SPATIO–TEMPORAL CHANGE ASSESSMENT OF MORPHOLOGY OF GLACIERS OF SIKKIM STATE OF INDIAN HIMALAYAN REGION

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ABSTRACT: This study aims at analysing morphological changes of glaciers of Sikkim. Two important morphological parameters such as area and length of three high altitude glaciers, having three different (large, medium and small) sizes have been considered to analyse and understand the trends of change over the years 2000 and 2015. LANDSAT 5 TM (Thematic Mapper) and LANDSAT 8 OLI (Operational Land Imager) images were used in conjunction with SRTM DEM. Significant changes in terms of area and length have been observed in the sample glaciers of this region. Analysis of meteorological data pertaining to weather parameters such as maximum, minimum and average temperature as well as rainfall over the period of 1969 and 2016 exhibited an increasing pattern of minimum temperature, which in turn causes increment in average ambient temperature. These can relate to the causes of shrinkage of these glaciers. Whereas, throughout the entire observation period, the maximum temperature exhibits decreasing trend. Statistical techniques like Pearson's correlation coefficient, Two – tailed, Student's t-test value at $p < 0.05$ significance level confirms these observations. Alteration in the amount of snowmelt or change in atmospheric temperature can lead to shrinkage of glaciers, which would have negative impact on water supply downstream as well as other concurrent impacts in future.

1. INTRODUCTION

Glaciers are huge mass of body containing accumulated snow, ice, compact snow, rock sediment and water; where snow accumulation is greater than melting and sublimation, for more than hundred or thousand years. They move over landmass due to their own weight and according to the slope of the topography. They are an important indicator of the surrounding climatic condition. It has been observed that while all-India mean annual temperature has shown significant warming trend of 0.05°C/10yr during the period 1901–2003, the recent period 1971–2003 has seen a relatively accelerated warming of 0.22°C/10yr (Kothawale and Rupa Kumar, 2005). Change in climatic condition has its impact on the health of the glaciers. In last few years, Himalayan glaciers have generated interest among scientists. In most of the studies the focus is on the changing characteristics of snow cover of a region or of a particular glacier. Some other regional glacier inventories have been constructed in the past, for example for the western part of the Himalaya (Bhambri et al., 2011; Frey et al., 2012) but only a few are available for the eastern extremity of the Himalaya (Krishna, 2005; Bajracharya et al., 2011; Basnett et al., 2012, 2013; Bahuguna et al., 2014; Racoviteanu et al., 2015). Indian Himalayan Glaciers are located in mostly inaccessible terrain. The glaciers of Eastern Himalayan state of Sikkim fall under the regime of Teesta and Rangit river basins. These two rivers are considered the lifeline of Sikkim. Changing characteristics of glaciers would have direct impact on these rivers downstream. Different studies have established that changing climatic condition, i.e. changing temperature and precipitation pattern may influence the shape (area, length), amount of snow cover, mass balance, velocity and run-off of a glacier. Depending on size and thickness, the response time of a glacier to climate change varies.

This study was conducted for the duration of almost one and a half decade between the years 2000 and 2015. Spatio – temporal changes, i.e. changes in terms of length and area of three glaciers, namely Zemu (excluding Nepal Gap and Tent Peak), Changsang and Tistakhangtse have been inferred. For this, only remote sensing based area and length analysis was undertaken. With changing time frame, it was observed that there was a general receding pattern of the glacier snouts and the amount of reduction was not uniform for all glaciers. Among these three glaciers, the highest change in terms of area (35.53%) and length (32.35%) had been observed in Changsang glacier.

2. STUDY AREA AND DATA USED

Sikkim is a landlocked state of India (Fig. 1) situated in the Himalayan Mountains falling between 27˚07’04’’N - 28˚07’26’’N/ 88˚00’51’’E - 88˚55’25’’E. Almost the entire state is characterized by hilly terrain having an elevation ranging between 280 metres and 8586 metres. Khangchendzonga (8,586 m), the third highest peak of the world is situated at the border of Nepal and Sikkim. Sikkim is bordered by China’s Tibetan Autonomous Region (TAR) to the north and east, Bhutan to the south-east, Indian state of West-Bengal to the south and Nepal to the west. These three glaciers are located in the North District of Sikkim (Table 1). Climatically, this area, i.e. this eastern part of the Himalaya is dominated by the South Asian summer monsoon circulation system (Bhatt and Nakamura, 2005), thus causing monsoon rains during the months of May – September. This climate particularity causes a “summer-accumulation” glacier regime type, with accumulation and ablation occurring simultaneously in the summer (Ageta and Higuchi, 1984).

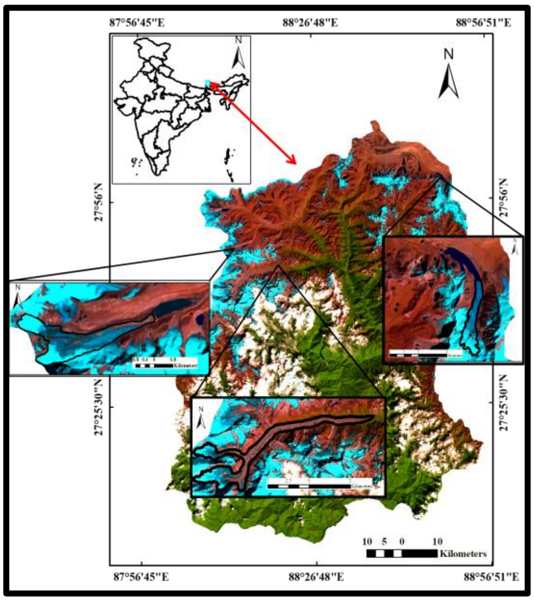

Figure 1: Study Area and location of glaciers studied

Table 1: Details of the three glaciers studied

Glacier Name	Location	Elevation (m)	Median Elevation (m)
Zemu (excluding Tent Peak and Nepal Gap)	27°42’28”N, 88°11’13”E	4197 - 6865	5531
Changsang	27°48’39”N, 88°13’09”E	5431 - 6291	5861
Tistakhangtse	27°57'22.89"N, 88°49'20.25"E	5364 - 6272	5818

LANDSAT 5 and LANDSAT 8 images were used for this study. The study area is mostly found cloud covered during the snow ablation period (April – September). The LANDSAT images were obtained on 16 day gap basis; therefore there were very limited number of scenes available for observation. The images from LANDSAT 7 were not used because such images were acquired SLC - off (Scan LINE Correction) mode. Therefore, only images from September month were used; although they were not completely free of clouds. In addition, SRTM DEM elevation data was also utilised. The details of remote sensing data used are shown in Table 2.

Table 2: Remote Sensing data used

Date	Sensor	Resolution
2000/09/13	LANDSAT-5 TM	30 m
2005/09/11	LANDSAT-5 TM	30 m
2009/09/22	LANDSAT-5 TM	30 m
2015/09/07	LANDSAT-8 OLI	30 m
2011	Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) – elevation data	90 m

3. METHODOLOGY

LANDSAT 5 TM and LANDSAT 8 OLI ortho-rectified satellite images as well as Shuttle Radar Topographic Mission Digital Elevation Model were downloaded in .tif format. The imageries of September were partially affected by cloud coverage. In order to solve the problem, a cloud mask was generated and those pixels affected by cloud were replaced by next available 'clean' imagery. A PCA (Principal Component Analysis) based methodology was used to identify the cloud covered pixels, as PCA reduces the data redundancy in an image and brings out maximum information from it (Sibandze et al., 2014). The identified cloud pixels were then masked and replaced with next available clean imagery.

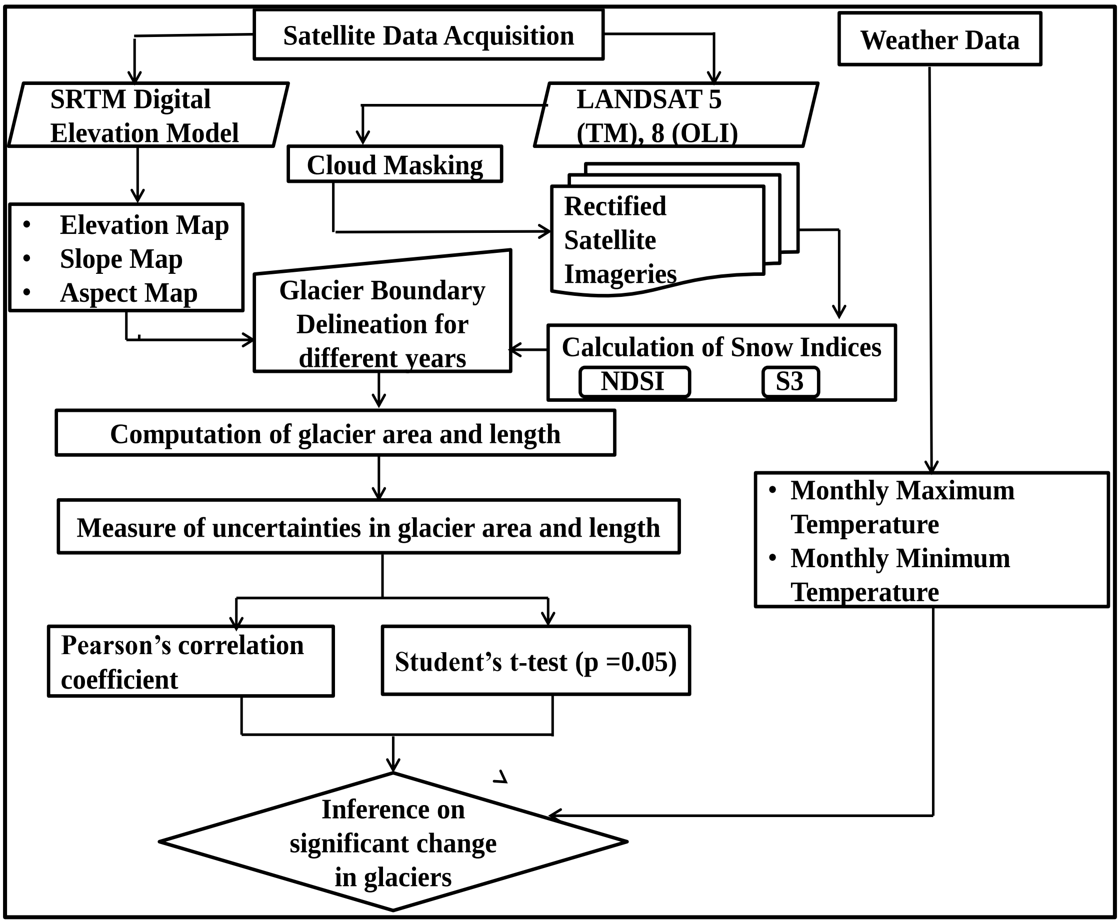

Figure 2: Methodology Flow chart

After the cloud masking, the digital numbers from these new images were converted to surface reflectance in order to compute the snow indices, namely NDSI (Normalised Difference Snow Index) and Normalised Snow Index (S3) which were useful for differentiating between snow with cloud cover and vegetation respectively. In order to delineate the glacier boundary, manual digitisation was performed. Initially, the glacier outlines provided by ICIMOD (International Centre for Integrated Mountain Development) and GLIMS (Global Land Ice Measurements from Space), as well as contour information from SRTM DEM (Digital Elevation Model) were taken into consideration to have a general idea about the location of the glaciers of the study area. The final boundaries for Zemu, Changsang and Tistakhangtse glaciers were digitised manually for the calculation of area and glacier length for ablation period for the four reference years 2000, 2005, 2009 and 2015. On the other hand the temperature and rainfall data for Gangtok (1765 m amsl) were procured from India Meteorological Department from 1969 - 2016 and were analysed. However, data used for the year 2016 covered the period only up to the month of March. The morphological changes that were mentioned for these glaciers, whether significant or not, were tested by two – tailed Student's t-test.

3.1 Computation of Indices

In order to obtain boundary and length of the glaciers, it was necessary to have a prior knowledge about the snow and non-snow-covered areas of the study area. To differentiate between snow covered and non- snow covered pixels, **Normalised Difference Snow Index (NDSI)** (Hall et al., 2002; Krishna, 2005; Racoviteanu et al., 2008; Basnett et al., 2012, 2013; Kour et al., 2015) has been used. Pixel values >0.4 was considered as snow covered. It is widely accepted and globally used to map snow cover area. NDSI can distinguish snow from cloud (Shimamura et al., 2006). Both snow and cloud have similar reflectivity in visible electromagnetic spectrum. But in shortwave-infrared (SWIR) band, snow has low and cloud has high reflectance.

$$\mathrm{NDSI} = \frac{\mathrm{Ref.Green\ band} - \mathrm{Ref.SWIR\ band}}{\mathrm{Ref.Green\ band} + \mathrm{Ref.SWIR\ band}} \tag{1}$$

Where, Ref.Green band = reflectance value from green band
Ref.SWIR band = reflectance value from shortwave infra-red band

For further refinement, another index known as **Normalized Snow Index (S3)** has been used to demarcate the snow cover area mixed with vegetation (Shimamura et al., 2006; Kour et al., 2015). It uses red and near infra-red bands as well as short-wave infra-red band. Areas having reflectance >0.18 is considered as snow covered area and snow covered area that is mixed with vegetation exhibits a reflection value between 0.05 and 0.18.

$$\mathrm{S3} = \frac{\mathrm{Ref.NIR\ band} * (\mathrm{Ref.Red\ band} - \mathrm{Ref.SWIR\ band})}{(\mathrm{Ref.NIR\ band} + \mathrm{Ref.Red\ band}) * (\mathrm{Ref.NIR\ band} + \mathrm{Ref.SWIR\ band})} \tag{2}$$

Where, Ref.NIR band = reflectance value from Near Infra-red band
Ref.Red band = reflectance value from Red band
Ref.SWIR band = reflectance value from Shortwave Infra-red band

3.2 Calculation of Area

One of the important steps was the demarcation of boundaries of the glaciers out of the snowfields. Survey of India (SOI) toposheets (on 1:50000 scale) were not accessible for most of the parts of the study area due to defence related restrictions as Sikkim shares its boundary with three neighbouring countries namely, Nepal (West), TAR of China (North) and Bhutan (East) respectively. Therefore resources available from satellite imageries were the main source of analysis. During digitisation, the part of those glaciers which were covered with glacial lake was not included within the glacier boundary. This followed the computation of areas of the glaciers. During digitisation, the SRTM DEM was used to drape over the satellite imagery in order to understand the three dimensional perspective of the glacier. During digitizing the glaciers for area calculation, there is always a chance of misinterpretation while including the pixels under the polygon. Basnett et al. (2013) suggested a method to calculate the uncertainty in glacier area change. This method was developed to check the uncertainty in mapping glacier area change around the glacier snout. But in this study, all the pixels around the entire polygon of the glaciers were considered in order to understand the overall area change of a glacier; thus only 'mapping uncertainty' of the polygon was considered (Table 3). As the accurate delineation of glacier snout position only from satellite imagery can be erroneous, therefore following formula was used to derive the mapping uncertainty.

$$\mathrm{Mapping\ Uncertainty} = \mathrm{N} * \frac{\mathrm{A}}{2} \tag{3}$$

Where,
N= Number of pixels along the glacier boundary
A= Area of the pixel

Glacier boundary of the year 2015 was used for the calculation of uncertainty, as it was the latest observed area of these glaciers for the reference period of the study.

Table 3: Calculation of Mapping Uncertainty

	Pixel Size (m)	Pixel Area (Sq. Km)	No. of pixels around boundary (2015)	Mapping Uncertainty (Sq. m)	Mapping Uncertainty (Sq. Km)	Mapping Uncertainty/Year (Sq. Km)
ZEMU	30	0.0009	3039	1367550	1.368	0.091
CHHANGSANG			683	307350	0.307	0.020
TISTAKHANGTSE			573	257850	0.258	0.017

3.3 Deriving the Length of Glaciers

Besides calculating the area, the corresponding lengths of these glaciers were also calculated in order to analyse the changes in glacier snout position. For computation of the length of individual glacier, a centreline was drawn for each glacier. In order to compute the centreline of a glacier, the computation must start from top i.e., head of the glacier up to the terminus i.e. tongue of the glacier and must consider the longest line drawn automatically. The line must start from the highest elevation point of the accumulation zone. Here for the computation of glacier centreline, an automated tool named Polygon to Centerline Tool for ArcGIS, developed by Tom Dilts (2015) (obtained from the website of Arc-GIS) has been used. The value obtained from the centreline of the glacier was considered as the length of the glacier. The length has been calculated for all four years.

3.4 Analysis of Temperature and Rainfall Data

In order to have an idea about the general trend of temperature and rainfall of Sikkim, both temperature and rainfall data obtained from India Meteorological Department from Gangtok (1765 m amsl) have been taken under consideration to analyse the general weather pattern. The data have been analysed on monthly basis both as yearly (1969 – 2016) and decade-wise (1969 –'78), (1979 – '88), (1989 – '98), (1999 – 2008), (2009 – 2016) for Gangtok Station. The observatory is situated outside the glacier regime. Therefore the statistics obtained from this data gives an overall representative idea about the weather scenario of the entire state.

3.5 Determination of Significance of correlation between variables

A correlation has been established between glacier area and years of observation as well as glacier length and years of observation for each glacier discussed above.

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (3)$$

where, r = pearson's correlation coefficient
n= no.of samples
x = dependent variable
y = independent variable

In order to determine the significance of the correlation between time scale and area as well as length change of these three glaciers, two – tailed Student's t-test with (n-2) degrees of freedom (df) has been used. The calculation for significance test was done for 22 glaciers of Sikkim. The result obtained for these three glaciers have been represented here. With the changing number of samples, the't' value varies, which is reflected in p- value.

$$t = r\,(\sqrt{(n-2)})/\sqrt{(1-r^2)} \quad (4)$$

Where, r = Pearson's correlation coefficient
n = no. of samples

4. RESULTS AND DISCUSSION

From the study, it has been observed that there is a general recessing pattern in the area and length of the observed glaciers within the observed time (years 2000- 2015) period. Generally, the melting of snow is more prominent in the south facing slopes of the Himalayas. But none of the above mentioned three glaciers are prominently southern slope facing. North facing slope is the major slope of Tistakhangtse and Changsang glaciers, whereas Zemu has east-facing slope. In spite of that Tistakhangtse and Changsang has developed glacial lakes which are associated with recession of the glacier snouts. Zemu has also developed small patches of supraglacial lakes. Within this specified observed period, the three glaciers have not receded at uniform rate. Within the observed span of 15 years, Zemu and Changsang has receded 0.17 Sq. Km/year (±0.091Sq.Km/year) and 0.16 Sq. Km/year (±0.020 Sq. Km/year) respectively; whereas Tistakhangtse has receded at a rate of approximately 0.04 Sq. Km/year (±0.017 Sq. Km/year) (Fig. 3).

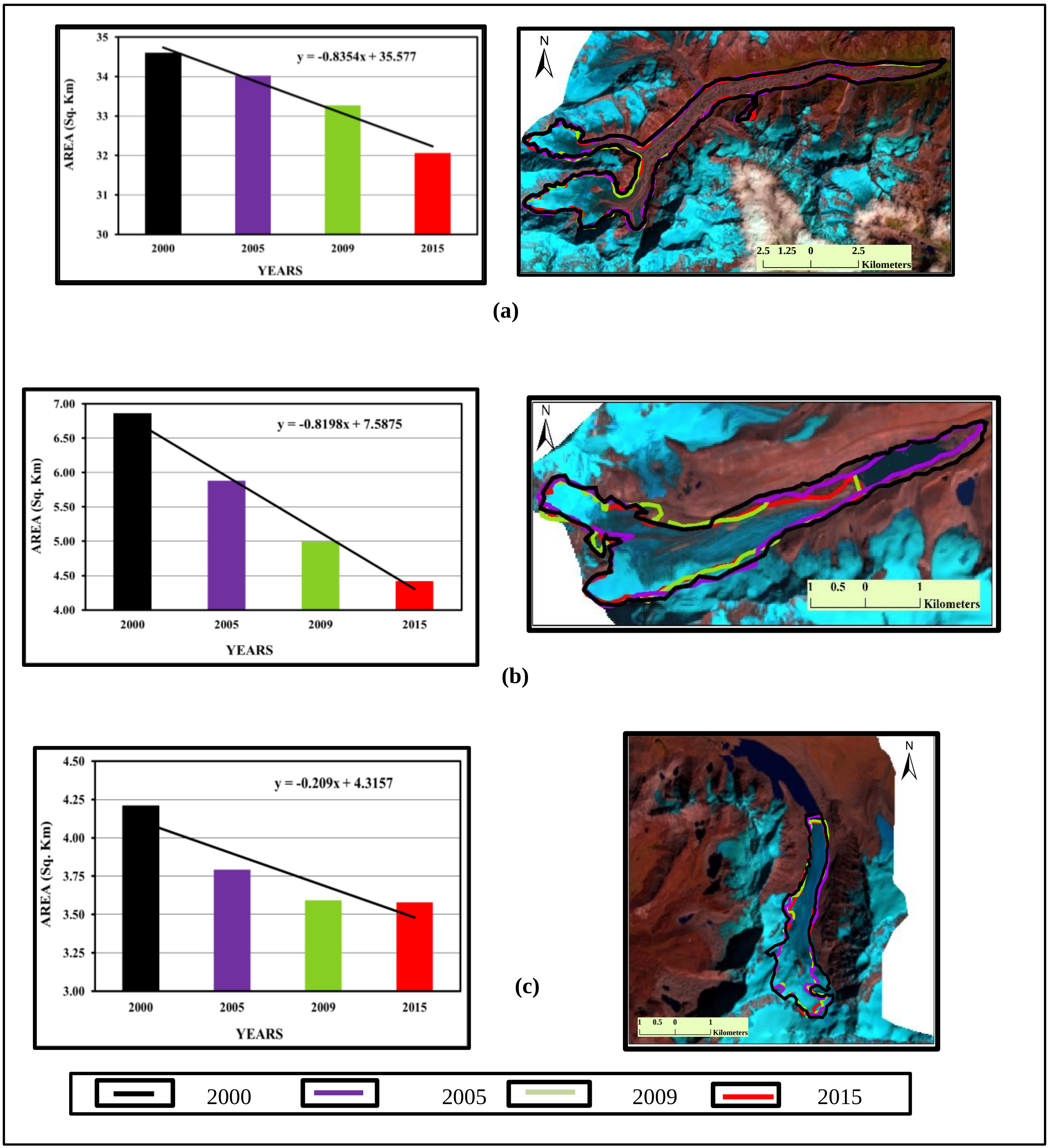

Figure 3: Area wise change observed in (a) Zemu, (b) Changsang and (c) Tistakhangtse Glacier

On the other hand, lengthwise, maximum change was observed in Changsang, which has receded at a rate of approximately 0.18 Km/year (±0.095 Km/ year). The lowest change in length has been observed in Tistakhangtse (0.04 Km/year, ±0.013 Km/ year) and Zemu (0.04 Km/ year, ±0.019 Km/ year). A further analysis of the glaciers on 5 year interval basis exhibits that area-wise there is higher rate of area and length loss in the case of Zemu. In Changsang the area loss followed an increasing order, the highest change has been observed during 2005-2009. Year 2009 onwards, a decreasing trend of area change has been observed. The same pattern has also been observed in terms of the length of Changsang (Fig. 3). Maximum reduction in length has been observed during the years 2005-2009. A sharp reduction in the recession rate has been observed from year 2009 onwards. Tistakhangtse, on the other hand shows a decreasing trend of the area with slow progressive recession. Even though the maximum change was observed between the years 2000 – 2005, the total length of the glacier decreased with progressive recession. Highest rate of length change has been observed during 2009-2015. Statistically, two – tailed Student's t-test with (n-2) degrees of freedom (df) also proved the result for both area and length of these glaciers (Table 4 & Table 5).

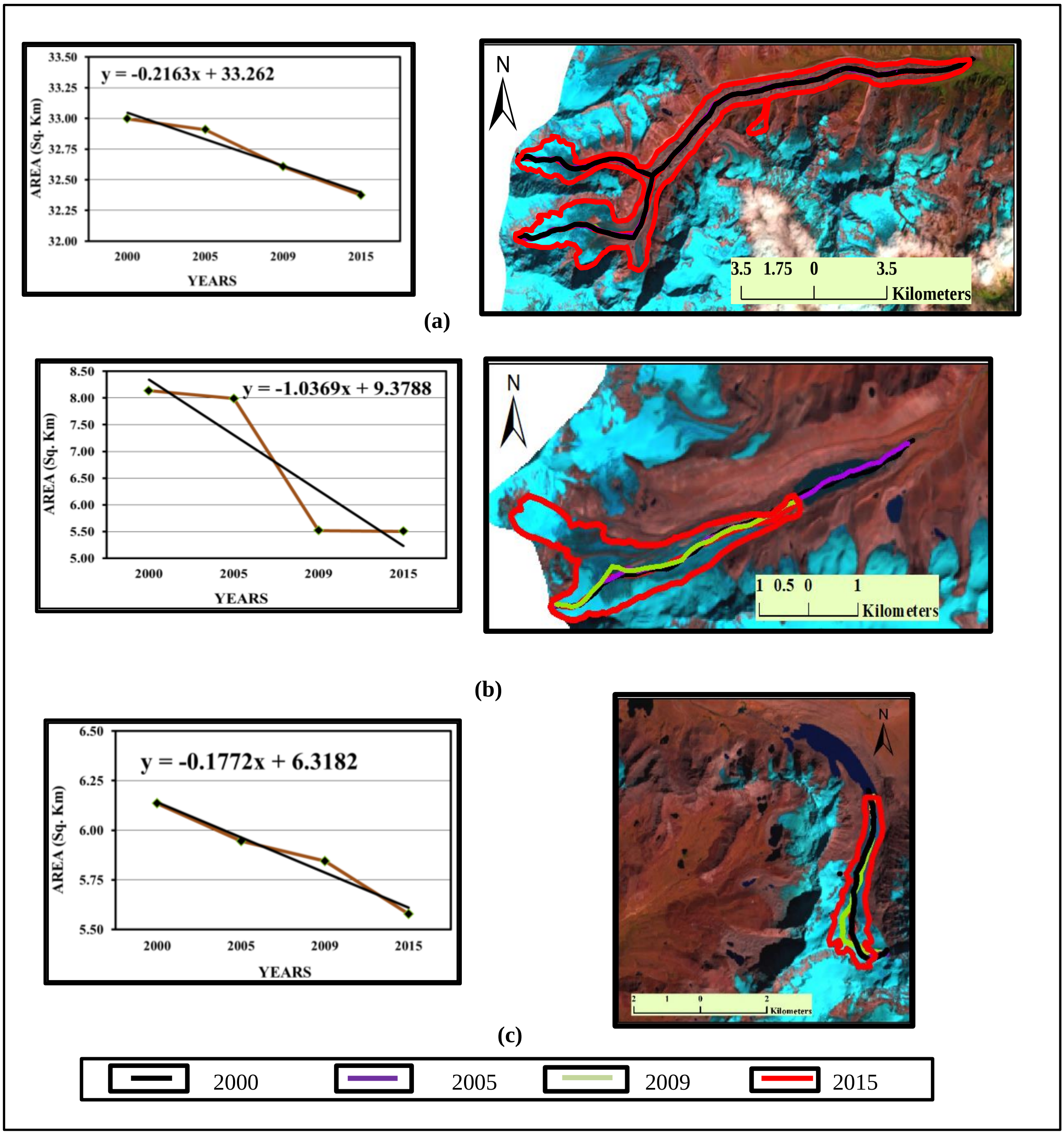

Figure 4: Length wise change observed in (a) Zemu, (b) Changsang and (c) Tistakhangtse Glacier

Table 4: Significance test for glacier area change

	ZEMU	CHANGSANG	TISTAKHANGTSE
Correlation coefficient (r)	-0.90	-0.99	-0.99
t- value	-34.87	-24.63	-9.08
p –value (Significance level 0.05)	< .00001	< .00001	< .00001

Table 5: Significance test for glacier length change

	ZEMU	CHANGSANG	TISTAKHANGTSE
Correlation Coefficient (r)	-0.977	-0.878	-0.995
t- value	-20.30	-8.21	-46.70
P value (Significance level 0.05)	< .00001	< .00001	< .00001

The correlation coefficient determines whether two paired sets of data (here years of observation and glacier area as well as years of observation and glacier length) are related or not. Strong negative linear correlation has been observed for both area and length of these glaciers with years of observation; which simply signifies that with increasing years, area and length loss are getting prominent. To check whether this correlation is significant enough or not, the student's t-test was performed for both area and length of respective glaciers. The test was initially performed over 22 glaciers of Sikkim, thus the no.of samples (n) is 22. The p-value was calculated at 0.05 significance (95% confidence) level. Since the p- value for both area and length change is much smaller than 0.05, therefore it can be infered that, the area and length loss of these glaciers over time is statistically significant (Table 4 & Table 5).

Decade wise analysis of IMD weather data (Fig.5) exhibits that during the entire observation period, the maximum temperature exhibited a gradual descending order, whereas, the minimum temperature was found to be rising. In this paper the morphological analysis were conducted between 2000 and 2015. Hence more focus was given in the analysis of weather data of the corresponding period.

Between 1999 and 2007, there is a general trend of decreasing maximum temperature in snow accumulation period and rising maximum temperature during the ablation period. Whereas, the minimum temperature for that entire decade for both accumulation and ablation period exhibited an increasing trend thus leading to warm nights. During the ablation period, rising day time temperature, coupled with warm nights may have accelerated the melting of snow. During the years 2009 to 2015, the decreasing trend for maximum temperature increased for both snow accumulation and ablation period, whereas the rise in minimum temperature was mostly observed to be limited to ablation months (May, June and September respectively). Highest rise in minimum temperature (2.77°C) from the base year 1969 has been observed during October (beginning of snow accumulation period).

5. Conclusion

The glaciers of high altitude of the Himalayas are abode of permanent snow. They are the major source of perennial supply of water downstream. Statistically it is proved that these three glaciers have been showing a receding pattern both area and length-wise. From further analysis of the weather data, it has been observed that there is a gradual rise in minimum temperature, which may imply more night time warming, signifying that the atmosphere is trapping more heat in the night, which eventually might have led to a warmer night than a warm day and significant indicator for change in local weather condition. Since the study has been done on the basis of only one weather station, there is a need of further confirmation whether this change in weather phenomenon is local or regional. Slope and aspect of these glaciers might not have not played any significant contribution regarding the recesssion of them. This changing behaviour of the climate can be one of the factors for morphometric changes, which was observed to be recessionary in case of these three observed glaciers. Alteration in the amount of snowmelt or change in atmospheric temperature can lead to shrinkage of glaciers, which would have negative impact on water supply downstream in future. Further scope of this work is to derive detail inferences on the behavior of other significant glaciers of this region for more conclusive understanding of recessionary trends vis-à-vis temperature change.

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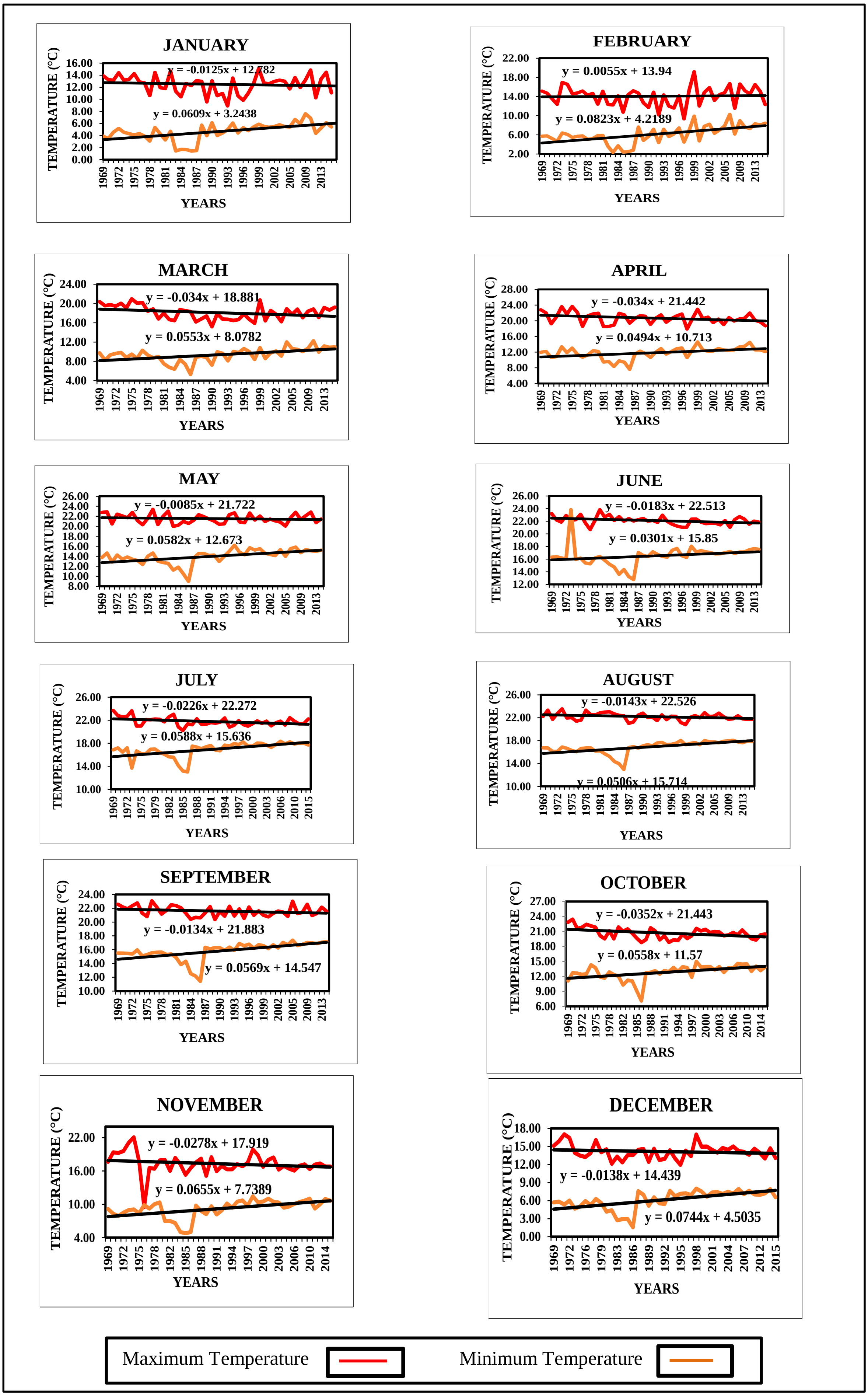

Figure 5 : Maximum and Minimum Temperature variation of Gangtok (1969 – 2016, upto March)

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