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Estimation of Past and Future Mass Balance of Glaciers of Sikkim Himalaya using Energy Balance Modelling Approach and Regional Climatic Projections

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Abstract: In this study, the mass balance of Sikkim Himalayan glaciers is computed by the energy balance modeling approach using REMO and APHRODITE data. According to the present work, the glaciers show a mass balance of ~0, +0.31 and –0.32 m w. e. yr^{-1} for time periods 1981-1990, 1991-2000 and 2001-2005.

To investigate the possible changes in the near future (2006-2049) and far future (2070-2099), REMO data under different representation concentration pathway scenarios 2.6, 4.5 and 8.5 are also analysed. For the time period 2006–2100, RCP2.6, RCP4.5 and RCP8.5 give an average mass balance of -0.75 m w. e. yr^{-1}, -1.04 m w. e. yr^{-1} and -1.4 m w. e. yr^{-1}, respectively. The results are comparable to other studies. This study is one of the few studies carried out to estimate the mass balance of glaciers using only climate model data.

Keywords: Mass balance; Energy balance; Representative Concentration pathway; REMO**.**

Introduction

Fresh water is an important resource and mountain regions provide a substantial proportion of freshwater to the world (Viviroli et al., 2020). Regional water availability is affected by glacier retreat and thinning (Zemp et al., 2019). Himalayan glaciers are an important freshwater resource in Asia and hence have become a widely studied area. But because of the difficult terrain and extreme weather conditions of these regions, collecting continuous field data is very difficult (Azam et al., 2018). For this reason, less observational data is available from these areas and also it is hard procuring the available data. Hence, remote sensing became a suitable method to study glaciers a long time back (Paul et al., 2004; Agrawal and Tayal, 2013; Agrawal et al., 2014). Gradually climate model data has also become popular to study glacier-atmosphere interactions in these regions (Rounce et al., 2020; Kumar et al., 2019).

Glacier mass balance is being widely studied (Azam et al., 2018) as changes in mass balance and area of the glacier are correlated with climate change (Zemp et al., 2019). It is reported that glacier mass changes are negative in all regions over the latest observational decade, from 2006 to 2016. Mass balance of glaciers in South America is −1.0 m water equivalent (w.e.) per year; in the Caucasus, Central Europe, Alaska, and Western Canada and the USA is −0.8 m w.e. yr^{-1}, that is in the Southern Andes, it is –1.18 m w.e. yr^{-1}, while in Central Asia it is –0.15 m w.e. yr^{-1}, etc (Zemp et al., 2019). In the Himalayan region, mass balance is studied using a glaciological or on-field method only on 24 glaciers where the longest continuous series is only 12 years for Chhota Shigri Glacier (–0.56 ± 0.40 m w.e. a^{-1} over 2002–14) (Azam et al., 2018). Bolch et al. (2012) and Singh et al. (2018) have compiled mass balance data from a large number of studies based on glaciological/geodetic/hydrological/AAR

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methods. Between 1999 and 2004, Gardelle et al. (2013) estimated mass balances for glaciers of the Pamir-Karakoram-Himalaya (PKH) region using the geodetic method for the period 1999-2011. They found Eastern and Central Himalaya glaciers' mass balance ranged from –0.22±0.12 m w.e. a–1 to –0.33±0.14 m w.e. a–1. Shean et al. (2019) estimated total High Mountain Asia glacier mass change of −0.19 ± 0.03 m w.e. a–1 from 2000-2018 using the geodetic mass balance method.

Mass balance of glaciers is also studied using the energy balance approach (Rastogi and Ajai, 2014; Huintjes et al., 2015; Azam et al., 2014; Rupper and Roe, 2008). Rupper and Roe (2008) used two atmospheric quantities, temperature and positive degree days from NCEP-NCAR reanalysis data along with AWS data to develop a surface energy and mass balance model over central Asia. Rastogi and Ajai (2014) analysed the energy balance of Gangotri and Chhota Shigri glaciers using field meteorological data for November – December 2011 and albedo from the MODIS data set. They observed that the monthly average value of total heat flux during November and December 2011 on Gangotri glacier is 85.53 and 74.30 W/m^2, respectively. And the monthly average value of total heat flux during November and December 2011 on the Chhota Shigri glacier is 57.64 and 73.35 W/m^2 respectively. Kumar et al. (2015) developed a REMO glacier scheme for the first time to study over Karakoram-Himalayan glaciers, which simulates glacier climate interactions reasonably well and gives changes in mass balance and areal extents of the glaciers.

The Himalayan region is very large. Here the focus is on the Sikkim glaciers of Eastern Himalaya. From the Eastern Himalaya mass balance for only a few glaciers is reported (Azam et al., 2018). Mass balance using the glaciological method is reported for Changme Khangpu glacier for the period 1979-1982 to be –0.16 m w.e. a^{-1} (Bolch et al., 2012). Using glaciological and geodetic methods, mass balance for Gangju La glacier Bhutan is reported to be –1.12 to –2.04 m w.e. a^{-1} between 2003 and 2014 (Tshering and Fujita, 2016). Shean et al. (2019) have reported a mass balance of –0.55 m w.e. a^{-1} from 2000 to 2018 using the geodetic mass balance method for the eastern Himalayan region. Geodetic mass balance for Eastern Himalayan glaciers is reported by some studies, with the time period lying between 1974 and 2014, varying from –0.17 to –0.69 m w.e. a^{-1} (Azam et al., 2018).

Racoviteanu et al. (2015) reported ~13% glacier area loss during 1962-2000 in Sikkim. Frey et al. (2014) reported that the mean ice thickness for Eastern Himalayan glaciers obtained using different remote sensing methods is close to 50 m. There are no GPR thickness measurements for the Sikkim region. Climatology studies are also limited.

Summer-accumulation type glaciers receive most of their annual precipitation during summers. They are more sensitive towards changes in temperature and precipitation because their main accumulation period and ablation period coincide (Ageta and Higuchi, 1984; Sakai et al., 2015). Glaciers of Sikkim are summer accumulation type glaciers. They are located in monsoon-influenced regions which face wastage and are more sensitive to climate change (Lobil et al., 2014). Basnette et al. (2013) reported an increase of 1.03ºC in the mean annual air temperature at Gangtok IMD station during 1987-2011; maximum winter temperature rose by 1.13ºC and summer minimum temperature rose by 1.0ºC. For the period of 1900–2002 over the Brahmaputra basin in the eastern Indian Himalaya and Tibetan Plateau, Immerzeel (2008) also reported an increase of 0.06 ºC/decade. Racoviteanu et al. (2015) stressed the need for more accurate temperature and precipitation data in this region. Sharma et al. (2018) observed that South Lhonak Lake in Sikkim Himalaya has been rapidly expanding over the past few decades. The lake size showed a length change of 1.6 km during the period 1976-2016. The above mentioned studies suggest that the mass balance of Sikkim Himalayan glaciers is being impacted by climate change and needs to be studied further.

In the present study, the mass balance of Sikkim Himalayan glaciers is estimated for the time period 1981-2005 (past) using REMO data and APHRODITE data. To investigate the possible changes in the near future (2006-2049) and far future (2070-2099), REMO data under different Representation Concentration Pathways (RCPs) of greenhouse gases, RCP2.6, RCP4.5 and RCP8.5 are also analysed.

Data Sets Used

REMO

Regional Model (REMO) data from the COrdinated Regional Climate Downscaling Experiment (CORDEX), with resolution 0.44°×0.44°, was downloaded from http://esg-cccr.trop met.res.in/esgf-web-fe/. Monthly longwave upwelling radiation, longwave downwelling radiation, shortwave upwelling radiation, shortwave downwelling radiation, sensible heat flux and latent heat flux were downloaded for the time period 1981-2005 (historical). These parameters along with precipitation are also downloaded for different Representation Concentration Pathways 2.6, 4.5 and 8.5 for the time period 2006-2049 (near future) and 2070-2099 (far future) over north-east India.

APHRODITE

The daily Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of water resources (APHRODITE) data of resolution 0.25° × 0.25° for the time period 1981–2005 was downloaded from http://www.chikyu.ac.jp/precip/ (Yatagai et al., 2012). APHRODITE's daily gridded precipitation is a long-term (1951 onwards) continental-scale daily product. It contains a dense network of daily rain-gauge data for Asia, including the Himalayas, south and SE Asia and mountainous areas in the Middle East.

Methodology

Mass balance (b) for the study region is computed using the energy balance modelling approach. Here the mass balance is computed using the following equation:

$$b = \text{Accumulation} - \text{Melt} - \text{Sublimation} \tag{1}$$

Melt and sublimation are computed using REMO data. The glaciers in Sikkim are located at an altitude range of approx. 4,800 to 7,000 m asl. The annual average air temperature at 2m height from glacier surface is –4.4 °C (Agrawal and Tayal, 2015). So precipitation is solid because of sub-zero conditions. Dimri et al. (2018) have found the rate of warming to be 0. 3 °C/decade for RCP2.6 and 0.3–0.9 °C/decade for RCP8.5. Even if the temperature increases by a rate of 0.3°C/decade for all the scenarios, the temperature on the glacier remains below zero, so the precipitation from REMO is likely to be solid. So, it is assumed that all the precipitation is solid and getting accumulated. Hence accumulation is the precipitation taken from APHRODITE data, which is reanalysis data prepared from the field rain gauge data. Mass balance and energy balance are computed for the time period 1981-2005.

Melt is computed using the net energy balance of the region. Melt is computed using the following equation:

$$\text{Melt} = \frac{Q_m}{\rho_w L_f} \text{ (Hock, 2005) (m w.e.)} \tag{2}$$

where Q_m = melt energy, L_f (latent heat of fusion) = 334 KJ/kg, ρ_w (density of water) = 1000 kg/m^3.

Melt or ablation is calculated from the net energy flux Q_m as calculated below:

$$Q_m = \Delta Q = Q_{ns} + Q_{nl} + Q_l + Q_s + Q_g + Q_p \tag{3}$$

Each term has units W/ m^2. (Hock, 2005; Oerlemans, 2001)

where Q_{ns} = Net shortwave radiation

Q_{nl} = Net longwave radiation

Q_l = Latent heat flux

Q_s = Sensible heat flux

Q_g = Sub-surface heat flux

Q_p = Advected heat from rain-water falling on snow

Net shortwave radiation flux

$$Q_{ns} = SWR\downarrow - SWR\uparrow \tag{4}$$

$SWR\downarrow$ = Incoming shortwave radiation flux

$SWR\uparrow$ = Outgoing shortwave radiation flux

Q_g and Q_p are neglected in this study and are not included in the calculations.

Net Longwave Radiation Flux

Incoming longwave radiation is emitted by atmospheric components (vapour, aerosols, clouds) as a function of their temperature. Outgoing longwave radiation is emitted from the glacier or snow surface as a function of its temperature and the properties of the surface.

$$Q_{nl} = LW\downarrow - LW\uparrow \text{ (Oerlemans, 2001)} \tag{5}$$

LW ↓ = Downwelling longwave radiation flux

LW ↑ = Upwelling longwave radiation flux

Sensible Heat Flux and Latent Heat Flux

Sensible heat flux (SHF) is the heat transfer between the surface and air mass when there is a temperature difference between them. It depends on the temperature difference between atmosphere and snow pack surface, wind speed, surface roughness and the stability of the air. Latent heat flux (LHF) is the heat used in the phase change of ice to water vapour occurring because of the difference in water vapour pressure of air close to the glacier surface and saturation vapour pressure at snow/ice surface. It is responsible for the mass loss by sublimation.

The methodology described in this section is applied to compute the MB by energy balance modeling approach using REMO data. Variables downloaded are used as input in equation (3) for the computation of melt energy. Melt energy is computed and equation (2) is used to compute the melt. APHRODITE precipitation downloaded and computed melt are used for MB estimation.

The same methodology is applied for mass balance computation from REMO data for scenarios RCP2.6, 4.5 and 8.5. Since no APHRODITE precipitation is available for different scenarios, precipitation from REMO data is used in the MB calculations.

Radiation fluxes are sensitive to surface properties like albedo, roughness, topography and local meteorological conditions. But due to the lack of availability and accessibility of field data from the study region, no field data is used in the study. Hence, the climate model data could not be downscaled to glacier scale (surface and elevation) for the study. The calculations are done directly from the model data.

The data is extracted, for coordinates 27°43'29" N and 88°19'27" E, from files using open-source software, Grid Analysis and Display System (GrADS) software.

Results and Discussion

Past Mass Balance

The mass balance for the Sikkim glaciers is estimated using the energy balance approach as mentioned in equations (1) to (5). According to the energy balance method, the results obtained show that the glaciers a melt of 1.2, 0.69 and 1.2 m w. e. yr^{-1} for time periods 1981-1990, 1991-2000 and 2001-2005. From latent heat flux, the glaciers are showing sublimation of 1.03, 1.1 and 1.02 m w. e. yr^{-1} for time periods 1981-1990, 1991-2000 and 2001-2005. According to Aphrodite precipitation data, the region has received precipitation of 2.2, 2.1 and 1.9 m w. e. yr^{-1} for time periods 1981-1990, 1991-2000 and 2001-2005. Thus, the mass balance of the glaciers as seen in this work for the time periods 1981-1990, 1991-2000 and 2001-2005 is ~0, +0.31 and –0.32 m w. e. yr^{-1}.

According to the analyses carried out in this study using climate model data, the mass balance for the glaciers during the time period 2001-2005 is –0.32 m w.e. yr^{-1}. This value is close to the results published by other studies for eastern Himalayan glaciers like –0.44±0.2 m w. e. yr^{-1} using ice-flow velocity method for Sikkim glaciers during the period 2010-2014 (Agrawal and Tayal, 2018); –0.6 m w.e. yr^{-1} for the time period 2010-2020 (Rounce et al., 2020); –1 m w.e. yr^{-1} over a time period of 2000-2016 from climate model $REMO_{glacier}$ (Kumar et al., 2019); –1.12 to –2.04 m w.e. a–1 between 2003 and 2014 using glaciological and geodetic methods for Gangju La glacier Bhutan (Tshering and Fujita, 2016) and –0.55 m w.e. a^{-1} from 2000–2018 using geodetic mass balance method (Shean et al., 2019).

To study the possible future changes in the mass balance of the study region, data from model integrations available from different representative pathways are utilised (Moss et al., 2010).

Future Mass Balance using RCP2.6, RCP4.5 and RCP8.5

Turbulent heat fluxes, SWRnet, LWRnet and net energy balance are computed using RCP 2.6 data. From the analyses it is observed that the mean latent heat flux, sensible heat flux, long wave radiation, shortwave radiation and net energy balance are –48, 8.6, –73, 143 and 27 W/m^2 respectively. Energy balance components computed using RCP 4.5 data gave the mean latent heat flux, sensible heat flux, long wave radiation, shortwave radiation and net energy balance to be –50, 13, –76, 146 and 34 W/m^2. Energy balance components computed using RCP 8.5 data gave the mean latent heat flux, sensible heat flux, long wave radiation, shortwave radiation and net energy balance to be –49, 16, –78, 150 and 40, respectively. At the decadal level, from 2006-2100, SHF is showing decreasing trend after 2060 and rest of the energy balance components are not showing any trends in RCP 2.6. Dimri et al. (2018) noticed that T mean from RCP 2.6 scenarios rises till 2060 and afterwards becomes weak and Tmean climatology continues to fall till the end of the century. According to them the reason for such a behaviour can be attributed to the emission strategies under RCP 2.6, which assumes full participation of all countries in capping the total GHG emissions, thereby known as mitigation scenario. Since RCP 2.6 proposes to reduce the emission as well as radiative forcing below the baseline level; this trait might have translated indirectly from the response of the driving GCMs to the RCP 2.6. Since SHF is directly affected by the temperature, it is possible that the downward trend noticed in SHF post-2060 in this study is due to the weakening of Tmean climatology in the model as found by Dimri et al. (2018).

In RCP 4.5, SWR is showing an increasing trend from 2006 to 2100. In RCP 8.5, SHF and SWR show an increasing trend from 2006-2100. Dimri et al. (2018) have observed that under RCP 8.5, there is a consistent rise in temperature until the end of the 21st century. The reason behind this warming is also reflected in this study through increasing trends of SWR and SHF of the region. The energy balance components for different scenarios are given as supplementary material in Table S1.

The energy balance approach gives the MB of the glaciers of the region varying from –0.097 to –0.92

Table S1: Energy balance components and mass balance as shown at decadal scale from 2006-2100 for RCP (a) 2.6, (b) 4.5 and (c) 8.5

RCP 2.6	*2010*	*2020*	*2030*	*2040*	*2050*	*2060*	*2070*	*2080*	*2090*	*2100*
Latent Heat Flux	-45.42	-48.33	-48.33	-46.67	-48.75	-47.92	-47.5	-50.83	-47.5	-47.5
Sensible Heat Flux	7.5	8.5	10.92	10.08	11.83	7.58	9	6.58	5.16	5.16
LWR	-78.33	-80	-78.33	-67.5	-73.33	-75.83	-69.16	-72.5	-62.5	-62.5
SWR	138.08	138.75	144.08	141.91	145.16	138.92	139.33	138.5	135.83	135.83
Net Energy Balance	21.83	18.92	28.33	37.83	34.92	22.75	31.67	21.75	31	31
MB	-0.388	-0.097	-0.629	-0.92	-0.736	-0.212	-0.84	-0.161	-0.272	-0.272

(a)

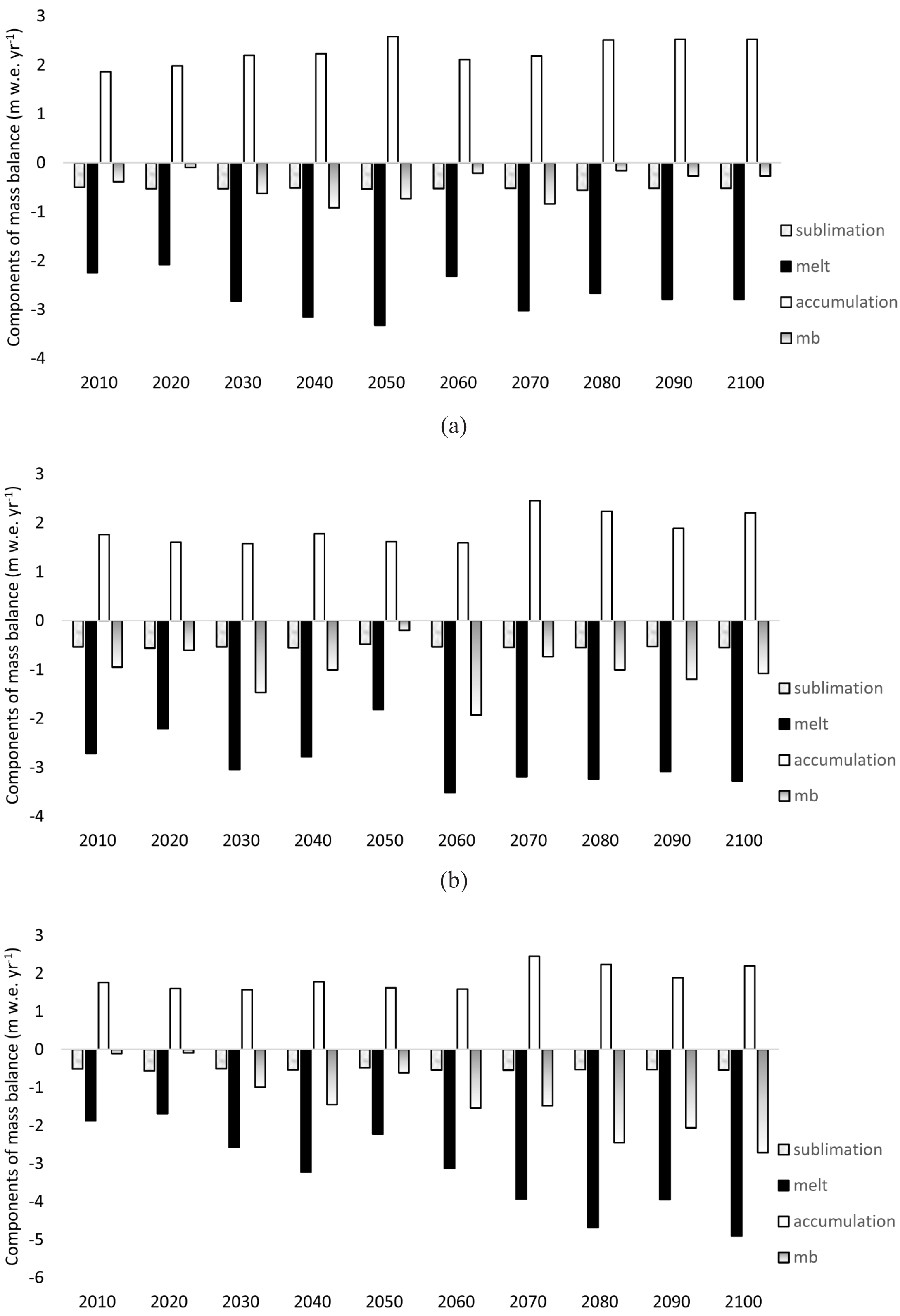
RCP 4.5	*2010*	*2020*	*2030*	*2040*	*2050*	*2060*	*2070*	*2080*	*2090*	*2100*
Latent Heat Flux	-48.75	-51.25	-48.75	-50.42	-50.42	-48.75	-49.58	-50	-50	-50
Sensible Heat Flux	14.42	9.58	12.67	10.92	10.91	13.75	15	15	16.67	16.67
LWR	-78.33	-81.66	-71.67	-74.16	-71.66	-73.33	-75.83	-75	-83.33	-83.33
SWR	142.83	144.16	142.33	146.08	146.08	146.92	147	148.17	152.92	152.91
Net Energy Balance	30.16	20.83	34.58	32.42	41.58	38.58	34	37.33	36.25	36.25
MB	-0.952	-0.603	-1.467	-1.003	-0.196	-1.925	-0.734	-1.003	-1.196	-1.077

(b)

RCP 8.5	*2010*	*2020*	*2030*	*2040*	*2050*	*2060*	*2070*	*2080*	*2090*	*2100*
Latent Heat Flux	-46.67	-50.83	-46.25	-48.75	-50.83	-49.17	-49.58	-48.33	-48.33	-49.16
Sensible Heat Flux	5.083	3.42	8.75	15.91	16.33	15.33	18.66	24.66	25.83	27.92
LWR	-75	-76.66	-76.67	-82.5	-71.67	-78.33	-82.5	-82.5	-80	-77.5
SWR	136.75	140.16	142.5	151.17	147.17	149.16	158.75	160.16	159.75	158.16
Net Energy Balance	20.166	16.08	28.33	35.83	48.08	37	45.33	54	57.25	59.41
MB	-0.105	-0.0876	-0.991	-1.449	-0.608	-1.541	-1.479	-2.45	-2.057	-2.71

(c)

in RCP 2.6, from –0.196 to –1.925 in RCPs 4.5 and from –0.087 to –2.71 m w.e. yr-1 in RCP 8.5 for the time period 2006-2100. The change in radiation budget for different scenarios, RCP 2.6, 4.5 and 8.5, gives sublimation, melt, accumulation and mass balance for the region as shown in Figure 1.



(c)

Figure 1: Sublimation, melt and mass balance for the region under (a) scenario 2.6, (b) scenario 4.5 and (c) scenario 8.5.

Azam et al. (2018) have reported the energy balance from regions like central Himalaya, the Karakoram, western Himalaya, west Kunlun Mountains, western Qilian, south west Tianshan, south west TP, south east TP, central TP, south central TP and many more for different time periods. In these regions, the values of net radiation, sensible heat flux, latent heat flux and net energy balance vary from 5 to 188, 5 to 63, –64 to 19 and 14 to 230, respectively, depending on the time of the year and location of the region. From the regions reported in a study by Azam et al. (2018), southwest Tian Shan is closest to our study region. They have given net radiation, sensible heat flux, latent heat flux and net energy balance for the time period 16 June to 7 Sept 2005 to be 63, 14, –54 and 23 W/m^2. These energy balance component values are close to the energy balance values estimated in this work from REMO data using RCP 2.6, 4.5 and 8.5 dataset. Hock et al. (2019) have projected time series of glacier mass evolution for 2015–2100 from six glacier models forced by multi-mean and individual Global Circulation Models and RCP 2.6, RCP 4.5 and RCP 8.5 emission scenarios. According to them, the global mass balance is from approx. –0.5 to –1 m w. e. a^{-1} in RCP 2.6, approx. –0.5 to –1.5 m w. e. a^{-1} in RCP 4.5 and approx. –0.5 to –4 m w. e. a^{-1} in RCP 8.5. Results obtained in this paper have a similarity to the results projected by Hock et al. (2019). This study is one of the few studies in which the glacier mass balance is estimated using climate model data. The results involve uncertainties due to the way the climate model parameterises the different variables of the climate and the coarser resolution of the data used. The main limitation of the study is the lack of validation and downscaling steps due to the unavailability of field data. But the results are comparable with those from other studies.

Conclusion

Sikkim is surrounded by Tibet, Nepal and China. A recent study carried out by Brun et al. (2017) gives the mass balance of glaciers of these regions using the geodetic method for the time period 2000-2016. According to their paper, the mass balance pattern observed in the Tien Shan region is −0.28±0.20 m w.e. yr^{-1}. Mass balance observed in Bhutan and the East Nepal region are −0.42±0.20 m w.e. yr^{-1} and −0.33±0.20 m w.e. yr^{-1}, respectively. According to Agrawal and Tayal (2018), where mass balance is computed from the conventional ice-flow velocity method using satellite data, for glaciers during the time period 2010-2014, it is –0.44 m w.e. yr^{-1}. According to Rounce et al. (2020) and Kumar et al. (2019), the mass balance of eastern Himalayan glaciers is estimated, using climate model data, to be –0.6 m w.e. yr^{-1} and –1 m w.e. yr^{-1} respectively. The mass balances reported in the above given studies are closer to the mass balance computed for the Sikkim region using REMO data for the time period 2001-2005. This suggests that even climate model data can be used to compute the mass balance of glaciers of a region.

The mass balance of the Himalayan glaciers of Sikkim for time periods 1981-1990, 1991-2000 and 2001-2005 is estimated to be ~0, +0.31 and –0.32 m w. e. yr^{-1}, respectively. To further investigate the future possible mass balance of the glaciers in the Sikkim region, REMO data under different representation concentration pathway scenarios, such as 2.6, 4.5 and 8.5 are also analysed. RCP 2.6, 4.5 and 8.5, for the time period 2006-2100, are giving an average mass balance of -0.75 m w.e. yr^{-1}, –1.04 m w.e. yr^{-1} and –1.4 m w.e. yr^{-1}, respectively.

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