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Monitoring of snow surface temperature in North-West Himalaya using passive microwave satellite data

K K Singh[1,$,*], S K DewaIi[1], Dhiraj Kumar Singh[1], V D Mishra[1] & Manjinder Kaur[2]
[1]Snow and Avalanche Study Establishment (SASE), Chandigarh 160 036, India
[2]Shaheed Bhagat Singh State Technical Campus, Ferozepur 152 004, India
[$]E-mail: kamal.kant@sase.drdo.in

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Snow surface temperature (SST) is an important snow parameter, which affects the energy balance of the region and thus, acts as an indicator of climate change. In Himalaya, due to ruggedness and inaccessibility of its terrain, it is very difficult to collect the SST data using conventional measurement techniques. Remote sensing based satellite data has the potential and is used widely to estimate SST. In the present study, passive microwave satellite data of Special Sensor Microwave Imager (SSM/I) sensor has been used for monitoring the SST at different locations in North-West (NW) Himalaya. A 85 GHz frequency channel, which provides only the near surface information because of its less penetration power in comparison to other available frequencies of the sensor, is observed best for SST monitoring. The monthly and seasonal average SST values are estimated for the period 1988-2012. The temporal variation of SST values in Pir-Panjal, Great Himalaya and Karakoram Himalayan ranges are analyzed for the period 1988-2012. The geospatial maps of SST are drawn to represent the monthly and seasonal trend of SST values spatially.

Keywords: Himalaya, Snow surface temperature

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1 Introduction

Snow cover over the northern hemisphere ranges from 2×10^6 km^2 in pre-winter to 45×10^6 km^2 during peak winter[1]. The large seasonal variability of snow affects the climatic conditions of the region due to change in albedo[2] and other snow metrological parameters. Snow also turns into a natural hazard in the form of avalanches, which affects the safety of human lives and property. Apart from this, the snow cover variation influences tourist movement and other development activities of a region. Therefore, knowledge of the dynamic snow cover is very important.

In North-West (NW) Himalaya, the snow cover area increases with the onset of winter during November and subsequently, recedes April onwards. The temperature is one of the main factors responsible for the dynamic nature of snow in Himalaya and hence, its monitoring is very important to understand the variations in the snow cover. Kothawale & Kumar[3] have reported that the mean annual temperature over India has increased by 0.5°C in the last century. According to Bhutiyani *et al.*[4], the air temperatures in the NW Himalayas are having increasing trend with higher rate of increase during the winter season. Dimari & Kumar[5] have analyzed the warm and cold events in winters during the period 1975-2006. They observed an increasing trend in temperature at some specific locations. Thus, overall an increase in temperature has been observed in most of the parts of the Himalaya. However, its long term monitoring is one of the important issues, which can play important role in better understanding of the climate of this region.

As most of the area in NW-Himalaya is having very rugged terrain and remains inaccessible during the winter, hence, it is very difficult to monitor this region using the conventional techniques. However, remote sensing satellite data based techniques are found useful for collecting information from such larger areas and to study the changes in snow and glacier properties[6-12]. The optical data observed is very useful for estimation of snow surface properties. However, one of the major problems with the use of optical data is the cloud cover and because of its smaller wavelength, it is not able to penetrate the clouds. Thus, during cloudy days, the optical data is not able to provide the snow cover information.

However, because of longer wavelength and high penetration power, passive microwave satellite data can be used to provide snow cover information in all weather condition.

Various researchers have used Landsat Thematic Mapper data for surface temperature estimation[13-15]. For Indian Himalaya also, studies are conducted for estimation of SST by Raj *et al.*[16] and Negi *et al.*[17] using Landsat ETM$^+$ and Moderate Resolution Imaging Spectroradiometer (MODIS) data, respectively. Negi *et al.*[17] have used split window technique for SST estimation and found good correlation between the satellite estimated and ground measured SST values. Singh *et al.*[18] have used 85 GHz frequency of SSM/I sensor to identify the snow covered areas in Himalaya using the monthly averaged brightness temperature (T_B) data. SSM/I data has also been attempted to formulate algorithms for snow depth and snow water equivalent estimation in Indian Himalaya[11]. The microwave response of 19 and 37 GHz frequencies for moist/dry snow is studied in the Pir-Panjal and Great Himalaya range, respectively[19]. Recently, the ground based passive microwave radiometer data collected from the Great Himalaya and Pir-Panjal ranges of NW Himalaya have been used to study the characteristics of T_B of snow with varying snowpack properties and also to estimate the snow depth[20].

In the present study, passive microwave satellite data of SSM/I sensor has been used to estimate SST. Because of the less penetration power in snow, 85 GHz frequency has been observed best. For the estimation of SST in different ranges of Himalaya, emissivity values of snow in respective range are required. In the present study, emissivity values of snow are used directly from Singh *et al.*[21]. SST values have been estimated using these emissivity values and T_B data. The monthly and seasonal average SST values for different locations of NW Himalaya have been estimated for the period 1988-2012. The trend analysis of the SST data has been performed and increase and decrease in SST values on decadal basis are estimated. The inter comparison of the SST data for different Himalayan range, *i.e.* Pir-Panjal, Great Himalaya and Karakoram has also been done.

Table 1 — Specifications of SSM/I sensor

SSM/I central frequency, GHz and polarization	19 (H,V)	22 (V)	37 (H,V)	85 (H,V)
Band width, MHz	240	240	900	1400
Sensitivity, K	0.8	0.8	0.6	1.1
IFOV, km x km	69 x 43	60 x 40	37 x 29	15 x 13

2 Data used

In the present study, SSM/I sensor data has been used along with manually collected SST data from various field observatories locations of Snow and Avalanche Study Establishment (SASE). SSM/I is a seven-channel, four-frequency, orthogonally polarized, passive microwave radiometric system that measures atmospheric, ocean and terrain microwave brightness temperatures at 19.35, 22.2, 37.0, and 85.5 GHz. Specifications of SSM/I are given in Table 1.

3 Methodology

The methodology adopted is given in the flow chart (Fig.1). In the present study, Arc GIS software is used for processing of data. From SSM/I sensor data T_B values of different observatories location of SASE are extracted.

The SST is estimated using Eq. (1):

$$SST = TB/\varepsilon \qquad \ldots(1)$$

where, ε, is the emissivity of snow.

In the analysis, ε values 0.89, 0.80 and 0.79 are used for Pir-Panjal, Great Himalaya and Karakoram Himalayan range, respectively[21].

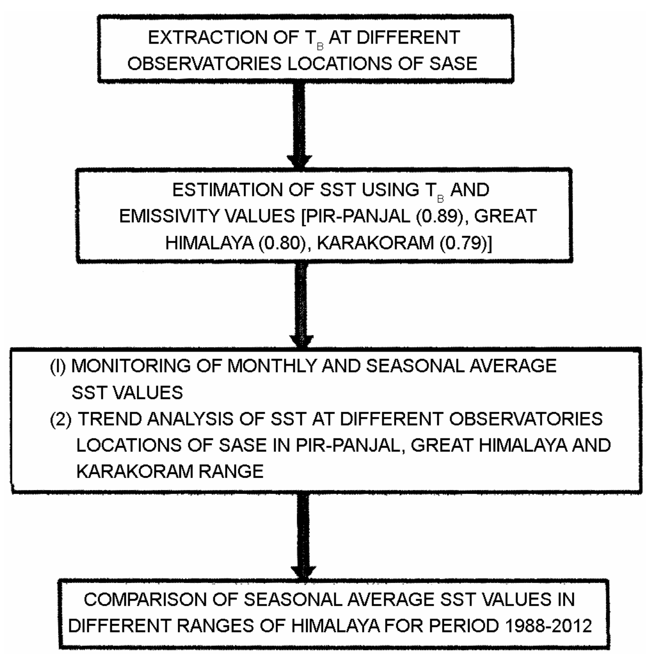


Fig. 1 — Methodology used for SST monitoring

To study the changes in the SST, the anomaly in the SST data is calculated to determine whether there is any signal of warming over the region. The rate of increase or decrease in monthly averaged SST values is estimated and the values are further used to calculate the rate on decadal basis. The seasonal average SST values are also estimated and analyzed. In the present study, the season is considered the period when the snow is present on the ground, so the period between November and May is taken into consideration. However, the presence or absence of snow is also validated by cross checking the manually collected field observations. In order to represent the monthly and seasonal trend of SST values spatially, the Inverse Distance Weighting (IDW) interpolation module in Arc GIS Software is used and the geospatial maps are made.

4 Study area

The present study is conducted for NW Himalaya (Fig. 2), which has been categorized in lower Himalaya (Pir-Panjal range), middle Himalaya (Great Himalayan range) and upper Himalaya (Karakoram range)[22]. The average altitude of Pir-Panjal range lies between 2000 and 4000 m. Pir-Panjal range generally experiences heavy snowfall from December to March. The mean seasonal temperature after analyzing 20 years data in this range (Dhundi sector of Pir-Panjal range) is found to vary between -1.5°C and 2.8°C (Ref. 23).

Great Himalayan range has relatively low temperatures and lesser snowfall than Pir-Panjal range. It receives dry snow between mid-December and end of January. The general rise in temperature from mid-February onwards, moistens fresh snowfall; and after March, the fresh snowfall is often accompanied with wet snowfall or light rain. In Great Himalayan range (Drass sector of Great Himalayan range), generally, the temperature remains lower in comparison to Pir-Panjal range. The mean seasonal temperature of this sector remains below -10°C (Ref. 23). Altitude of this range varies from 3500 to 5300 m.

The Karakoram range has extremely cold conditions, it receives dry snow and is highly glaciated. In most of the places, its altitude is more than 5000 m (Ref. 22). The mean seasonal temperature of Karakoram range varies between -14.4°C and -23.3°C for northern region; -14°C and -23.7°C for central region; and -13.0°C and -20.7°C for southern region[23].

Overall, the temperature of Pir-Panjal range is high in comparison to other two Himalayan ranges. Though, different ranges have different snow

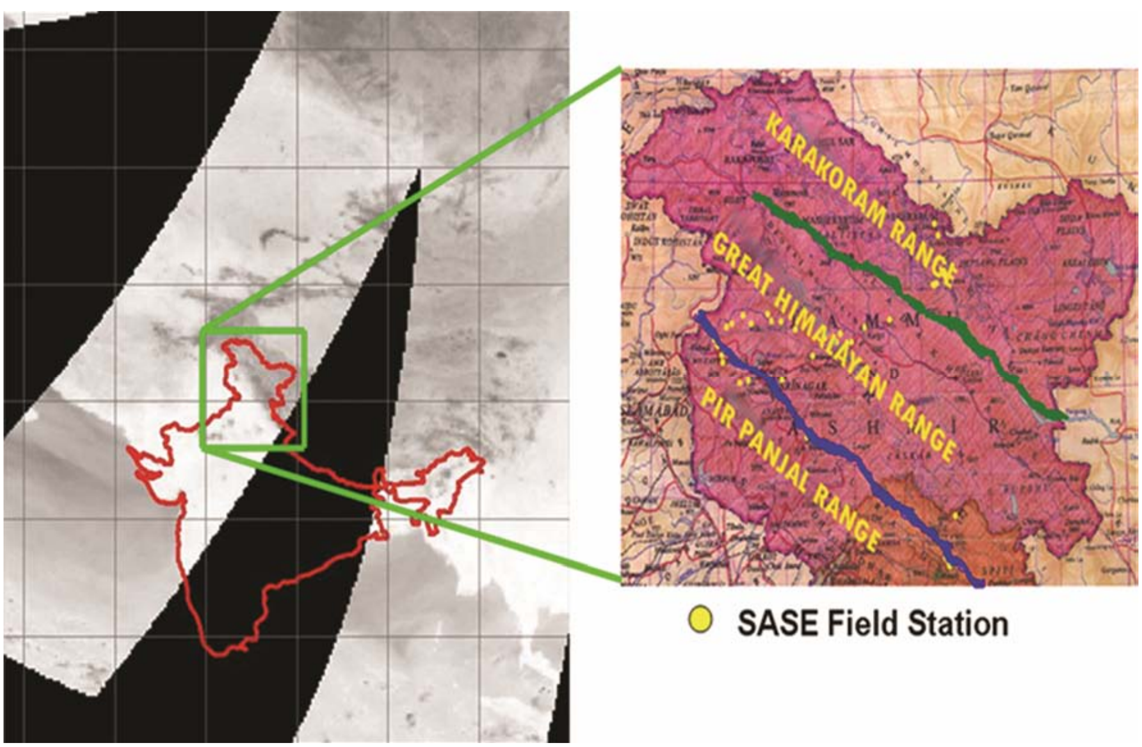


Fig. 2 — Study area in NW Himalaya depicting different ranges and SASE field observatories locations

characteristic, which affects local weather and energy balance of the region and also play role in avalanche initiation. In the present study, SST values are estimated for ten observatories locations of SASE in Pir-Panjal, seven in Great Himalaya and nine in Karakoram.

5 Results and Discussion

5.1 Variation of monthly average SST values

5.1.1 Variation of monthly average SST values (Pir-Panjal range)

The estimated monthly average SST values of last three decades for ten observatories locations of SASE in Pir-Panjal range are analyzed. The details of the observed results are given in Table 2. Out of ten observatories, only two have shown decreasing trend. Figure 3(a) shows the variation of monthly average SST values during 1988-2012 for Kanzalwan region in Pir-Panjal range. The anomaly in SST values is shown in Fig. 3(b). From the monthly average SST values, a decreasing trend in SST is observed for Kanzalwan with a decadal increase of 0.99°C per decade. The anomaly in the estimated SST data shows the sign of warming over the region. The SST of the region depends on various snow metrological factors; and ambient temperature of the region is one of the important amongst them. Gusain *et al.*[23] and Shekhar *et al.*[24] have analyzed the ambient temperature data, collected manually from different observatories locations of SASE in different Himalayan ranges. From the analysis, they observed a positive trend in ambient temperature for most of the areas of Pir-Panjal range. Only some locations have shown the negative trend and that is mostly due to the local climatic and topographic effects prevailing in the region. Thus, the trend in SST values observed in the present study has also been observed in ambient temperature of the respective region.

From Table 2, the rate of change in SST values on decadal basis is observed maximum for Haddan Taz and lowest for Gulmarg location in Pir-Panjal range. Similar results are reported for ambient temperature by Gusain *et al.*[25] in the respective region.

Table 2 — Trend of monthly averaged SST values and decadal increase/decrease in Pir-Panjal range

Station name	Trend (positive/ negative)	Rate of SST change, °C, on decadal basis
Gulmarg	+ve	0.08
Banihal	-ve	1.48
Dhundhi	- ve	2.86
Solang	+ ve	0.67
SASE	+ ve	0.53
Stage 2	+ ve	0.42
Haddan Taz	+ ve	3.34
Pharkiyan	+ ve	1.10
Z-Gali	+ ve	2.82
Kanzalwan	+ ve	0.09

Table 3 — Trend of monthly averaged SST values and decadal increase/decrease in Great Himalaya range

Station name	Trend (positive/ negative)	Rate of SST change, °C, on decadal basis
Patseo	+ ve	0.98
Drass	- ve	3.19
Pather	+ ve	0.002
Kill Nala	+ ve	0.50
Niru	- ve	2.11
Sonamarg	- ve	1.64
Kaksar	+ ve	2.11

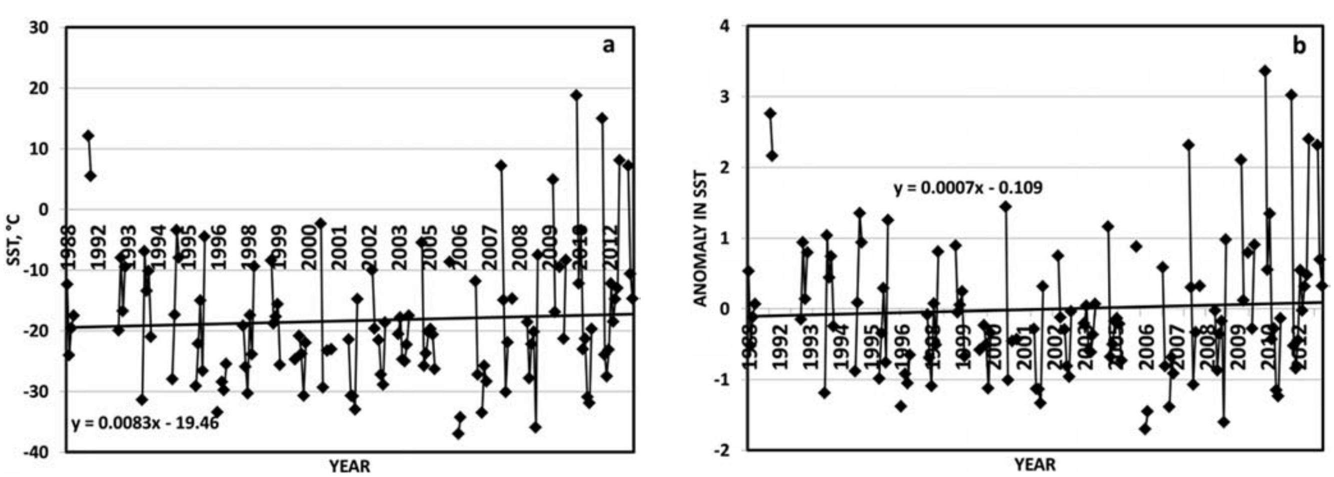


Fig. 3 — (a) Variation of monthly average SST values; (b) Anomaly in SST values (Kanzalwan)

5.1.2 Variation of monthly average SST values (Great Himalaya range)

The estimated monthly average SST values of last three decades for seven observatories locations of SASE in Great Himalaya range are analyzed. The details of the observed results are given in Table 3. Out of seven observatories, three have shown decreasing trend in SST values. From Table 3, the rate of change in SST values on decadal basis is observed maximum for Drass and minimum for Pather location in Great Himalaya range. The results are observed similar to study conducted by Gusain *et al.*[25] for ambient temperature of the region. Figure 4(a) shows the variation of monthly average SST values during the period 1988-2012 for Patseo region in Great Himalaya range. The anomaly in SST values is shown in Fig. 4(b).

From the monthly average SST values, an increasing trend has been observed at Patseo with a decadal increase of 0.98°C per decade. The anomaly in the SST data indicates the warming trend in this region.

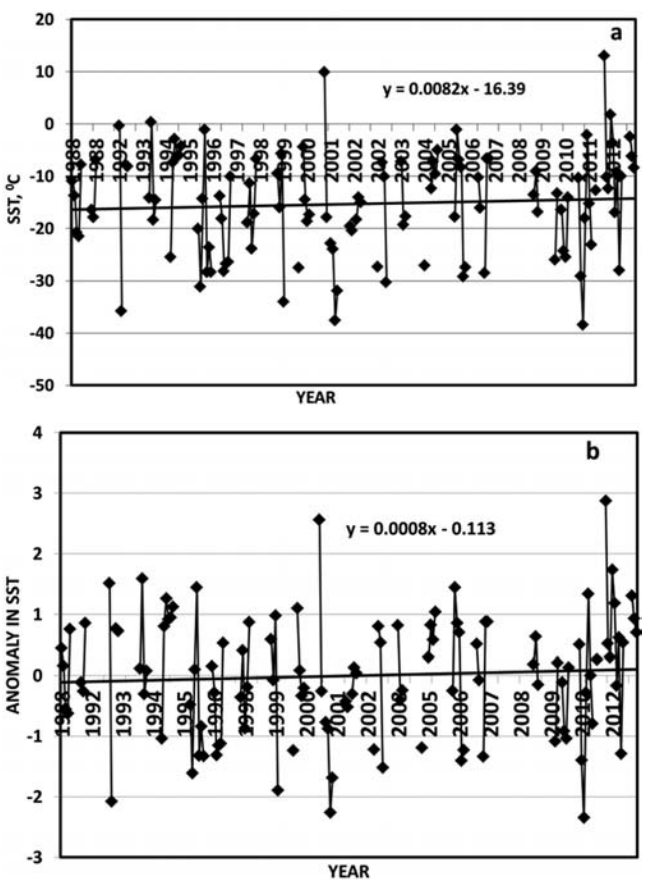


Fig. 4 — (a) Variation of monthly average SST values; (b) Anomaly in SST values (Patseo)

5.1.3 Variation of monthly average SST values (Karakoram Range)

The estimated monthly average SST values of last three decades for nine observatories locations of SASE in Karakoram range are analyzed. The details of the observed results are given in Table 4. Out of nine observatories, five have shown decreasing trend in SST values. From Table 4, the rate of change in SST values on decadal basis is observed maximum for Siala and minimum for Bahadur location in Karakoram range. Similar results were also reported by Gusain *et al.*[25] for ambient temperature in the respective region. Figure 5(a) shows the variation of monthly average SST values during period 1988-2012 for Kumar region in Karakoram Himalaya range. The anomaly in SST values is shown in Fig. 5(b). From the monthly average SST values, a decreasing trend is observed at Kumar with a decadal decrease of 1.63°C per decade. The anomaly in the SST data indicates the cooling trend in this region.

5.2 Trend analysis of seasonal average SST values at various locations in Pir-Panjal, Great Himalaya and Karakoram range

The estimated seasonal average SST values of last three decades for different observatories locations of SASE in Pir-Panjal, Great Himalaya and Karakoram range are analyzed. The details of the observed results for the mentioned Himalayan ranges are summarized and given in Tables 5a, 5b and 5c, respectively.

5.3 Variation of seasonal average SST values in different ranges of NW Himalaya (1988-2012)

The estimated seasonal average SST values for the period 1988-2012 for different observatories locations in mountain ranges of NW-Himalaya are analyzed and shown in Figs. 6-8. In order to estimate the average SST of the range, the average of SST of all the observatories lying in that range are taken into consideration.

Table 4 — Trend of monthly averaged SST values and decadal increase/decrease in Karakoram range

Station name	Trend (positive/ negative)	Rate of SST change, °C, on decadal basis
Kumar	- ve	1.63
Siala	- ve	2.78
Base Camp	+ ve	2.53
Jawala	+ ve	2.63
Rewari	+ ve	1.14
Billa Base	+ ve	0.54
Bahadur	- ve	0.08
Zullu	- ve	0.92
Chandan	- ve	0.23

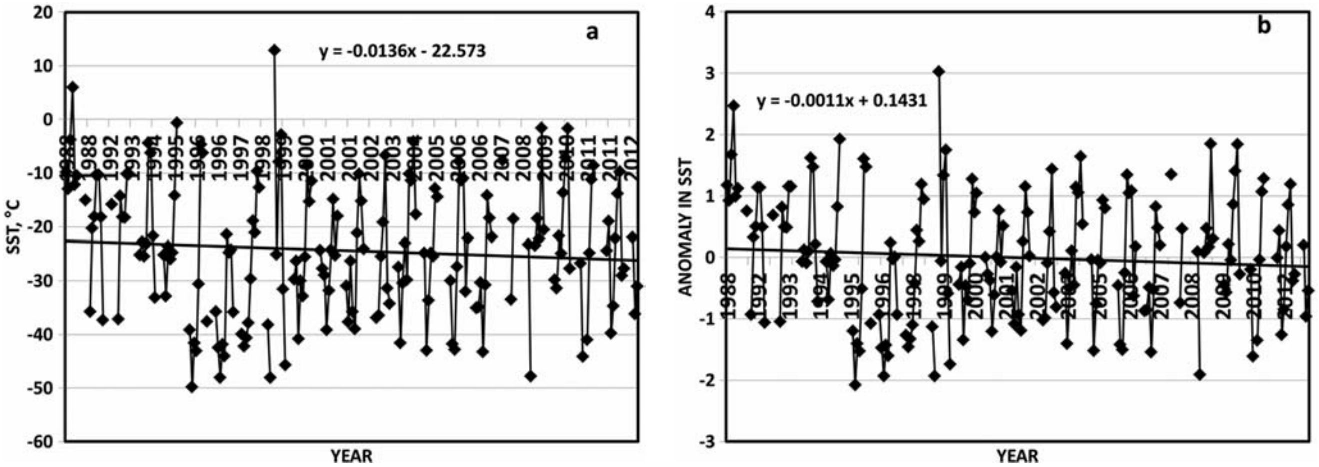


Fig. 5 — (a) Variation of monthly average SST values; (b) Anomaly in SST values (Kumar)

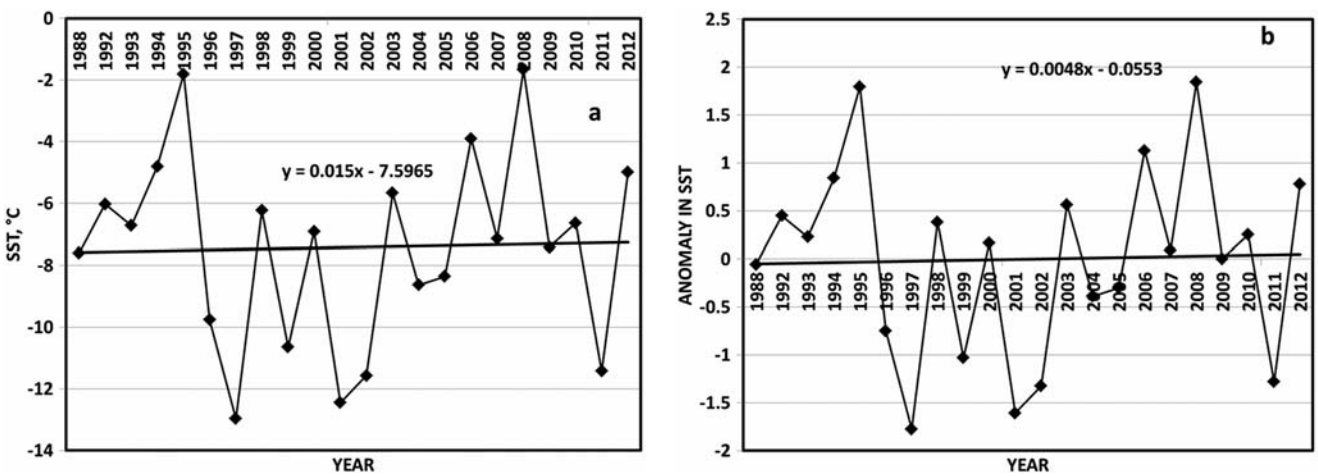


Fig. 6 — (a) Variation of seasonal average SST values in Great Himalaya; (b) Anomaly in SST values

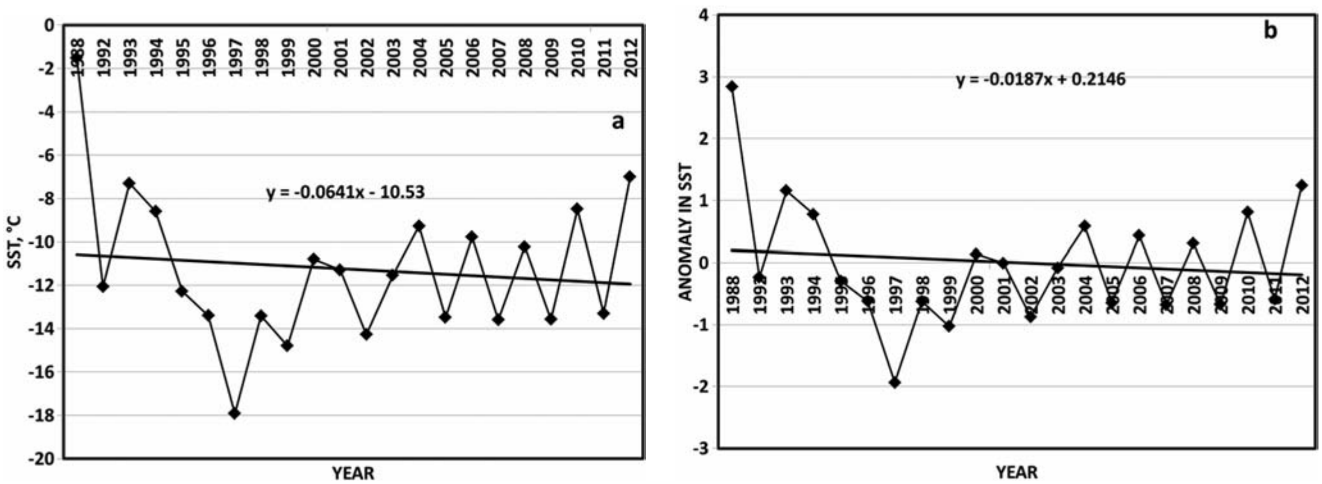
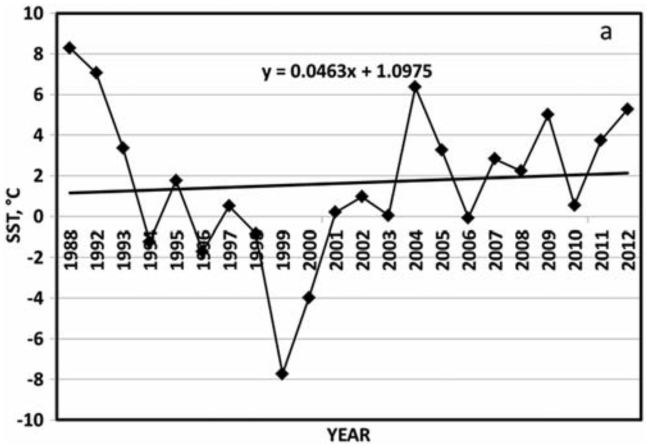


Fig. 7 — (a) Variation of seasonal average SST values in Karakoram; (b) Anomaly in SST values



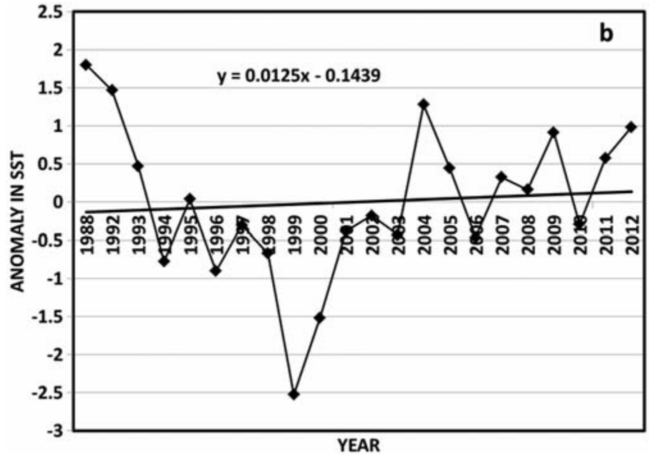


Fig. 8 — (a) Variation of seasonal average SST values in Pir-Panjal; (b) Anomaly in SST values

Table 5 — Trend analysis of seasonal average SST values at different locations in: (a) Pir-Panjal; (b) Great Himalaya; and (c) Karakoram range

Station name	Trend (positive/ negative)	Rate of SST change, °C, on decadal basis
(a) Pir-Panjal range		
Gulmarg	+ ve	0.61
Banihal	- ve	2.69
Dhundhi	- ve	3.93
Solang	- ve	2.43
SASE	+ ve	0.14
Stage 2	+ ve	0.72
Haddan Taz	+ ve	2.13
Pharkiyan	+ ve	0.22
Z-Gali	+ ve	0.62
Kanzalwan	- ve	2.37
(b) Great Himalaya Range		
Station name	Trend (positive/ negative)	Rate of SST change, °C, on decadal basis
Patseo	- ve	2.88
Drass	- ve	3.75
Pather	+ ve	0.59
Kill Nala	- ve	0.11
Niru	- ve	2.87
Sonamarg	- ve	2.91
Kaksar	- ve	0.67
(c) Karakoram Range		
Station name	Trend (positive/ negative)	Rate of SST change, °C, on decadal basis
Kumar	- ve	2.61
Siala	- ve	3.74
Base Camp	+ ve	1.29
Jawala	+ ve	2.82
Rewari	+ ve	1.06
Billa Base	- ve	0.65
Bahadur	- ve	1.17
Zullu	- ve	1.51
Chandan	- ve	0.96

Table 6 — Seasonal trend and decadal quantitative increase/decrease in SST (NW Himalaya)

	Trend (positive/ negative)	Rate of SST change, °C, on decadal basis
Great Himalaya	+ ve	0.15
Karakoram	- ve	0.64
Pir-Panjal	+ ve	0.46

5.3.1 Variation of seasonal average SST values (Great Himalaya range)

From the seasonal average SST values, an increasing trend is observed with a decadal increase of 0.15°C per decade. The anomaly of the data shows warming trend in the region, however, with low rate.

5.3.2 Variation of seasonal average SST values (Karakoram range)

From the seasonal average SST values, a decreasing trend is observed with a decadal decrease of 0.64°C per decade. The anomaly also shows a cooling trend in the region.

5.3.3 Variation of seasonal average SST values (Pir-Panjal range)

From the seasonal average SST values, an increasing trend is observed with a decadal increase of 0.15°C per decade. The anomaly of the data shows the warming of the range. The details of the observed results are summarized in Table 6. The analysis shows a positive trend in SST values for Great Himalaya and Pir-Panjal range, however, a negative trend is observed for Karakoram range.

5.4 Comparison of seasonal average SST values in different ranges of NW Himalaya (1988-2012)

From the comparison (Fig. 9), it can be seen that SST values are lowest in Karakoram range in comparison to Pir-Panjal and Great Himalaya. The variability in SST values is observed lesser in Karakoram and Great Himalaya, however, high variations in SST values is observed in Pir-Panjal range.

5.5 Geospatial map of monthly average SST values

The map (Fig. 10) shows the positive and negative trend in monthly average SST values in last three decades. From the geospatial map, it is observed that the rate of change in SST values on monthly basis varies from –0.026°C to 0.043°C.

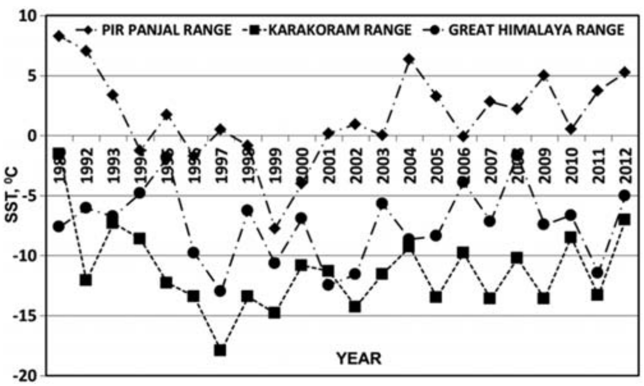


Fig. 9 — Comparison of SST values (1988-2012) in different Himalayan ranges

5.6 Geospatial map of seasonal average SST values

The map (Fig. 11) shows the positive and negative trend in seasonal average SST values in last three decades. From the map, it is observed that the rate of change in SST values on seasonal basis varies from –0.39°C to 0.27°C. These maps are found very useful for determinig the warming and cooling zones in the NW Himalaya with reference to the snow surface temperature.

6 Conclusion

SST values are monitored for NW Himalaya for the period 1988-2012. The trend analysis of monthly average SST values show that for most of the observatories locations, the trend in SST values is positive for Pir-Panjal and Great Himalaya range. However, in Karakoram, the trend in SST values is observed negative for most of the locations. This trend of monthly average SST values indicate the warming in Pir-Panjal and Great Himalaya, but cooling in Karakoram range. The seasonal average SST values show the same trend for Pir-Panjal and Karakoram range. However, for Great Himalaya, an

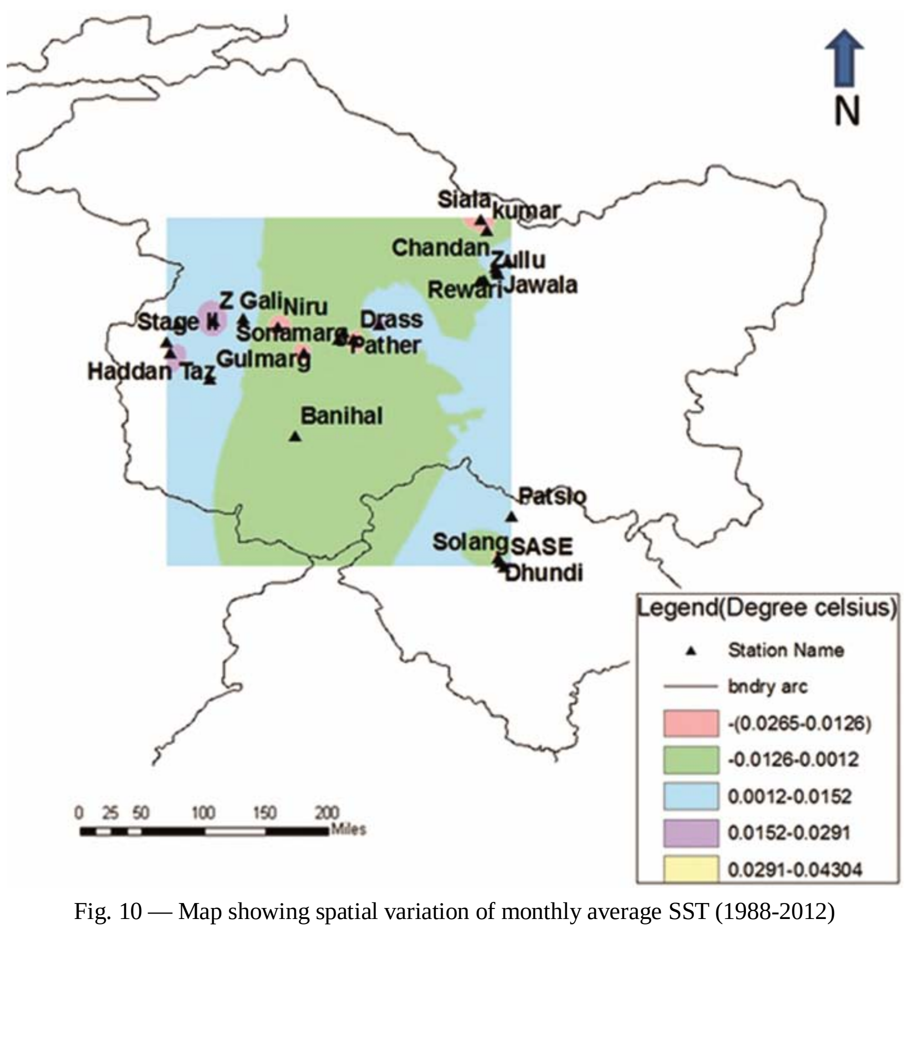


Fig. 10 — Map showing spatial variation of monthly average SST (1988-2012)

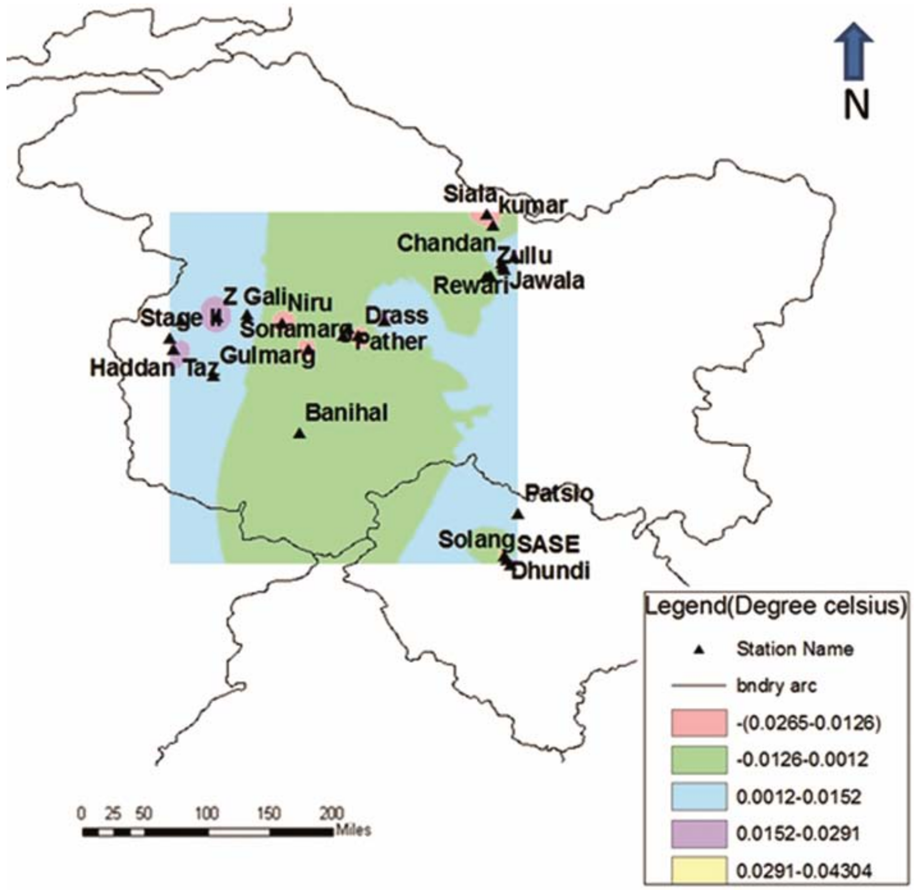


Fig. 11 — Map showing spatial variation of seasonal average SST (1988-2012)

opposite trend is observed. The comparison of SST values between different ranges indicate lower values of SST in Karakoram and Great Himalaya range throughout the observation period. The SST values are observed comparatively higher in Pir-Panjal range. The geospatial maps showing the monthly and seasonal trend of SST values of NW Himalaya have been able to represent the warming and cooling zones in NW Himalaya. This information of SST obtained in the present study plays an important role in estimation of energy balance in the region and can also be used as one of the inputs for avalanche forecast of the region.

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