CHANGING TEMPERATURE EXTREMES IN THE NORTHWEST HIMALAYAS

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Key-words: Himalayan region; North Kashmir river catchment region; Climate variability; Trend detection; Kashmir Valley.

Abstract. Fluctuation in Earth's climate occurs on different time-scales. The climate system is changing in response to both natural and human variables. The impacts of climate warming in mountainous regions are variable, because of large variations in altitude within small distances. The study focuses on a Himalayan region which is more susceptible to temperature fluctuations as has been reported by many studies. Moreover, the region is ecologically more sensitive to climatic fluctuations which could affect the eco-system services of the region. The entire water resource of the Kashmir Valley is a progeny of the Himalayas. The present paper aims to investigate the highest maximum temperature trend in the North Kashmir river catchment region from 1977 to 2011, using the Mann-Kendall and Sen Slope statistic which are robust statistical methods for calculating the trend in hydrometeorological parameters. The data have shown an upward trend for all the stations at α 0.001, 0.01, 0.05 and 0.1. The Pahalgam Station, which happens to be the highest altitude station taken up for the study, shows a rise in temperature extremes for the entire season. The increasing temperature extremes have resulted in the reduction of the snow and glacial cover which, in turn, has affected the hydrological characteristics of the river network in the study-area. The trend is more intense in the eastern part of the study-area, which happens to be the abode of large glaciers and snow fields.

1. INTRODUCTION

The first decade of the 21st century was the warmest recorded since modern measurements have been in place (1850). This was marked by dramatic climate and weather extremes, such as the European heat wave of 2003, the 2010 floods in Pakistan, the hurricane *Katrina* in the United States of America, the cyclone *Nargis* in Myanmar and long-term droughts in the Amazon Basin, Australia and East Africa (WMO, 2013). The mountains and the cold climate regions act as a primary indicator of climate change. Large-scale climate variability is generally exhibited by the more extended mountainous regions, such as the Himalayas, the Alps, the Andes, the Rockies, etc. (Beniston *et al.*, 1997). The world's major river systems owe their origin and stability to the high-altitude mountainous regions which drives the global hydrological cycle. In the regional context, the Himalayas play a critical role in the hydro-meteorological aspects of the major river basins in South Asia (Fowler and Archer, 2005; Singh, Arora, 2007). The high-altitude regions show a greater sensitivity to climatic warming as indicated by the temperature records from Nepal (Shrestha *et al.*, 1999) and China (Liu and Chen, 2000). The trends in climatic elements like temperature, seasonal total snowfall amount and seasonal total snow-water equivalent on a regional scale over the Northwestern Himalayas have not been adequately addressed (Bhutiyani *et al*., 2007, 2009; Shekhar *et al.*, 2010; Dimri and Das, 2011). Consistent with increasing surface air temperatures in the Northwestern Himalayas (Pant and Borgaonkar, 1984; Li and Tang, 1986; Seko and Takahashi, 1991; Shrestha *et al.*, 1999; Thompson *et al.*, 2000; Kang *et al.*, 2010), Many studies have reported that maximum and minimum temperatures have shown an upward trend during recent decades (Bhutiyani *et al.*, 2007, 2009), which is equally true for other large mountain ranges too (Beniston *et al.*, 1997; Diaz and Bradley, 1997; Beniston, 2003). Several studies made by researchers have confirmed the fact that the rate of warming is higher in the Himalayan region than the global

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average and temperature differences are higher during winter and autumn than in summer (Shrestha *et al.*, 1999; Liu and Chen, 2000; New *et al.*, 2002; Xu *et al.*, 2009). Trend detection studies conducted in the Indian sub-continent and the Himalayan region have revealed temperature warming (Arora *et al.*, 2005; Fowler and Archer, 2006; Bhutiyani *et al.*, 2007; Jaswal, 2010; Pal and Tabbaa, 2010). The Brahmaputra Basin witnessed an increase of 0.6°C from 1900 to 2000 (Immerzeel, 2008) The Himalaya mountainous region and the Tibetan Plateau experienced a warning of 1.0°C and 1.1°C respectively, during the pre-monsoon period. The study conducted by Jhajharia and Singh (2010) contradicted the findings of Immerzeel (2008) regarding the air temperature trend in the eastern Himalayas during the pre-monsoon period. However, the findings of Jhajharia, and Singh (2010) are in complete agreement with the findings of Immerzeel (2008) as both studies have identified a warming in the monsoon and post-monsoon seasons alike. Since for a couple of decades, temperature extremes intensifying almost throughout the Himalayan region, its water resource has been badly affected. There has been a shift in land-use practices owing to the deteriorating water resources in the study-area. The study was intended to add a quantitative dimension to the increasing trends in temperature extremes.

2. STUDY-AREA

Spatially, the North Kashmir river catchment region lies between 34º 12′ 09″ to 34º 41′ 55″ north latitude and 73º 54′ 37″ to 75º 35′ 10″ east longitude as shown in Figure 1. The study-area is a northwestern Himalayan region. The eastern part is the abode of a few important glaciers which play a crucial role in the hydrology of the River Sind. The central and western catchments are rain-fed, thus, having a strong seasonal effect on the waterflow. The North Kashmir Rivers have carved their valleys draining the southern slopes of the North Kashmir Himalaya, which is a massive topographic barrier. It encloses the Kashmir Valley on the north and north-east.

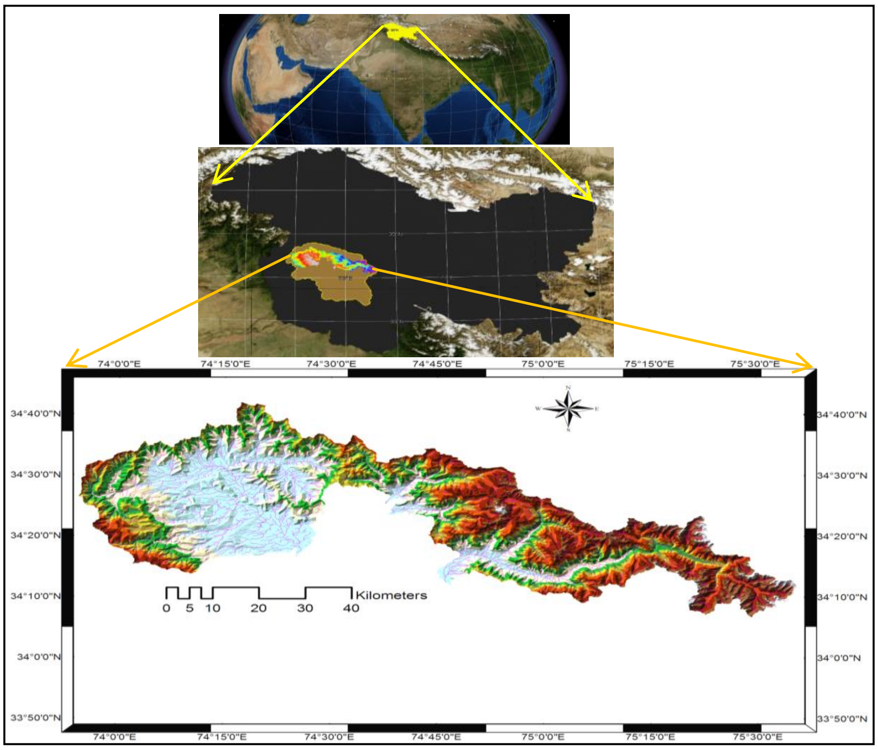

Fig. 1 – Location of the study area.

Four major tributaries of the River Jhelum and the Wular Lake, namely Sind, Ein, Madhumati and Pohru make up the North Kashmir river catchment region. Although it rains throughout the year, rainfall is not uniformly distributed. Most rainfall is concentrated in the spring season.

3. DATASETS AND METHODOLOGY

The North Kashmir river catchment region does not have an adequate number of meteorological stations. Only one meteorological station, Kupwara, exists within the study-area. The Thiessen polygon method has been used to identify the representative stations for different parts of the study-area. The western part is represented by the Kupwara Station. The central and the eastern parts are represented by the Srinagar and Pahalgam stations, respectively (Fig. 2). The highest maximum temperature data from 1977 to 2011 were acquired from IMD, Pune. The trend analysis has been performed using the non-parametric Mann-Kendall test along with the Sen Slope Estimator. The Mann-Kendall test identifies only the trend, but the Sen Slope is a good estimator of the trend magnitude. The statistical tests were carried out using VB Macro developed by the Finnish Meteorological Institute, Finland.

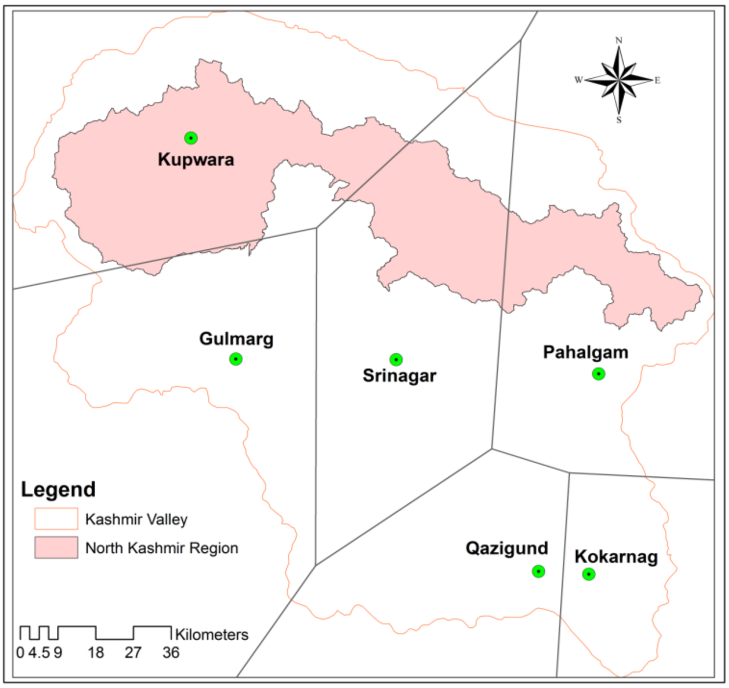

Fig. 2 – Representative meteorological stations with Thiessen polygons.

3.1. Mann-Kendall Test

The Mann-Kendall test can be viewed as a non-parametric test for zero slope of the linear regression of time-ordered data versus time as illustrated by Hollander and Wolfe (1973, p. 503). The test is applicable if the time series obeys the linear model:

$$x_i = f(\mathrm{t}_i) + \varepsilon_i \qquad (1)$$

Where *f (t)* is a continuous monotonic increasing or decreasing function of time and the residuals ε_i can be assumed to be from the same distribution with zero mean. It is therefore, assumed that the variance of distribution is constant in time.

If n is 40 or less, the following procedure may be used. When n exceeds 40, the normal approximation test is used (Gilbert, 1987). The following procedure is applied when there is only one datum per time unit is taken, which may be a day, a week, a month, and so on.

Let $Sgn\left(x_j - x_k\right)$ be an indicator function that takes on the values 1, 0 or -1 according to the sign:

$$\mathrm{sgn}(\mathrm{x}_j - \mathrm{x}_k) = \begin{bmatrix} 1 & If\,(\mathrm{x}_j - \mathrm{x}_k) > 0 \\ 0 & If\,(\mathrm{x}_j - \mathrm{x}_k) = 0 \\ -1 & If\,(\mathrm{x}_j - \mathrm{x}_k) < 0 \end{bmatrix} \qquad (2)$$

The Mann-Kendall statistic is computed as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k=1}^{n} \mathrm{sgn}(\mathrm{x}_j - \mathrm{x}_k) \qquad (3)$$

Where x_j and x_k are the annual values in years j and k, $j > k$, respectively

When n is above 40, the normal approximation test described given below is used. Actually, Kendall (1975, p. 55) proposes that this method may be used for n as small as 10 unless there are many tied groups. In order to apply the normal approximation test to the time-series data, the first step is to compute the variance of S, which is done by the following equation:

$$VAR(\mathrm{S}) = \frac{1}{18}\left[n(\mathrm{n}-1)(2\,\mathrm{n}+5) - \sum_{p=1}^{q} t_p(\mathrm{t}_p - 1)(2\,\mathrm{t}_p + 5) \right] \qquad (4)$$

Here q is the number of tied groups and t_p is the number of data-values in the p^{th} group

The values of S and $VAR(S)$ are used to compute the test statistic Z as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{VAR(\mathrm{S})}} & If \quad S > 0 \\ 0 & If \quad S = 0 \\ \dfrac{S+1}{VAR(\mathrm{S})} & If \quad S < 0 \end{cases} \qquad (5)$$

The presence of a statistically significant trend is evaluated using Z value. A positive (negative) value of Z indicates an upward (downward) trend. Statistic Z has a normal distribution. To test for either an upward or downward monotone trend (a two-tailed test) at α level of significance, H_0 is rejected if the absolute value of Z is greater than Z_1-$\alpha/2$, where Z_1-$\alpha/2$ is obtained from the standard normal cumulative distribution tables. The statistical tests used in the macro computes the trend at 0.001, 0.01, 0.05 and 0.1 significance levels of α.

3.2. Sen's Method

Sen Slope is a non-parametric method that gives the magnitude of the slope (Change per time unit). It is used in cases in which the trend is assumed to be linear. This means that $f\,(t)$ in equation (1) is equal to

$$f\,(\mathrm{t}) = \mathrm{Qt} + \mathrm{B} \qquad (6)$$

Where Q is the slope and B is a constant.

To get the slope estimate Q in equation (6) we first calculate the slopes of all data-value pairs by using the formula:

$$Q_i = \frac{x_j - x_k}{j-k} \qquad (7)$$

Where x_j and x_k are data-values at times (or during time periods) j and k, respectively and where j > k and N is the number of data-pairs for which j > k. The median of these N values of Q is Sen's estimator of slope. If there is only one datum in each time-period, then N' = n (n -1)12, where n is the number of time-periods.

If there are n values x_j in the time series, we get as many as $N = n\,(n\text{-}1)/2$ slope estimates (Q_i). Sen's estimator of slope is the median of these N values of Qi. The N values of Qi are ranked from the smallest to the largest and Sen's estimator is:

$$\begin{aligned} Q &= Q_{[(N+1)/2]}\ if \quad N \quad is \quad Odd \\ Q &= \frac{1}{2}\left(Q_{[N/2]+Q[(N+2)/2]}\right) if \quad N \quad is \quad even \end{aligned} \qquad (8)$$

The procedure in VB macro computes the confidence interval at two different confidence levels; α = 0.01 and α = 0.05, resulting in two different confidence intervals. A 100 (1-α) % two-sided confidence interval about the true slope may be obtained by the non-parametric technique given by Sen (1968b). The procedure given above is based on the normal distribution which is valid for n as small as 10 unless there are many ties. This procedure is a generalization of that given by Hollander and Wolfe (1973, p. 207) when ties and/or multiple observations per time period are present.

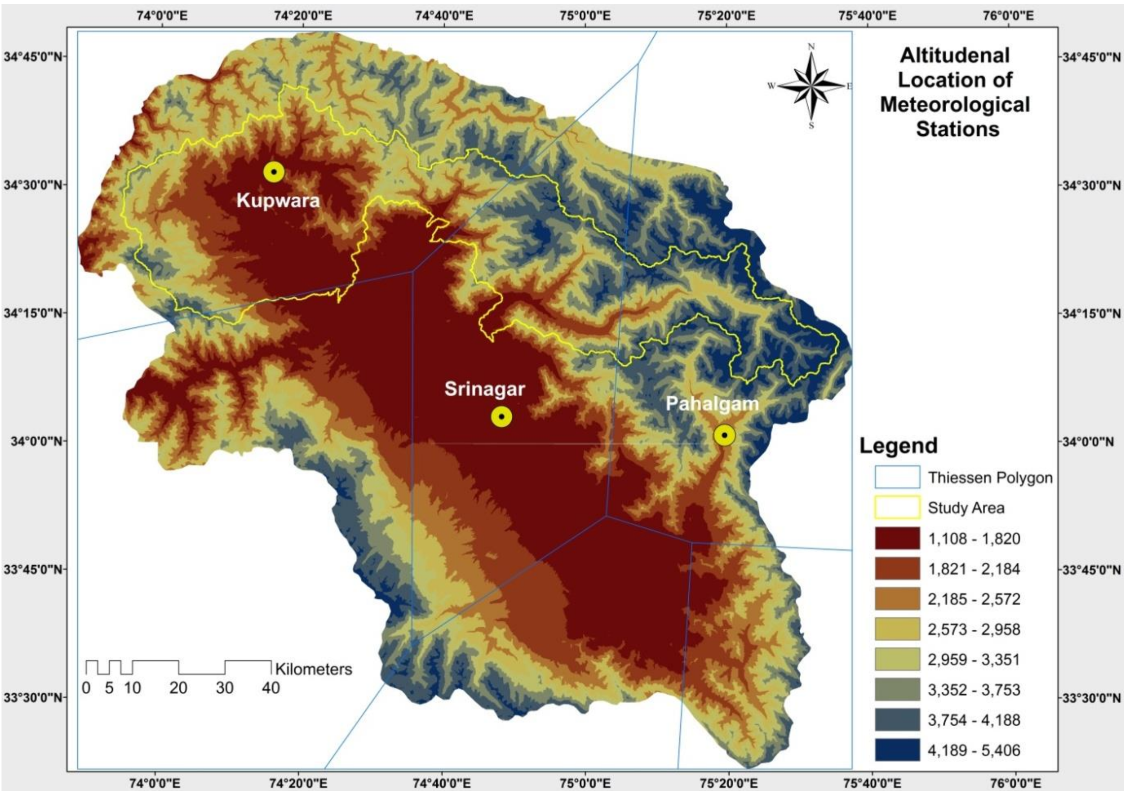

Fig. 3 – Altitudinal location of representative meteorological stations.

At first we compute:

$$C_{\alpha} = Z_{1-\alpha/2}\sqrt{VAR(\mathrm{S})} \qquad (9)$$

Where $VAR(S)$ was defined in equation (4) and $Z_{1\text{-}\alpha/2}$ is obtained from the standard normal distribution.

Next $M_1 = (N - C_{\alpha})/2$ and $M_2 = (N + C_{\alpha})/2$ are computed. The lower and upper limits of the confidence interval, Q_{min} and Q_{max} are the M_1^{th} largest and the $(M_2 + 1)^{th}$ largest of the N-ordered slope estimates Q_i. If M_1 is not a whole number, the lower limit is interpolated. Correspondingly, if M_2 is not a whole number, the upper limit is interpolated.

4. RESULTS

The test statistic related to the long-term seasonal highest maximum temperature (1977–2011) for the Kupwara, Pahalgam and Srinagar stations is given in Table 1.

Table 1

Test statistic for highest maximum temperature.

	Season	Z Value	Level of Significance (α)	Sen Slope
Kupwara	Winter	2.70	0.01	0.05
	Spring	3.41	0.001	0.08
	Summer	1.61	Nil	0.03
	Autumn	3.84	0.001	0.06
Pahalgam	Winter	2.98	0.01	0.09
	Spring	2.86	0.01	0.07
	Summer	2.03	0.05	0.02
	Autumn	3.55	0.001	0.04
Srinagar	Winter	2.68	0.01	0.05
	Spring	2.29	0.05	0.05
	Summer	-0.58	Nil	-0.01
	Autumn	2.50	0.05	0.04

Kupwara Station

The statistics calculated from the Mann-Kendall and the Sen Slope Estimator is given in Table 1. The highest maximum temperature in the winter season is showing an increasing trend with a Z value of 2.70 and slope value of 0.05.

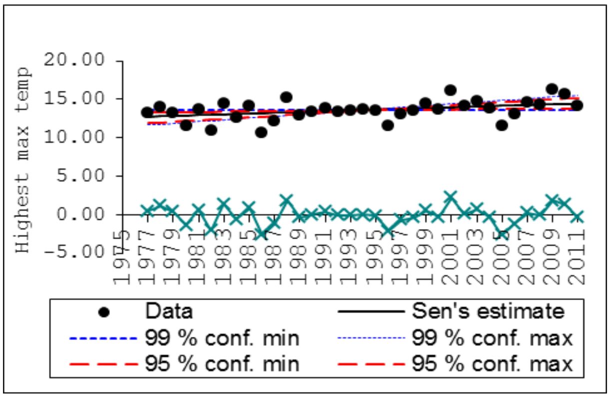

Fig. 3 – Winter Highest Maximum Temperature.

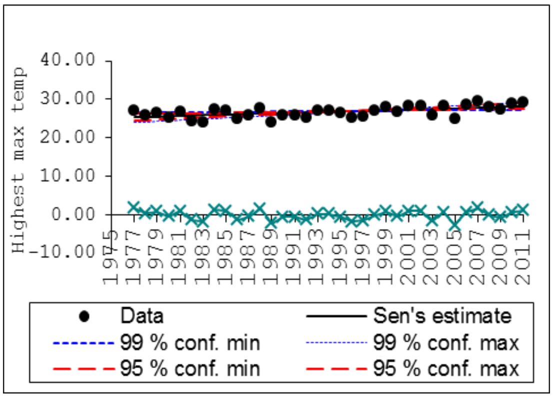

Fig. 4 – Spring Highest Maximum Temperature.

The trend is increasing statistically at the 99 percent level of confidence. The narrow angle between the confidence limits at 95 and 99 percent also confirms the fact that the trend is increasing at the significant statistical level of confidence (Fig 3). The autumn season indicates an increasing trend in the highest maximum temperature at the Kupwara Station from 1977 to 2011 (Fig. 6). The trend is positive at α 0.001. The statistical tests have calculated an increasing trend at the 99.9 percent confidence level.

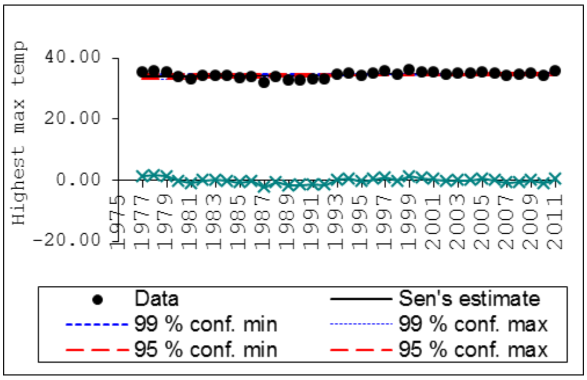

Fig. 5 – Summer Highest Maximum Temperature.

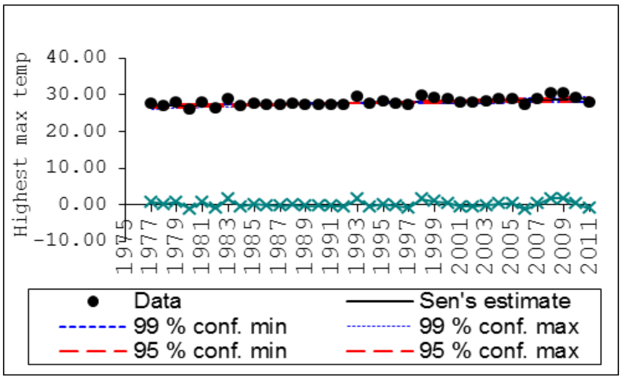

Fig. 6 – Autumn Highest Maximum Temperature.

Though the summer highest maximum temperature shows an increasing trend, it is not statistically significant (Table 1 and Fig. 5). The Z value is 1.61, which is very close to the normal distribution value of 1.64 at 90 percent confidence level. The autumn season also shows an increasing trend with a Z value of 3.84. The trend is significant at α 0.001. Almost, all data points fall within the confidence limits as it is obvious from Figure 6. The spring season has also shown an increasing trend in temperature extremes recorded at Kupwara Station, with a slope magnitude of 0.08, which is by no means a small increase in temperature.

Pahalgam Station

Pahalgam Station registered an increasing trend in the highest maximum temperature recorded from 1977 to 2011 for all the seasons. The winter highest maximum temperature reveals a positive trend with a Z value of 2.98. The trend is significant at α 0.01, which means a linear trend of data at 99 percent confidence level. Almost all data points fall within the confidence limits except for a few data-values at the beginning of the time-series (Fig. 7).

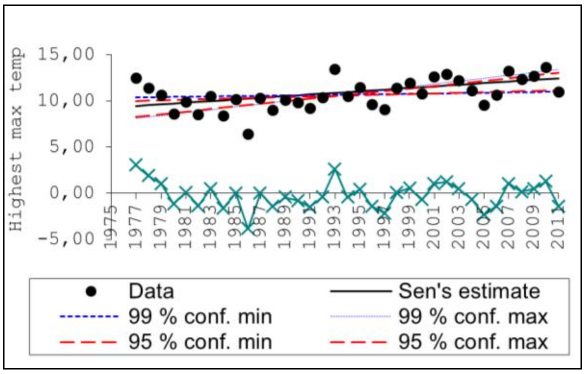

Fig. 7 – Winter Highest Maximum Temperature.

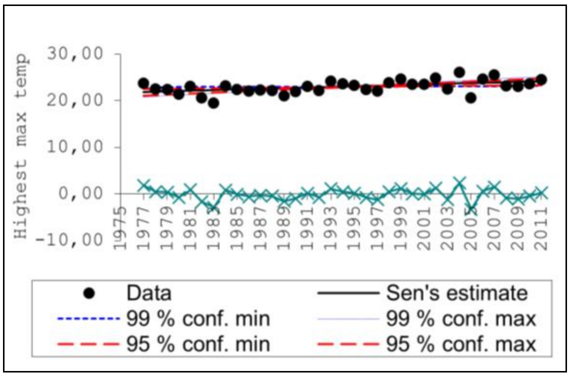

Fig. 8 – Spring Highest Maximum Temperature.

The slope of the trend line is 0.09. Spring and summer also show an increasing trend with 99 percent confidence level. The Z value for the spring and summer seasons, as calculated by the Mann-Kendall test, is 2.86 and 2.02, respectively. The Sen Slope test estimates a slope value of 0.07 for the spring season and of 0.02 for the summer season (Table 1).

The autumn season projects a trend at 99.9 percent confidence level, but the trend magnitude is not very high. Similarly, the summer season reveals a soft positive trend as compared to the winter and spring season. The linear model applied to the time-series befits the data shown in Figures 9 and 10.

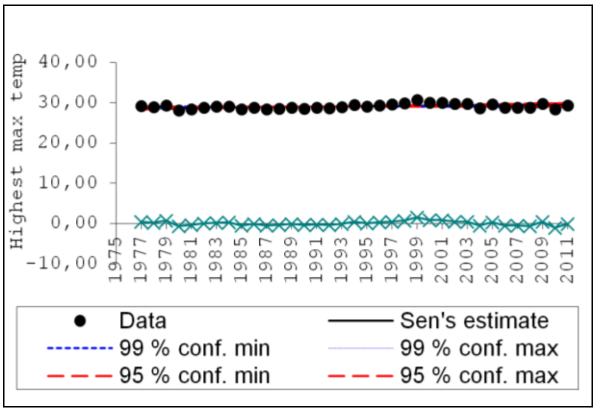

Fig. 9 – Summer Highest Maximum Temperature.

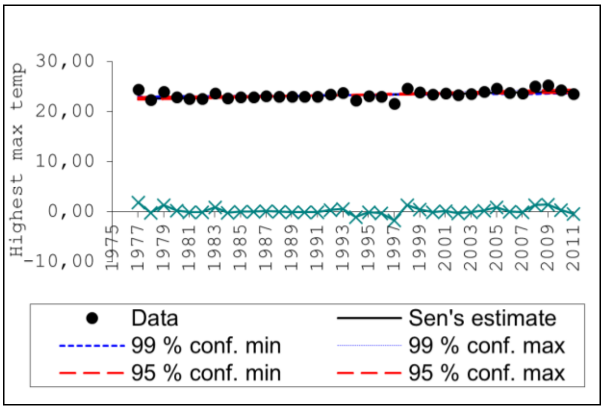

Fig. 10 – Autumn Highest Maximum Temperature.

Srinagar Station

The winter highest maximum temperature witnessed an increasing trend from 1977 to 2011 (Table 1 and Fig. 11). The data observed at Srinagar Station depict an increasing trend with a confidence level of 99 percent. Figure 11 clearly shows that the absolute values of the highest maximum temperature increased during the later part of the time-series with a slope trend of 0.05.

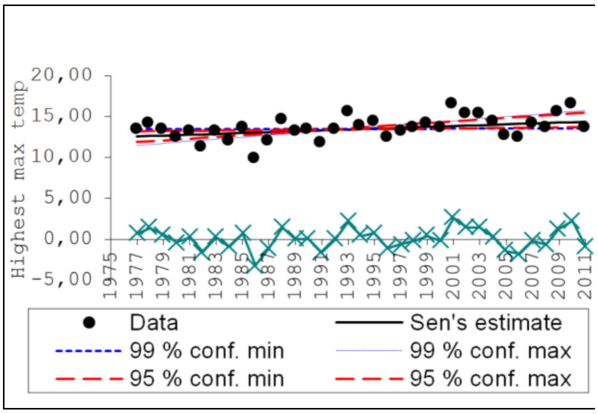

Fig. 11 – Winter Highest Maximum Temperature.

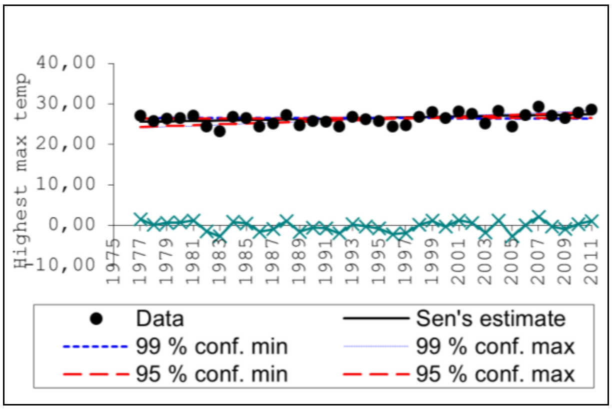

Fig. 12 – Spring Highest Maximum Temperature.

The spring season also reveals an increasing monotonic trend at 95 percent level of confidence with a slope of 0.05.

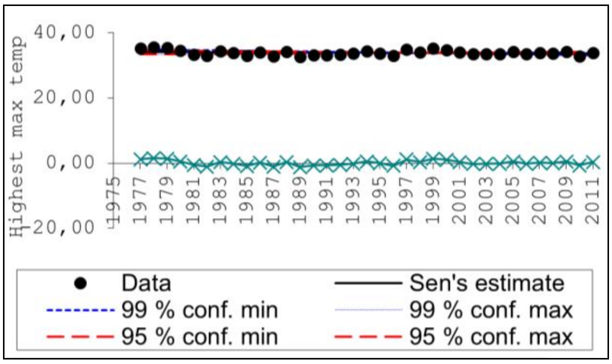

Fig. 13 – Summer Highest Maximum Temperature.

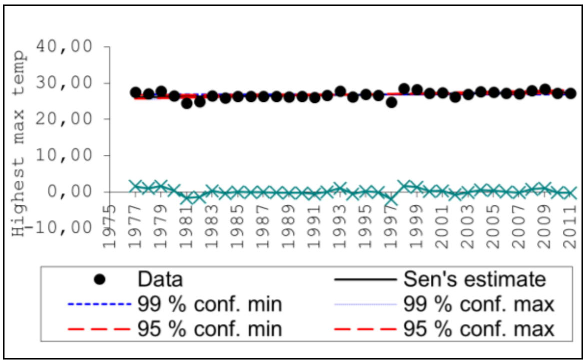

Fig. 14 – Autumn Highest Maximum Temperature.

The trend is missing in the summer season, but the autumn season shows up a trend at 95 percent level of confidence with a slope of 0.04.

5. DISCUSSION

The meteorological stations taken up for the study are located in different altitudinal zones (see Fig. 3). The increasing temperature in the high-altitude areas could be disastrous for the already degrading water-resource of the region. The eastern part of the study-area has some important glaciers and snow fields which regulate the hydrological regime of the Sind River that drains the area. An increasing winter temperature would mean a decrease in snowfall. Spring-time warming accelerates the snowmelt process in the higher reaches, badly affecting the discharge pattern of the streams. The unprecedented warming of the high-altitude regions in the study-area has further resulted in frequent cloudbursts and incessant rains. The diminishing water resource may start up a process of land-use transformation in the region which is indeed happening at a small scale. The study does not point to any specific altitude-related trends as all high-and-low-altitude stations are projecting somewhat a similar behaviour with regard to the extreme temperature trends, but the magnitude of the trend is a bit higher at the comparatively high-altitude stations.

6. CONCLUSIONS

The study was aimed at investigating the trends in highest maximum temperature in North Kashmir river catchment region from 1977 to 2011. The study-area is covered by three meteorological stations, namely, Kupwara, Pahalgam and Srinagar which are located in different altitudinal zones. The dynamics of hydrology in glacierised basins is closely associated with the air temperature. In the Himalaya, July and August are generally the warmest months (Thayyen & Gergan, 2010), when there is enough heat energy available for melting the winter-time snowpack and glacial ice. The decreasing temperature with altitude sets perfect conditions for the formation of glaciers and snow fields. The increasing temperature in the winter season reduces the extent of glacier areas. The Srinagar, Shimla and Leh stations in the north-west Himalayas had shown a warming trend in the last century (Bhutiyani *et al.*, 2007). The Himalayas experienced rising temperature trends in the 20th century (Shrestha *et al.*, 1999; Immerzeel, 2008) which accelerated the melting process of the winter snowpack and of glacier ice. The high-altitude regions show greater data variability than the low-altitude ones. The stations identified for the study, except for Srinagar, do not have long-term datasets available, which makes it difficult to assess the long-term climate dynamics in the study-area. However, the recent increase in the extreme air temperature is highly consequential to the number of ecosystem services in the Himalayan region.

REFERENCES

Arora, M., Goel, N.K., Singh, P. (2005), *Evaluation of temperature trends over India*, Hydrol. Sci. J., **50**, *1*, pp. 81–93.

Beniston, M. (2003), *Climatic change in mountainous regions: A review of possible impacts*, Clim. Change, **59**, pp. 5–31.

Beniston, M., Diaz, F.D., Bradley, R.S. (1997), *Climatic change at high elevation sites: An overview*, Clim. Change, **36**, pp. 233–251.

Bhutiyani, M.R., Kale, V.S., Pawar, N.J. (2007), *Long-term trends in maximum, minimum and mean annual air temperatures across the northwestern Himalaya during the twentieth century*, Clim. Change, **85,** pp. 159–177.

Bhutiyani, M.R., Kale, V.S., Pawar, N.J. (2009), *Climate change and the precipitation variations in the northwestern Himalaya*, 1866–2006; Int. J. Clim., **36**, pp. 535–548.

Diaz, H.F., Bradley, R.S. (1997), *Temperature variations during the last century at high elevation sites*, Clim. Change, **36**, pp. 253–279.

Dimri, A.P., Das, S.K. (2011), *Wintertime climatic trends in the western Himalayas*, Clim. Change, **111**, pp. 775–800.

Fowler, H.J., Archer, D.R. (2005), *Hydro-climatological variability in upper Indus basin and implications for water resources*, In: Regional hydrological impacts of climate change – impact assessment and decision making (eds) Wagner T *et al*., Proceedings of Symposium S6 held during the Seventh IAHS Scientific Assembly at Foz do lguacu, Brazil, IAHS Publ., **295**, pp. 131–138.

Fowler, H.J., Archer, D.R. (2006), *Conflicting signals of climatic change in the Upper Indus Basin*, J. Climate, v. **19**, pp. 4276–4293.

Gilbert, R.O. (1987), *Statistical methods for environmental pollution monitoring*, Van Nostrand Reinhold, New York.

Immerzeel, W. (2008), *Historical trends and future predictions of climate variability*, International Journal of Climatology. **28**, pp. 243–254.

Jaswal, A.K. (2010), *Recent winter warming over India–spatial and temporal characteristics of monthly maximum and minimum temperature trends for January to March*, Mausam, v. **111**. Pp. 45–66.

Jhajharia, D., Singh, V.P. (2010), *Trends in temperature, diurnal temperature range*, International Journal of Climatology.

Kang, S., Xu, Y., You, Q., Flugel, W.A., Pepin, N., Yao, T. (2010), *Review of climate and cryospheric change in the Tibetan Plateau*, Environ. Res. Lett. **5**, doi: 10.1088/1748-9326/5/1/015101.

Li, C., Tang, M. (1986), *Changes of air temperature of Qunghai–Xizang plateau and its neighborhood in the past 30 years*, Plateau Meteorol. **284**, pp. 2156–2159.

Liu, X., Chen, B. (2000), *Climate warming in the Tibetan Plateau during recent decades*, Int. J. Climatol, v. **20**, pp. 1729–1742.

New, M., Lister, D., Hulme, M., Makin, I. (2002), *A high resolution data set of surface climate over global land areas*, Climate Research, v. **21**, pp. 1–25.

Pal, I., Al-Tabbaa, A. (2010), *Long-term changes and variability of monthly extreme temperatures in India*, Theor. Appl. Climatol., v. **100**, pp. 45–46.

Pant, G.B., Borgaonkar, H.P. (1984), *Climate of the hill regions of Uttar Pradesh*, Him. Res. Develop. **3**, pp. 13–20.

Seko, K., Takahashi, S. (1991), *Characteristics of winter precipitation and its effects on glaciers in Nepal Himalaya*, Bull. Glacier Res., v. **9**, pp. 9–16.

Shekhar, M.S., Chand, H., Kumar, S., Srinivasan, K., Ganju, A. (2010), *Climate change studies in the western Himalaya*, Ann. Glaciol., **51**, pp. 105–112.

Shrestha, A.B., Wake, C.P., Mayewski, P.A., Dibb, J.E. (1999), *Maximum temperature and trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal from period 1971–94*, Journal of Climate, v. **12**, pp. 2775–2787.

Singh, P., Arora, M. (2007), *Water resources potential of Himalayas and possible impact of climate change*, Jalvigyan Sameeksha, v. **22**, pp. 109–132.

Thompson, L.G., Yao, T., Thompson, E.M., Davis, M.E., Handerson, K.A., Lin, P.N. (2000), *A high resolution millennial record of the South Asian monsoon from Himalayan ice cores*, Science **289**, pp. 1916–1919.

Xu, J., Grumbine, E.R., Shrestha, A., Eriksson, M., Yang, X., Wang, Y., Wilkes, A. (2009), *The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods*, Conservation Biology, v. **23**, vo. *3*, pp. 520–530.

Hollander, M., Wolfe, D.A. (1973), *Nonparametric Statistical Methods*, John Wiley and Sons, New York, 503 p.

Thayyen, R. J., Gergan, J.T. (2010), *Role of glaciers in watershed hydrology: preliminary study of a "Himalayan catchment"*, The Cryosphere **4**, pp. 115–128.

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