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A Climate Change Study: Downscaling of Climatic Parameters and Their Assessment Over East Rathong Glacier of Eastern Himalayan Region

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Abstract: In this study monthly Temperature Lapse Rates and basic downscaling technique of subtracting means are used to construct temperature (T) series over East Rathong glacier by using multiple data sets from Automatic Weather Stations (AWS) at Himalayan Mountaineering Institute (HMI), Gangtok Indian Meteorological Department (IMD), Yuksum and ERA5reanalysis data. Precipitation (P) over glacier is estimated using Gangtok IMD data and downscaled ERA5 data. The P data is downscaled using local scaling factor method. Change in volume of 0.180 km^3(from 1962 to 2020) estimated using satellite data are used to construct Mass Balance (MB) series for the glacier. It is observed that the glacier is losing its mass with increasing T, Aerosol Optical Depth (AOD) (from 0.1 in 1980 to 0.2 in 2020), and increasing Pmainly during June-July-August months when temperatures are already high. This study is important as it used multiple data sets along with field data extracted from the literature to study climatic impacts on East Rathong glacier. Data generated from this study may be used in mass balance projection of the glaciers in the absence of field data.

Keywords: Downscaling; Mass balance; Himalayas; Glacier; ERA5 data.

Introduction

A glacier is a mass of ice, water and debris which flows from higher to lower altitudes under the influence of gravity. Glaciers around the world are an important source of fresh water for people living in and around mountainous regions and downstream also for the major river systems of the world (Aggarwal et al., 2021). The discharge from the snow and glacial melt is important to meet the domestic and agricultural needs of the mountainous people (Viviroli et al., 2020). They are also an important source of income for mountainous people by attracting tourists with their scenic beauty (Morrison and Pickering, 2013). They have significant social and economic impacts through water resources or glacial hazards (Wagnon et al., 2013). Glacial lake outburst floods (GLOFs) and glacier collapse are some examples of glacier hazards. The Kedarnath tragedy is an example of a disaster caused by GLOF. Increased runoff in the Mandakini River due to the dewatering of a glacial lake near the Chaurabari glacier along with heavy rainfall in mid-June of 2013 led to this disaster (Kulkarni, 2013). The Chamoli disaster of February 2021 happened due to an avalanche of rock (land slide) and ice (glacier collapse) (Shugar et al. 2021). Thus, glacier mass loss affects regional runoff and global sea level (Zemp et al., 2015) which, in turn, is responsible for insecurities related to water and global warming.

Perturbations in the temperature and precipitation of a region can be studied by analysing changes in the

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length, area, thickness and mass balance of a glacier (Nye, 1963; Agrawal and Tayal, 2013, 2015; Kulkarni et al., 2021). The change in the mass of a glacier over a stated span of time gives its mass budget. The mass balance of a glacier is estimated using various methods like the glaciological method (Azam et al., 2018; Tshering and Fujita, 2016; Cogley et al., 2011), geodetic method (Gardell et al., 2013; Shean et al., 2019), change in volume method using satellite data (Agrawal and Tayal, 2015), surface energy balance method using AWS data (Rupper and Roe, 2008) or glacier evolution model using climate model data (Rounce et al., 2020; Aggarwal and Mandal, 2021). Mass balance estimation schemes may range from simple relation between air T and MB to spatially distributed energy balance models which involve micrometeorology (Oerlemans and Klok, 2002).

To develop accurate MB models long term temperature and precipitation data from the field is required. But field data paucity is a common hindrance faced by scientists while studying glaciers, especially in high-mountain regions like the Himalayas. For this reason, satellite and climate model data are being widely used to study glaciers (Aggarwal and Mandal, 2021). Meteorological data taken from satellites and climate models is downscaled, depending on the availability of field data from the region, to reconstruct the long-term weather conditions of the region. In downscaling a large (or larger) scale predictor is transformed to the expected value of a local-scale predictand (Maraun et al., 2010). There are several techniques available to carry out downscaling of the data like analog, local scaling, and dynamical scaling methods, etc (Salathé, 2003). Statistical downscaling approaches are classified into Perfect Prognosis, Model Output Statistics and Weather Generators (Maraun et al., 2010). In this study, precipitation and temperature data taken from European Centre for Medium-Range Weather Forecasts Re-Analysis version 5 (ERA5) are downscaled to assess the impacts of temperature and precipitation on the MB of a glacier. Mahto and Mishra (2019) found that the performance of ERA-5 is better than the other reanalysis products for the hydrologic assessments in India, in this study also ERA 5 reanalysis data is used. Fresh snow has a very high albedo of 0.8–0.9 and is crucial for the maintenance of Earth's energy budget and impacts local temperatures, glacier mass balance and runoff. Snow surface albedo reduces when the snow gets contaminated. Thind et al. (2021) have reported the presence of light-absorbing impurities in the snow surface of western Himalayan glaciers showing air pollution reaching high altitudes and affecting the surface energy budget of glacier valley by altering the albedo of the snow. Agrawal et al. (2014) have reported an increase in aerosol optical depth (AOD) by 19.12% for the time period 2001-2011, an increase in black carbon optical depth by 7.19% for the time period 2000-2007, an increase in the concentrations of carbon dioxide (4.42%) and methane (0.61%) for the time period 2003-2011 and an increase of 0.7°C in Modern Era-Retrospective Analysis for Research and Applications (MERRA) temperature at 500 hPa during the time period 1979-2011 in Sikkim. They have reported an average rate of loss of the glacierised area of Sikkim region, from 1976 to 2013, to be ~2.21 km^2 /year. From this, it is visible that the mass balance of a glacier is a function of many climatic factors (Ageta and Higuchi, 1984; Oerlemans and Klok, 2002) like solar radiation, temperature, precipitation, wind velocity, aerosols, sea surface temperatures (especially in the case of West Antarctica), etc. All these factors show annual variation over the globe. In this study, the impact of temperature (T), precipitation (P) and aerosol optical depth (AOD) on the mass balance of the East Rathong glacier of Eastern Himalaya is studied.

Sikkim Himalaya is a part of the Eastern Himalayan region. Due to the rugged terrain of the region, very less field data is available from the region. Hence most of the studies available from this region are carried out remotely. Tista and Rangit rivers, which are fed from snow and glacial melt, are important source water in Sikkim. Sikkim has 449 glaciers and 14 potentially dangerous glacial lakes (Sharma et al., 2022). Racoviteanu et al. (2015) estimated that the region lost 20% of its glacierised area during 1962-2020. Impacts of climate change are visible in the Sikkim region in the form of the loss of glacierised areas and the formation of glacial lakes. Hence, this study is carried out in the Sikkim Himalayan region.

Study Region

The study is focused on the Eastern Himalayas of Sikkim, which have mountainous topography ranging from 300 to 8598 m asl. The highest concentration of glaciers is between 5000 and 6000 m asl. According to IMD data, the region receives an annual precipitation of 2000–4000 mm. East Rathong is a clean glacier located at 27.5669 N, 88.1002 E, in East Rathongbasin of north-west Sikkim. It is a south-east facing, summer-nourished glacier, i.e. a glacier where accumulation takes place in the summer season. In 2011, the glacier was 6300 m in length, 0.188 km^3 in volume and 3.942 km^2 in area.

Total altitudinal range of the glacier is 2000 m with an elevation range from 4637 m to 6800 m. The mean elevation of the ablation zone of the glacier is 4700 m a.s.l. and the mean elevation of the accumulation zone of the glacier is 6200 m a.s.l. (Agrawal and Tayal, 2013).

The location of the glacier, and AWS stations at HMI base camp, Yuksum and Gangtok IMD are shown in Figure 1.

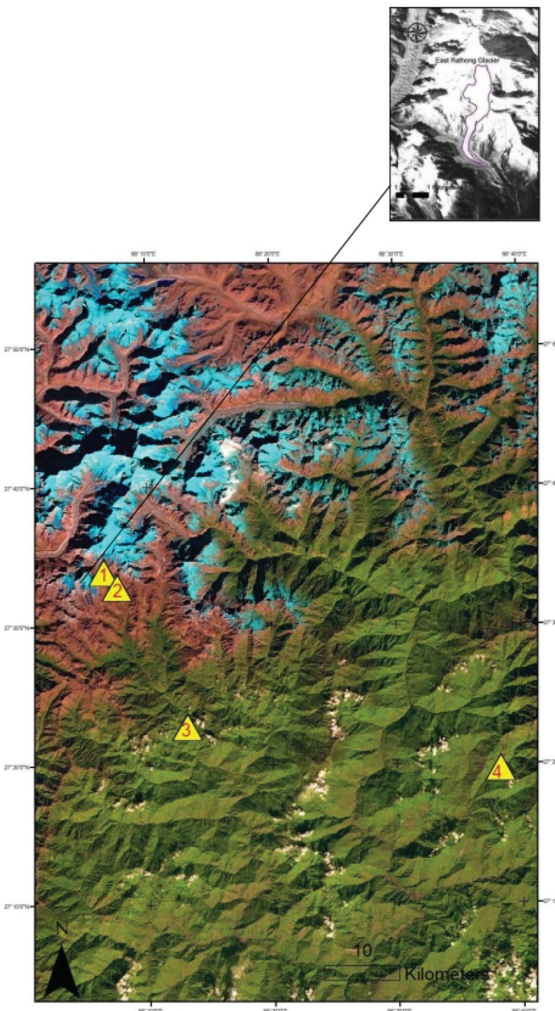

Figure 1: The figure shows location of the glacier (1, inset showing glacier boundary demarcated on CORONA aerial photograph), AWS stations at HMI base camp (2), Yuksum (3) and Gangtok IMD (4). In the figure, cyan colour is glacierised region, the brown colour is the mountain region and the green colour is the forest cover area.

Data

AWS Data

Monthly mean air temperature and precipitation for the time period 1966-2000 of Gangtok IMD station (1650 m asl, 27.3336 N, 88.6336 E) downloaded from http://www.imd.gov.in/section/nhac/mean/Gangtok.htm.

AWS recorded temperature data for the time period May 2017 – April 2018 at Yuksum station (1742 m asl, 27.3777 N 88.2202 E), AWS temperature and precipitation data for the same time period at HMI base camp (4474 m asl, 27.5494 N, 88.1290 E) are taken from the graphs and text of Vashisht and Tayal (2021). Figure 2 shows the monthly mean temperatures from May 2017 to April 2018 at the HMI base camp and Yuksum. Temperature lapse rate (TLR) calculations above and below treelines are also taken from Vashisht and Tayal (2021). The monthly average TLRs are shown in Table 1.

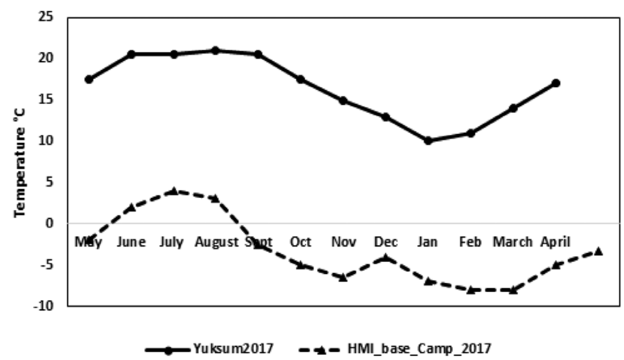

Figure 2: Monthly mean temperatures from May 2017 – April 2018 at HMI base camp and Yuksum.

Table 1: Monthly TLRs (in °C/100 m) below and above the treeline (Vashisht and Tayal, 2021). The authors have reported the treeline in Sikkim around ~4000 m asl

Mean monthly temperature lapse rates		
Month	*Below treeline*	*Above treeline*
Jun-17	-0.53	-0.57
Jul-17	-0.50	-0.55
Aug-17	-0.48	-0.58
Sep-17	-0.52	-0.59
Oct-17	-0.59	-0.63
Nov-17	-0.57	-0.34
Dec-17	-0.41	-0.04
Jan-18	-0.36	-0.14
Feb-18	-0.50	-0.36
Mar-18	-0.62	-0.64
Apr-18	-0.63	-0.68
May-18	-0.56	-0.58

Reanalysis Data

One of the reanalyses of global climate and weather is ERA5. Currently, data are available from 1979 onwards. Data available from 1950-1978 is a preliminary extension of the data and has not been used in this study. ERA5 has a much higher temporal (hourly output) and spatial resolution (31 km horizontal resolution, 137 levels spanning the Earth's surface up to 0.01 hPa) than those of previous global reanalyses. It captures much finer details of atmospheric phenomena than in previous, lower-resolution, global reanalyses (Hersbach et al., 2020).

Using the laws of physics, reanalysis combines model data with observations from across the world into a globally complete and consistent dataset. To estimate the state of the atmosphere newly available observations are combined with previous forecasts in an optimal way (Piani et al., 2010; Maurer et al., 2010; Gudmundsson et al., 2012).

Monthly mean air temperature and precipitation for the time period 1979-2021 over the Sikkim region (over the grid with Gangtok IMD station, i.e., 27°3336 N, 88.6336 E) are taken from ERA5 reanalysis data. The data is downloaded from https://cds.climate.copernicus.euportal. More details of the data are given in Table 2. The data is extracted using climate data operator (CDO) software.

Table 2: Details of the climate variables used

Name of Reanalysis data	ERA5		
Resolution of data	31 km		
Variables	Precipitation	tp	kg m^{-2} s^{-1} (converted to mm/mon)
	Temperature	t2m	Kelvins (K) (converted to °C)

Landsat Data

Landsat 8 image, scene number 'LC813904 12020360LGN00', acquired on 25th December 2020 was downloaded from Earth Explorer. The study also used results obtained on the area and volume of the East Rathong glacier by Agrawal and Tayal (2013). Using Landsat and CORONA data, they obtained the area and volume of the glacier (Table 3). CORONA satellite photographs were collected using the first generation of U.S. photo intelligence satellites. More than 860,000 images of the Earth's surface were collected between 1960 and 1972.

Table 3: East Rathong glacier's area, volume and from 1962 to 2020

	Area (km^2)	*Volume (km^3)*	*Mass Balance (m w.e. yr^{-1})*
1962	4.63	0.235	-0.15
1976	4.58	0.224	-0.19
2000	4.14	0.201	-0.26
2011	3.94	0.188	-0.46
2020	3.48	0.170	-0.46

Aerosol Optical Depth Data

The degree to which the transmission of light is prevented by absorption and scattering of light is known as Aerosol Optical Depth (AOD). It is also defined as the extinction coefficient (fractional depletion of radiance per unit path length) over a vertical column of unit cross section.

MERRA-2 instM_2d_gas_Nx: 2d, monthly mean, Instantaneous, Single-Level, Assimilation, Aerosol Optical Depth Analysis V5.12.4 (M2IMNXGAS) is downloaded from https://disc.gsfs.nasa.gov/datasets/M2IMNXGAS_5.12.4/summary. The Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) is a National Aeronautics and Space Administration (NASA) atmospheric

Table 4: Summary of the datasets used

Type of data	*Parameter*	*Region*	*Time period*	*Altitude m asl*	*Source*
AWS data	T, P	Gangtok IMD station	1966-2000	1650	IMD website
	T	Yuksum station	May 2017 – April 2018	1742	Vashisht and Tayal, 2021
	T	HMI base camp	May 2017 – April 2018	4474	Vashisht and Tayal, 2021
ERA5 reanalysis data	T, P	Grid over Gangtok IMD station	1979-2021		Copernicus portal
MERRA-2	AOD	Over Gangtok grid	1980-2020		Giovanni website
Landsat	area	Over East Rathong glacier	25th Dec 2020		Earth explorer

reanalysis for the satellite era using the Goddard Earth Observing System Model, Version 5 (GEOS-5) with its Atmospheric Data Assimilation System (ADAS), version 5.12.4. The focus of the MERRA project is on historical climate analyses for a broad range of weather and climate time scales. MERRA-2 is continuing as an ongoing climate analysis and covers the period 1980-2020. Summary of all the data sets used in the study is given in Table 4.

Methodology

Glacier Volume and Mass Balance

East Rathong glacier's area and volume from 1962 to 2011 (Table 3) are taken from Agrawal and Tayal (2013). The glacier area is estimated using a methodology based on the calculation of the Normalized Difference Snow Index (NDSI) and is discussed in Agrawal and Tayal (2013). The authors calculated the volume of the glacier using the volume–area scaling method (Bahr et al., 1997) and the slope-dependent method. Volumes calculated were also found to be close to values found using the ice-flow velocity method (Agrawal and Tayal, 2015).

Following Agrawal and Tayal (2015), the annual time series of volume for the time period 1962–2020 is reconstructed by linear interpolation of volumes between two successive satellite images by assuming that the rate of volume change of the glacier remains constant between two successive datasets. Volume loss of a glacier between two consecutive years multiplied by a factor of 0.9 and divided by the area of the glacier provides the mass balance of the glacier in m w.e. per year. The density of ice is taken as 900 kg m^{-3} (Oerlemans, 2001). Landsat image of 25th December 2020 is used to estimate the area and volume of the glacier for 2020 using manual delineation and volume area scaling respectively. Manual delineation is done using ArcGIS 10.1 software. Since no good cloud free images could be acquired between 2011 and 2020, the area and volume of the glacier could not be determined in between.

Volumes could not be estimated for every year of the study period. They are estimated for years for which good quality data was available and it is assumed that the volume change between two years for which the volumes could be estimated is constant.

Downscaling of ERA5 Data

Temperature and precipitation data from ERA5 are downscaled before use. For precipitation downscaling, the local scaling method is used as described in Salathé (2003). Initially, seasonal means (DJF, MAM, JJA, SON) are computed from 1966-2000 for IMD Gangtok and from 1979-2021 for ERA5 data. The seasonal means from IMD data are termed as $\langle P_{obs} \rangle$ and from ERA5 are termed as $\langle P_{model} \rangle$. Scaling factors (s) are computed using data for the time period 1979-2000 and equation (1):

$$s = \langle P_{obs} \rangle / \langle P_{model} \rangle \quad (1)$$

The average scaling factor is estimated for every season. Seasonal means are computed for the reanalysis of data from 1979-2021. These seasonal means are multiplied by the average scaling factors. Since the value obtained is the seasonal mean (mean of three months), the values for every season are multiplied by three. A sum of the values estimated for all the seasons is summed to get the final annual precipitation value. Thus, downscaled precipitation is estimated by fixing the seasonal means.

Gangtok IMD and ERA5 monthly mean temperature data from 1979-2000 are taken. The difference between IMD and ERA5 data is estimated for every month of all the years. The mean of the differences for every month is estimated. These monthly means are the bias in the reanalysis data. These monthly means are added to the reanalysis temperature data. The reanalysis temperature is thus downscaled. The downscaled temperature data for 2017-2018 and Gangtok IMD station data, after applying TLRs below treeline to them from Table 1, are found to be reasonably close to the temperature from Yuksum AWS station (Figure 3).

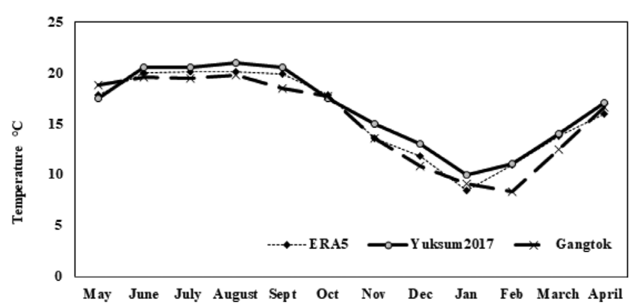

Figure 3: Comparison of ERA5 downscaled temperature data for May 2017 - April 2018 and Gangtok IMD station for year 2000, after adding monthly TLRs below treeline to them for altitude 1742 m asl.

Estimating Temperatures on the Glacier

Temperature over the glacier, for 1966-2020 is estimated. Monthly TLRs are superimposed on the temperature data series obtained from the Gangtok IMD station and downscaled reanalysis data. For altitudes 1650 to 4000 m asl, TLR below treeline is used. And for altitude 4001-4700 m asl, TLR above treeline is used. Annual averages are estimated from the new data set obtained after superimposing monthly TLRs on the temperature data series. The temperature obtained after applying TLRs is termed as $Gangtok_{TLR}$ and $ERA5_{TLR}$.

$Gangtok_{TLR}$ for the year 2000 and $ERA5_{TLR}$ for May 2017 – April 2018 are not too far from the temperatures observed at HMI base camp (Figure 4).

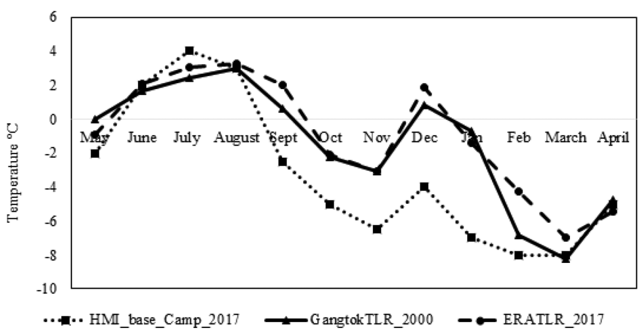

Figure 4: Comparison of HMI base camp monthly average temperature data for May 2017 – April 2018 with $ERA5_{TLR}$ data for May 2017 – April 2018 and $Gangtok_{TLR}$ for year 2000.

Plots are made to see the trends in MB, T, P and AOD datasets.

Results

Length, volume and area of East Rathong Glacier in the year 2011 were 6300 m, 0.188 km^3 and 3.942 km^2, respectively (Agrawal and Tayal, 2013). From the analysis carried out in this study it is found that in 2020, the glacier is 6058 m in length, 0.170 km^3 in volume and 3.670 km^2 in area. Thus, during the last decade, the glacier has been retreating at a rate of 24.4 m/yr and has lost a volume and area of 0.018 km^3 and 0.270 km^2 respectively. Area, volume and MB of East Rathong glacier from 1962-2020 are given in Table 3.

Mass balance of the glacier has become more negative over the decades. Correspondingly the Aerosol Optical Depth also shows an increasing trend over the past 30 years (Figure 5). The temperature and precipitation of the region are also increasing (Figure 6).

Discussion

Glaciers are an important source of fresh water all around the world. Climate change impacts are easily

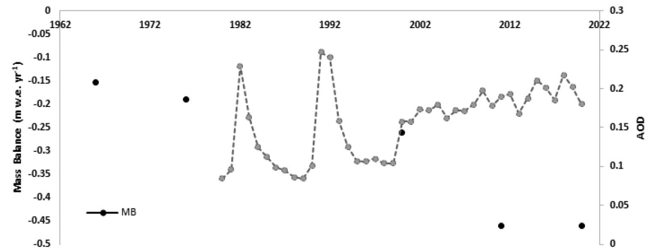

Figure 5: Mass balance of East Rathong glacier showing negatively increasing trend from 1962 to 2021 and AOD is showing increasing trend over Sikkim region from 1980 to 2020.

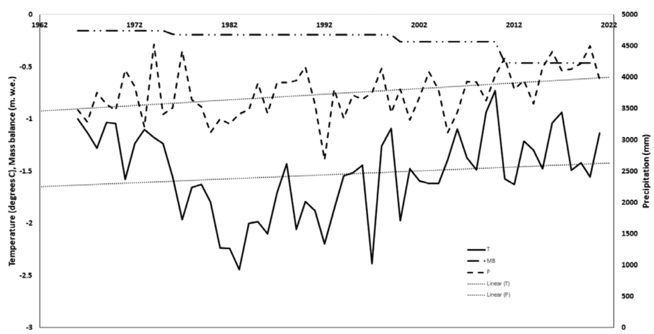

Figure 6: Temperature and precipitation patterns over Sikkim region and mass balance series of East Rathong glacier from 1966 to 2020.

visible in glacierised regions because of the sensitivity of glaciers to minor fluctuations in temperature and precipitation. Water stress, glacier collapse, GLOFs are some of the climate change impacts seen in glacierised regions all around the world (Aggarwal et al., 2021). Timely implementation of mitigation and adaptation measures in these regions is crucial because the vulnerability of mountain regions is high due to their difficult access and complex terrain. Also, the magnitude of losses incurred due to every disaster is very high. A large number of adaptation options are implemented all around the world, e.g. disaster risk reduction, installation of early warning systems, artificial glaciers or ice stupas, education and awareness campaigns, economic diversification, adoption of modern agricultural practices, artificial snow making, improved water storage systems, implementation of water laws and pricing, rationing, increased hydrological monitoring, etc. (Aggarwal et al., 2021), to control the stresses induced by climate change.

To implement effective policies in any region, which can control the intensity of negative impacts of climate change, detailed information on the region is required. This information is limited to mountain regions.

Moreover, very limited field data has been collected to date from the eastern Himalayan regions (Sharma et al., 2022). Some AWS data, which could be downloaded from the IMD website and extracted from the literature, is successfully used to downscale ERA 5 data over the Sikkim region. The newly constructed temperature and precipitation data series show increasing trends in temperature and precipitation over the region. The mass balance of East Rathong glacier, located in Sikkim, shows an increasingly negative trend.

Eastern Himalayan glaciers are summer accumulation-type glaciers. They receive maximum precipitation during the south-east monsoon, i.e., June-July-August (JJA) when the temperatures are also high. Thus, there is a possibility that the precipitation received on the glacier, especially in the ablation zone of the glacier, is more in the water phase than in the solid phase. And the precipitation received in the form of snow or solid phase is melting away from ablation regions simultaneous due to higher temperatures of summer. Strong increasing trend is observed in precipitation in JJA (Figure 7). Thus, increase in precipitation in this region is enhancing the melting rate of the glaciers instead of the rate of accumulation.

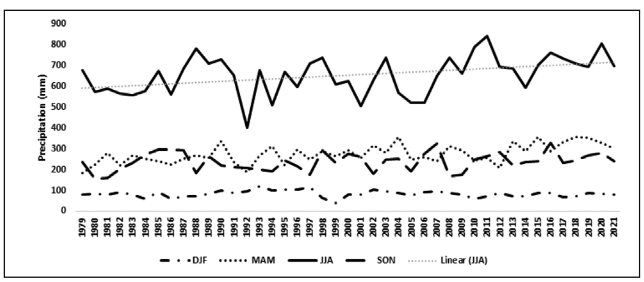

Figure 7: Seasonal precipitation of the region.

Changes in temperature, precipitation and melting of East Rathong glacier is correlated to increase in AOD data over this region. The results suggest that increase in air pollution is affecting the temperature, precipitation and glacier melting patterns of Sikkim Himalayan region.

Conclusions

Monthly TLRs and basic downscaling technique of subtracting means are used to construct temperature series over the glacier along with multiple data sets. Precipitation over glacier is estimated using downscaled ERA5 data.Change in volume estimated using satellite data are used to construct mass balance series for the glacier. It is observed that the glacier is losing its mass with increasing temperature, AOD and increasing precipitation mainly during JJA season.Various studies reporting presence of aerosols over glacierised regions suggest scope of policy implementation to control air pollution in these pristine regions to control temperature rise and accelerated melting of glaciers caused by air pollutants.

This study is important as it shows that how multiple data sets and data extracted from the literature can be used for glacier studies. Data generated from this study may be used in mass balance projection of the glaciers in the absence of field data.

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