551.509 : 551.524

Observed and simulated winter temperature over Gurudongmar area, North Sikkim, India

ARCHISMAN BARAT, P. PARTH SARTHI*, SUNNY KUMAR,

PRAVEEN KUMAR and ASHUTOSH K. SINHA

Department of Environmental Sciences, Central University of South Bihar, Gaya – 824 236, India

(*Received 14 February 2019, Accepted 10 October 2019*)

***e mail : drpps@hotmail.com**

सार – भूमंडलीय उष्णन का क्रायोस्फीयर पर इसका प्रभाव गंभीर चिंता का विषय है। सिक्किम और पूर्वी हिमालय के अलग-अलग भूदृष्य और विभिन्न जलवायु क्षेत्र एक चित्र की भाँति हैं। सतह के वायु तापमान की दीर्घकालिक जलवायु प्रवृति पर क्रायोस्फीयर के अध्ययन पर और अधिक ध्यान देने की आवश्यकता है। गुरुडोंगमर क्षेत्र बहुत महत्वपूर्ण है क्योंकि यह क्षेत्र ग्लेशियरों से घिरा हुआ है और यहाँ ठंडा रेगिस्तान और त्सो ल्हालाम (TsoLhamo) झील भी है। कई शोधकर्ताओं ने गुरुडोंगमर झील (17,800 फीट की ऊंचाई पर स्थित) का अध्ययन ग्लेशियल लेक आउटबर्स्ट फ्लड्स (GLOFs) के संदर्भ में किया है, और इसे अत्यधिक जोखिम वाली झील माना गया है जो भूमंडलीय उष्णन और जलवायु परिवर्तन से काफी हद तक प्रभावित हो रही है। वर्तमान अध्ययन का उद्देश्य सिक्किम के अध्ययन वाले क्षेत्र पर हाल के दिनों में और भविष्य के समय में तापमान की प्रवृत्ति की जांच करना है। अध्ययन क्षेत्र पर दिसंबर-जनवरी-फरवरी (डीजेएफ) के सर्दियों के महीनों में बढ़ते हुए मॉडल और सिम्युलेटेड ग्रिडिड तापमान डेटा की बढ़ती प्रवृत्ति को देखते हुए माना जाता है। तापमान में वृद्धि भविष्य की समय अवधि के लिए पाई जाती है। इसे बढ़ते खतरे और स्थानीय क्रायोस्फीयर वातावरण में बदलाव से जोड़ा जा सकता है।

ABSTRACT. The global warming and its impact on the cryosphere is a matter of serious concern. The Sikkim and the Eastern Himalaya are a canvas of vivid landscapes and of different climate zones. The study of cryosphere needs more attention on long term climatic trends of surface air temperature. The Gurudongmar area is very much important because this area is surrounded by glaciers and as well as cold desert and TsoLhamo Lake nearby. The Gurudongmar lake (located at an altitude of 17,800 ft) has been studied by several researchers in the context of Glacial Lake Outburst Floods (GLOFs) and reported a high risk lake which is being largely affected by global warming and climate change. The present study is aimed to investigate the trend of temperature in recent past and in future time periods over the study area of Sikkim. The observed and model's simulated gridded temperature data is considered to inkling of rising trend in winter months of December-January-February (DJF) over the study area. An increase in temperature is found for the future time period. This can be linked to the increasing hazard risk and change in local cryosphere environment.

Key words – Temperature trends, Sikkim Himalaya, Cryosphere, Gurudongmar.

1. Introduction

The linkage between global warming and cryosphere is now a well-understood phenomena, however, the impacts to these fragile environments are a matter of multidisciplinary research (Bolch *et al*., 2012; Raj *et al*., 2013; Sharma and Shreshtha, 2016; Aggarwal *et al*., 2017; Pant *et al*., 2018; Bolch *et al*., 2019). The Sikkim and the Eastern Himalaya in India is a biodiversity hotspot (Kumar, 2012) where climate change is a major concern (Ravindranath *et al*., 2011; Deb *et al*., 2015). Of late the region of Sikkim Himalayas and its snow-fed area has been studied by many researchers (Kulkarni *et al*., 2011; Racoviteanu, 2014; Sharma and Shreshtha, 2016; Pant *et al*., 2018; Debnath *et al*., 2018; Bhattacharya *et al*., 2018; Shukla *et al*., 2018), however, the study on temperature variation is least focused over this part of India. Dash *et al*. (2012) has documented the temperature trends for past and future for entire North East India (NEI) where an overview about the temperature trends including the Sikkim Himalaya has been presented, using Coupled Model Intercomparison Project Phase 3 (CMIP3) data, in a detailed manner and an increase in temperature is reported. The negative impact of climate change has been discussed by several researchers over Sikkim. Sharma and Sreshtha (2016) found that multiple impacts of increasing temperature are evident over the Sikkim, *viz.*, warmer winter, drying up of water springs, low crop yields and incidences of mosquitoes in winter and the study is based on the air temperature data from Gangtok and Tadong meteorological stations. It is to be mentioned here that due to this lack in meteorological station network the climatic study is difficult for the rest of the Sikkim including the present study area. A few other researchers have also been documented past climate change (Jain *et al*., 2013) along with future (Kumar and Dimri, 2018) projection for entire NEI, not only for the state of Sikkim. The Sikkim Himalayas are very complex terrain and Sikkim contributes a small portion to the NEI area, beside this, land cover and the local environment of Sikkim is also somewhat different from the other NEI states, therefore there is a need of separate study tailored for these areas which will not only address the past temperature trends but also project the future trends. For the projection of temperature during the future time period, models are probably the best possible approach. Using Coupled Model Inter Comparison 3 (CMIP3) data, Deb *et al*. (2015) showed a rise in temperature over the Sikkim by using CMIP3 GCM data only. Ravindranath *et al*. (2012) using CMIP3 temperature and rainfall data found no impact on forests of Sikkim. On the other hand, Kumar and Prabhu (2012) found that increasing temperature can trigger Glacial Lake Outburst Floods (GLOFs) in Sikkim. By the perusal of the literatures, it is evident that there is a need of detail study of change in surface air temperature focused over the Sikkim. The future projections using CMIP5 data can give the scientific community a better picture of the temperature signals over the area. To answer these questions, the objective of the present research is to characterize the past and future trends of temperature over the north Sikkim (as the north Sikkim is dominated by snow, therefore the proposed objective may be useful for impact assessment over the area) using modelling approaches. For this purpose observational as well as Global Climate Model (GCM) and dynamically downscaled Regional Climate Model (RCM) simulated surface air temperature data are considered. Both (GCM and RCM) have their own pros and cons and have their own benefits over each other (Eden *et al*., 2014; Xu *et al*., 2018; Patwardhan *et al*., 2018), hence for this study both types of the model simulated data are considered.

2. Data and methodology

2.1. *Study area*

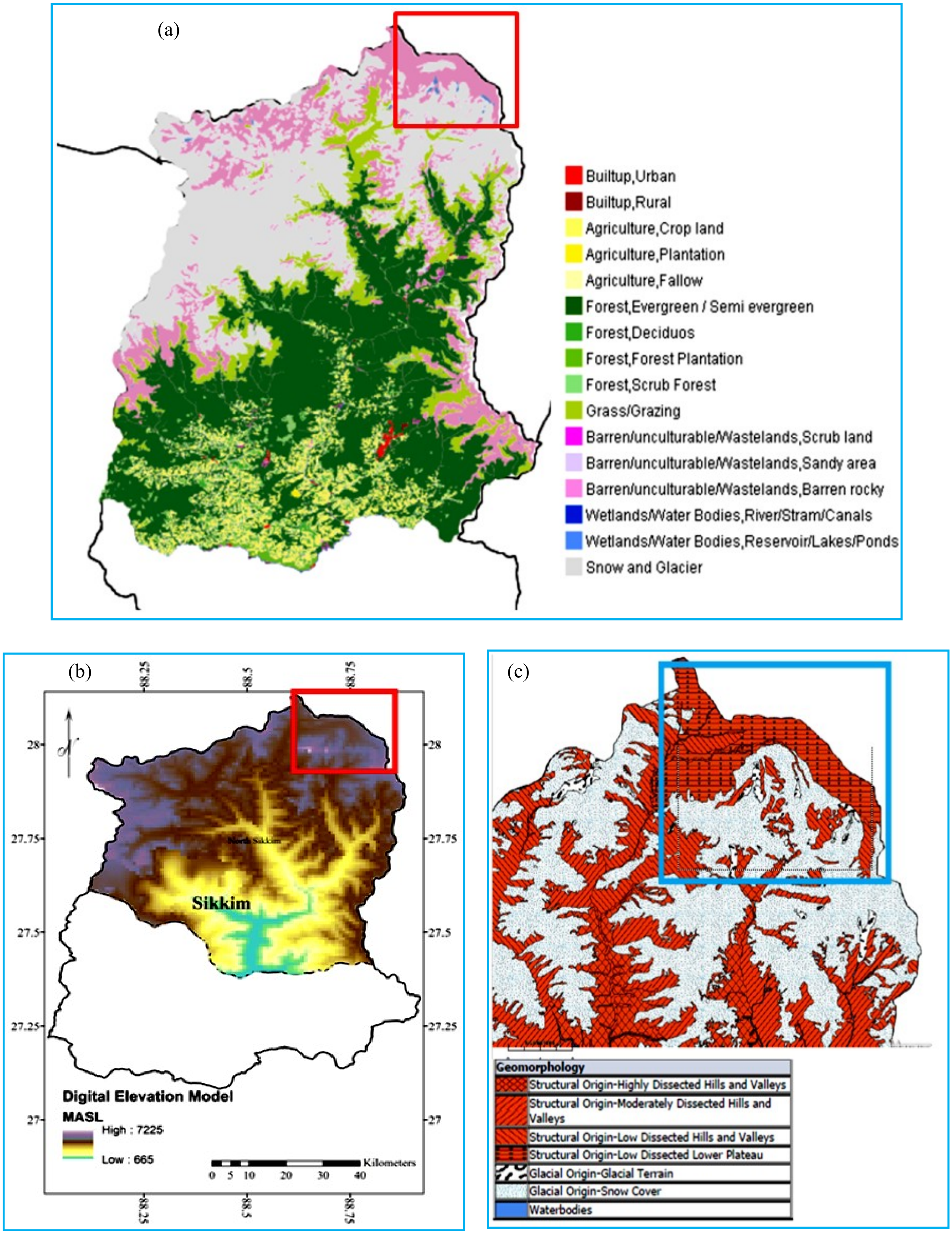
The state of Sikkim exhibits a multitude of Land Cover and elevation heterogeneity [Figs. 1(a&b)]. The Gurudongmar area is located in the administrative district of North Sikkim and is comprised of cold desert and Alpine meadow mainly of glacial origin [Fig. 1(c)]. Apart from Gurudongmar, the TSoLhamolake is also located here. The Gurudongmar lake (located at an altitude of 17,800 ft) and with other Glacial lakes of Sikkim has been studied by several researchers in the context of Glacial Lake Outburst Floods (GLOFs) (Kumar and Prabhu, 2012; Shukla *et al*., 2012; Shukla *et al*., 2018) and unanimously these researches found a high risk regarding these lakes; mainly triggered by global warming and climate change. Hence, an in depth analysis of temperature is much needed over the study area.

2.2. *Data*

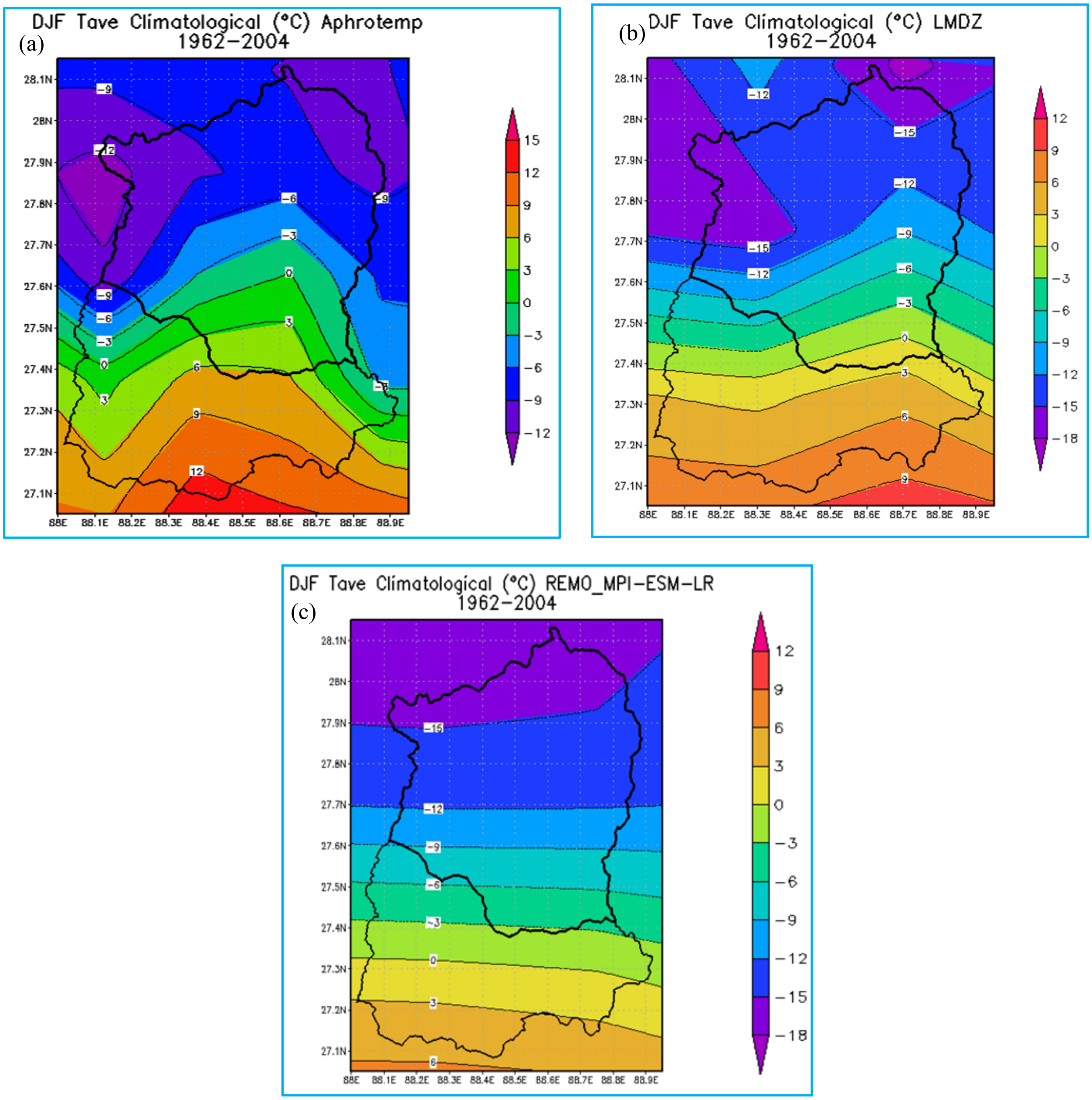
The present study has carried out using observational (Yasutomi *et al*., 2011) as well as GCM and RCM (both under Historical experiment of Coupled Model Intercomparison Project Phase 5 (CMIP5) simulated gridded dataset of surface air temperature. For the projection of future time period, high resolution GCM (LMDZ) and RCM (REMO) are considered under RCP4.5 experiment. The datasets are chosen on the basis of highest available grid points on finer spatial resolution over the study area for GCM, Regional Climate Model (RCM) and observational dataset. Under the CMIP5 framework the GCM (LMDZ) considered is having high spatial resolution. Due to its telescopic zooming property, the data contains irregular grids with maximum resolution of around 0.3° × 0.3° (~35 km × 35 km) over India. The data is available under Historical and Representative Concentration Pathways (RCP) 4.5 experiments only. The RCM selected for the study is the REMO with MPI-ESM-LR forced as driving GCM under the COordinated Regional Climate Downscaling Experiment-South Asia (CORDEX-SA) experiment. REMO experiments over the CORDEX-SA domain provide a high resolution data over the study area. As the study area is having high spatial heterogeneity over a small extent, therefore high spatial resolution is a must needed criterion. As the chosen datasets are of high resolution, at least two grid points are found to fall on the North Sikkim District where the study area is located. The detail of the data set is given in Table 1.

2.3. *Methods*

The individual winter months (December, January and February) are analysed as well as seasonal analysis for combined December, January and February (hereafter DJF) has been carried out. The time frame of 1961-2005 for historical and 2019-2071 for projections (RCP4.5) are considered for study, however to ensure each DJF is comprised of three months the time frame of 1962-2004 and 2020-2070 are considered for seasonal experiment. For each experiment at least initial 10 year data (*viz*., 1951-1961 for historical & 2006-2020 for RCP45) are not taken to minimize the error during spin up time of model.



Figs. 1(a-c). Study area showing (a) The Land Use Land Cover (Source:http://bhuvan.nrsc.gov.in/bhuvan_links.php) (b) Digital Elevation Model (GTOPO-DEM) (Source: http://clima-dods.ictp.it/regcm4/) (c) Geomorphology (Source: http://bhuvan.nrsc.gov.in/bhuvan_links.php). The Study area is shown in colored hollow box

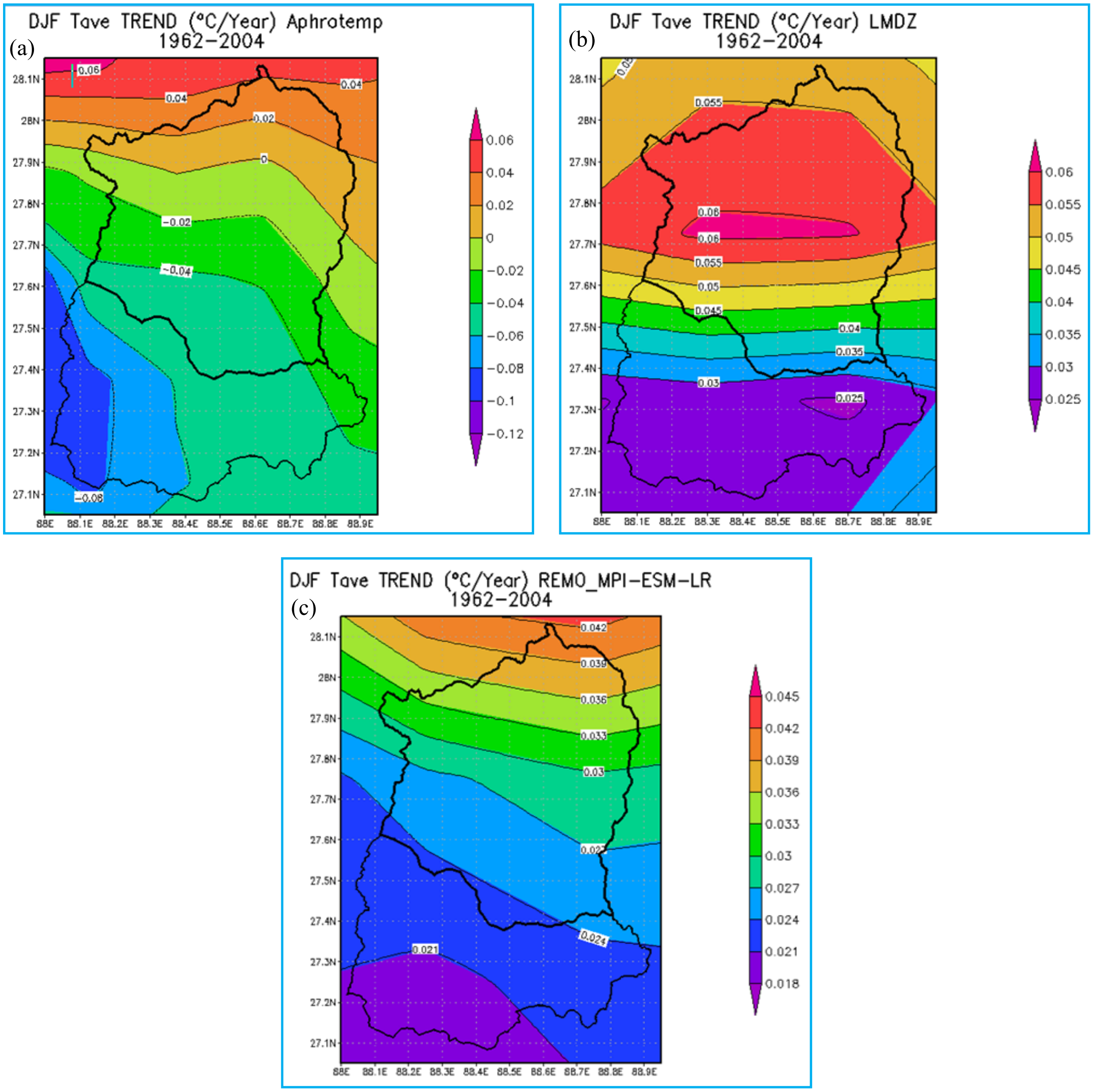


Figs. 2(a-c). DJF Climatology during 1962-2004 for (a) AphroTemp, (b) LMDZ (High Resolution GCM) and (c) REMO_MPI-ESM-LR (RCM)

TABLE 1

Details of dataset used

Dataset	Experiment	Spatial Resolution	Temporal Resolution	Time Frame	Source
AphroTemp	Observation	0.25° × 0.25°	Monthly	1961-2005	http://www.diasjp.net/
LMDZ	GCM-Historical	Irregular grids appx 0.31° × 0.31° (~35 kilometers × 35 kilometers)	Monthly	1961-2005	http://cccr.tropmet.res.in/
REMO (MPI-ESM-LR)	RCM-Historical	0.44° × 0.44°	Monthly	1961-2005	http://cccr.tropmet.res.in/
LMDZ	GCM-RCP4.5	Irregular grids appx 0.31° × 0.31° (~35 kilometers × 35 kilometers)	Monthly	2019-2071	http://cccr.tropmet.res.in/
REMO (MPI-ESM-LR)	RCM- RCP4.5	0.44° × 0.44°	Monthly	2019-2071	http://cccr.tropmet.res.in/



Figs. 3(a-c). DJF Trend in average temperature (°C/Year) during 1962-2004 for (a) AphroTemp (b) LMDZ (High Resolution GCM) (c) REMO_MPI-ESM-LR (RCM)

The trend analysis is carried out using the non-parametric Mann-Kendall Test on MiniTab® software (http://support.minitab.com/en-us/minitab/17/MKTREND.mac). Mann-Kendall test is used to determine existence and significance of a trend in the considered data (Singh *et al*., 2008; Kumar *et al*., 2010) and is considered to be a good tool for assessing the climate change (Ezber *et al*., 2007). The Mann-Kendall test checks the null hypothesis of no trend against the alternative hypothesis for the existence of any increasing or decreasing trend. It is defined for N number of data points as follows:

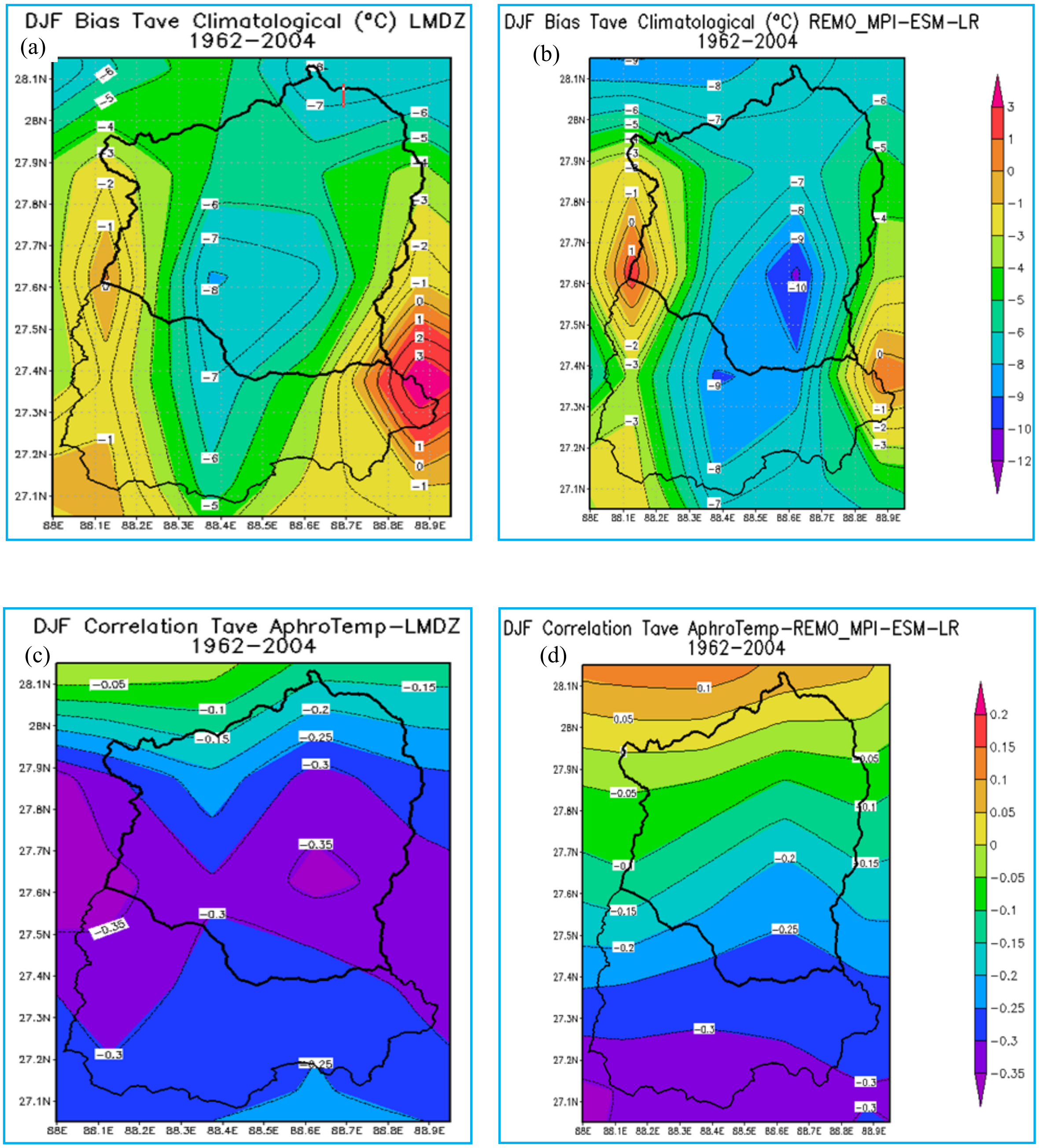
$$\text{MK Test Statistic(S)} = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} sgn(x_i - x_j) \quad (1)$$

where,

$$sgn\,(x_j - x_i) = 1 \text{ if } (x_j - x_i) > 0$$

$$= 0 \text{ if } (x_j - x_i) = 0$$

$$= -1 \text{ if } (x_j - x_i) < 0$$

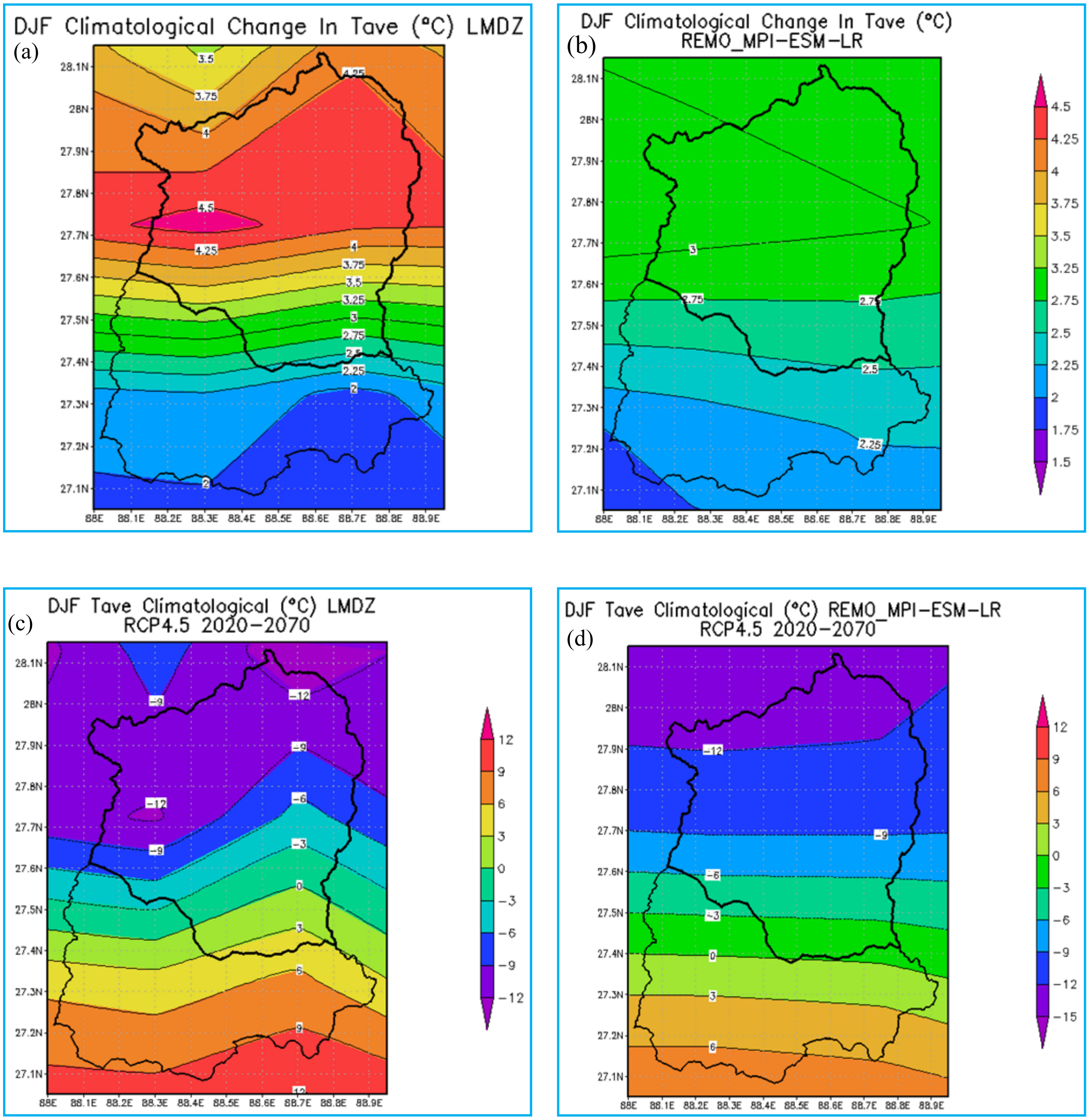


Figs. 4(a-d). DJF Climatological Bias (°C) during 1962-2004 between (a) LMDZ minus AphroTemp (b) REMO minus AphroTemp & Correlation over Each Grid Point between (c) AphroTemp & LMDZ and (d) AphroTemp & REMO

The temporal trend analysis over each grid point is done using trend analysis package in Climate Data Operator software and Sen's Slope estimator (Sen, 1968) in MiniTab® software. The temporal trend is calculated over study area for visualizing the temperature regime. The temporal correlation for each of the grid point of both models is also performed.

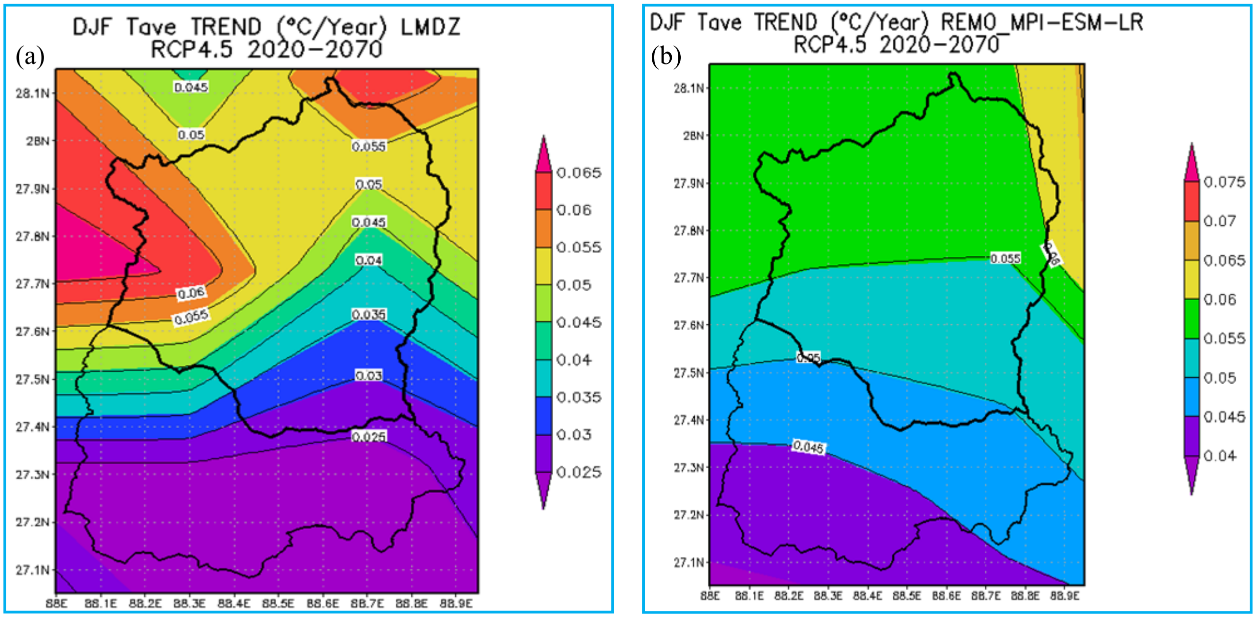
3. Results and discussion

In Figs. 2(a-c), the historical climatology is analysed. It seems that both model is failed to quantify the actual magnitude of average temperature and exhibits cold bias, however the LMDZ (GCM) is better in capturing the spatial pattern of temperature, while REMO (RCM) showed a flatter appearance and failed to capture the local



Figs. 5(a-d). DJF Climatological change in (°C) for (a) LMDZ RCP4.5 minus LMDZ-Historical (b) REMO RCP4.5 minus REMO-Historical and Climatology of RCP4.5 experiment (2020-2070) for (c) LMDZ and (d) REMO_MPI-ESM-LR

spatial variations. This higher accuracy maybe due to the high resolution of the GCM or the telescopic zooming techniques employed, however the model performance is beyond the scope of current research, hence the causes are not analysed in detail. Over the study area however, both model shows almost similar results as in DJF climatology, the temperature gradient decreases from south to north in Sikkim and remain below -10 °C over the study area. In Fig. 3(a), the trend analysis for recent past showed an increment of 0.01-0.04 °C/year over study area in observation data. Results show that the model REMO [Fig. 3(c)], the shows better accordance on spatial pattern with observation than the model LMDZ [Fig. 3(b)], in capturing the trend over entire Sikkim. However, for the study area both model shows comparable magnitude of 0.05 °C/year in LMDZ and 0.03-0.045 °C/year in REMO.



Figs. 6(a&b). DJF Trend in average temperature (°C/Year) in RCP4.5 experiment for (a) LMDZ (High Resolution GCM) (b) REMO_MPI-ESM-LR (RCM)

TABLE 2

Statistics of trend analysis of observation and historical and RCPs experiments

Dataset	Significant Increasing Trend (MK-Test)				Sen's Slope			
	D	J	F	DJF	D	J	F	DJF
(A) Historical/Observation								
(*i*) AphroTemp	Y	-	-	Y	0.022	0.020	0.019	0.020
(*ii*) LMDZ	Y	Y	-	Y	0.064	0.079	0.012	0.055
(*iii*) REMO (MPI-ESM-LR)	-	Y	Y	Y	0.005	0.070	0.051	0.045
(B) RCP4.5								
(*i*) LMDZ	Y	Y	Y	Y	0.086	0.077	0.048	0.062
(*ii*) REMO (MPI-ESM-LR)	Y	Y	Y	Y	0.067	0.054	0.064	0.058

If these findings are compared with other researcher's work over Sikkim, where station data are used for study and an increment of 0.057 to 0.08 °C/year (Sharma and Shreshtha, 2016) is reported, the current results are in agreement with those studies. It is found that the rate of warming in winter is most significant (Chettri *et al*., 2010) over the eastern Himalayas from both previous studies and the present research. The winter minimum temperature of nearest meteorological station at Gangtok is also earlier reported to be increased (Seetharam, 2008). Because objective of this study is confined to analysis of the trend in average temperature for past and future time period and not the selection of best model, hence both models are considered for future projections, however, at the same time the temporal correlation over each grid and bias with respect to observed data is calculated to highlight the strength and weakness of the models simulation. In Figs. 4(a&b), it is found that the both model shows different pattern of spatial bias, in the study area both model shows a cold bias of -7 °C. The correlation map [Figs. 4(c&d)] shows poor correlation value however the correlation is better over study area in both of the models than in comparison with the other parts of Sikkim. The future projections show an increment of 3-4 °C over the study area (Figs. 5(a&b)]. In Figs. 5 (c&d), the possible future climatology is analysed. Both Models show different patterns and REMO is showing much flat gradient of temperature. The possible trend for the future (in °C/year) is also studied in the simulations [Figs. 6 (a&b)]. The results pointed towards a rise of about 0.05 °C/year in both the models. Though the spatial pattern varied yet the models exhibit the same rise in temperature over the study area under RCP 4.5 scenario. Dash *et al*. (2012) found an increase of 5 °C by the end of this century over entire NEI in model simulations, the present study over the North Sikkim using different datasets also gives an inkling of the same type of phenomenon. The Mann-Kendall test and Sen's Slope estimator (Table 2) also shows an increasing trend in DJF for all of the experiments, however, the results for individual months varies in terms of magnitude of increasing trend amongst the models and this may be because of variation in model physics and orography representation.

4. Conclusions

Though the models did exhibit a lot disparity between them and as well as in comparison with the observed data, yet in all datasets, an increase in DJF average temperature is noted. As far as the Gurudongmar region is concerned, past trends are comparable between simulations and observations, hence, the future projections may be considered in the policy making for the region. Though these glaciers are summer accumulation type (Pelto, 2017) and the summer precipitation will affect the snow cover primarily, yet, the constant increment in winter temperature will surely impact these areas also. Because of the further increase in temperature for future time period (RCP4.5) is also found, it can be said that under those conditions, it will increase the risk of Glacial Lake Outburst Flood (GLOFs) as well as will trigger further destruction to the cryosphere environment.

Acknowledgement

The Authors are thankful to the data providers (IITM-Pune, CORDEX, IISRO-BHUVAN, ICTP, and DIAS (Japan) & AphroTemp) and to the Central University of South Bihar for the needed computation facilities. Authors are also thankful to the anonymous reviewers for their valuable comments and suggestions which significantly improved the quality of the paper.

The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Aggarwal, S., Rai, S. C., Thakur, P. K. and Emmer, A., 2017, "Inventory and recently increasing GLOF susceptibility of glacial lakes in Sikkim, Eastern Himalaya", *Geomorphology*, **295**, 39-54.

Bhattacharya, A., Ghosh, S. and Mukherjee, K., 2018, "Multi-decadal mass budget and area change of some eastern Himalayan glaciers (Nepal-Sikkim) using remote sensing techniques", In: 2018 4th International Conference on Recent Advances in Information Technology (RAIT), 1-6, IEEE.

Bolch, T., Kulkarni, A., Kaab, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M. and Bajracharya, S., 2012, "The state and fate of Himalayan glaciers", *Science*, **336**, 6079, 310-314.

Bolch, T., Shea, J. M., Liu, S., Azam, F. M., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A. and Zhang, G., 2019, "Status and change of the cryosphere in the Extended Hindu Kush Himalaya Region", In *The Hindu Kush Himalaya Assessment*, 209-255, Springer, Cham.

Chettri, N., Sharma, E., Shakya, B., Thapa, R., Bajracharya, B., Uddin, K., Choudhury, D. and Oli, K. P., 2010, "Biodiversity in the Eastern Himalayas: Status, trends and vulnerability to climate change", *Technical report 2*, International Centre for Integrated Mountain Development (ICIMOD)

Dash, S. K., Sharma, N., Pattnayak, K. C., Gao, X. J. and Shi, Y., 2012, "Temperature and precipitation changes in the north-east India and their future projections", *Global and Planetary Change*, **98**, 31-44.

Deb, P., Shrestha, S. and Babel, M. S., 2015, "Forecasting climate change impacts and evaluation of adaptation options for maize cropping in the hilly terrain of Himalayas: Sikkim, India", *Theoretical and Applied Climatology*, **121**, 3-4, 649-667.

Debnath, M., Syiemlieh, H. J., Sharma, M. C., Kumar, R., Chowdhury, A. and Lal, U., 2018, "Glacial lake dynamics and lake surface temperature assessment along the Kangchengayo-Pauhunri Massif, Sikkim Himalaya, 1988-2014", *Remote Sensing Applications: Society and Environment*, **9**, 26-41.

Eden, J. M., Widmann, M., Maraun, D. and Vrac, M., 2014, "Comparison of GCM and RCM-simulated precipitation following stochastic post processing", *Journal of Geophysical Research: Atmospheres*, **119**, 19, 11,040-11,053.

Ezber, Y., LutfiSen, O., Kindap, T. and Karaca, M., 2007, "Climatic effects of urbanization in Istanbul: A statistical and modeling analysis", *International Journal of Climatology*, **27**, 5, 667-679.

Jain, S. K., Kumar, V. and Saharia, M., 2013, "Analysis of rainfall and temperature trends in northeast India", *International Journal of Climatology*, **33**, 4, 968-978.

Kulkarni, A. V., Rathore, B. P., Singh, S. K. and Bahuguna, I. M., 2011, "Understanding changes in the Himalayan cryosphere using remote sensing techniques", *International Journal of Remote Sensing*, **32**, 3, 601-615.

Kumar, B. and Murugesh Prabhu, T. S., 2012, "Impacts of climate change: Glacial lake outburst floods (GLOFs)", Climate Change in Sikkim Patterns, Impacts and Initiatives. Information and Public Relations Department, Government of Sikkim, Gangtok.

Kumar, D. and Dimri, A. P., 2018, "Regional climate projections for Northeast India: An appraisal from CORDEX South Asia experiment", *Theoretical and Applied Climatology*, **134**, 3-4, 1065-1081.

Kumar, P., 2012, "Assessment of impact of climate change on Rhododendrons in Sikkim Himalayas using Maxent modelling: Limitations and challenges", *Biodiversity and Conservation*, **21**, 5, 1251-1266.

Kumar, V., Jain, S. K. and Singh, Y., 2010, "Analysis of long-term rainfall trends in India", *Hydrological Sciences Journal-Journal des Sciences Hydrologiques*, **55**, 4, 484-496.

Pant, N. C., Ravindra, R., Srivastava, D. and Thompson, L., 2018, "The Himalayan cryosphere: Past and present variability of the third pole", *Geological Society*, London, Special Publications, **462***,* 1, 1-6.

Patwardhan, S., Kulkarni, A. and Rao, K. K., 2018, "Projected changes in rainfall and temperature over homogeneous regions of India", *Theoretical and Applied Climatology*, **131**, 1-2, 581-592.

Pelto, M., 2017, "Gurudongmar Glacier Retreat and Teesta River Hydropower, Sikkim", (https://blogs.agu.org/fromaglacierspers pective/2017/05/02/gurudongmar-glacier-retreat-teetsa-river-hydropower-sikkim/).

Racoviteanu, A., Arnaud, Y., Williams, M. W. and Manley, W. F., 2014, "Spatial patterns in glacier characteristics and area changes from 1962 to 2006 in the Kanchenjunga-Sikkim area, eastern Himalaya", *The Cryosphere*, **9**, 505-523.

Raj, K. B. G., Remya, S. N. and Kumar, K. V., 2013, "Remote sensing-based hazard assessment of glacial lakes in Sikkim Himalaya", *Current Science*, **104**, 3, 359-364.

Ravindranath, N. H., Rao, S., Sharma, N., Nair, M., Gopalakrishnan, R., Rao, A. S., Malaviya, S., Tiwari, R., Sagadevan, A., Munsi, M. and Krishna, N., 2011, "Climate change vulnerability profiles for North East India", *Current Science*, **101**, 3, 384-394.

Ravindranath, N. H., Sharma, N., Sagadevan, A., Jayaraman, M. and Munsi, M., 2012, "Climate change and its impacts on forests of Sikkim", Climate change in Sikkim patterns, impacts and initiatives, Information and Public Relations Department, Government of Sikkim, Gangtok.

Seetharam, K., 2008, "Climate change scenario over Gangtok", *Mausam*, **59**, 3, 361-366.

Sen, P. K., 1968, "Estimates of the regression coefficient based on Kendall's tau", *Journal of the American statistical association*, **63**, 324, 1379-1389.

Sharma, R. K. and Shrestha, D. G., 2016, "Climate perceptions of local communities validated through scientific signals in Sikkim Himalaya, India", *Environmental monitoring and assessment*, **188**, 578.

Shukla, A., Garg, P. K. and Srivastava, S., 2018, "Evolution of glacial and high-altitude lakes in the Sikkim, Eastern Himalaya over the past four decades (1975-2017)", *Frontiers in Environmental Science*, **6**, p81.

Shukla, D. P., Dubey, C. S., Singh, R. P., Mishra, B. K. and Luthra, T., 2012, "GLOF susceptibility of Sikkim Himalayas", The 27th Himalaya-Karakoram-Tibet Workshop (HKT), p36.

Singh, P., Kumar, V., Thomas, T. and Arora, M., 2008, "Changes in rainfall and relative humidity in river basins in northwest and central India", *Hydrological Processes*, **22**, 16, 2982-2992.

Xu, Z., Rhoades, A. M., Johansen, H., Ullrich, P. A. and Collins, W. D., 2018, "An intercomparison of GCM and RCM dynamical downscaling for characterizing the hydroclimatology of California and Nevada", *Journal of Hydrometeorology*, **19**, 9, 1485-1506.

Yasutomi, N., Hamada, A. and Yatagai, A., 2011, "Development of a long-term daily gridded temperature dataset and its application to rain/snow discrimination of daily precipitation", *Global Environmental Research*, **15**, 2, 165-172.