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Timberline formation and relationship with climatic variables of Indian central Himalaya: role of topography

Priyanka Sah[1], Subrat Sharma[2] & Shaik Rehana[1]

[1]Lab for Spatial Informatics, International Institute of Information Technology - Hyderabad, Gachibowli, 500032 Hyderabad, Telangana, India

[2]University of Ladakh, Leh 194 101 (Ladakh UT) India

Corresponding Author: Subrat Sharma - subrats@rediffmail.com

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Abstract

The young and rapidly rising Himalayas, with their diverse landscapes and ecosystems, are highly vulnerable to climate change impacts. This study explores relationship between spatially different timberline altitudes and geological regions of the Indian Himalayan region. First time, geological and topographical influence of mountainous terrain on formation of high-altitude timberline in the Indian Central Himalaya has been described. Total 2,750 km of timberline was mapped using Landsat 8 (30 m) satellite images. Timberline occurs between 2600m and 4365m amsl altitude in the Indian Central Himalayan region but predominance (~75%) was between 3200m and 3800m amsl. Geologically different regions have different representations of timberline altitudes. Maximum occurrence was in the Greater Himalaya (77% of the total timberline, mean timberline altitude 3599m asl) followed by the Lesser Himalaya (17%, mean altitude 3424m asl) and Trans Himalaya (6.3%, mean altitude 3723m asl). Timberline around summits which is far away from permanent snowline was not present in the Trans Himalaya, and was mostly present in the Lesser Himalaya (between two major geological faults). It was observed that occurrence of geological faults created habitats in greater number of Island Type Timberline (ITL), and also brought higher segmentation in Continuous Type Timberline (CTL). The average annual temperature was 9.9°C ± 3.41, ranging from 1.0°C to 18.3°C, with average annual rainfall of 1049 ± 183 mm, varying between 609 mm and 1448 mm. CTL areas had high rainfall peaks in July (275 mm) and August (269 mm), with lower winter levels, while ITL areas experienced consistently higher rainfall year-round, peaking in July (325 mm) and August (255 mm). CTL temperatures dropped significantly with elevation, from 3.7°C in January to below -5.5°C, whereas ITL temperatures remained milder and more stable, ranging from 1.4°C to 5.16°C. In the high ranges of Indian Central Himalaya, geological disturbances accounted for the segmentation in continuity and created habitats for isolated timberlines. These observations indicate that geological factors have a considerable role in giving shape to continuation of high elevation forests and upper limits of timberline. At local scale topography is an obvious way to size up the landscape and influencing distribution of high-altitude tree species.

Keywords: Himalaya, Timberline, Geology, Topography, APHRODITE, Climate,

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Preprint. Discussion started: 27 January 2025

1. Introduction

The Himalaya Mountain range, stretches over 2500 km from east to west (Le Forte 1975), were formed due to collision of Indian and Eurasian plates. Indian plate collided with Eurasia between 65 million years ago (Ma) and 45 Ma, and later on the uplift of the Himalayan Mountain ranges started (Powell & Conaghan 1973). During a long timeframe in the history of earth, geologically different ranges and mountains originated those appear form south to north in the following manner - as Siwalik Hills, Lesser Himalaya, Greater Himalaya, and the Trans Himalayan region (including Tibetan Plateau). Due to collision of plates and folding of earth crust altitudes were created which are important factor to create contrast in habitat, climate and flora.

Altitudes in Himalayan ranges rise abruptly, resulting in a diversity of ecosystems ranging from subtropical broadleaf forests to alpine meadows above the timberline. High elevation limit of forests (as the term described in this paper), represents one of the most conspicuous vegetation boundaries in mountains (Daubenmire 1954; Holtmeier 2009; Körner 1998). Forest vegetation in the timberline zone of the Indian Central Himalaya consists of three dominant physiognomic types (Singh and Singh 1987), i.e., Evergreen broad leaved (*Quercus semicarpifolia, Rhododendrons spp*.), Deciduous broad leaved (*Betula utilis*, *Acer spp., Pyrus spp*.), and Evergreen needle leaved (*Abies spp., Taxus baccata spp., Pinus wallichiana*), however, the spatial distribution and pattern of high-altitude timberline reflect the overreaching influences of geological history, lithology and landforms. Three types of treelines (climatic, orographic, and anthropogenic) have been described (Holtmeier and Broll 2005) where orographic timberline are located below the potential forest advance under given climatic conditions.

Climate, as a primary factor, controls geographic distribution of plants, influences ecology of vegetation, and changes are responsible for range shifts of plants (Forman 1964; Kumar 2012; Telwala et al. 2013). In mountains, heat and water conditions directly affect tree growth along the altitudinal gradients, and growth of trees has been strongly correlated with the environmental conditions (Nedlo et al. 2009; Liang et al. 2010). The position of the timberline/treeline depends on multi-factors, especially, the temperature is commonly held to be the main abiotic factor caused constrains the growth and regeneration of tree species (Körner 1998, 2003, 2012; Holtmeier and Broll, 2007; Jump et al. 2007; Harsch et al 2009). Globally, temperature limits of high-altitude treelines have been described (Körner and Paulsen 2004).

In recent years mapping of timberline in Himalaya has drawn attention due to its sensitivity to changing climate, and its potential use as indicator of climate change in mountains

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

(Bharti *et al*. 2011 & 2012; Singh *et al*. 2012; Barry1994; Kanka *et al*.2005; Sah et al. 2023b; Latwal et al. 2023). Remote sensing approach has advantages of synoptic view, repeated coverage and use of various sensors to identify the different objects. With few field observations this can be a significant tool in timberline mapping and monitoring. With advancement of geospatial techniques even canopy at treeline, and treeline ecotone have been explored (Danzeglocke 2005, Singh *et al.* 2012). Usual description of the timberline of the Himalayan region is that runs parallel to the permanent snowline below the alpine meadows in the inner Himalayan ranges (having permanent snowline), however, Sah and Sharma (2018) described timberline habitats in the Himalayan region far away from the usual occurrence. These timberlines exists below or above the altitude which was not perceived by the field biologists for regional section of the Himalaya. Based on spatial locations (i.e., spatial arrangement) and distance from permanent snowline, these have been described as (i) Continuous Timberline (CTL, which runs parallel to the permanent snowline in the inner Himalayan ranges), and (ii) Island Timberline (ITL, around small summit regions, away from the permanent snowline in outer Himalayan ranges where permanent snow does not occur). The later ones have not been described in any global datasets on treeline/timberline.

Temperature and precipitation are crucial in governing timberline dynamics, especially in climate-sensitive transition zones, where warming is expected to cause timberlines to shift upslope (Harsch et al., 2009). Climatic conditions in mountains are related to the elevation and locations, where altitude causes steep environmental gradients, particularly in the Himalaya (Singh et al. 2018). The present study explores (i) topographical influence of mountainous terrain on presence of timberline in the Indian Central Himalayan region, (ii) describes spatial and temporal variation of timberline in different geological formations of the regions, and (iii) relates the climatic parameters with timberline elevations.

2. Study Area

The Himalayas has main three thrust faults that formed during isostatic adjustment: The Main Central Thrust (MCT), The Main Boundary Thrust, and The Main Frontal Thrust (MFT). The MCT is a mylonitic zone separating the Higher Himalayan crystalline from the lower Tertiary sediments in the Lesser Himalayas and MBT divides the Nappes of the Lesser Himalaya from the Siwalik (Korup *et al*.2006).

Indian Central Himalaya (Uttarakhand State) extends between latitude $28^0$43’N and $31^0$28’N and longitude $77^0$34’E and $81^0$03’E, and is spread in an area of about 53,483 km^2. Geologically, from south to north, the region can be divided into (i) Siwalik hills separated by

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

Main Boundary Fault towards north (ii) Lesser Himalaya, where most of the human settlement occur, moderate slopes largely below 2500m asl are separated by Main Central Thrust towards north, (iii) Greater Himalaya is located north of the Main Central Thrust, where some of the highest peaks of the world occur, and (iv) Trans Himalaya. The drainage system is part of The *Ganga* River system of Indian Himalayan region in which various rivers and tributaries (snowfed and rainfed) originating from different watersheds contribute.

The Siwalik (i.e., outer most ranges) is the youngest part of the entire Himalayan region and structurally characterised by broad open folds and comprises a series of parallel ridges (Sharma 1989), Geographically it corresponds to the Siwalik range- foothills ranging in elevation from 250-1000m.The lesser Himalayan zone lies between the Main Central Thrust (MCT) and Main Boundary Thrust (MBT). The greater Himalaya situated at an altitude of 3000m to over 7000m (Sorkhabi 2010). The Trans-Himalaya is the rain shadow region just behind the main peaks of the towering Himalayan Mountains, it includes the Tibetan Plateau, the Ladakh, etc.

Nearly 45% of the total study area is under forests (FSI 2015). The two third of the mountainous landscape (66.8%) has an altitude of less than 2500m asl (Sharma & Phartiyal 2014). Altitudinal zonation of the state between 2500m (lower limit of occurrence of high-altitude forest types) and 4500m asl (upper limit of forests) indicates that only 17% area of the state is available for forest types occurring in high elevations (Fig. 1), and 16.2% of the area in the state is above 4500m asl which is occupied largely by permanent snow, glaciers, rocks, and moraines (Sah & Sharma, 2018).

3. Data and Methodology

The methodology employed in extracting temperature and precipitation data from the APHRODITE dataset and timberline mapping aligns with previous studies conducted by Sah & Sharma (2018), , Latwal et al. (2023), and Sah et al. (2023a, 2023b).

3.1 Timberline Mapping

Methodological approaches for mapping of timberline were adopted by following Sah & Sharma (2018), Latwal et al. (2018) and Sah and Latwal 2022 which involves several stages including data selection, pre-processing such as radiometric and geometric correction, and the delineation of the timberline through visual interpretation. Satellite images from Landsat 8 (Table 1), with a spatial resolution of 30 meters, were used to derive timberline for the year 2015. Digital Elevation Model (DEM) sourced from ASTER data, also with a 30-meter

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

resolution, from the United States Geological Survey (USGS) portal (https://earthexplorer.usgs.gov/) for extracting the timberline elevation.

In the challenging terrain of the Himalaya mountains, characterized by rugged topography, a knowledge-based interpretation technique was applied to the satellite images to delineate the timberline (Sah & Sharma 2018; Latwal et al. 2018; Sah and Sharma 2023). This approach, relying on visual interpretation, was preferred due to the difficulties auto-extraction methods face in such complex landscapes. The timberline was identified by tracing an isoline that connects the highest edges of forests. Natural obstacles such as landslides and rocks caused breaks in this line. At few locations of CTL and ITL timberline ground observations were taken for validation of satellite based timberline mapping, and for inaccessible sites high-resolution Google EarthTM images were used for verification. The elevation, aspect, and slope of timberline were extracted by merging the timberline data (line in GIS) with the DEM. ArcGIS was employed for spatial analyses and for extracting attribute data related to the timberline across the study area. Topography, including slope, aspect, and elevation, was identified as a significant factor influencing the presence of the timberline.

3.2 Timberline Climate and homogeneity

Following Latwal et al. (2023), a temporal change analysis covering the period from 1976 to 2015 was done for both continuous and isolated timberlines in Sikkim Himalayan Region. The changes observed were categorized as either 'shift' (upward movement) or 'no change' (stationary position) relative to the base year, 1976. Data scarcity is a prevalent issue in the Himalayan region, particularly regarding meteorological data, especially in higher elevations. To address this, various gridded and modelled datasets were explored for the present study.

Among the available options, the APHRODITE (Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation) daily gridded precipitation dataset stood out. This dataset offers long-term coverage from 1951 onwards and covers a continental-scale area, including the Himalayas and surrounding regions. It integrates data from a dense network of daily rain-gauge observations, providing a valuable resource for studies related to climate change, water resource assessment, statistical downscaling, and model validation (Yatagai et al. 2012; Sah et al. 2023b; Latwal et al. 2023).

The APHRODITE precipitation data, with its extensive historical record and high spatial resolution, was preferred over other options, such as the high-resolution Worldclim dataset (e.g., 1x1km) or lower-resolution data from IMD (grided data at 1° resolution). This

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

preference was due to its suitability for various applications and its reliability as a benchmark for gridded precipitation estimations.

To obtain air temperature (daily mean) and daily precipitation (rainfall) data at timberline altitudes of Indian Himalayan Region, gridded data with a resolution of 0.25° from APHRODITE for years 2015 were extracted. Annual mean temperature and total annual rainfall were then derived from these daily datasets. Temperature in mountainous regions varies significantly due to topographic factors across different months (Barry 1992). To understand these variations, climatic variables (mean of Temperature and Precipitation) were calculated along the timberline altitude for monthly basis. This approach provides a comprehensive view of timberline climatic conditions throughout the year (2015). To extract the temperature and precipitation along the timberline altitude the bilinear interpolation algorithm was used due to its computational efficiency and quality (Dilip et al. 2014). It is particularly useful for downscaling meteorological input data which are already gridded (Schulla and Jasper 2007). This interpolation was employed to harmonise the resolutions of the temperature and precipitation datasets, ensuring compatibility for analysis purposes. This interpolation technique, known for its computational efficiency and accuracy, was particularly useful for downscaling meteorological input data that are already gridded.

One Automatic Weather Station (AWS) at the timberline altitude is installed (Tunganath). Observed data of AWS and the point data from APHRODITE were compared and monthly rainfall and temperature, and the coefficient of determination (R^2) was calculated to determine relationship between the AWS and Aphrodite data. Additionally, the p-value was computed for regression to assess the statistical significance of the observed correlations. The linear regression analysis revealed a strong correlation between the AWS and Aphrodite datasets for both rainfall and temperature. For rainfall, the R^2 value of 0.92 with a statistically significant p-value < 0.001 indicates a strong relationship between observed and gridded data. Similarly, the temperature data showed an R^2 value of 0.85 and p-value < 0.001. These results demonstrate that Aphrodite effectively captures the seasonal trends observed in both rainfall and temperature, confirming its reliability for monitoring climatic patterns, despite some discrepancies in absolute values.

4. Results

4.1 Spatial attributes of timberline

The total running length (2,750 km) of the entire timberline of the Indian Central Himalayan region, was broken at several places due to topographical barriers. The total

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

mapped timberline was divided into 91 segments of CTL and presence of 32 segments of ITL in far locations. The total mapped timberline in the Indian Himalayan region is divided into 91 segments of CTL and 32 segments of ITL. The mean timberline elevation (hereafter TLE) of the entire length (including both types i.e., CTL & ITL) was 3570m asl (±248m) (Sah & Sharma 2018).

4.2 Timberline: Different Geological Landforms

This study first time describes study presents first time spatial distribution of Himalayan timberline in geologically different mountain ranges (Trans Himalaya, Greater Himalaya, and Lesser Himalaya, Fig. 2) and their influence. From north to south of the Himalaya, timberline occurrence was minimal (6.3% of the total timberline) in the Trans Himalayan region due to very high altitudes and arid climate. Occurrence of the natural trees is limit to some valleys and extensions. In this region of the Indian Central Himalaya, minimum and maximum elevations of timberline were 3043m and 4365m asl, respectively, with a mean timberline elevation of 3723m (±242m). Maximum presence of trans-Himalayan timberline (56% of the total) was between an altitudinal range of 3600-4000m asl (Fig. 3). In the trans-Himalayan region, only CTL was present, at 28 locations. The total length of the CTL was 172 km (representing 6.3% of the total timberline of the Indian Central Himalaya, and 6.9% of the total CTL type of the study area).

In south to the Trans-Himalayan region, Greater Himalayan region hosts the maximum length (77%) of the total timberline of the Indian Central Himalayan region. In this region, minimum and maximum elevations of timberline were 2602m and 4364m asl, respectively, and mean timberline elevation was 3599m (±229m), which was nearly 150m lower than the Trans-Himalayan region. The maximum timberline in this region (63% of the Greater Himalaya) occurred between an altitudinal range of 3400-3800 m asl (Fig. 3), and this region hosts both types (CTL and ITL) of timberlines but more of the CTL. The total length of CTL was ~2018 km (73% of the total timberline of the Indian Central Himalayan region, and 81% of the total CTL). This CTL type in the Greater Himalayan region was present at 86 locations. The total length of ITL in this region was 100.4 km (3.7% of the total timberline of the Indian Central Himalaya, and ~38% of the total ITL). ITL in the Greater Himalya consisted of 16 island-type habitats around summits of the Greater Himalayan Region away from the permanent snow.

Further south to the Great Himalayan ranges, the Lesser Himalayan region has only ~17% of the total timberline of the Indian Central Himalaya. In this region, minimum and maximum elevations of timberline were 2601m and 4153m asl, respectively, and mean

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

timberline elevation was 3424m (±248m), nearly 150m below the mean timberline elevation of the Greater Himalaya. From south to the north of the Himalayan ranges, mean timberline elevation increases (3424m>3599m>3723m) indicating range of altitudinal habitats due to high elevations but total suitable area (appropriate altitude and moisture) is limited in the middle range, i.e., Greater Himalaya.

75% of the timberline length (maximum) of the Lesser Himalayan region occurred between altitudinal range of 3200-3600 m asl (Fig. 3), and both types (CTL and ITL) of timberline were present. The total length of CTL was ~295km (~11% of the total timberline of the Indian Central Himalaya, and 12% of the total CTL). This CTL type was present at 17 locations. The total length of ITL in the Lesser Himalayan region was 164.6 km (6% of the total timberline of the Indian Himalayan region, and 62% of the total ITL). ITL in the Lesser Himalaya consisted of 22 island-type habitats around summits of the Lesser Himalaya.

Broad ranges of the Indian Central Himalaya have many numerous geological faults within, those have played a role in developing summits with high elevations in outer ranges. This is apparent from presence of more locations of ITL type of timberline (surrounding of a summit, Fig. 4), which has higher presence at lower altitudes. Due to these inconsistency in the landforms, high segmentation of CTL was also observed. In the high ranges, geological disturbances account for the segmentation and presence of isolated timberlines. These observations indicate that geological factors have a considerable role in giving shape to high-elevation forests and formation of spatially distinct timberlines in the Himalayan region.

4.3 Temperature and Rainfall at Timberline Altitudes (Annual and Monthly Pattern)

4.3.1 Annual mean temperature and total rainfall

The annual mean temperature and total annual rainfall of year 2015 in the different altitudinal bands of entire timberline altitudes are presented in Fig. 5. Average annual mean temperature for entire timberline altitudes was 9.9℃ ± 3.4℃, average annual rainfall was 1049 ±183 mm. In general, temperature and rainfall at timberline altitudes was decreasing with increasing altitude (temperature r^2=0.88, precipitation r^2=0.87).

Among the two spatially different timberlines, ITL altitudes (isolated peaks away from the permanent snowline) were warmer (Fig. 6a) than the same timberlines altitudes of CTL (close to permanent snowline). Average annual mean temperature at ITL altitudes was 14.3℃ ±1.2℃ (range 10.4 - 18.3℃ among the different altitudinal bands) while this value was 9.5℃ ± 3.2℃ (average) at CTL altitudes (range 1.0 - 17.0℃). This indicates that timberline habitats in outer Himalayan ranges (ITL) are warmer than the inner Himalayan ranges (CTL) which are

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

close to permanent snow and extending more high elevations than the former. This has direct implications in the outer Himalayan region on account of temperature change over the years, temperature lapse rate on the face of global warming, and anthropogenic activities.

However, CTl altitudes occur in larger elevational gradient (2600-4400m) than the ITL altitudinal gradient (2600-3900m), former receives total rainfall of 1043 mm along the gradient while it was nearly 50mm more in the shorter gradient of ITL. At a given elevation, the climatic parameters may differ considerably based on location, which in the present case is primarily distance from the snowy mountain ranges (i.e. permanent snowline). This difference is noticeable when comparing the timberline altitudes in the outer and inner ranges of Himalayan mountains. Lower altitudes of outer Himalayan ranges receive less rainfall than the similar altitudes in the inner Himalayan timberline altitudes (Fig. 6b) but this trend reverses above 3100m of timberline altitudes.

The annual rainfall decreased sharply with elevation in inner mountain ranges where CTL occurs than in outer mountain ranges where largely ITL occur (Fig. 6b). Local topography of timberline altitudes plays role in receiving rainfall (formation of local clouds or mountain barriers) hence at certain altitudinal bands dip or peak in rainfall appears along elevational gradient. The difference in rainfall increases with increase in elevation.

To compare the topographical influence on similar altitudes we took the common altitude band (CTL and ITL) from 2600m to 3900m. The outer Himalayan timberline altitudes, (largely ITL), appear to be warmer (exposed to the plains of India) and drier than the inner Himalayan timberline altitudes (mostly CTL), and this contrast becomes more pronounced towards higher elevations with reverse trend of precipitation. In this altitude band ITL were 1.3-4.8 °C warmer than the same band of CTL.

4.3.2 Monthly mean temperature and total monthly rainfall

Mean monthly temperature at elevational bands of CTL and ITL altitudes are presented in Fig. 7. Role of topography in local climate appears more on ITL altitudes (resulted from various fractures and abrupt summits of timberline habitats and aspects in the outer Himalayan ranges) where monthly temperature does not follow the altitudinal pattern (decrease in temperature with increase in altitude, however in dominating high altitude elevations of CTL altitudes in the inner Himalayan region this rule is followed (Fig. 7). Both side of the summer months (May-June), mean monthly temperature declines in very high regions of the CTL altitudes sub-zero temperature prevails for 3-4 months, however is not true for the same elevations of ITL altitudes (Fig. 7). To compare the role of locations we compared average temperatures of ITL and CTL between 3000-3500 m asl. Difference between the mean of CTL

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

and ITL was 3.7°C, which highlights a clear contrast between the Outer and Inner Himalayan Timberline altitudes. It is apparent that ITL consistently experiencing higher temperatures, in comparison to similar elevations of CTL. This temperature difference is crucial for understanding the climatic conditions that influence vegetation and ecosystem dynamics in the timberline zones of the Himalayan region.

Monthly rainfall in months of the year 2015 at different types of timberline altitudes are given in Table 2 and 3. Due to monsoonal pattern of climate, maximum rainfall occurs during the months from June to August, however, pre-monsoon month of March also received substantial rainfall at CTL altitudes (Table 2). Months of November and December were relatively dry months in the year 2015. Largely, a decrease in rainfall was observed with increase in CTL altitudes but at ITL altitudes due to topography (see altitude map in Fig. 1 for outer Himalayan ranges where most of the ITL occurs) elevations above 3200m asl receive more rainfall than the lower altitudes (Table 3) of timberline presence which is not true for same altitudes of CTL presence.

Overall, while both timberlines experience seasonal shifts, ITL areas receive consistently higher and more variable precipitation compared to CTL zones, reflecting their distinct climatic influences and hydrological dynamics. The Outer Himalayan Timberline (ITL) experiences warmer, more stable temperatures and higher, more variable rainfall compared to the Inner Himalayan Timberline (CTL). These differences reflect distinct climatic and hydrological conditions between the two zones, with ITL showing greater seasonal variations.

4.4 Climate (Annual mean temperature and total rainfall) at timberline altitudes of different geological ranges (Trans-, Greater- and Lesser Himalayan regions)

This study first time develops a relationship between the geological locations and timberline altitudes by analyzing the local climatic factors (temperature and rainfall in this case). Impact of location is clearly visible on climate of timberline altitudes (Fig. 8) which were more pronounced for mean annual temperature at different CTL altitudes of Trans- (4-6^{o}C), Greater- (8-11 ^{o}C), and Lesser Himalayan regions (12-16 ^{o}C) (Fig. 8a). Mean annual temperature at ITL altitudes (not present in the Trans-Himalayan region) of different geological ranges (Greater and Lesser Himalaya) were close (14-15 ^{o}C) to CTL altitudes of Lesser Himalayan region upto 3100m elevation but after that almost one degree less than the CTL altitudes of Lesser Himalayan region (Fig. 8a).

Impact of geological regions for total annual rainfall at timberline altitudes was more profound (Fig. 8b) particularly among the CTL altitudes. Total annual rainfall along altitudinal gradient of CTL presence varied considerably between Lesser Himalayan CTL (highest among all the CTL altitudes, ~1400mm) and Trans-Himalayan CTL altitudes (800-1000mm) while Greater Himalayan CTL lies in between (1000-1200mm) as it is physically present. ITL altitudes in Greater and Lesser Himalayan region behave closely on both the regions while overlapping at different altitudinal gradients of two geological regions (Fig. 8b). ITL annual rainfall among different geological regions falls within the range of 800mm to 1200mm (high on lower altitudes).

5. Discussion

This study provides a comprehensive analysis of timberline dynamics in the Indian Central Himalaya, focusing on its spatial distribution, geological influences, and climatic relationships. The findings reveal significant variation in timberline characteristics across different geological regions, viz., the Trans Himalaya, Greater Himalaya, and Lesser Himalaya. Timberline patterns are shaped by a combination of climatic conditions (temperature and precipitation), geological factors, and topographical influences. The studied timberline is primarily influenced by climate, as evident by the relationship between the location and elevation of existing forests (Fig. 8), making it a key ecological and vegetation boundary (Körner and Paulsen, 2004, Schickhoff, 2005; Korner, 1998). Geology play a significant role in timberline distribution in the Indian Central Himalaya, with regions featuring more geological faults exhibiting a higher number of island timberlines altitudes (ITL) and increased segmentation in continuous timberlines (CTL). This suggests that tectonic activity and geological disturbances contribute to create timberline habitats and fragmentation in high-elevation forests. Mass elevation effect of Himalaya (created due to tectonic activities) contributes to the highest treeline in the Northern Hemisphere, located on the southeastern Tibetan Plateau. Role of topography is more pronounced as apparent from influence of latitudinal presence (outer and inner Himalayan ranges in the present case) and mountain heights on timberline variation. In Scandinavian mountains, latitude explained 71% of the variation, while mountain height contributed nearly 20% (Odland, 2015).

Climatic conditions further influence timberline patterns, as ITL areas of outer Himalaya which are warmer and receive more rainfall than CTL regions closer to the permanent snowline in the inner Himalaya. Gradients of temperature and precipitation along altitudinal gradient illustrates how timberline elevation responds to local climate variations.

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

ITL regions experience a more moderate and variable climate, leading to consistently higher precipitation and warmer temperatures. In contrast, CTL regions face more extreme temperature variations and less consistent precipitation. Latwal et al. (2023) found that ITL sites in the Eastern Himalayan region warm more rapidly than CTL regions. The differential response highlights the greater resilience of ITL areas compared to the climate-sensitive CTL regions.

Rainfall plays a crucial role in influencing tree growth, phenology, and treeline dynamics. For example, regions of central and north-western Tibetan Plateau, having 50–300 mm of annual rainfall (Liao, 1990; Wang et al., 2011; Zhang et al., 2002; Zheng and Li, 1990), hosts highest treeline in the southeastern Tibetan Plateau (Yao and Zhang, 2015) while 500 mm of annual precipitation is needed for tree growth in this region (Hou, 1982a, 1982b).

Change in climate has been observed across the Himalayas and surrounding regions. In the Hindu Kush-Himalaya (HKH) region, a slight decline in precipitation was observed over a 114-year period but an increase in between (Ren et al., 2017). Between 1977 and 2015, total annual precipitation at the Island Timberline (ITL) and Continuous Timberline (CTL) increased at rates of 192 mm/decade and 96 mm/decade, respectively (Latwal et al., 2023). These rates surpass the observed increase of 49.6 mm/decade in annual precipitation between 1957 and 2005 at a lower altitude (1765 m asl) in Gangtok (Kumar, 2012). In contrast, Singh et al. (2018) reported a decreasing trend in annual cumulative precipitation, at a rate of 206.5 mm/decade, for the period from 1977 to 2013, based on IMD gridded data. This variability in precipitation trends across studies highlights the complex and region-specific nature of rainfall patterns in the Himalayas.

European Alps have experienced a temperature increase (+0.7°C) over the last century with more warming at higher elevations (Hansen et al., 2006). Himalayas have been warmed by 1.5°C between 1982 and 2006, with winter warming at 0.07°C per year and summer warming at 0.03°C per year (Shrestha et al., 2012; Peili et al., 2020). Studying moisture and seasonal variations, provides crucial insights into timberline dynamics in data-sparse alpine regions (Joshi et al., 2024). Trend of pre-monsoon warming, accompanied by rainfall, is thought to promote seedling establishment and facilitate the upslope movement of treelines in the Himalayan region (Singh et al., 2019). While temperature typically decreases with elevation, the relationship between elevation and moisture varies across regions, with moisture availability declining more sharply in the inner ranges of Indian Central Himalayan region (Latwal et al., 2023) but the present study describing the variations in timberline altitudes and geological locations underlying the problem of complicating predictions when predications are made only climate-induced timberline shifts (Tiwari et al., 2017; Schickhoff et al., 2015). Findings of present study highlight the complex interplay of temperature, moisture, and topography in shaping timberline dynamics across the Himalayan subregions.

The observed differences in timberline altitudes and climatic conditions align with broader trends in mountain ecosystems, where altitude, temperature, and precipitation are critical determinants of timberline position. The results of this study are aligned with previous studies on treeline dynamics (Holtmeier & Broll, 2005; Körner, 1998) and emphasize the importance of geological and climatic interactions in shaping timberline boundaries. This highlights the need for integrated approaches in understanding mountain ecology and climate change impacts. Himalayan studies require more robust long-term data to assess the response and position of timberlines to climate change.

Conclusion

This study presents the first examination of the geological and topographical factors in mountainous terrain those influence the formation of high-altitude timberlines in the Indian Central Himalaya. Landsat 8 satellite images were used to derive the two types of timberlines i.e., CTL and ITL. The results lead to the following conclusions:

- The Greater Himalayan region contained the majority (77%) of the total timberline, while only 6% was present in the Trans Himalayan region, and 17% in the Lesser Himalayan region.
- No timberlines were observed in the Siwalik Hills, indicating that tectonic activities could not make such thrust which can create elevations suitable to host high altitude timberlines.
- At a regional scale, both climate and geology play crucial roles in determining timberline distribution. However, at a local scale, topography is a key factor that shapes the landscape and significantly influences the distribution of tree species.

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Author contributions

Subrat Sharma contributed to the research idea and supervised the research analysis. Priyanka Sah is responsible for the material preparation, data analysis, and interpretation. Shaik Rehana contributed to the climatic analysis. All the authors contributed to writing of the paper and all of them read and approved the final manuscript.

Credit authorship contribution statement

Priyanka Sah: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Subrat Sharma: Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. Shaik Rehana: Writing – review & editing, Supervision, Investigation, Resources, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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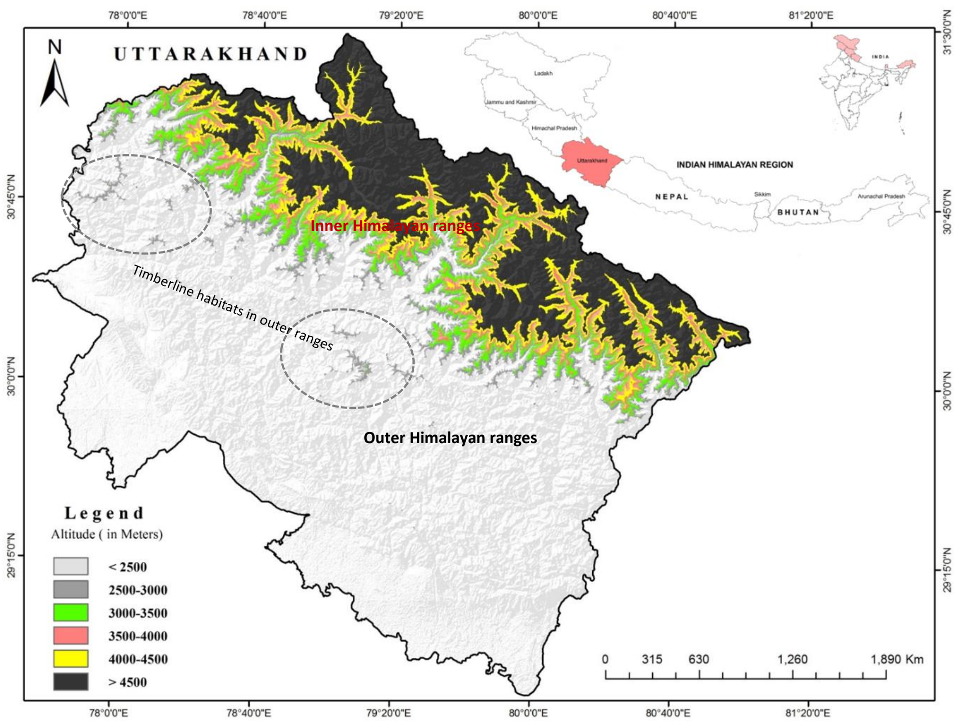

Figure 1. Indian Central Himalayan Region (largely spread over Uttarakhand State in Indian mountains) and altitude zones of the region (Sah and Sharma, 2018).

https://doi.org/10.5194/egusphere-2024-3155
Preprint. Discussion started: 27 January 2025

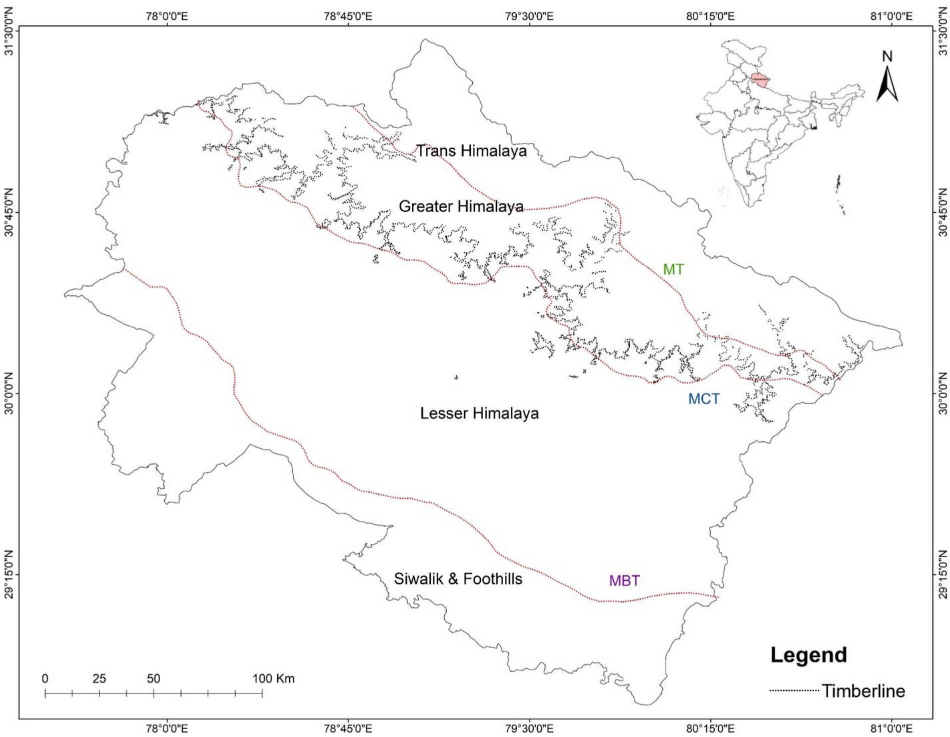

Figure 2. Spatial distribution of Timberline in different geological ranges of Indian Central Himalaya. MBT= Main Boundary Thrust separates “Siwalik” ranges with mountains of “Lesser Himalaya”. MCT= Main Central Thrust separates “Lesser Himalayan ranges” to the “Greater Himalaya”. MT= Main Thrust lies between Indian plate and Eurasian Plate, north of the MT is Trans-Himalayan region which includes part of Tibetan Plateau.

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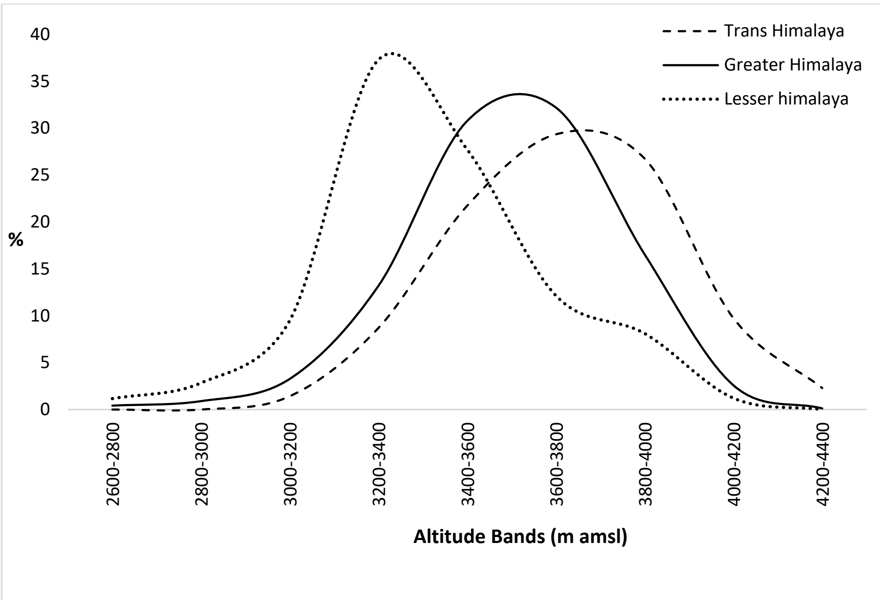

Figure 3. Distribution of mapped timberline altitude (Fig. 2) along elevational bands in different geological mountain ranges of the Indian Central Himalayan Region.

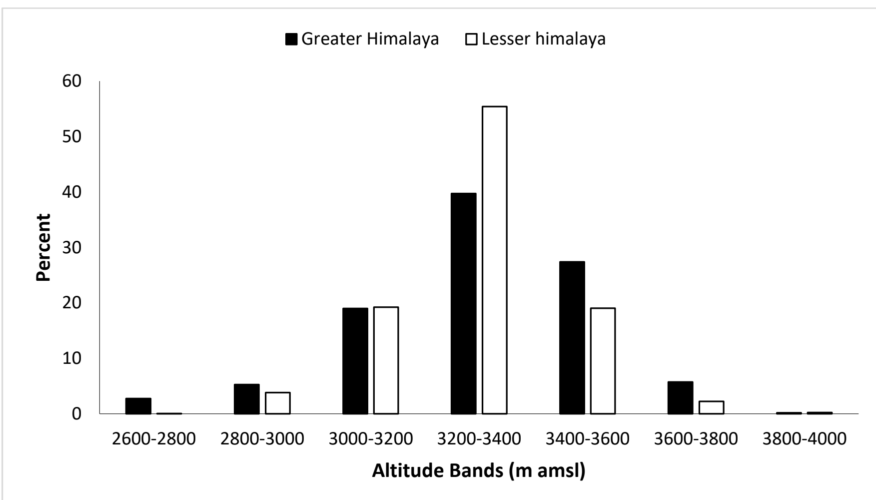

Figure 4. Distribution of Island Type Timberline (*ITL, see Introduction for description of this type*) along elevational bands in different geological mountain ranges of the Indian Central Himalayan Region.

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Preprint. Discussion started: 27 January 2025

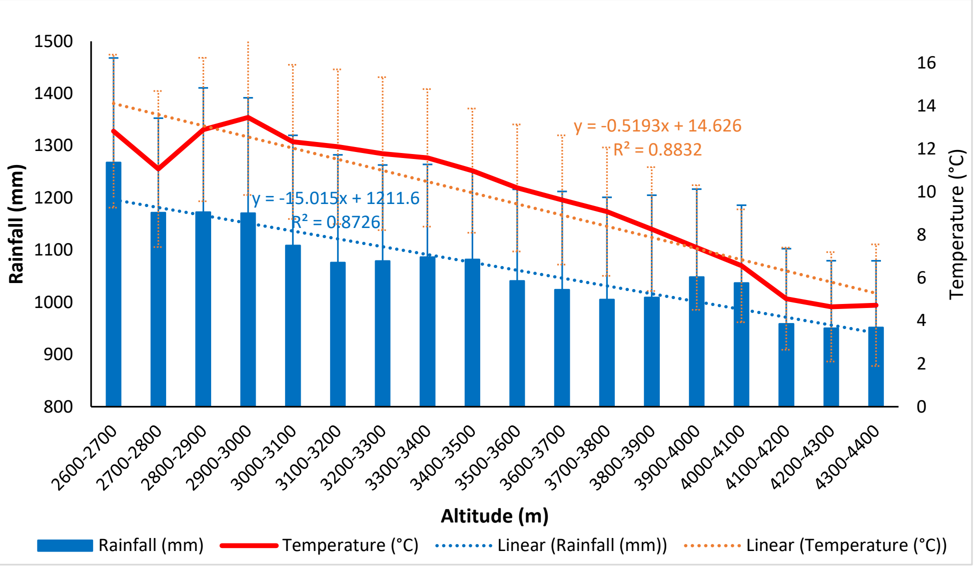

Figure 5. Annual mean temperature and total annual rainfall (Year 2015) along altitudinal bands of timberline mapped in the Indian Central Himalayan region.

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Preprint. Discussion started: 27 January 2025

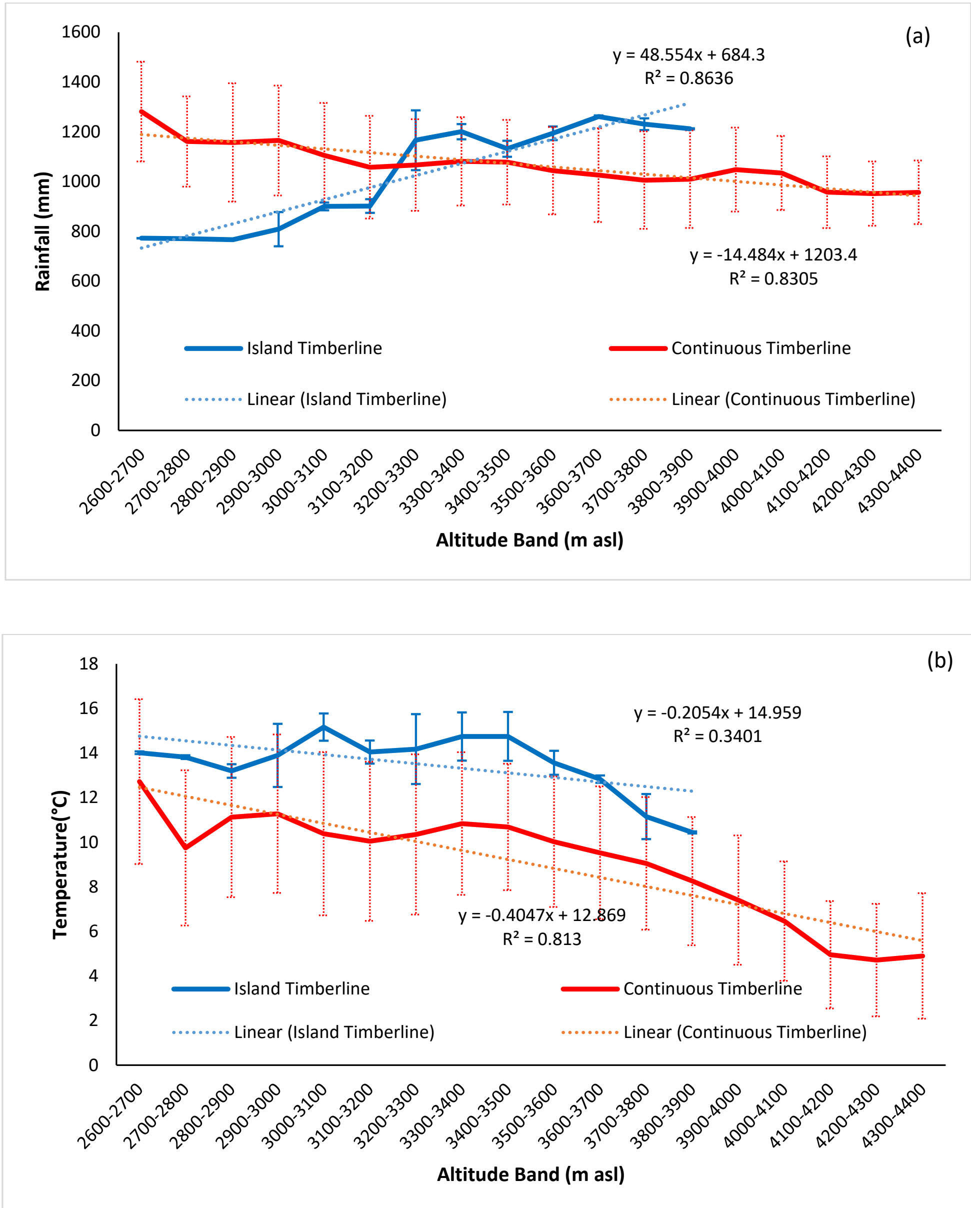

Figure 6. Annual mean temperature and total annual rainfall (b), in the year 2015 in elevation bands of two different types of timberline altitudes. (a) Continuous- (CTL), and (b) Island Type Timberline (ITL). (*See Introduction for description of these type*).

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Preprint. Discussion started: 27 January 2025

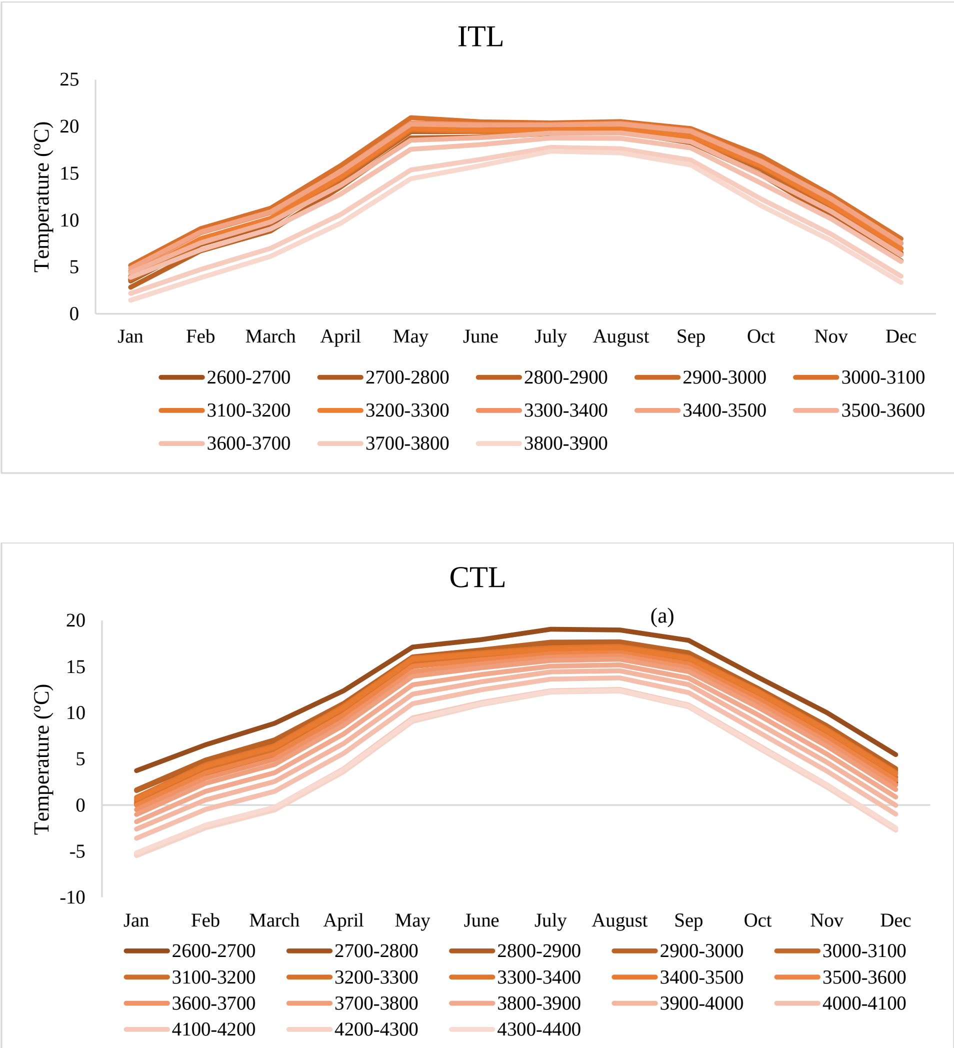

Figure 7. Mean monthly temperature in the year 2015 in various altitudinal bands of two different types of timberline [Continuous- (CTL), and Island Type Timberline (ITL)]. (*See Introduction for description of these type*).

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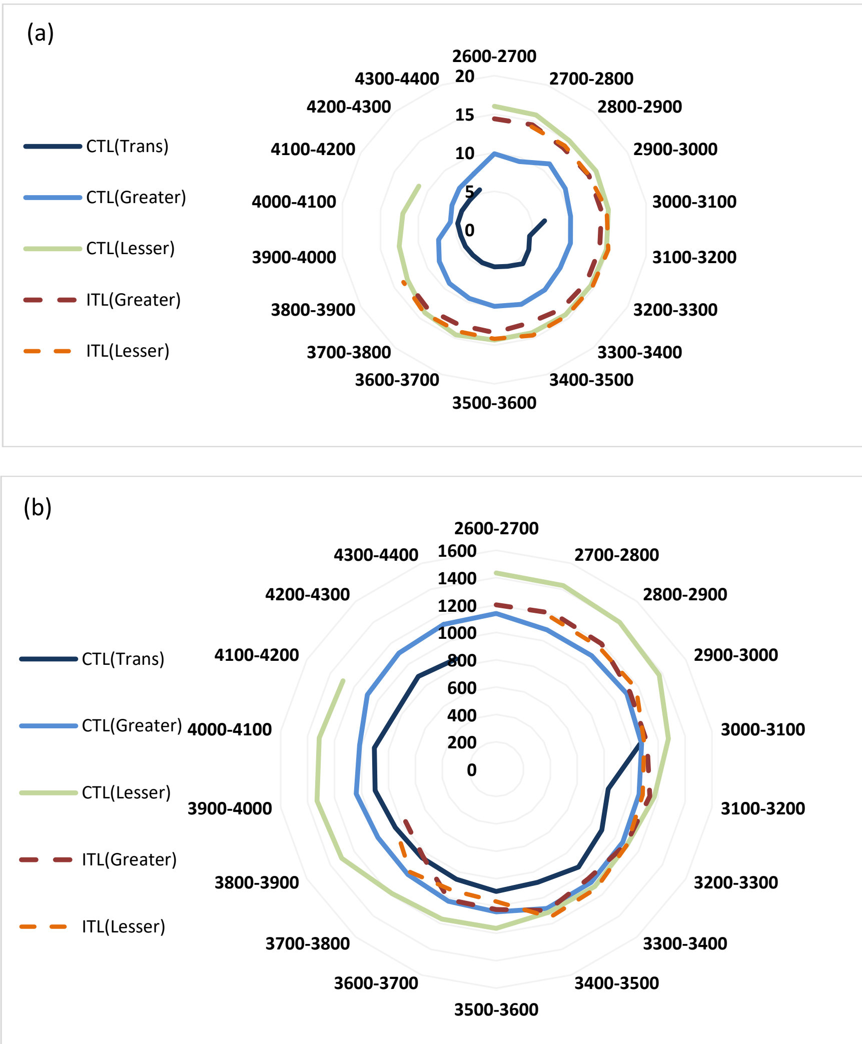

Figure 8. Comparison of Annual Mean Temperature (a) and Total Rainfall (b) in the year 2015 distributed in various elevation bands of two different types of timberline altitudes [Continuous- (CTL), and (b) Island Type Timberline (ITL), *see Study Area for description of these type*] located in various geologically different mountain ranges of Trans-, Greater- and Lesser Himalayan region.

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Table 1. Specification of Landsat 8 satellite data used for timberline mapping

Satellite/Sensor	Date of Acquisition	Resolution(m)	Scene ID
OLI/TM	2015-12-15	30/15pan	LC81440392015349LGN00
	2015-11-20	30/15pan	LC81450392015324LGN00
	2015-12-22	30/15pan	LC81450402015356LGN01
	2015-12-29	30/15pan	LC81460382015363LGN00
	2015-12-29	30/15pan	LC81460392015363LGN00

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Preprint. Discussion started: 27 January 2025

Table 2. Average monthly rainfall in different altitudinal gradients of Continuous Timberline in the year 2015.

Altitudinal Bands (m asl)	Rainfall in different Months (mm)											
	Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
2600-2700	74	76	151	83	53	195	275	270	78	22	1	3
2700-2800	72	84	146	69	45	167	260	234	60	18	1	4
2800-2900	70	83	145	70	45	170	256	232	60	18	1	6
2900-3000	71	86	146	69	44	168	264	234	58	18	1	6
3000-3100	70	88	145	64	42	156	252	213	50	16	2	7
3100-3200	68	90	144	60	41	146	241	199	46	15	2	8
3200-3300	67	90	143	59	40	145	249	204	45	15	2	8
3300-3400	67	90	141	59	39	147	257	210	44	15	2	8
3400-3500	67	90	141	58	39	147	257	209	43	15	2	8
3500-3600	66	91	140	57	39	139	244	199	43	14	2	8
3600-3700	67	92	141	58	39	136	234	191	43	14	2	8
3700-3800	66	93	141	56	39	131	227	185	43	13	2	8
3800-3900	67	92	141	57	39	134	226	186	44	14	2	7
3900-4000	71	88	143	60	39	147	238	196	45	15	1	5
4000-4100	71	90	142	58	38	144	234	192	44	15	1	5
4100-4200	67	95	136	49	35	127	217	172	38	12	1	6
4200-4300	69	96	137	49	35	126	213	169	38	12	1	5
4300-4400	69	96	141	52	39	128	206	165	41	12	2	6

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Preprint. Discussion started: 27 January 2025

Table 3. Average monthly rainfall in different altitudinal gradients of Island Timberline in the year 2015.

Altitudinal Bands (m asl)	Rainfall in different Months (mm)											
	Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec
2600-2700	58	116	154	50	37	59	132	96	36	7	6	19
2700-2800	58	116	154	49	37	59	131	95	36	7	6	19
2800-2900	58	118	154	49	37	59	129	93	36	7	6	19
2900-3000	57	112	149	50	38	65	153	116	36	8	6	19
3000-3100	52	96	130	51	40	82	210	172	35	9	4	18
3100-3200	50	90	119	48	39	92	222	181	33	9	3	15
3200-3300	63	88	125	50	35	158	326	255	40	15	2	8
3300-3400	72	81	140	56	32	190	322	245	40	18	1	3
3400-3500	70	69	146	62	36	191	281	214	40	19	1	2
3500-3600	78	65	159	80	49	211	257	217	55	22	1	2
3600-3700	81	67	163	88	53	218	265	237	65	22	1	2
3700-3800	78	79	156	79	52	186	263	245	70	21	0	2
3800-3900	77	85	152	74	51	170	261	247	72	20	0	2