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Estimation of temperature lapse rate in a snowfed river basin of northwest Himalaya using satellite remote sensing inputs

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Abstract
Conventionally temperature lapse rate (TLR) in mountainous regions is calculated based on the in-situ air temperature data collected in sparsely located metrological stations. These in-situ temperature recordings are point data and are collected manually. Satellite remote sensing provides an alternative to above stated issues, as satellite data is continuous providing synoptic viewing and represents potentially unbiased recordings. In the present study the monthly TLR was simulated for Jhelum river basin using satellite remote sensing inputs. Inter-seasonal and inter-annual variation in the TLR was assessed using MODIS (Moderate Resolution Imaging Spectroradiometer) and ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) sensor data. Land Surface Temperature (LST) values retrieved from MODIS were correlated with the values from ASTER Digital Elevation Model (DEM) which showed a strongly correlated, inverse relationship. The results show that the TLR in Jhelum basin ranges from −4.8 to −8.0 °C/km with strong inter-seasonal variation.

Keywords: Himalayas, Jhelum, MODIS, ASTER, Temperature lapse rate (TLR), Remote Sensing

1. Introduction

Quantification of variation of temperature with elevation (temperature lapse rate, TLR) in Himalaya is important for accurate hydrological modeling and for understanding of long term cryospheric changes. However such evaluation is a challenging task due to unavailability of long term temperature data and regional complex climatology combined with rugged topography. In such mountainous regions dense network of metrological observatories are required to efficiently represent the regional temperature variation with respect to elevation [1, 2]. TLR which is an important input to any hydrological model is often assumed to deplete linearly with altitude. Many past studies have assumed constant value of TLR (−6.5 °C/km) to create basin temperature grids for streamflow simulation [2, 3, 4, 5, 6, 7]. In most of the studies this constant value of TLR was attributed to free atmospheric lapse rate [8].

Most of the hydrological model designed for the snowmelt simulation requires partitioning of river basin into altitudinal zone based on the relief of the entire catchment. The daily mean air temperature data available for each altitudinal zone is interpolated based on the assumed value of TLR (decrease in temperature values with increment in elevation) [9]. However, in mountainous regions in-situ meteorological observatories recording air temperature are sparsely distributed and thus robust database pertaining to air temperature of all the elevation zones in a catchment is generally unavailable. Further, these air temperature recordings are prone to error as they are measured manually. However, TLR evaluated from remotely sensed land surface temperature (LST) and digital elevation model (DEM) retrieved from satellite data gives a continuous database which provides synoptic viewing and represents potentially unbiased recordings [10].

In complex ecosystem like Himalaya, assumption of a constant free atmosphere TLR for the estimation of air temperature may induce inaccuracy in the hydrological simulations, since it may not represent the regional atmospheric conditions, especially at river basin level [11]. Thus in the present study monthly TLR values were evaluated pertaining to the Jhelum (snowfed) river basin of Northwest Himalaya (NWH) using satellite remote sensing inputs and ancillary data. Further inter-annual and inter-seasonal variations in the TLR are discussed.

2. Study area

Jhelum basin is the largest and most westerly located basin in the Indus river system. It is located between 33°22′30″ N to 34°40′06″ N latitude and 73°30′16″ E to 75°28′09″ E longitude (Fig.1).

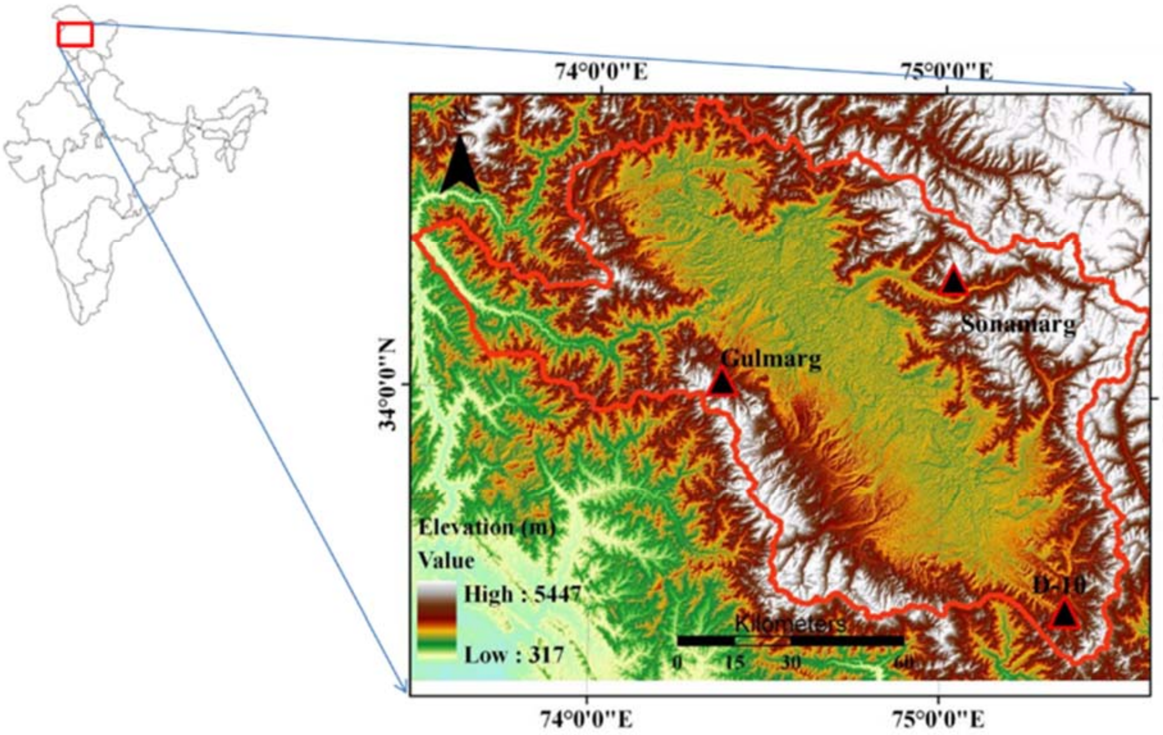


Fig 1: Location of Jhelum Basin in Himalayan mountain system

The total catchment area covers an area of 14664 km^2. The river Jhelum originates at a small spring called ‘Verinag’ in the banihal sub-basin. The river is an important water resource for the Kashmir Valley. It has two major tributaries; Liddar and Sind both originating on the eastern side of the basin in the windward mountains of Greater Himalayan range. The basin has tropical to sub-temperate type of climate. The basin is marked by heavy snowfall during peak winter months (January and February). There are three metrological observatories of Snow and Avalanche Studies Establishment (SASE) is located in the basin; Gulmarg, Sonamarg and D-10 (Fig.1).

3. Data Used

The data used in the study is shown in table 1.

Table 1: Data used in the study

Data type	Details	Source
MODIS (MOD11A1)LST products	2007-08 and 2008-09 with spatial resolution of 1 km	https://ladsweb.nascom.nasa.gov/
ASTER (GDEM V2) DEM Product	Spatial resolution 30 m	http://gdem.ersdac.jspacesystems.or.jp/
Surface and air temperature data of Jhelum river basin	Daily maximum and minimum air temperature data from Jhelum river basin	SASE meteorological stations (Gulmarg, Sonamarg and D-10)

MODIS - Moderate Resolution Imaging Spectroradiometer; ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer; MOD11A1 - MODIS/Terra LST/E Daily L3 Global 1 km Grid product; GDEM V2 - Global Digital Elevation Model Version 2; LST – Land Surface Temperature; DEM
– Digital Elevation Model

4. Methodology

The methodology followed for estimation of TLR is shown in Fig.2. MOD11A1 LST product provides surface temperature and emissivity value at pixel level (spatial resolution of 1 km). MODIS (Moderate Resolution Imaging Spectroradiometer) sensor data onboard Terra satellite was selected because of its fine radiometric resolution, large swath, dynamic range of spectral resolution and calibration with high precision in thermal infra-red (TIR) bands. These bands are specifically designed for retrieval of surface temperature properties of sea and land in addition to atmospheric parameters. MOD11A1 products are generated using multiple methods. In this product temperature and water vapor profiles of atmosphere are retrieved through number of atmospheric channels onboard MODIS sensor. TIR bands (20-33) are capable of detecting cirrus clouds and snow, thus, acquiring information about snow surface, emissivity and temperature with minute error. Multiple bands of MODIS in the mid-infrared range are provided with onboard corrections for solar radiations which further enhance accuracy of surface temperature estimation. Seven TIR bands allow application of a novel day night algorithm which is based on co-location measurements and simultaneous retrieval of surface temperature and spectral emissivity. This algorithm does not require any information about temperature and water vapor column (WVC quantity) of atmosphere [10, 12-13].

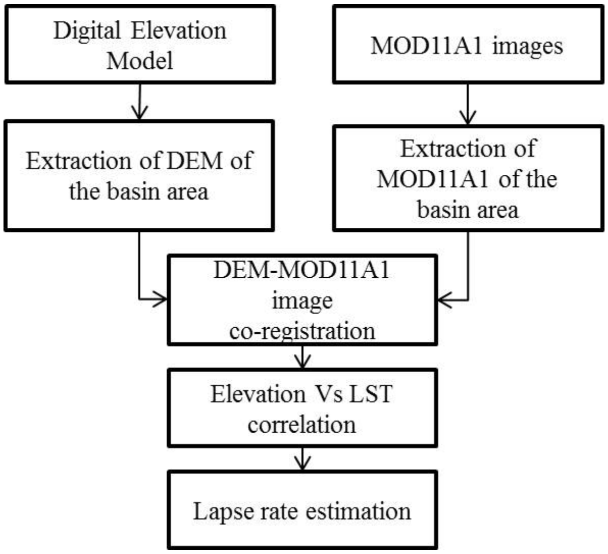


Fig 2: Flowchart showing various steps involved in lapse rate estimation

The HDF-EOS file was processed and imported to ERDAS Imagine 9.1. The LST products were provided in the sinusoidal projection which was then re-projected to UTM and WGS84 system. In order to avoid any redundancy and geolocation error, the LST images were co-registered with the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) DEM. All the LST images were then multiplied by calibration and scale factor of 0.02 and subtracted by 273 to convert the temperature values to degree Celsius mode [14].

In Jhelum basin, due to lack of strong network of meteorological observatories no ground observation on LST is available. Therefore, LST values obtained from MOD11A1 product were compared to *in-situ* air temperature values of respective meteorological stations. Subsequently the LST values were plotted with elevation values and rate of change of LST with elevation was analyzed based for the years 2007-08 and 2008-09. The equation of regression line simulated by these plots can be understood as follows Eq.1.

$$Y = -mX + c \tag{1}$$

Where, X = altitude value; Y = value of temperature; −m = slope of the line (negative sign denotes the inverse relationship); and c = constant of linear equation. The value of constant 'm' also represents rate of change of temperature with change in elevation which can be defined as temperature lapse rate. The lapse rate values estimated for each month for the river basin is based on different LST products from different dates [10].

5. Results and discussion

The present study was conducted in a Himalayan river basin where a robust network of ground measurements of LST is unavailable. The LST values recorded at various metrological observatories were compared with the LST values retrieved from the MODISA11 product. Fig.3 depicts linear relationship between satellite derived LST and *in-situ* air temperature of Jhelum basin. It shows high coefficient of correlation (R^2) values and indicates that air temperature values are in general higher than LST values. Further, this shows that air temperature and LST are directly correlated and hence LST values can be taken as strong indicator of air temperature values. Fig.4 shows that temperature follows a similar variability pattern as elevation. Based on these assumptions the LST values were plotted with elevation values and rate of change of LST with elevation were analyzed (Fig.5-6).

Fig. 5-6 shows a strong negative linear correlation between LST and elevation values. The comparative analysis shows that surface temperature follows a similar pattern of elevation in Jhelum basin. The scatter plots for the river basin show that temperature decreases with an increasing altitude in a strong linear relationship.

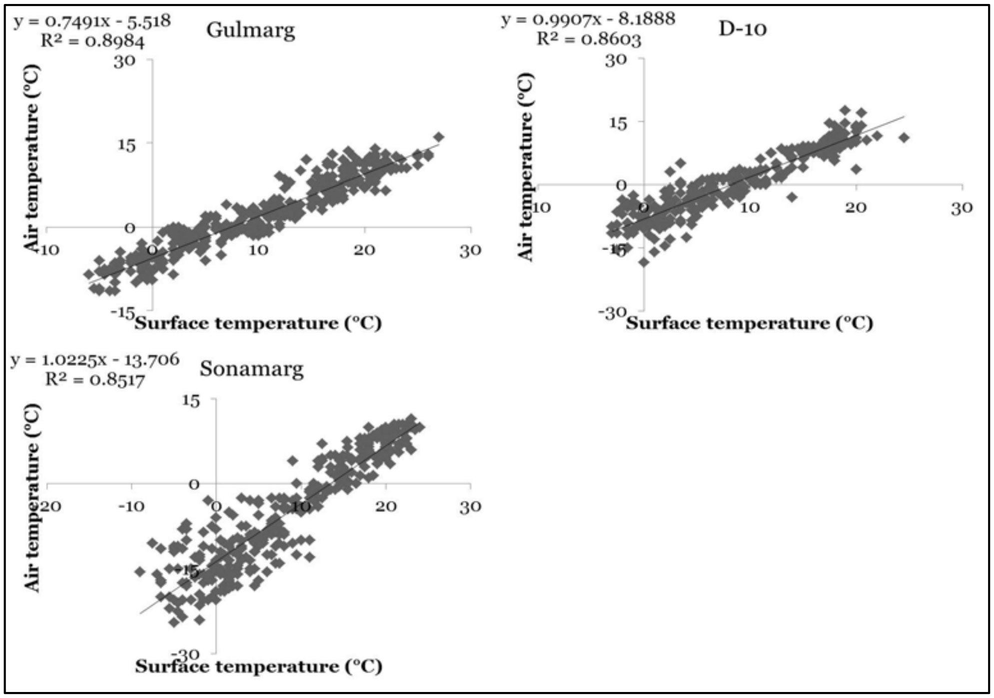


Fig 3: Linear relationship between satellite-derived surface temperature and in-situ air temperature of three observatories located in Jhelum basin

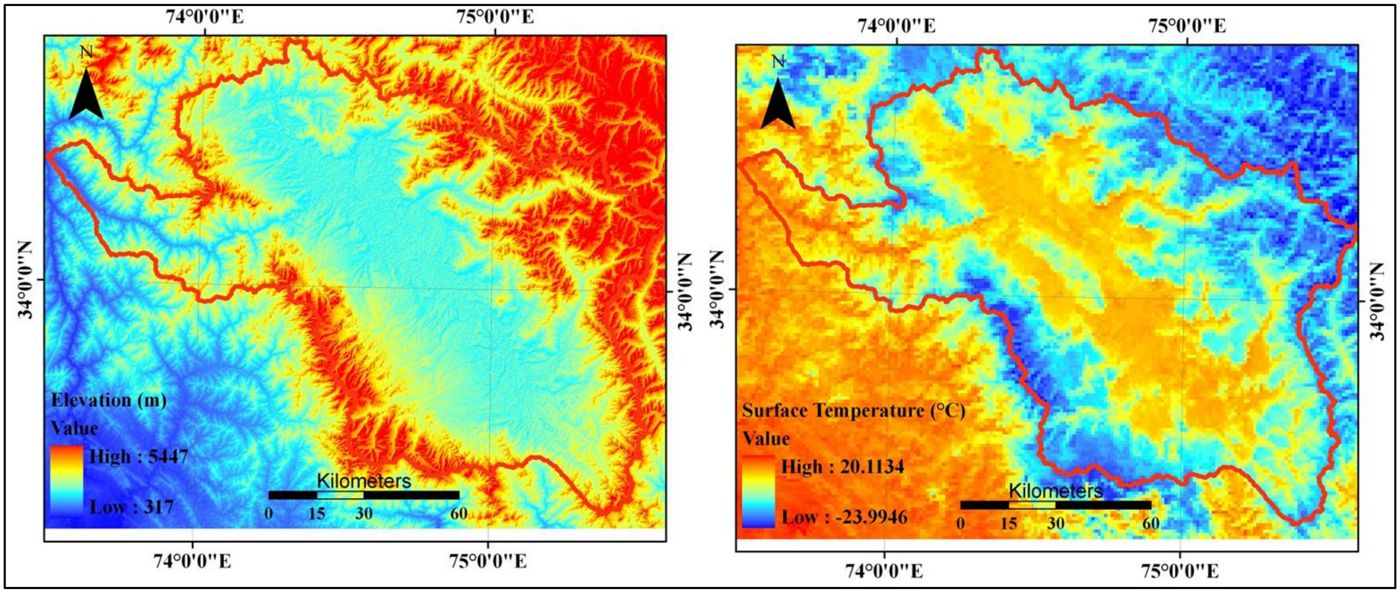


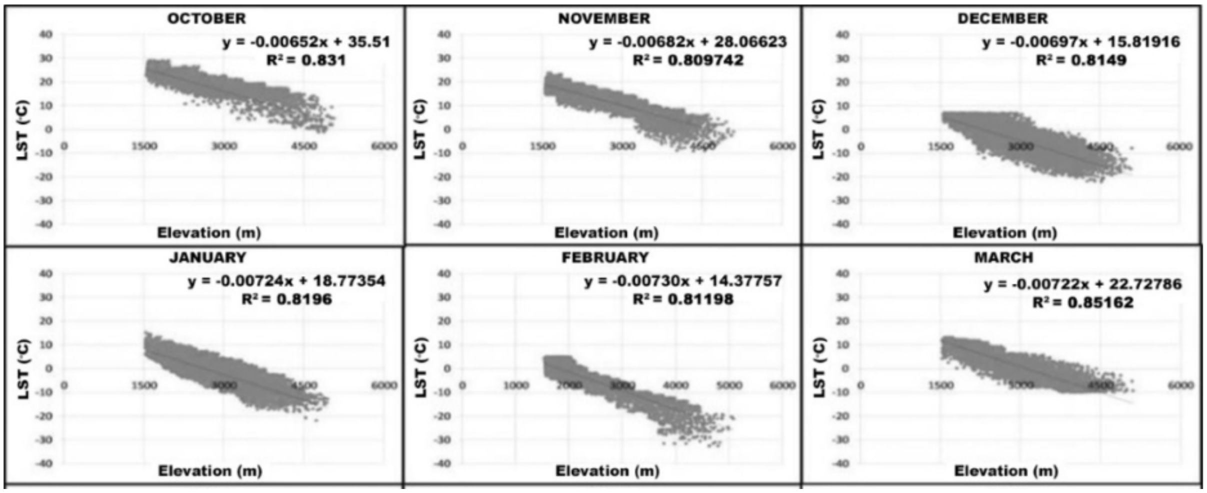
Figure 4: Distribution of LST (MOD11A1 data dated 2nd Dec2009) across Himalayan ranges and the corresponding elevation values (DEM)

This phenomenon has also been reported by various researchers for Satluj river basin [10, 15] in which a negative relationship was observed between elevation and surface temperature. In the studies the authors have compared LST prepared from NOAA AVHRR and MODIS, and have supported the findings with air temperature retrieved from ground observatories. In the present study lapse rate values were estimated for twelve different dates representing each month of the year 2007-08 and 2008-09 from MODIS data. Insignificant difference was observed in lapse rate values of different months of 2007-08 and 2008-09, with consistent seasonal variation. The slope of regression equation is equivalent to lapse rate of the month (Table 2) (Fig.5-6).

The estimated TLR was not constant but varies with region and season. The exercise was repeated for another corresponding year in order to infer any inter-annual variation in TLR values. However, analysis shows that in both the year negligible difference were observed in monthly TLR values. The seasonal cycle of monthly mean TLR is shown in Table 2. The results show that TLR change substantially throughout the year, with highest rate of change of temperature was observed in February month (−8 °C/km and −7.3 °C/km). The minimum TLR in Jhelum basin same was observe during August month (−4.9 °C/km). The maximum lase rate value during winter months can be attributed to high temperature difference existing between low-lying valley regions and highly elevated snowfields. Low lapse rate values were observed in peak summer and monsoon months. In these months, temperature significantly increases in highly elevated areas resulting in seasonal depletion of snow-glacial cover, thus resulting in depletion of rate of change of temperature with elevation.

Table 2: Lapse rate values (unit (°C/km) of Jhelum river basin

Month	Jhelum
October	−6.6
November	−6.8
December	−7.0
January	−7.2
February	−7.3
March	−7.2
April	−6.5
May	−6.1
June	−5.7
July	−5.2
August	−4.9
September	−6.2



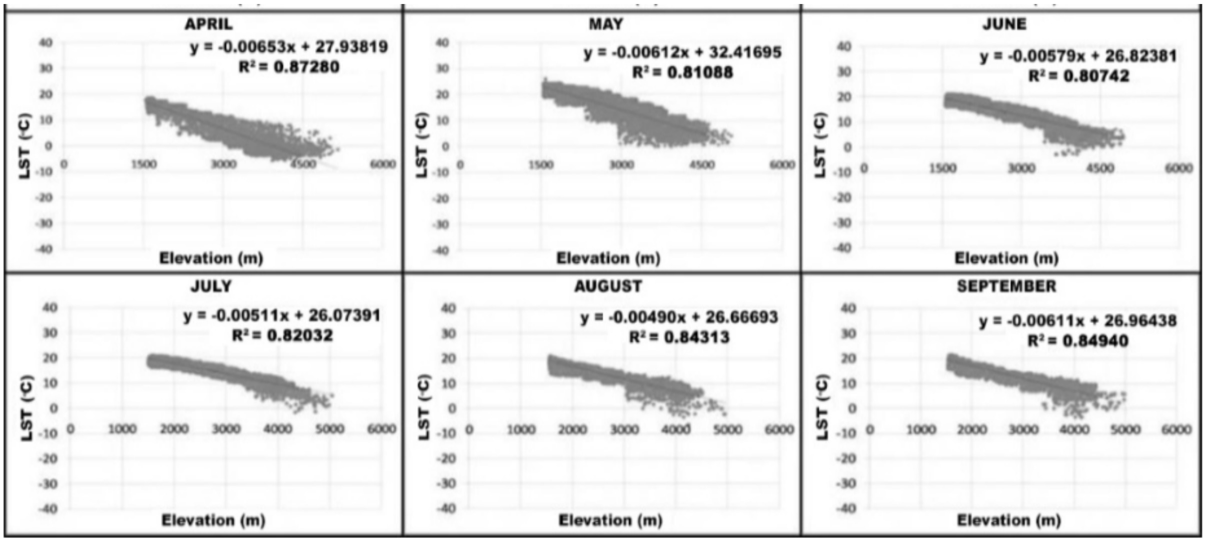


Fig 5: Relationship between temperature and elevation in different months of 2007-08 (Jhelum basin)

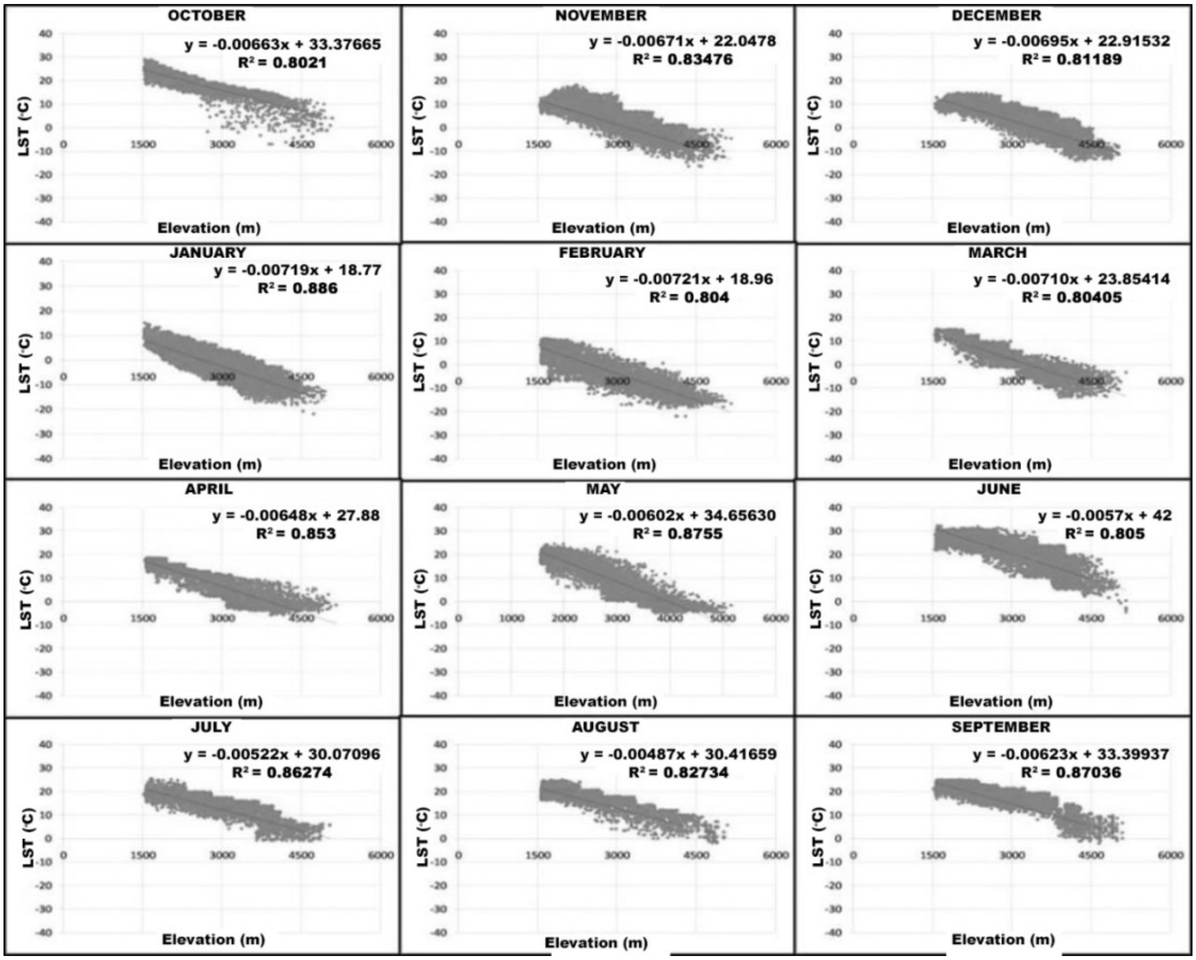


Fig 6: Relationship between temperature and elevation in different months of 2008-09 (Jhelum basin)

6. Conclusions

In hydrological studies pertaining to any mountainous region, accurate air temperature is pre-requisite. In regions like NWH where metrological observatories recording temperature data are sparse, observed point data is not sufficiently representative. In such conditions TLR values evaluated from satellite data can be an effective substitute for the manual observations. This remotely sensed data provides. Further these satellite based LST values has many advantages over manual recordings like; availability of continuous data with large area coverage and negligible human induced errors. In the present study, monthly TLR was estimated for the Jhelum river basin using the MODIS sensor data and DEM for 2007-08 and 2008-09. Evaluated TLR values for the Jhelum basin varies from −4.9 °C/km to −7.3 °C/km. High inter-seasonal with negligible inter-annual variability was observed in the estimated TLR values.

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