Trans. Inst. Indian Geographers
ISSN 0970-9851
Indexed in Scopus

Objective climate classification of Himachal Pradesh and Punjab: A clustering based approach

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Abstract

Delineation of climatic zones within a wider geographical area assists in understanding climatic behaviour. Climate categorization is not purely a mathematical objective procedure as the boundary between climatic divisions is mostly adjusted subjectively. Several climate classifications have been proposed based on empirical and observational data from stations or observatories. So far, climate research has mostly concentrated on large areas but has failed to address climatic zonation at the local scale. As a result, large spatial scale studies fail to represent true local climate. This is especially true of mountainous areas, where climatic controls vary significantly due to topographical complexity and the localized influence of the atmosphere. Therefore, an understanding of local climates is treated important which may improve global climate impact assessment. In this study, the climatic regions in parts of north western India were identified. Regularized gridded data (temperature and precipitation) provided by India Meteorological Department (IMD) was used for regionalization for the reference period 1986-2015. The climatic regionalization was done through an objective process of 'k means clustering' approach where Himachal Pradesh and Punjab were divided into five thermal regions and nine precipitation regions. However, the final decision on number of climatic zones was subjected to visual interpretation by taking into account local topographic characteristics. This study is based purely on climatic data while the boundaries were adjusted subjectively with an expertise of local climate.

Keywords: *Climatic zones, gridded data, regionalization, clustering.*

Introduction

Climate of a region is expressed by elements of weather and topography; it is an expression of long-term average atmospheric conditions that have a compelling influence on ecosystem functioning and human activities. Climate is mutable and its character changes under natural as well as anthropogenic influences leading to shift in seasonality, change in variability and manifestation of extreme events (Talchabhadel *et al*, 2018). Such climatic changes in turn trigger alterations in agricultural patterns, productivity, ecosystem functioning, water regime, economy and more importantly human health and well-being (Fraedrich *et al*, 2001; Aparecido *et al*, 2016)

A region with homogenous atmospheric elements constitutes one climate zone (Júnior and De Carvalho, 2012). The demarcation of climatic zones within a larger geographical space helps to understand climatic behavior besides modelling regional climate (Kalvova *et al*, 2003) for projected patterns and implications. Climate classification is not an objective process of producing mathematical results; the boundaries between climate regions to a large extent are determined subjectively. So far, many climate classifications have been proposed based on empirical and observational data of limited stations/observatories. However, in the wake of ongoing environmental problems like ozone depletion, increase in greenhouse gases (GHGs), observed and projected global warming scenarios, heat stress, and many other related extreme events, the information on changing nature of climate character in any region needs to be updated. The most common global climate classifications available are those of De Martonne (1926), Koppen (1936), Thornthwaite (1943), Flohn (1950), Geiger (1954), Holridge (1967), Strahler and Strahler (1987), Camargo (1991), Basalirwa (1995); each with its own limitations. Several new parameters such as cloud cover, insolation, aerosols, stratospheric ozone, and sometimes pollutants are included within the scope of climate classifications. However, choice for precipitation and temperature data remains the most reliable for long term climate projections (Fedemma, 2005; Kottek *et al*, 2006; Beck *et al*, 2018). In recent years, availability of gridded data has initiated a growing demand for georeferenced climatic regionalization (Zubler *et al*, 2014; Schumacher *et al*, 2020) which could facilitate visualization as well as help in identification of representative climate data recording stations.

So far, climate research has focused largely on global/large regions for present and modeled predictions but rarely address climatic zonation at a local scale (Talchabhadel and Karki, 2019). Such problem is conspicuous for mountainous areas where climate controls vary substantially due to topographic complexity and resultant localized effect of atmosphere (Keim *et al*, 2003). Hence, the usual large spatial scale studies do not necessarily represent true local climate. Therefore, it is important that global climate models (GCMs) and climate products are validated with an understanding of local climates that may positively affect climate impact assessment (Allen and Ingram, 2002; Gebrechorkos *et al*, 2019.)

This study attempted a statistical clustering approach for objective climate zonation for Himachal Pradesh and Punjab using temperature and precipitation variables spatially distributed in regular grids. Himachal Pradesh and Punjab have strong physiographic, climatic and hydrological links; development of this entire region is dependent on availability of fresh water resources largely stored as glaciers. Any sudden climatic aberration may threaten habitability, ecology, economy (mainly agriculture, managed ecosystems and tourism) as well as ongoing attempts to develop the region sustainably.

Study area

The study area forms roughly a quadrilateral region situated between 29°30′N to 33°12′N latitudes and 73°55′E to 79°04′E longitudes. This region is a part of the Himalayan system and adjacent Punjab Plains and has been grouped into 4 major physiographic zones: (a) the Punjab plains, (b) the Siwaliks, (c) the Middle Himalayas consisting of the Dhauladhar and Pir-Panjal ranges, and (d) the Great Himalayas. Positioned between a hot desert in the southwest and a cold desert in

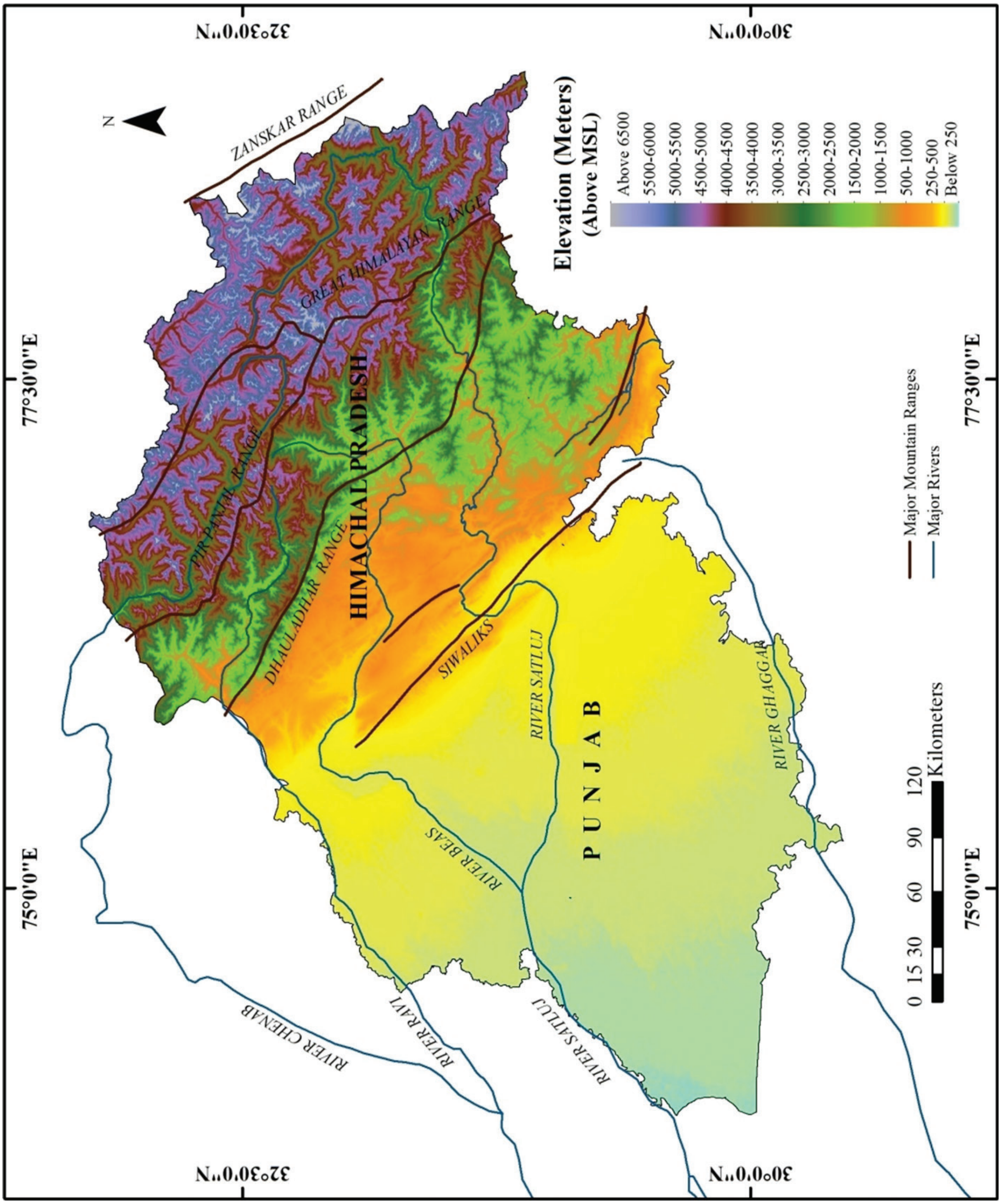

Fig. 1: Study area: Himachal Pradesh and Punjab

Source: ASTER, Global Digital Elevation Model (GDEM) the northeast, this region possesses multiple altitudinal zones (Fig. 1) ranging from 250 to 7000 meters above mean sea level. Consequently, climatic regime too is diverse. The Punjab Plains experiences hot dry semi-arid to subtropical climate, while mountainous Himachal Pradesh displays climate character of sub-humid tropical to cool alpine and cold arid nature (Sharma *et al*, 2017, 2018, 2022). On one side, the study area has places like Dharamshala in Himachal Pradesh that receive extremely high annual rainfall (above 2900 mm) while southwestern Punjab receive scanty rainfall (below 320 mm). The temperature range also presents similar contrasts with maximum value exceeding 46°C in southwestern Punjab and minimum temperature dipping well below minus 15°C in north-eastern Himachal Pradesh.

Objectives

The study area from climatological perspective forms a small spatial unit having wide climate gradients. However, in the absence of clear demarcation of climate zones, analysing changes in its climatic regime offer serious challenges. Therefore, an objective classification of climatic zones is needed for better monitoring the changes in climatic regime. This paper aimed at providing a climate classification for the study area based on clustering approach to identify various zones of thermal and precipitation regime.

Data sources and methodology

Increased availability of regularized gridded data on temperature and precipitation variables at finer spatial scale has enabled researchers to attempt number of climate classification schemes (Flores, 2008; Beck *et al*, 2018) that are not based solely on station wise climate data. To overcome the problem of low spatial coverage and non-representative shadow zones of meteorological stations, this study utilised daily gridded temperature (1°*1°) and precipitation (0.25°*0.25°) data from India Meteorological Department (IMD) for the period 1986-2015. Different grid size was selected for temperature (1°*1°) and precipitation (0.25°*0.25°) data as this study focussed on utilization of smallest spatial resolution of gridded data available with IMD for precise delineation of climatic boundaries. The gridded data provides an objective way of determining extent and borders of climate regions. In this study, few other important variables like sunshine hours, potential evapotranspiration and ground frost frequency were intentionally excluded to avoid over intensification of variables that are otherwise highly correlated.

The datasets of IMD are pre-processed using Shephard's interpolation method and does not have the effect of inhomogeneity. However, temperature and rainfall indices are sensitive to changes in location, exposure, equipment, and observation practice. Therefore, datasets were treated for quality control to remove data inconsistencies and errors using a quality control procedure proposed by Haylock *et al* (2006). For this purpose, the QC module of 'RclimDex 1.1' software was used. Firstly, all missing values were replaced and recoded as -99.9 (an acceptable format that software recognizes as 'Not Available' or NA) and secondly, all erroneous values were replaced into NA such as: daily maximum temperature less than daily minimum i.e., Tmax < Tmin etc. The outliers were identified using methodology given by Zhang *et al* (2005) to check whether or not mean value of daily temperature and rainfall variables fall within the range of ±4 standard deviations (SD).

The zonation was based on spatial clustering method. In the field of climatology, no single method of climate regionalization has been accepted as most satisfying. Researchers have used different methods like Principal Component Analysis (Al-Jerash, 1985; Almazroui *et al*, 2015; Jiang *et al*, 2020) and clustering-based method (Begert, 2008; Metzger *et al*, 2013; Zhang and Yan, 2014; Netzel and Stepinski, 2016; Zerouali *et al*, 2022). Statistical clustering is often viewed as the most satisfying method that group set of similar objects into clusters based on partition of data. This multivariate technique examines a linear connection between elements of climatological data sets (Cherry, 1996; Khatibi & Saberi, 2020). These individual clusters are created in such a way that objects within the cluster are similar but differ greatly with objects from other clusters. The clusters with significant similarity in temperature and precipitation data represent a climate zone.

In this study clustering has been done with an objective of grouping of spatial grid points within which grid points of similar affinity are grouped. There are various ways in which clustering can be done; *hierarchical clustering* and *k-means clustering* are the two most used methods. Hierarchical clustering organizes clusters in a nested fashion where smaller clusters are organized under a bigger cluster and hence it is computationally demanding. The *k*-means, on the other hand, follows a simple approach where all data objects are classified into number of clusters based on how close these objects are to each other i.e., from their nearest mean distance. Such clustering has proved to be an efficient approach of analyzing complex climate system into a simple ecological-physiographical based meaningful climate regionalization. Each cluster is defined by its constituent objects and by its centroid.

The centroid μi, where i= 1…*k* for each cluster refers to the point at which sum of distances from all objects in that cluster are minimized.

$$\mathbf{J(V)} = \sum_{i=1}^{c} \sum_{j=1}^{ci} (\|x_i - v_j\|)^2$$

where, $(\|x_i - v_j\|)$ is the Euclidean Distance between xi and vj

ci is the number of data points in ith cluster
c is the number of cluster centres

The clustering is performed using iterative refinement technique which finally converges to an optimum value. Since *k*-means clustering requires specifying the number of clusters to be extracted, a number of iterations were performed with proposed iterations. The final decision on number of clusters to be represented as climatic zones was subjected to visual interpretation by taking into account local topographic characteristics. In temperature regime classification, no additional clusters were computed for northeastern Himachal Pradesh as this high mountainous region has very low or near zero population density. Since there is only one significant ground-based station at Kalpa, no two additional clusters were created as it would not have significantly improved the knowledge of climate of the region.

Results and discussion

Climatic zones in study area follow a transverse altitudinal zonation; temperature conditions decrease as one moves from southwest to northeast while precipitation distribution correlates with altitude and evapotranspiration. The following section

Fig. 2: Temperature variance plot

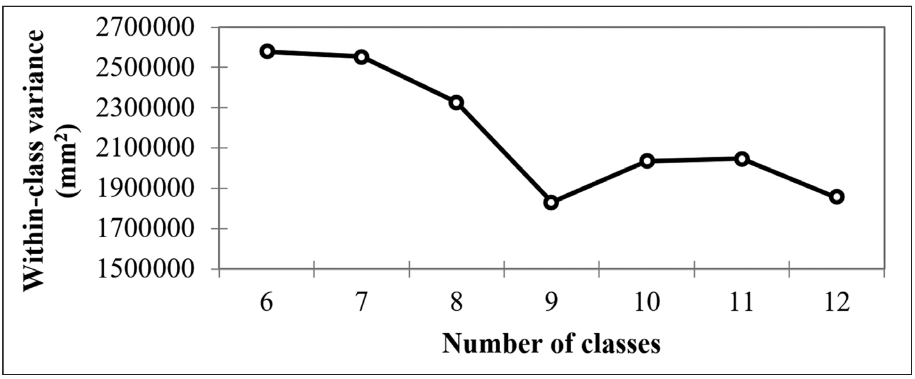

Fig. 3: Precipitation variance plot

Table 1: Variance of temperature

Variance (σ^2)	Classes		
	4	5	6
Within-class	14.428	6.176	3.457
Between-classes	164.174	172.427	175.145
Total	178.602	178.602	178.602

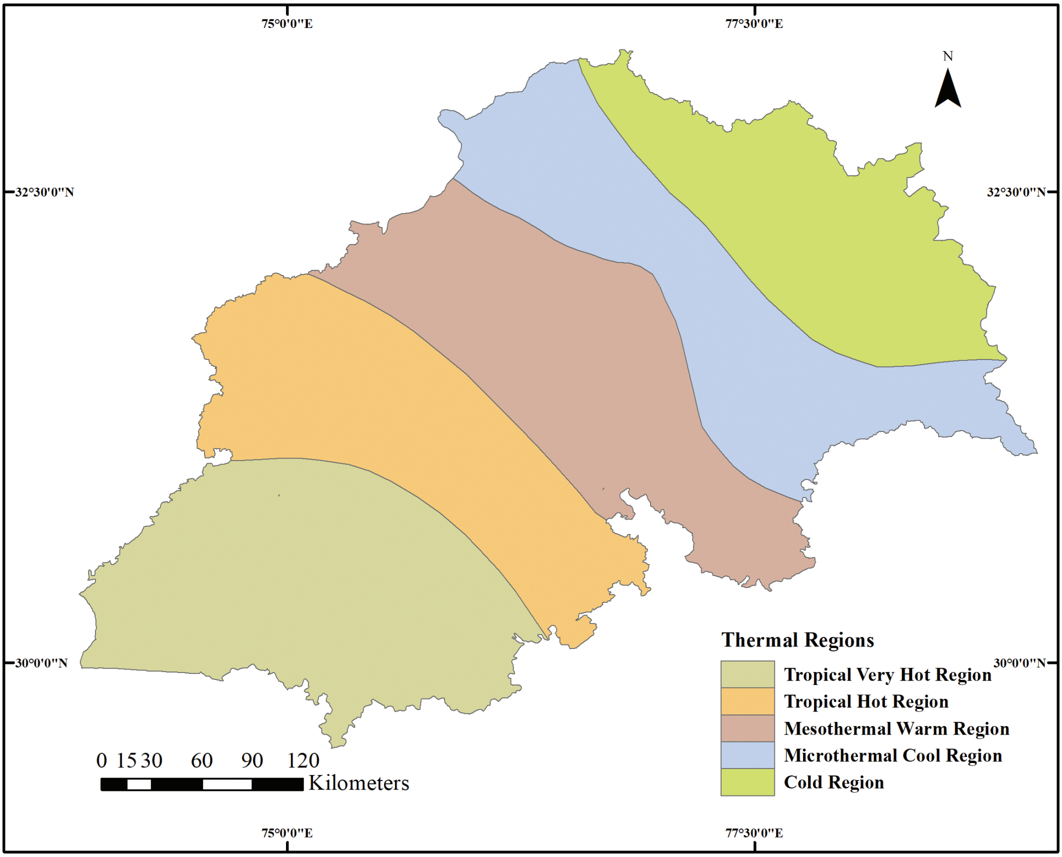

Fig. 4: Thermal regions of Himachal Pradesh and Punjab (1986-2015)

presents climatic regionalization of the study area in terms of 'thermal' and 'precipitation' regimes to understand the nature of heat distribution and hydrological balance in the region.

Thermal regime

The '*k*-means clustering' conducted on 17 grid points of 1°*1° spatial resolution distributed across the study area was based on a total of 3 iterations to identify optimum number of clusters with minimum variance between clusters and maximum variance among different clusters (Table 1 and Fig. 2) so as clear and distinct zones of thermal regimes could be constructed. Clustering is an iterative process in which for the first iteration, a starting point is chosen (either taken at random or not) for centre of the k classes with k objects. On second iteration, distance between the objects and the k centres is calculated and the objects are assigned to the nearest centres. Lastly centres are redefined from the objects assigned to the various classes and then reassigned depending on their distances from the new centres which may continue until convergence is reached. While defining boundaries of a region, homogeneity of defining element within a region is kept highest while maintaining maximum

Table 2: Thermal regime and characteristics

Region	Region nomenclature	Geographical range	Temperature characteristics (MAT = Mean Annual Temperature)
1	Tropical Very Hot Region	Southwestern Punjab plains comprising districts of Ferozepur, Fazilka, Faridkot, Muktsar, Bathinda, Moga, Barnala, Mansa and Sangrur	MAT 24.3°C Min. MAT 22.5°C Max. MAT 25.8°C Avg. Summer Temp. >38°C Peak Summer Temp. ~48°C Peak Winter Temp. ~0°C High insolation heat throughout the year; typically remains dry due to high evaporation rates.
2	Tropical Hot Zone Region	Central parts of Punjab covering districts of Amritsar, Tarn Taran, Jalandhar, Nawan Shahar, Kapurthala, S.A.S Nagar, Ludhiana, Patiala and Fatehgarh Sahib.	MAT 23°C Min. MAT 21.3°C Max. MAT 24.4°C. Similar thermal conditions like region 1 but average temperature is less warm.
3	Meso-thermal Warm Region	Siwalik Hills covering parts of Pathankot, Gurdaspur, Hoshiarpur, Roopnagar, S.A.S Nagar districts of Punjab and lower districts of Himachal Pradesh viz. Una, Hamirpur, Bilaspur, Solan and Sirmaur.	MAT 20.8°C Min. MAT 19.4°C Max. MAT 21.9°C Intermediate zone between continental climate and mountain climate; summers are hot and dry
4	Micro-thermal Cool Region	Situated between 2500-5000 meters between the Dhauladhar and the Great Himalayan ranges covering greater parts of Chamba, Kangra, Mandi, Una, Shimla, and Kullu districts.	MAT 19° C Min. MAT 17.7°C Max. MAT 20.5°C. Cool conditions prevail with temperatures much below 20°C during entire year.
5	Cold Zone	Northeastern Himachal Pradesh with average altitude above 5000 meters; covering the districts of Lahaul & Spiti and Kinnaur.	MAT 17°C. Min. MAT 16°C Max. MAT 17.8°C. Coldest zone; Winter temperature is below freezing point caused by low radiational heating from below.

Table 3: Variance of precipitation

Variance (σ^2)	Classes				
	6	7	8	9	10
Within-class	2580073	2554925	2328952	1830851	2034342
Between-classes	5537220	5562367	5788340	6286441	6082950
Total	8117292	8117292	8117292	8117292	8117292

Table 4: Precipitation regime and characteristics

Region	Region nomenclature	Geographical range	Precipitation Characteristics (MAR = Mean Annual Rainfall)
1	Tropical Arid Region	Southern-western parts of Punjab; receives scanty rainfall from SW monsoon in July-September and from the western disturbances during January-March.	MAR ≈ 275 mm; precipitation ranges between 240-300 mm a year due to small areal extent
2	Tropical Semi-Arid Region	Southern and western Punjab; Continental type of climate receiving moderate rainfall from southwest monsoon and from the western disturbances.	MAR ≈ 450 mm; precipitation ranges between 250-725 mm a year due to large areal extent
3	Tropical Dry Sub-humid Region	This zone mainly consists of area on the west of the Siwalik Hills (the Lesser Himalayas) in Punjab. This region constitutes parts of *Bist Doab* and *Majha* cultural region of Punjab plains.	MAR above 840 mm that reach to a maximum of above 1000 mm near Hoshiarpur. The lowest precipitation (750 mm) is recorded in southern parts of areas of Patiala.
4	Moist Sub-humid Region	Covers large part of middle Himachal Pradesh; adequate precipitation during monsoons in July-September. Rainfall decreases towards east.	MAR above 1250 mm. Maximum precipitation (1750 mm) on windward side of the *Dhauladhar* ranges, while minimum precipitation (800 mm) is received on the leeward side of the Great Himalayan Range.
5	Temperate Wet Region	The wettest zone with heavy orographic precipitation. Highest precipitation is recorded in Dharamshala, Manali, Kangra, Jogindernagar areas.	MAR above 2000 mm. Rainfall ranges between 1650 mm to 2500 mm. This receipt of very high intensity rainfall also finds expression in growth of dense deciduous forest in this region.
6	Temperate Moist Region	The second wettest zone of study area comprises of Pangi division of Chamba district in Himachal Pradesh. Fairly good rainfall is received during monsoons.	MAR above 1400 mm; Rainfall is equally distributed throughout the zone; annual maximum rainfall exceeds 1650 mm.
7	Temperate Sub-Moist Region	The zone covers greater parts of middle Himachal Pradesh and receives fairly good amount of rainfall during monsoon. Amount of precipitation decreases from east to west.	MAR ≈ 1074 mm. Maximum annual precipitation of 1378 mm witnessed in areas of leeward side of Dhauladhar ranges, and an annual minimum precipitation (868 mm) is received on the leeward side of Pir Panjal Range.
8	Alpine Semi-Arid Region	This zone lies on leeward side of the *Pir-Panjal* ranges covering northern parts of Lahaul & Spiti districts. Southwest monsoon rainfall fails to reach in this high-altitude region with open rocky surfaces and less vegetation.	MAR between 800-1250 mm. A large part of precipitation is received as winter snowfall. Annual precipitation ranges between 300 mm-2900 mm. Western part receives higher rainfall in comparison to the eastern part.
9	Alpine Arid Region	It comprises of eastern and southeastern Himachal Pradesh. Fairly low rainfall is attributed to high altitude and continentality effect of the Great Himalayan ranges that obstruct southwest monsoons. Lack of vegetation is characteristic feature of this zone.	MAR ≈ 650 mm; maximum annual rainfall reaches above 900 mm and minimum to 600 mm. Precipitation mainly occurs as snowfall during winters.

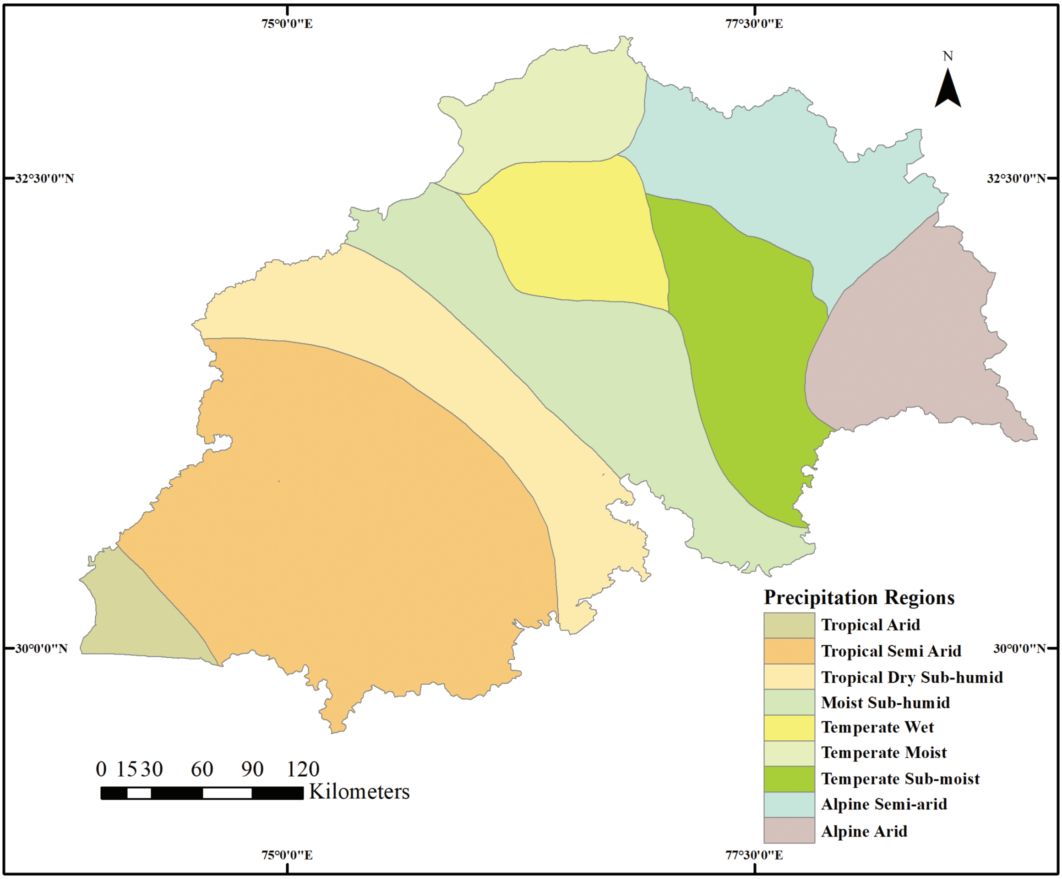

Fig. 5. Precipitation regions of Himachal Pradesh and Punjab (1986-2015)

heterogeneity with the neighbouring region. This forms the basis for identification of optimum number of classes with minimum variance within-class and maximum variance between-classes for defining of climatic region in an area.

Since half of grid points are located in mountainous terrain, a strict statistical analysis would yield erroneous results as clustering does not take into consideration influence of altitudinal variations, changes in slope and, aspect and duration of sunshine hours. As a result, clustering analysis was followed by a subjective interpretation of thermal regime wherein a visual interpretation was based on expert knowledge of research on local topographic influences on climatic regime of study area. The thermal regime of study region exhibits 5 major zones (Fig. 4 and Table 2) having distinct temperature.

Precipitation regime

Clustering was conducted for 168 grid points (0.25° * 0.25°); the large number of grid values allowed for more iterations to identify clusters with minimum variance between clusters (Table 3 and Fig. 3). The formation of precipitation zones needs careful attention as precipitation in the study area is received in various forms such as rain, hailstorms, snow etc. and from different sources like the southwestern monsoon (July-September), the western disturbances (December-March) and local evapotranspiration. Moreover, precipitation is also greatly influenced by other localized factors such as topography, altitude and aspects of slope. Hence these factors were given special attention during regionalization of precipitation zones at the time of interpretation and delineation of boundaries. Since mountain topography is characterized by orographic rainfall, the grid points exhibiting similar nature of precipitation pattern but statistically falling in neighbouring zone were appropriately included in same zone for simplification of boundaries.

A number of micro-precipitation zones exist in hilly terrain of Himachal Pradesh especially between the Siwaliks and the Pir Panjal ranges. These micro-precipitation zones were grouped into larger neighbouring zones to avoid over complication in the process of precipitation regionalization. The analysis of data reveals presence of 9 precipitation clusters (Fig. 5 and Table 4).

Summary and conclusion

This study on various clusters of thermal and precipitation regime reveals a collective influence of local topography, vegetation, direction of movement of rain bearing winds, regional weather system on climatic regionalization of the study area. The analysis proposes five major thermal zones (Tropical Very Hot Region, Tropical Hot Region, Mesothermal Warm Region, Microthermal Cool Region and Cold Region) and 9 precipitation zones (Tropical Arid, Tropical Semi-Arid, Tropical Dry Sub-humid, Moist Sub-humid, Temperate Wet, Temperate Moist, Temperate Sub-Moist, Alpine Semi-Arid, and Alpine Arid) based on statistical *k*-means clustering duly informed by expert knowledge of the area. These thermal and precipitation zones give distinct characteristics to each zone and have profound effect on hydrological, ecological, agricultural and social activities. This classification has potential to serve as a basic frame to ascertain direction and magnitude of climate change. Since, each occupancy and nature of dominant human activities in each zone has evolved in tandem with its climatic regime, any significant change in temperature and precipitation is explicitly going to be unwarranted. Moreover, this classification is expected to aid researchers to explore climate variability and extremes at micro scale to predict hydrological implications of climate projections.

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