011-14 and the RMSE value comes out to be 0.18.

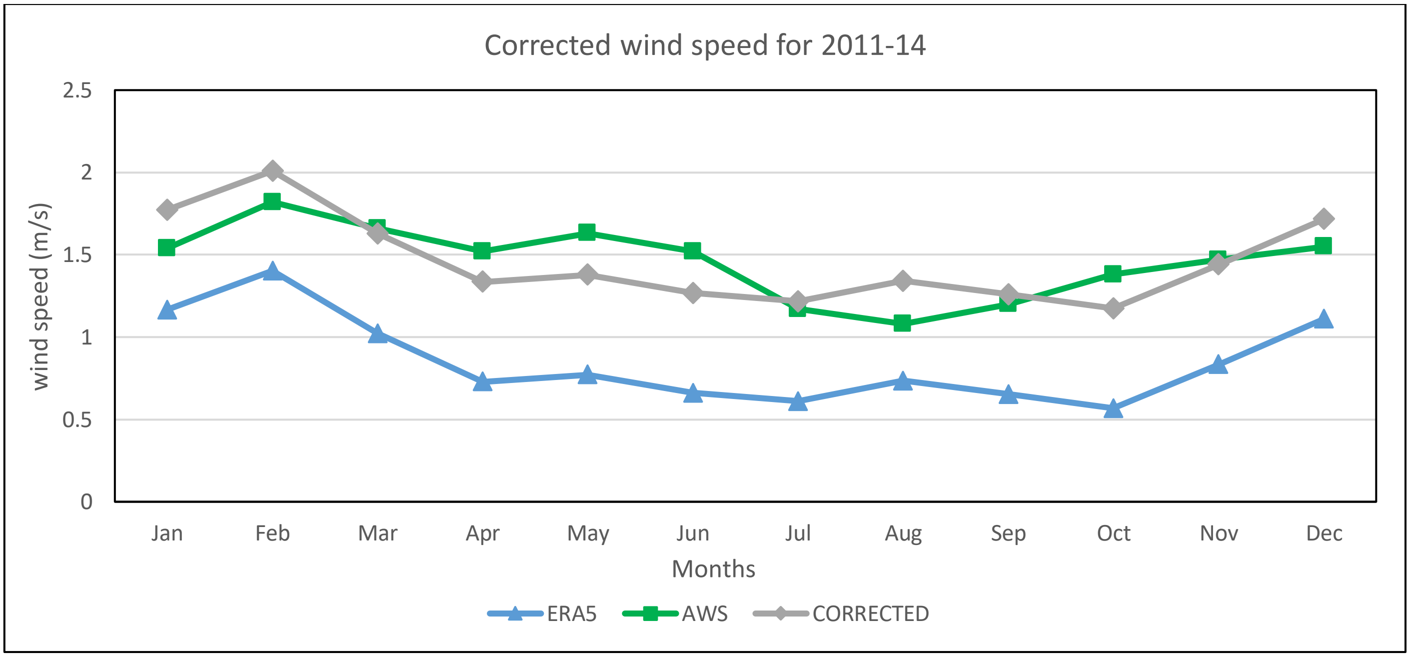
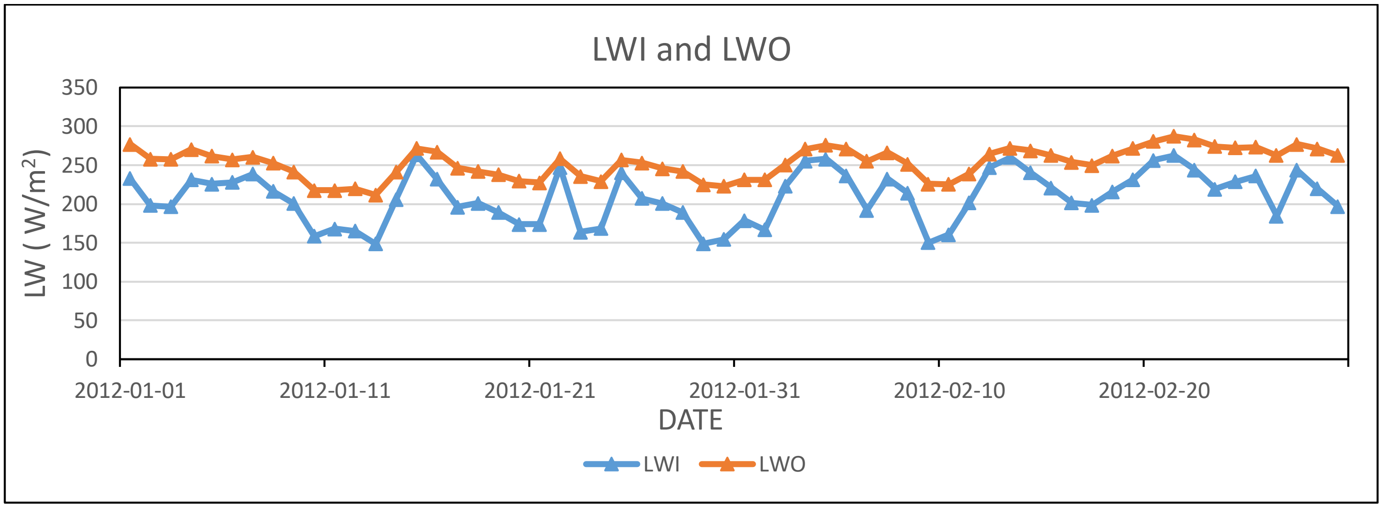


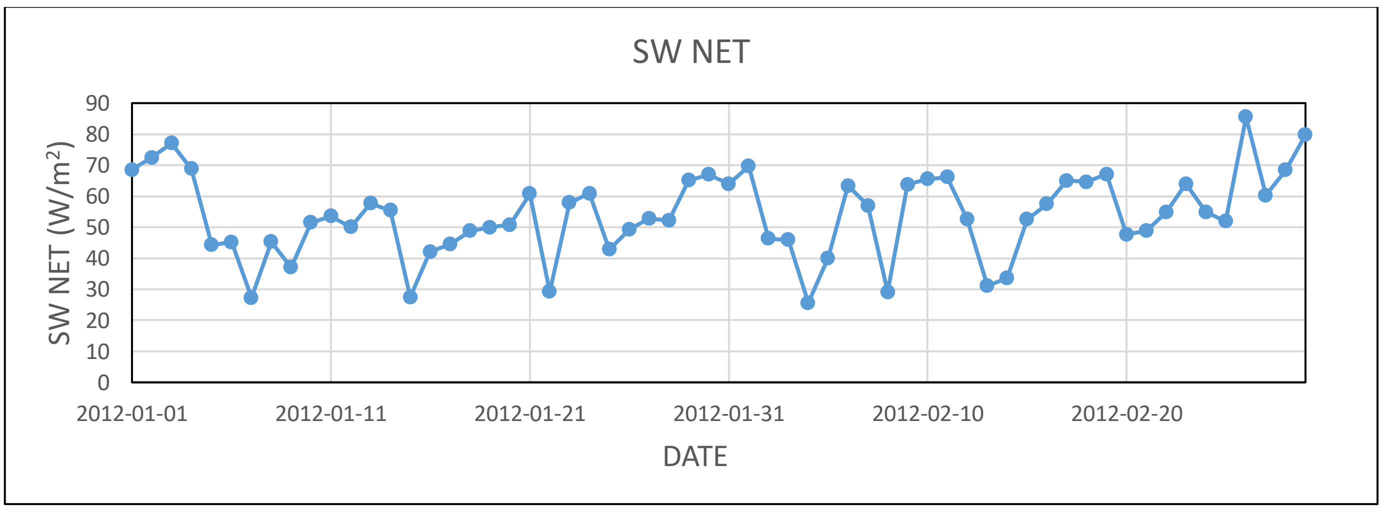
Figure 12: Bias correction for wind speed from 2011-14 using the LS method

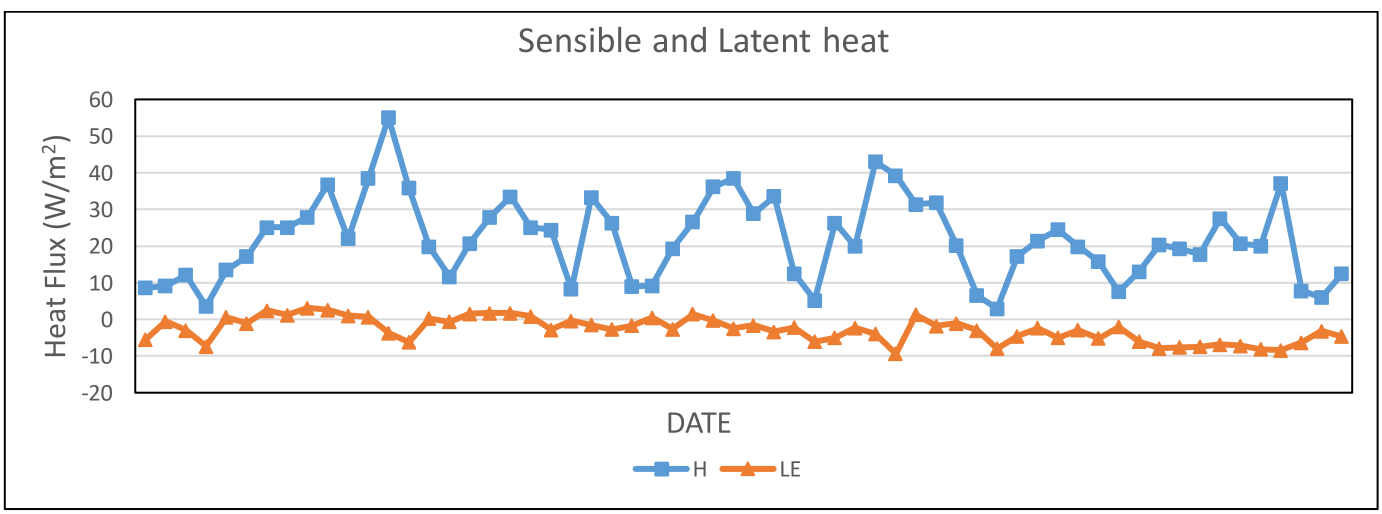
2. Seasonal trends and variability

2.1 Winter Season

Daily values for 60 days as representative of the winter period (1st Jan 2012 – 29th Feb 2012) are taken into account.







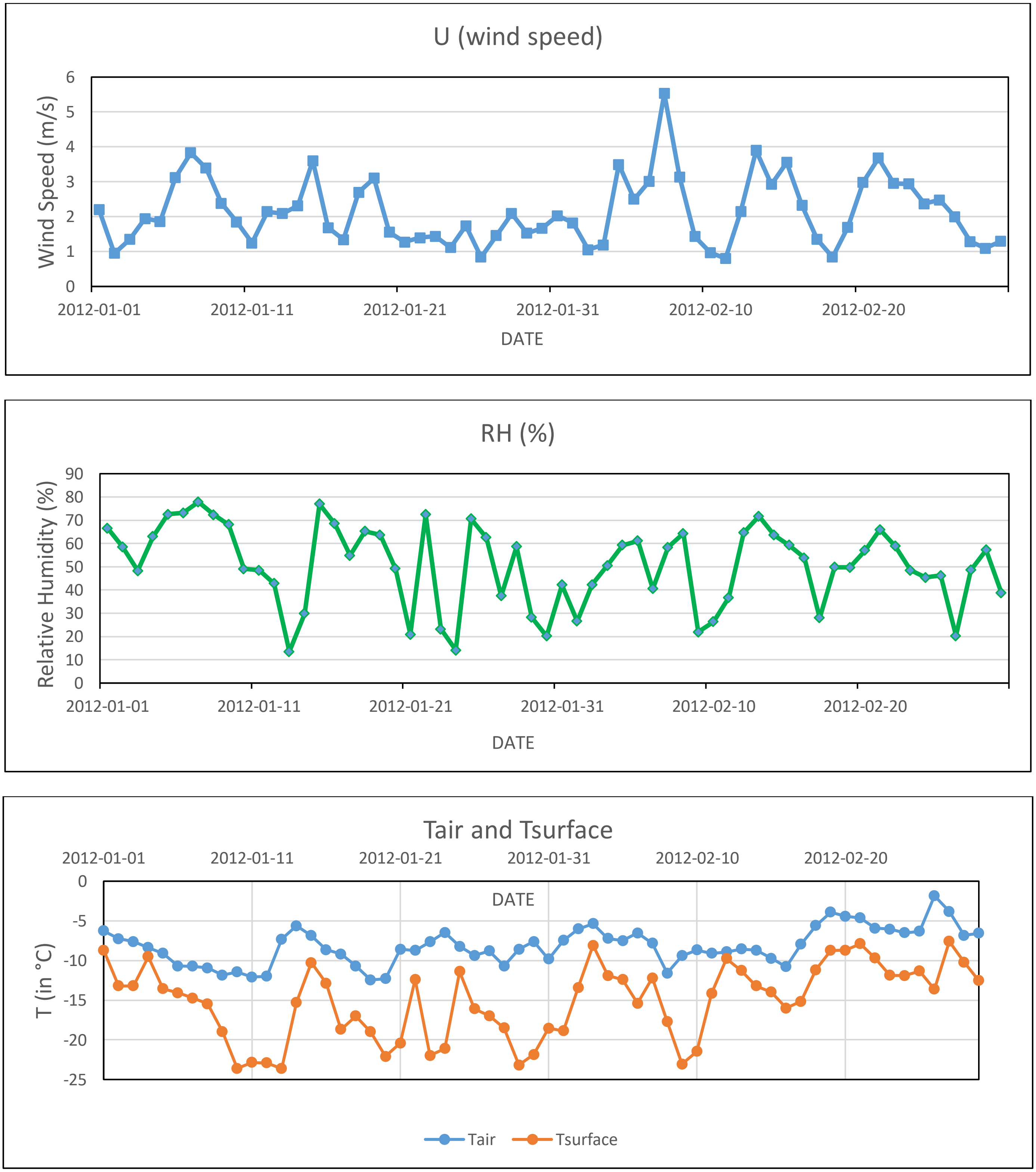
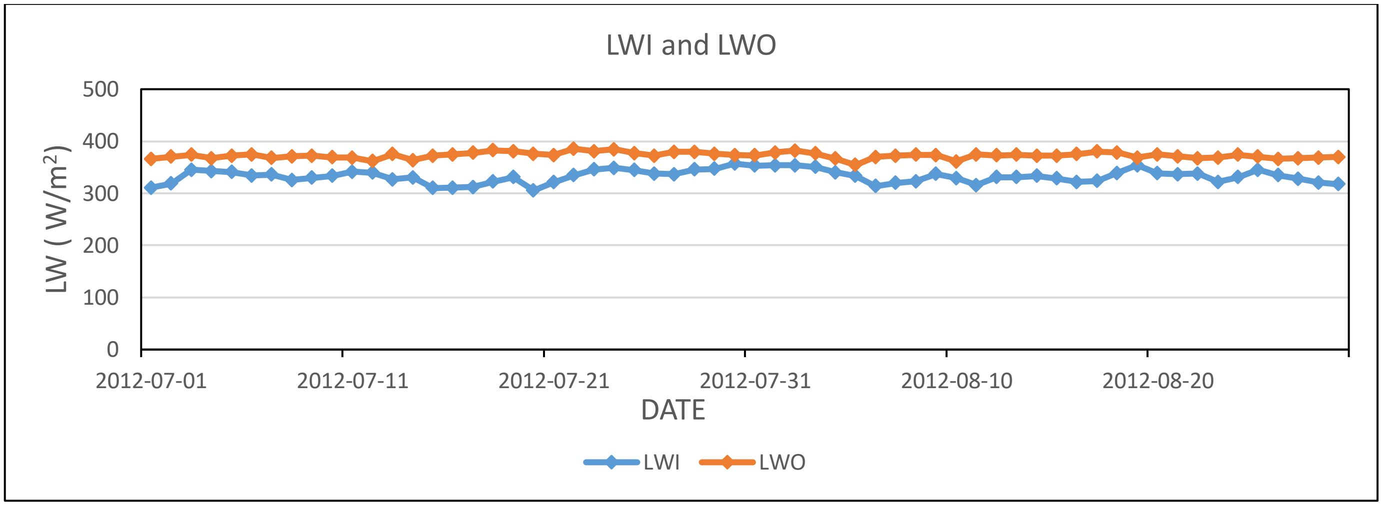
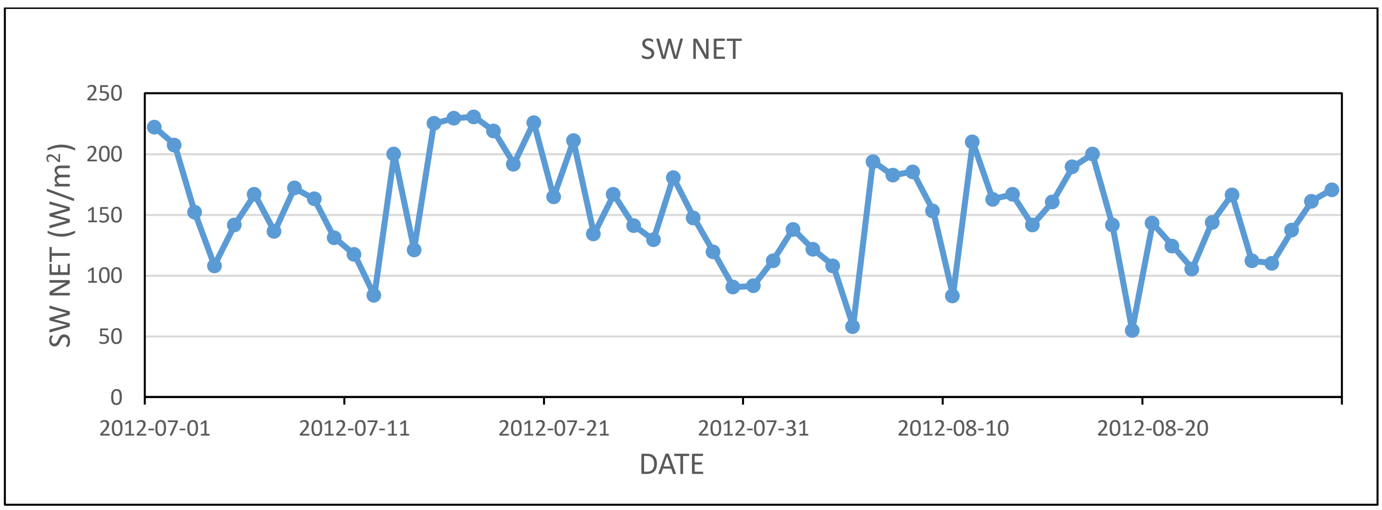


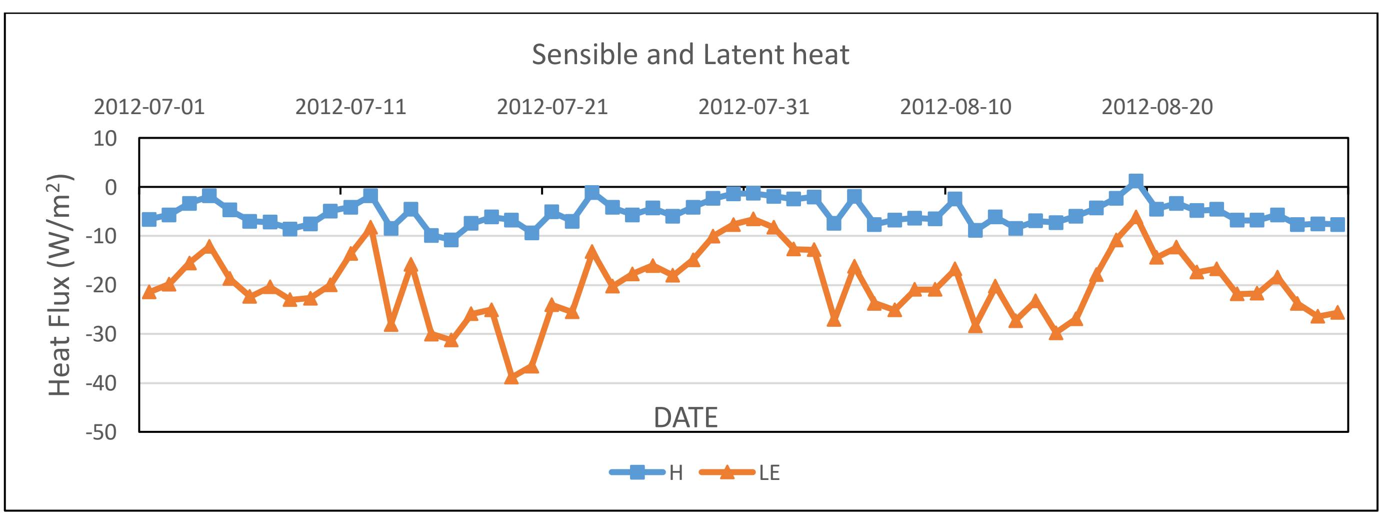
Figure 13: Meteorological variables calculated for the 60-day period during winter.

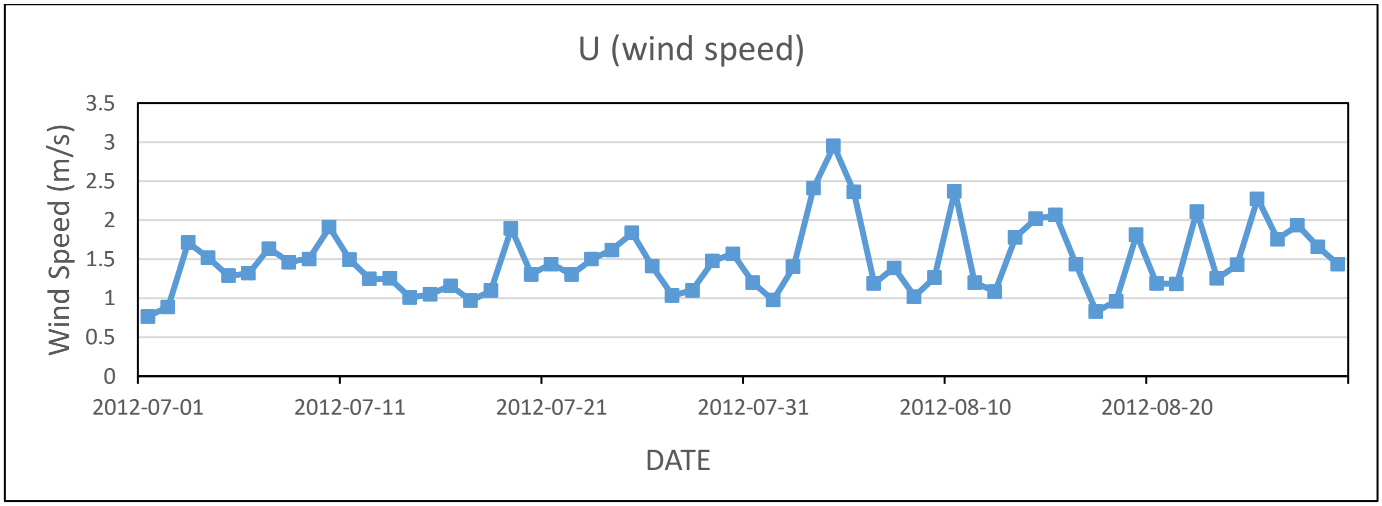
2.2 Summer Season

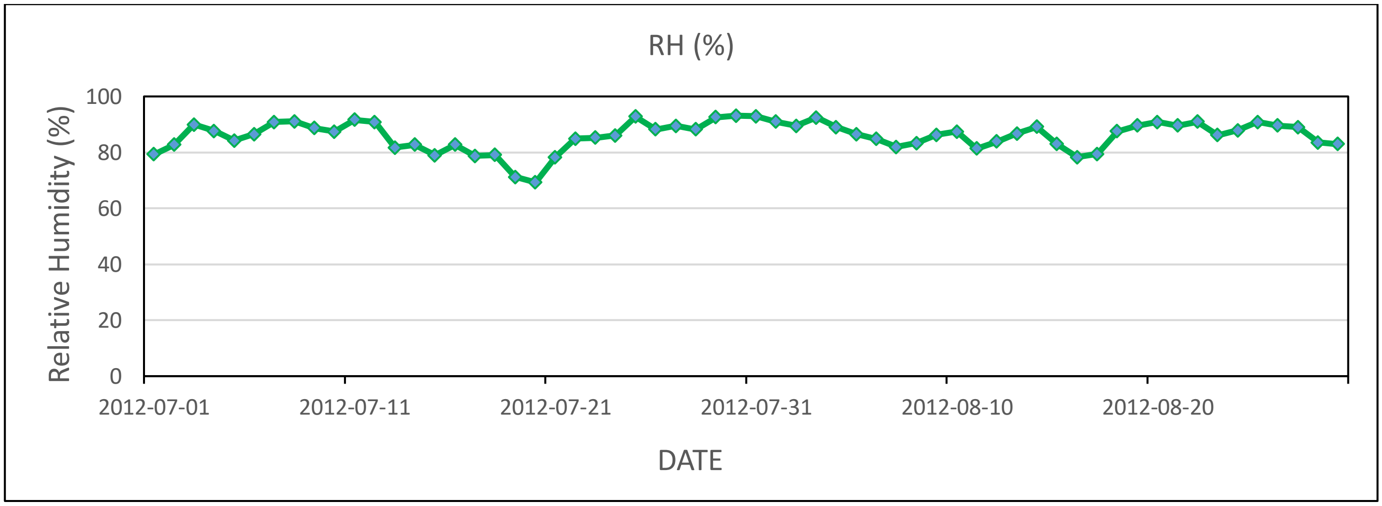
This period is taken from 1st July 2012 – 29th August 2012.











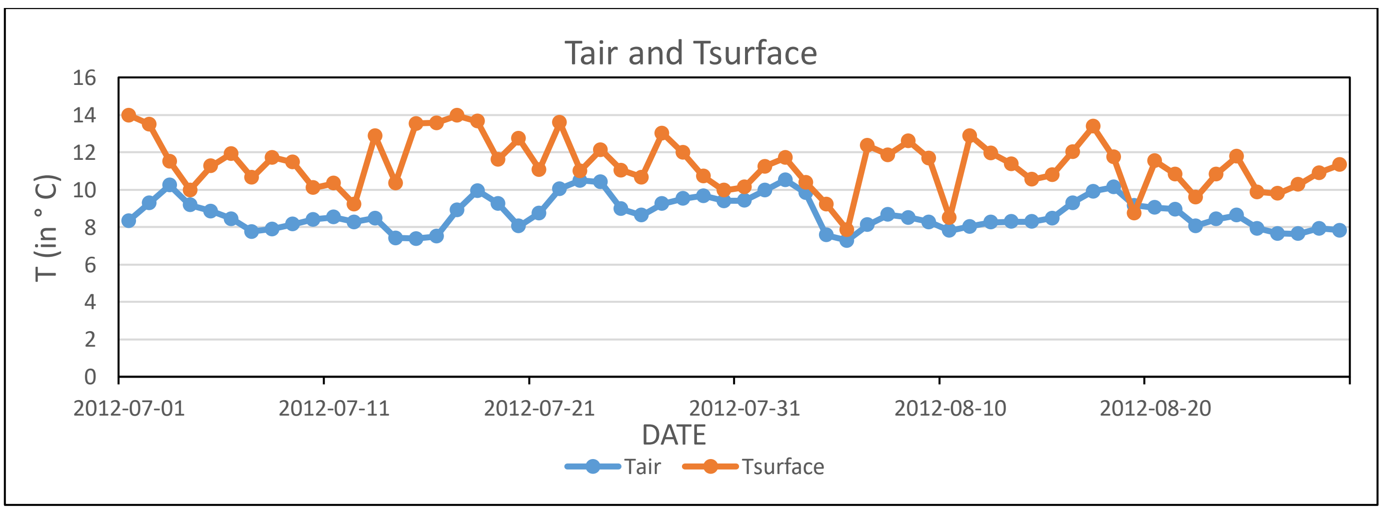
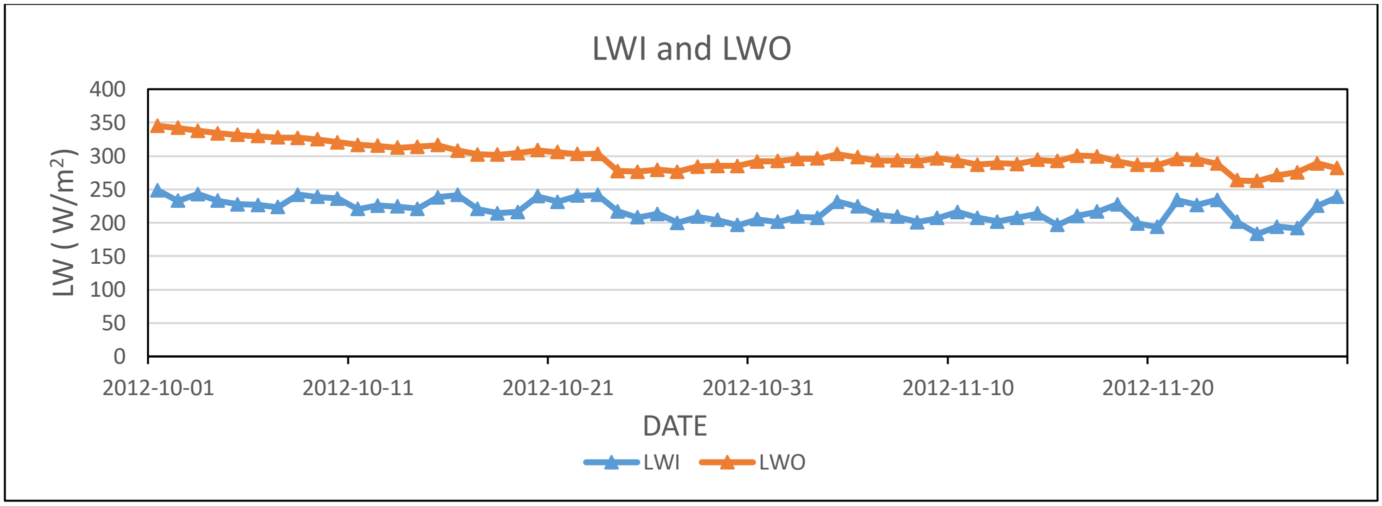
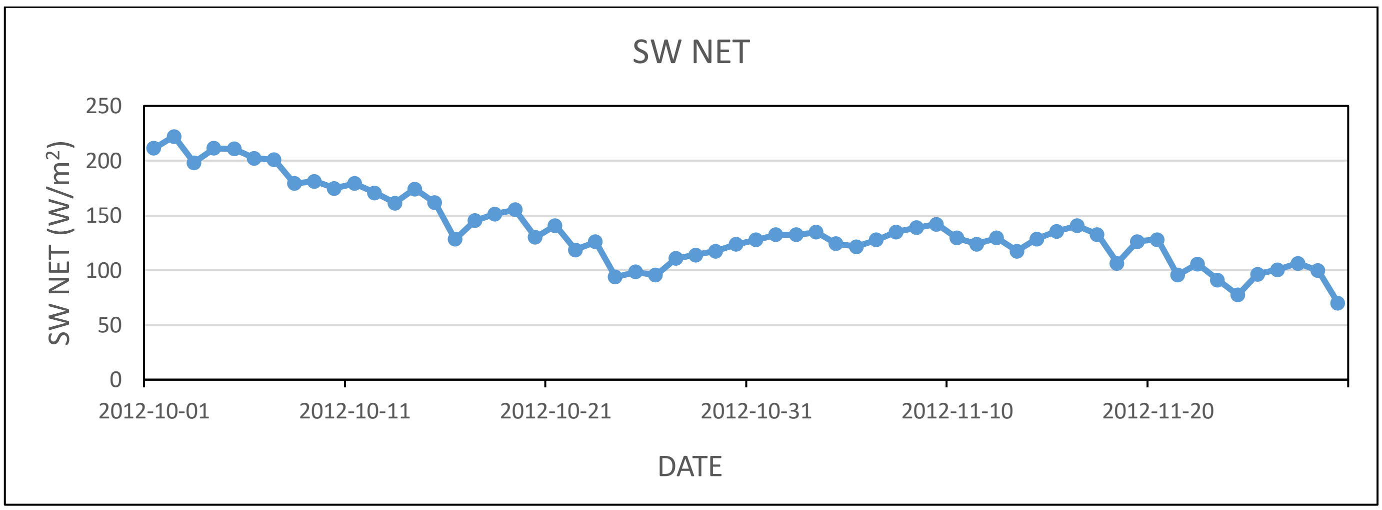


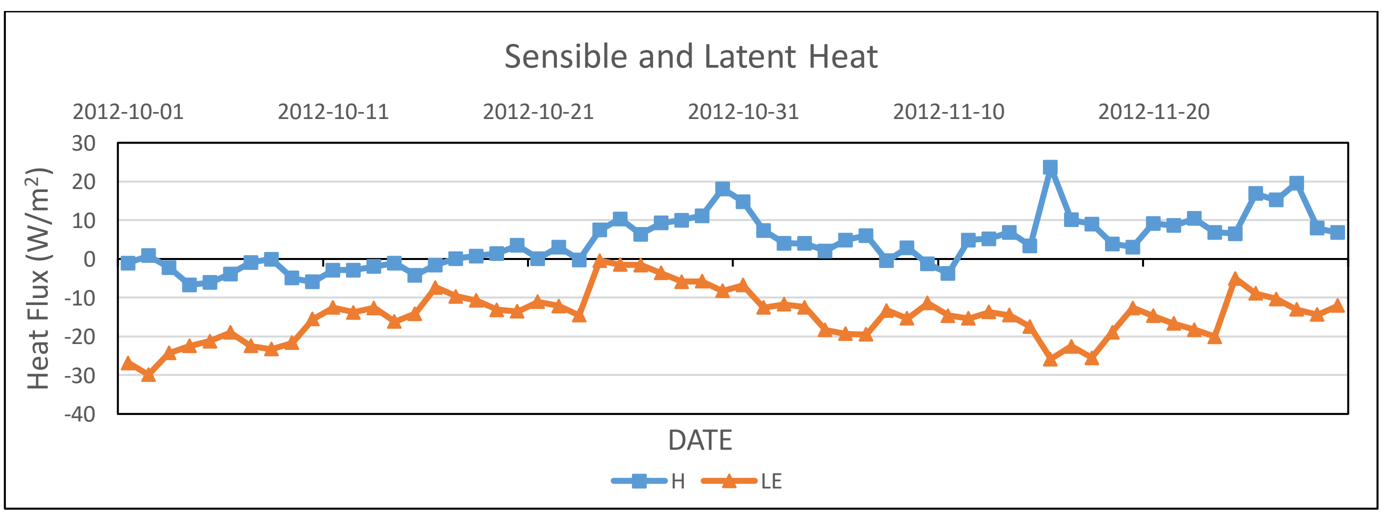
Figure 14: Meteorological variables calculated for the 60-day period during summer.

2.3 Post Monsoon Period

This period is considered from 1st October 2012 – 29th November 2012.







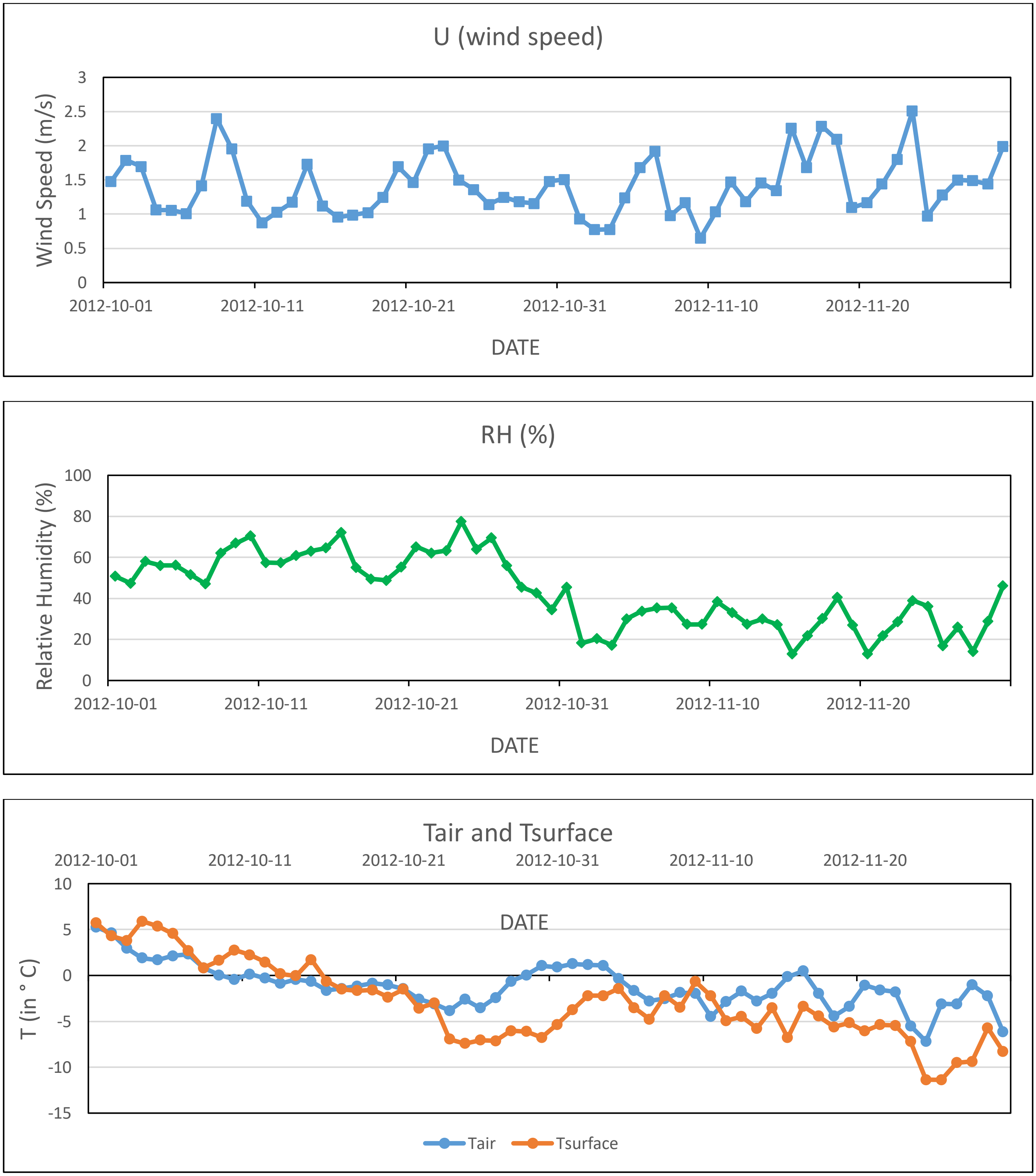


Figure 15: Meteorological variables calculated for the 60-day period during post monsoon.

As expected the radiation components (both longwave and shortwave) have a greater value in the summer season than in other periods. Winter season has the lowest value for radiation components while the post-monsoon period is in midway between these two. Net SR is highest in summer season (230.7 W/m^2 is maximum value) and as the winter season approaches its value is lowered. Sensible Heat (H) is highest in the winter season and lowest in the summer season. Latent Heat (LE) has the highest magnitude in the summer season and lowest in the winter season. RH is highest in the summer season with a maximum value of 93%, wind speed is highest in winter season reaching 2.13 m/s as the maximum value. The post-monsoon period can be thought of as a transition period where RH and wind speed decreased progressively. In winter, air temperature (T_a) is greater than surface temperature (T_s) leading to more sensible heat, while in summer season T_s is greater than T_a which in turn will promote melting.

3. Mass Balance Analysis

3.1 Comparison with other studies

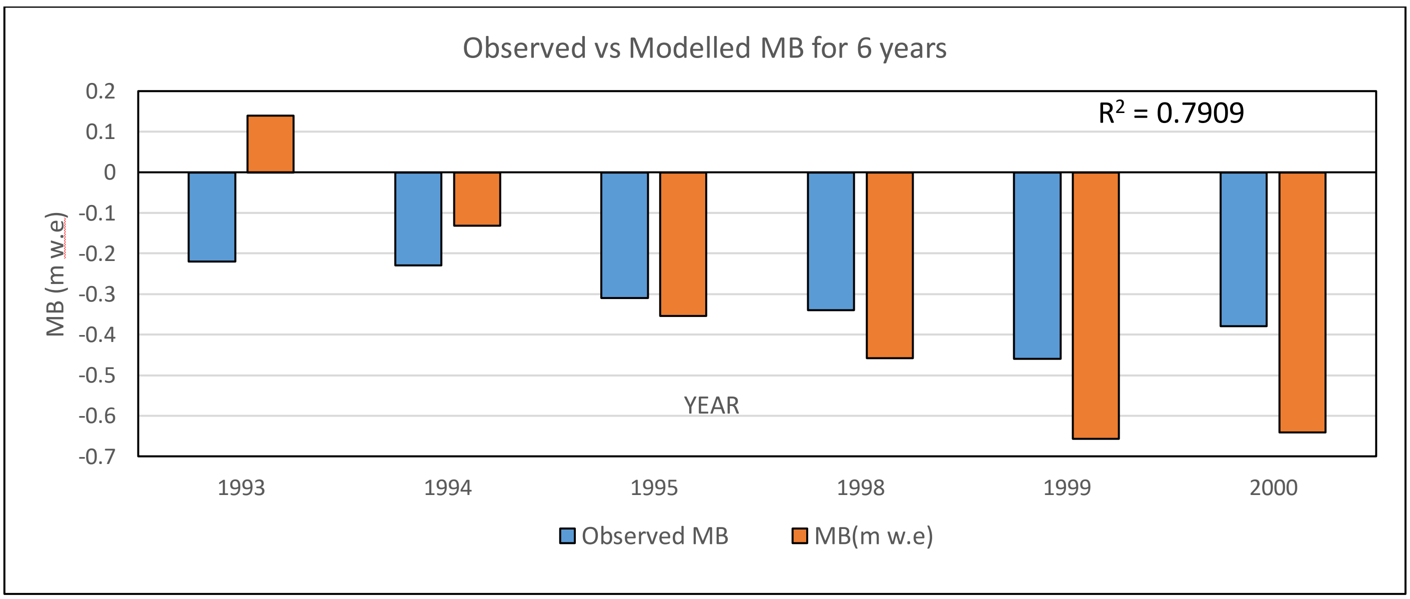


Figure 16: Modelled vs Observed MB profiles for 6 years

The reference data for comparison of MB is taken from Dobhal et. al. 2008 [5]. In that paper, six years of MB calculation study is performed from 1993-1995 and 1998-2000. To minimize the RMSE (root mean square error) between the OD and MD we have varied PG from +5% to +60% Km^{-1} and it is found that the best fit modeled mass balance profile (R^2 = 0.7909) is for PG = +35% Km^{-1} with an RMSE value of 0.209 m w.e. as shown in Figure 16. So, we have applied this PG for the whole dataset from 1979-2019 and long-term MB results are calculated.

3.2 Annual Mass Balance

The hydrological year is taken from 1st October to 30th September of next year. Figure 17 indicates that the most negative mass balance is -2.05 m w.e a^{-1} in 1985 and after that, the value of MB is always less than -1.0 m w.e a^{-1}. Some years also have positive MB like 1993 and 2005 while the most positive MB value is +0.56 m w.e a^{-1} in 2010. Negative MB values indicate that the glacier has been in a mass degradation phase constantly in the past.

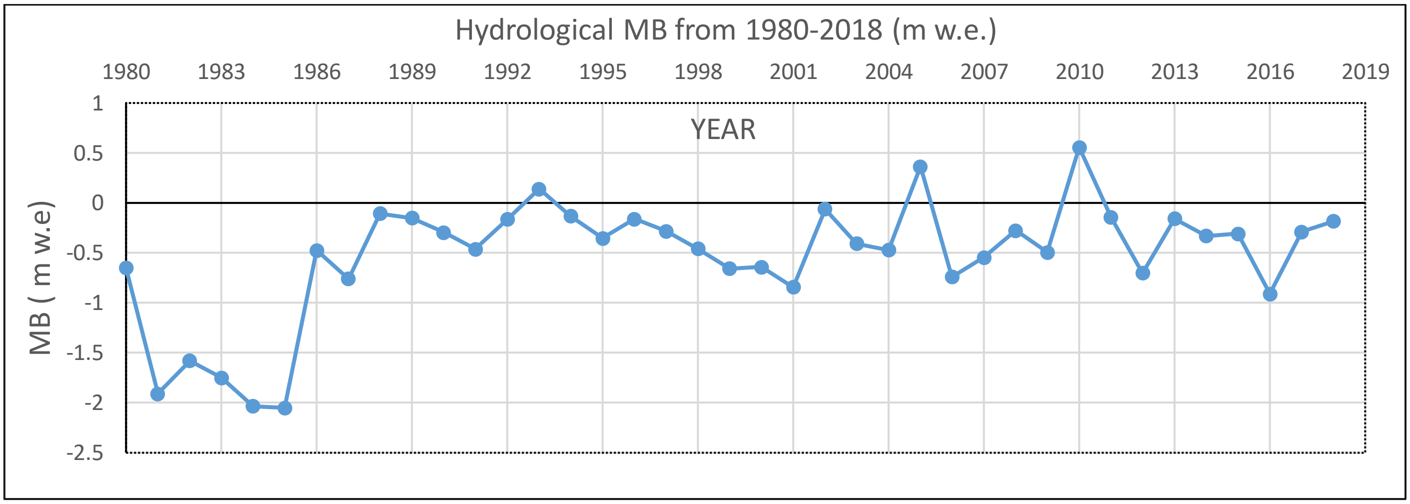


Figure 17: Hydrological Year Mass Balance from 1980-2018

3.3 Daily and Monthly MB

While annual MB is crucial for understanding the overall scenario of any glacier, monthly MB provides a better insight into how much and at what times the mass change is happening. So monthly as well as seasonal MB are required to understand glacier processes effectively.

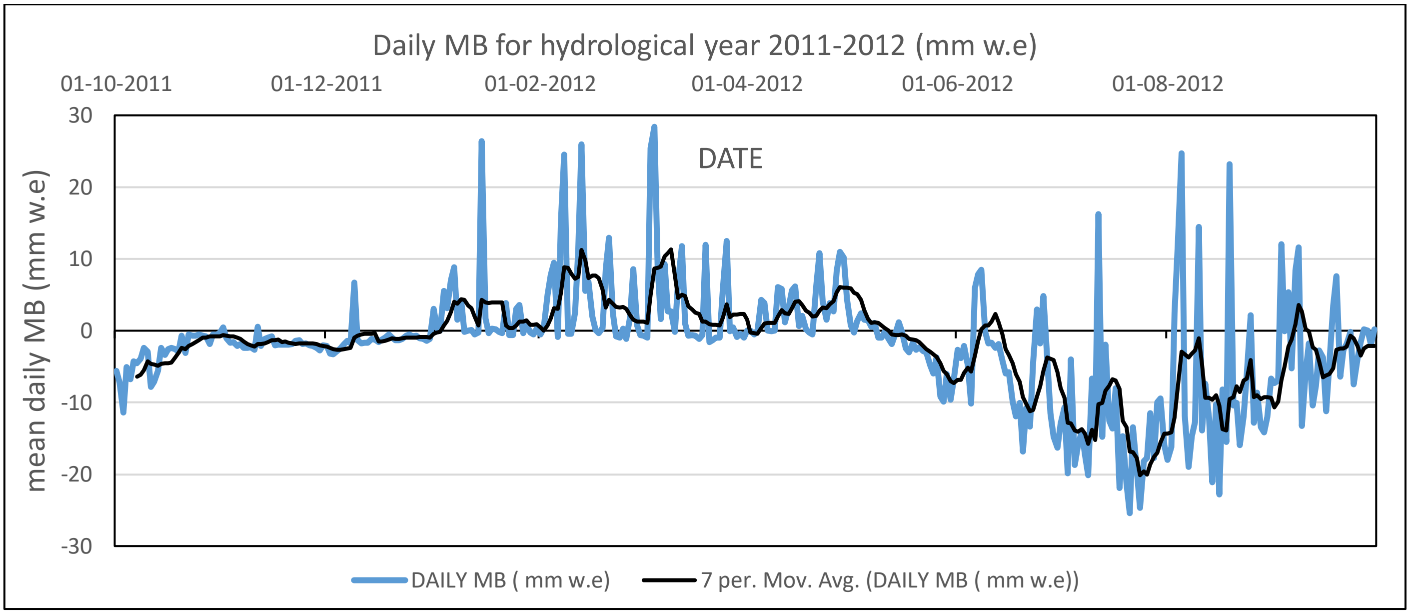


Figure 18: MB calculated in daily time steps for 2011-12

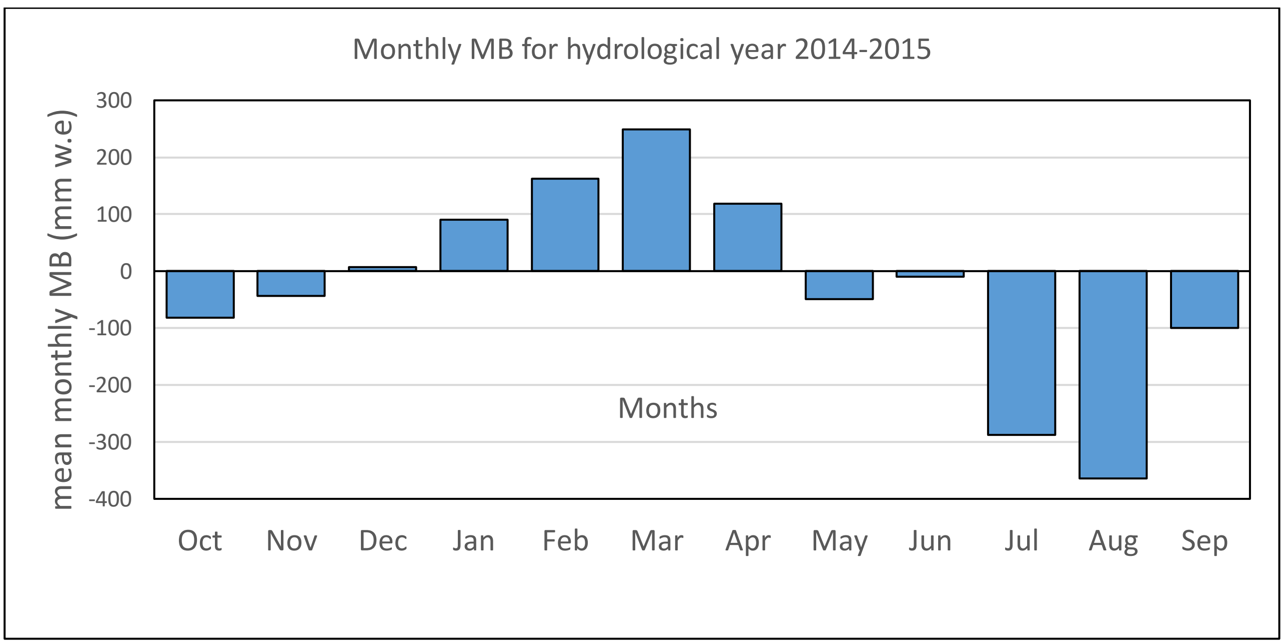


Figure 19: Mean monthly MB calculated for hydrological months (2014-15)

Figure 18 and 19 suggests that July, August, and September have significant negative MB (daily and monthly both), the 7-day running mean line shows clearly that after July daily MB is constantly negative while June has some positive daily MB peaks and hence less negative monthly MB than May. So these months account for melting while February, March, and April have significant positive MB which accounts for accumulation since Dokriani glacier receives heavy snowfall (solid precipitation) during this period.

3.4 Long Term MB and Annual Precipitation Correlation

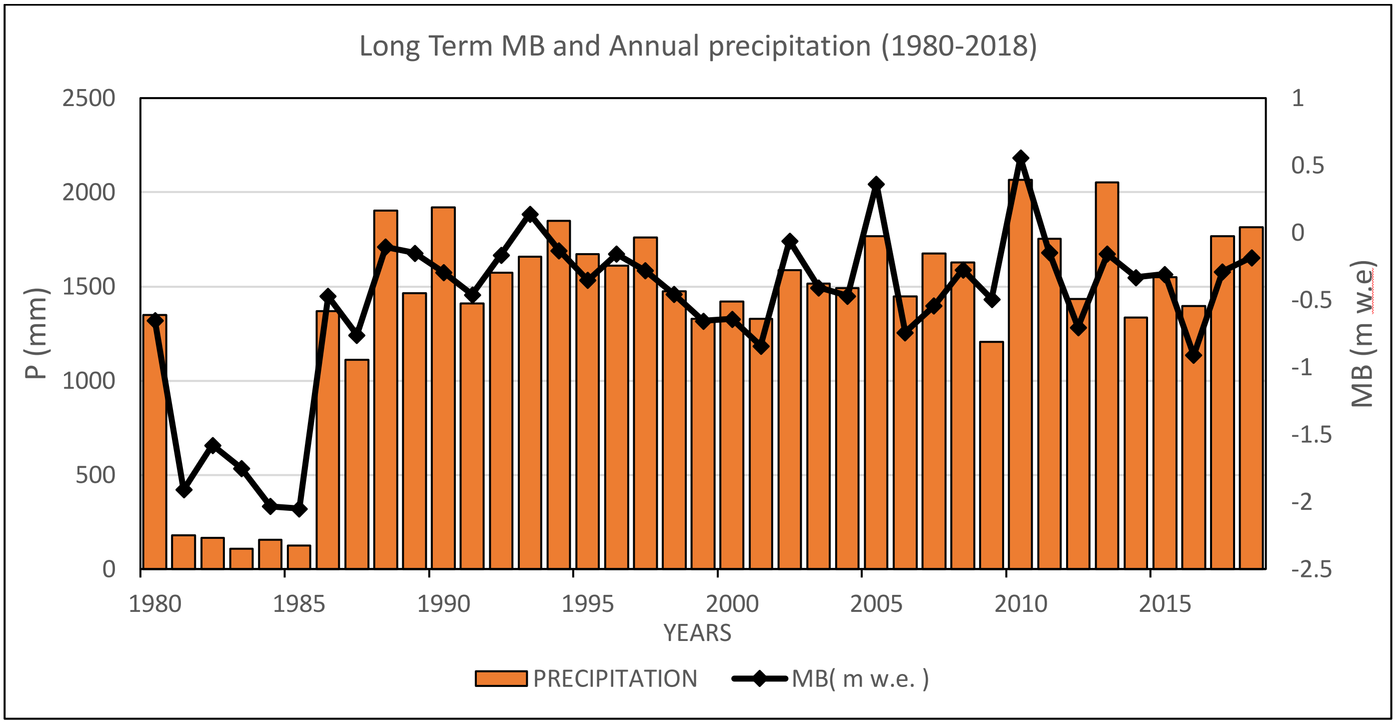


Figure 20: Hydrological MB and annual precipitation from 1980-2018

The long-term MB shows a significant correlation with the annual precipitation whereas no significant correlation is found with the annual mean temperature. The most negative MB values for the period 1981-85 are possibly due to a drastic reduction in the precipitation values at that period of time as shown in Figure 20. Also, the most positive MB in 2010 (+0.56 m w.e a^{-1}) can be thought of as a result of the highest precipitation (2066 mm) during that year as shown in Figure 20.

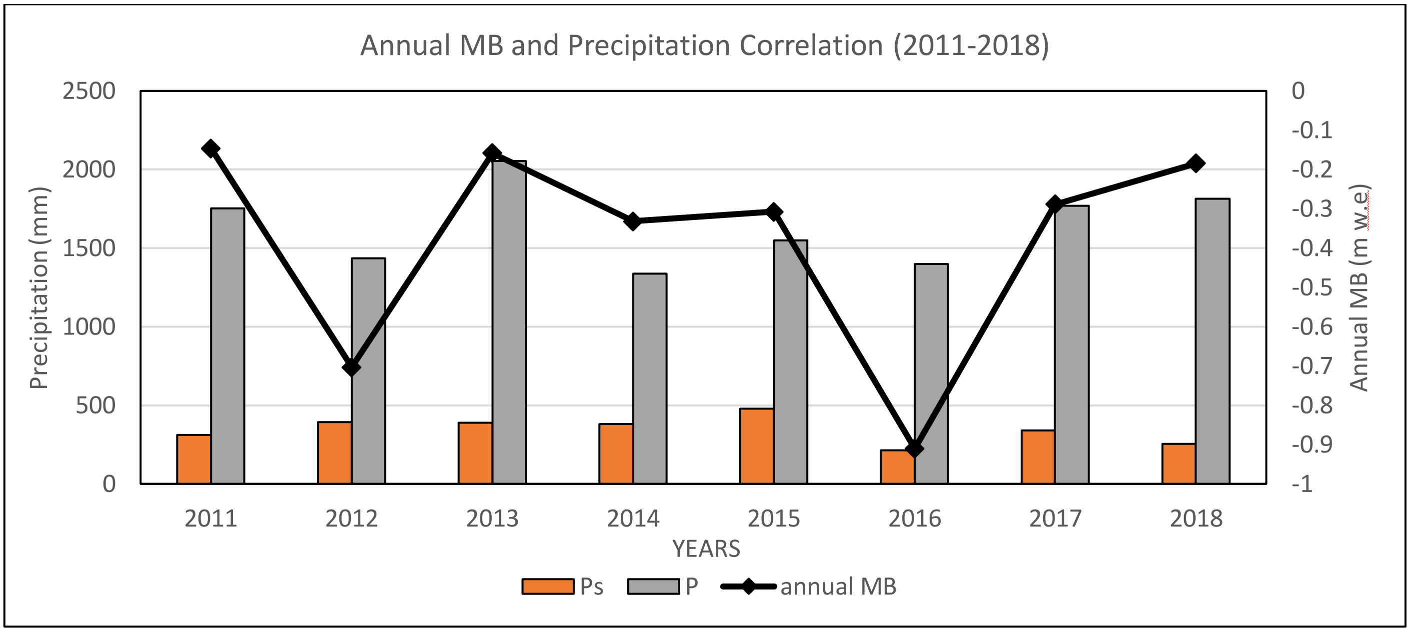


Figure 21: Total and solid precipitation (bar graphs) with annual hydrological MB (black line) for the current decade (2011-18)

Figure 21 shows the current decade's annual MB correlation with the annual precipitation (total as well as solid). The most negative MB of -0.91 m w.e a^{-1} during the current decade is in 2016 which is mainly due to the lowest solid precipitation of 215 mm which is less than half of the previous year 2015. Also, 2016 has the highest annual mean temperature of 4.41 °C (hottest year to date) so this would also have promoted melting. While temperature correlation is not significant its variability affects the annual MB.

3.5 Seasonal MB

Seasonal MB gives the best insights about the effects of changing climatic conditions and climate-glacier interactions. Using the mean monthly MB for 2014-15 (Figure 19), seasons are decided like the lowest negative MB indicates the start of the winter season (November) and the least negative MB as the start of the summer season (May). So, November-April is taken as the winter season and May-October as the summer season. Figure 22 shows the seasonal MB for the current decade showing the annual winter MB and the annual summer MB.

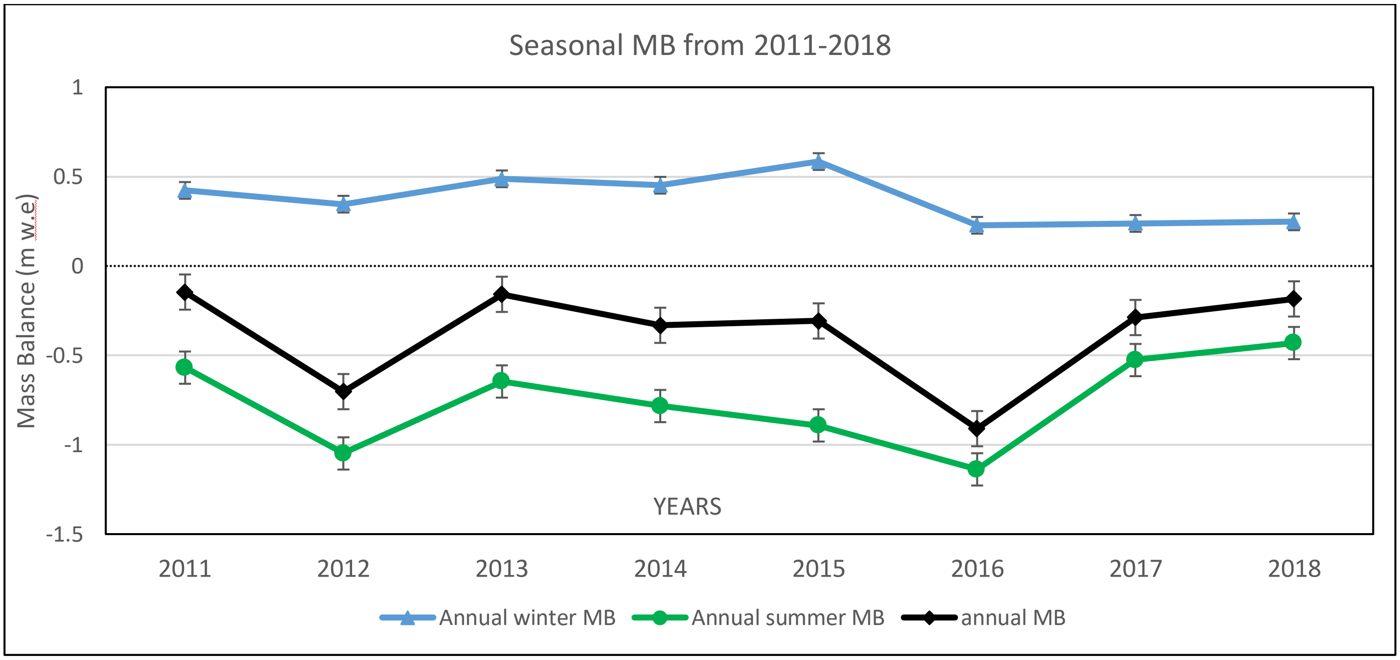


Figure 22: Annual and seasonal MB series with their corresponding error bars for the current decade

The year 2016 has the most negative summer MB and least positive winter MB resulting in the most negative annual MB for the current decade. The annual summer MB follows the same trend of the annual MB and varies from -0.43 m w.e. a^{-1} to -1.13 m w.e. a^{-1}. The annual winter MB has somewhat less variability from +0.23 m w.e. a^{-1} to +0.58 m w.e. a^{-1}. The maximum annual winter MB is in 2015 as a result of maximum solid precipitation for that year as shown previously in Figure 21.

Chapter 6

Conclusion and Scope for Future Work

We applied bias correction techniques and threshold parameters to calculate and correct the given dataset values. Finally, the modeled MB profile is tuned by varying precipitation gradient and minimizing the error between the observed and modeled MB. The above study suggests that the Dokriani glacier is retreating and continuously losing mass. Although the MB values have become less negative recently, the trend that other Himalayan Glaciers are following suggests that they all are undergoing a mass degradation phase [5]. Winter precipitation and surface temperature are the most important parameters and they control the overall behavior of Dokriani glacier. The glacier is influenced by the westerly disturbances and Indian Summer Monsoon [3].

We computed the long-term glacier MB from 1980-2018 using the modeled dataset of ERA5. Mean glacier degradation from 1980 to 2018 is found out to be -0.53 m w.e. a^{-1}. The glacier is more sensitive to precipitation variability and surface temperature variations. While long term MB is mostly negative, some years like 1993, 2005 and 2010 have a positive MB. Most negative MB values are during 1981-85 due to reduced annual precipitation during that period. Long term annual MB is significantly correlated to annual precipitation while annual mean temperature variations are also a factor. More field-based studies are needed for the proper calibration of modeled MB profiles. Also, the in-situ method must be applied at higher altitudes to better understand the topography of the regions like above 5900 m a.s.l. This will help us in understanding the accumulation zone of most of the Himalayan glaciers and their non-uniform composition.

Future work in this study would be to increase the accuracy of this model. We have neglected conductive glacier heat flux in our study which contributes to less than 1% as given in Azam et. al 2014 [6], while its distribution is quite complex inclusion of the same may give more precise results. Another factor that can be considered is the precipitation which falls on the glacier. Precipitation falling in any form has some initial energy which can be transferred to the surface and contribute to melting. While its effect is very less, we have not considered this in our study. Moreover, at present only one field study has been done for MB on Dokriani glacier and that too for only six years period in Dobhal et. al 2008 [5]. More field-based MB studies will provide better calibration and comparison to modeled data.

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