Assessment of Rainfall Variability in Ladakh amidst of evolving Climate

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Research Article

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Abstract

Ladakh is characterized by a cold desert and fragile ecosystem that is geographically connected to the Western Himalaya and highly susceptible to changing climate. In the current scenario, the region is receiving more extreme rain events, which have disturbed ecosystem balance and triggered disasters like flash floods and landslides. Therefore, a comprehensive study of rainfall patterns over the past 90 years has been done here, which provides insight into climate trends. In this study, the rainfall pattern has been statistically quantified on a tricadal (30-year period) and decadal (10-year period) basis from 1932 to 2021 by using gridded rainfall data from the Indian Meteorological Department (IMD) to analyze changes in rainfall in all four seasons, namely pre-monsoon, monsoon, post-monsoon, and winter, and calculate the trends by using non-parametric tests like Mann-Kendall (MK) and Sen's slope. The results indicate that certain seasons have seen higher rainfall than others. This study employs the precipitation concentration index (PCI) for rainfall variation estimation, accounting for overlapping time segments. PCI values show uniform and highly concentrated rainfall, which indicates the potential for extreme weather events. The study indicates a decadal shift possibly linked with broader climate cycles along with an increased frequency of extreme rain events. Long-term trends are visible in the tricadal analysis, with increased pre-monsoon rainfall in T1 (1932–1961) and decreased monsoon and post-monsoon rainfall in T2 (1962–1991) and T3 (1992–2022). This study is useful in water resources management, agriculture, and ecosystem services.

1. Introduction

Climate change is a complicated phenomenon and influenced by both human as well as natural elements such as the atmosphere, hydrosphere, geosphere along with the biosphere and human activities including land use changes, greenhouse gas emissions, and exploitation of natural resources. The intricate interaction between these factors drives the dynamics of the climate system. Increased population and side by side urbanization is a key culprit of global climate change and with the current trend it is estimated that the urban population reach to 8.5 billion in 2030, 9.7 billion in 2050 and 10.4 billion in 2100 (WHO, UNFPA 2023). The Himalayan region is characterized by exceptional ecological beauty and at the same time they are more sensitive to climate challenges (Tiwari et al. 2018). The Himalayas are widely distributed into four sub-regions on the basis of variation in stratigraphy and structure namely sub (also known as outer or Siwalik Hills), lesser, greater and Tethyan (also known as the Tibetan or trans) Himalaya (Basu 2013). Climate change is evident everywhere on the Himalaya but its potential impact varies from region to region (Mall et al. 2011). Urban and Sub-Urban areas are experiencing overheating, which contribute to extreme climatic phenomena such as heatwaves. Due to human interference and unprecedented urban development, this region is facing abrupt disbalance in climate pattern (Reilly et al. 2022). The human settlement is expanding from foothills to the higher altitude of the Himalaya. The human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years. This warming has led to widespread changes in weather and climate extremes, including changes in precipitation patterns (IPCC 2019) and variability. The Report of IPCC 2023 highlights that weather and climate extremes like intense precipitation and are being influenced by human-induced climate change. The study by Sharma et al. 2023 elaborate temporal trends and variability in rainfall across the Trans-Himalayan region using high-resolution observational datasets and climate model simulations which shows significant spatial and temporal variations in rainfall patterns, including changes in intensity, frequency, and distribution of rainfall events. In another study Kumar et al. 2023 assesses future rainfall variability over India using an ensemble of climate models and explores uncertainties in future projections of rainfall patterns, identifies hotspots of projected changes, and evaluates the implications for water availability, agriculture, and socioeconomic development. A comprehensive overview of the impact of climate change on rainfall variability in India suggest the influence of climate drivers such as El Niño and Indian Ocean Dipole, and the implications for water resources, agriculture, and ecosystems (Singh et al. 2022). There is one synthesis study which the influence of topography, monsoon dynamics, land-atmosphere interactions, and anthropogenic factors act as drivers of rainfall variability in the Himalayan. It identifies knowledge gaps in understanding regional-scale processes and calls for integrated approaches to address uncertainties in future projections (Joshi et al. 2023). These changes are evident from temperature rise (presence of elevation dependent warming additionally), disturbances in total rainfall pattern (effects of western disturbances, local and global circulation), glacier retreat, leading to glacier hazards, mega flood events, landslide, mudflow, rock flow etc., (Singh et al. 2021, Ougahi et al. 2022, Rani et al. 2022, Mall et al. 2023). The Himalayan glaciers have almost shrunk with 11% of the total surface area from 1990 to 2015 in 25 years and the temperate glaciers melt with faster rate than continental glaciers (Ji et al. 2022). .

There is extensive research on rainfall variability in India has already been done but there is lack of detailed studies focusing specifically on the Ladakh region to understand how climate change is impacting this unique climatic zone. This work contributes to filling that gap by providing a focused analysis of rainfall anomalies and spatial and temporal variation over nine decades in Ladakh. While many studies look at short-term variability, fewer focus on long-term trends spanning multiple decades and tricades. The work on seasonal rainfall anomalies in Ladakh contributes to the literature by providing detailed regional analysis and highlights decadal trends. In this context, our study focuses on Ladakh, a part of Trans-Himalaya, where the delicate ecosystem is under threat of climate change- induced heavy downpours and landslides. Despite being a rainfall-sparse zone with an average annual rainfall of only 100 mm, this region is receiving more liquid precipitation than the snowfall (Liaqat et al. 2022, Banerjee & Singh 2023). Over the 20th century, Leh (a city of Ladakh) experienced fluctuations in precipitation with winter rainfall showed a positive trend from 1941–1950 with 95.8 mm of annual precipitation but decreased in 1971 to 1980 with 86.4 mm. The 1971–1980 decade have an increase which followed by a decline in 1991–2000 with 66.5 mm of precipitation. Summer precipitation increased steadily until 1960 with 101.9 mm which is increasing for next 60 years and reached to 140 mm during 1951–1960 but a slight decrease was observed from 1961–1990 (Shafiq et al. 2016). This analysis aims to identify and discuss the variations in total rainfall across different seasons in Ladakh recognizing that while heavy rainfall events occur, climate change may also lead to extended periods of drought in the Western Himalayas.

2. Study Area

Ladakh is located in northwestern part of the greater Himalayan ranges and south of the Karakoram Hills of Indian Subcontinent (Fig. 1). Figure 1 is depiction of Digital Elevation Model (DEM) image of Ladakh which is plotted using SRTM data set to show the complex topography of the study region which is very much crucial for rainfall study because unique geography of Ladakh characterized with wide range of ecological zones, alpine meadows to cold deserts and known for high-altitude deserts barren landscapes, deep valleys, and snow-capped mountains (Schmidt et al. 2017). Ladakh lies at 34.209515° N, 77.615112° E and referred as a rain shadow zone for the South West Monsoon due to its leeward side of the Himalayas and which results into low annual rainfall of 20mm – 145mm (Soheb et al. 2022). The air is thin with cold-aridity and the winters are cold and dry with heavy snowfall at higher elevations. Despite these conditions, this region supports a diverse range of flora and fauna adapted to harsh environment. The overall population of Ladakh is approximately 275,000 according to the census of 2011 and majority them are military persons residing in Leh (the capital city of Ladakh) and Kargil (Brian et al. 2021). The glacier melt water is the prime source for their water requirement and this region rarely face any cloudburst and torrential rain events (Tuladhar et al. 2023).

But distinctive climatic conditions in Ladakh make it highly susceptible to climate change impacts, such as glacial retreat and changes in water availability due to increased temperature and intensified rainfall (Dar et al. 2022). These changes pose a threat to the wildlife, ecology and socio-economic stability of the region. The Fig. 2 representing the monthly averaged maximum and minimum temperature distribution over Ladakh in 50 years of IMD, datasets. There is a clear seasonal variation in temperatures with the warmest months are typically from June to August however the coldest months are from December to February which represent summer and winter season respectively. The temperature distribution is not uniform across the region which may be due to differences in elevation, topography, and other local factors. The central and eastern parts of the region tend to show warmer temperatures in the maximum temperature plots, while the minimum temperature plots show a more uniform distribution with some localized variations. The maximum temperature plots have a higher range of temperatures compared to the minimum temperature plots, which is typical as daytime temperatures have a wider variation. The maximum temperature plots show that some areas, particularly in the central region, get quite warm during the summer months, with temperatures reaching above 16 degrees Celsius. On the other hand, the minimum temperature plots show that during winter, temperatures can drop significantly, with some areas averaging below – 14 degrees Celsius. By comparing the maximum and minimum temperature plots for each month, we can see the diurnal temperature range (difference between the day's highest and lowest temperatures). This range seems to be larger during the summer months and smaller during the winter months. While the plots show averaged historical data, any long-term trends in increasing maximum or minimum temperatures may be an indicative of climate change.

The Fig. 3 shows the averaged mean temperature distribution and the average rainfall distribution over Ladakh in 50 years which clearly depict seasonal cycle in mean temperatures, with the warmest temperatures occurring in the summer months (June, July, August) and the coldest temperatures in the winter months (December, January, February), which may be influenced by factors such as altitude, topography, and local climate conditions. Some areas, particularly in the central and eastern parts of Ladakh, show warmer temperatures. Rainfall distribution also shows seasonal variation, with some months exhibiting higher average rainfall than others. The plots suggest that the monsoon months have higher rainfall, which is consistent with the South Asian monsoon pattern. Rainfall is not uniformly distributed across Ladakh, with some areas receiving more rainfall than others. This could be due to the orographic effect, where mountains influence the amount of precipitation an area receives. The winter months (December, January, February) and possibly the pre-monsoon months (April, May) appear to be drier, which is typical for Ladakh, a region that lies in the rain shadow of the Himalayas. The temperature plots indicate that Ladakh experiences a wide range of temperatures throughout the year, with significant differences between summer and winter temperatures. The rainfall plots suggest that Ladakh has a distinct wet season and dry season, which is important for water resources and agriculture in the region.

The plots represent 50-year averages, which may mask interannual, decadal and tricadal variability. Therefore, to understand the full climatological context we have done this study to examine individual years and mainly focusing on decadal and tricadal time frame to look into trends over time. A detailed investigation for rainfall data study spanning 90 years from 1932 to 2021 has been conducted to quantify the trends and variations in rainfall patterns over Ladakh. The study aims to understand the vulnerability of Ladakh’s fragile ecosystems to climate change and disturbed rainfall pattern.

3. Data and Methodology

In this research paper the Indian Meteorological Department (IMD) gridded rainfall data has been used to analyze rainfall patterns on the study area for all four seasons namely pre-monsoon, monsoon, post-monsoon and winter for the period of 90 years since 1932 to 2022. The months of March, April, and May (MAM) are considered the pre-monsoon season, while June, July, August, and September (JJAS) have been taken as monsoon. October and November (ON) represent post-monsoon season and winter months followed by December, January and February (DJF). The IMD gridded rainfall dataset provides spatially distributed rainfall information at a high resolution, allowing us to capture localized variations in rainfall across the region (Tiwari et al. 2016). The dataset provides a comprehensive representation of rainfall patterns over the Ladakh. In this study, time period is distributed in 9-decades and 3-tricades which is namely as 1932–1941 (D1), 1942–1951 (D2), 1952–1961 (D3), 1962–1971 (D4), 1982–1991 (D5), 1992–2001 (D6), 2002–2011 (D7), 2012–2021 (D8) and for tricades 1932–1961 (T1), 1962–1991 (T2) and 1992–2021 (T3). A flow chart of Methodology is given for all analysis (Fig. 4). The study is done using statistical test to analyze the data, including the Menn Kendall's Test, Modified Menn Kendall's Test, MK Sequential test, Theil Slope and Menn Kendall's with Sen's Slope Testand for variation calculation Precipitation Concentration Index (PCI) is plotted. Spatial Interpolation method is used for depicting the rainfall distribution and analyzing anomalies over the area. Ordinary Least Squares (OLS) Regression is used to model the linear relationship between PCI values and estimate the trend coefficients (Gauss, C. F., 1809). Sen's Slope Test is also carried out which was introduced by M.B. Sen in 1968 to estimate the slope of a trend line in a dataset, providing a robust measure of trend magnitude that is resistant to outliers. This analysis provides detailed information on the relationship between variables which is allowed for the estimation of trend coefficients. Along with these the decadal and tricadal anomalies are also calculated for seasonal analysis which give a better picture rainfall deviation.

3.1 Menn Kendall's Test, Modified Menn Kendall's Test and MK Sequential Test: To assess the trends and changes in rainfall patterns over time, we employed the Menn Kendall test, a widely used non-parametric, statistical method for trend detection method which is approved by the World Meteorological organization to estimate the trend in environmental time series data (Zhang & Liang 2020) and this test is proposed by Maurice G. Kendall and Basil Mann in 1948. The Menn Kendall test allows us to identify and evaluate the presence of significant trends in the time series data. In this test, every data point from a time series is compared to the remaining data points in a sequential manner. The number of times the remaining terms exceed the analysis term is calculated. The Modified Menn Kendall's Test is an extension of original method by incorporating adjustments to handle ties in the data, enhancing its applicability to real-world datasets with tied observations. The Menn Kendall's test provides information on the number of upward fluctuations (UF) and downward fluctuations (UB) in the time series (Zhang & Liang 2020). UF represents the count of increasing values, while UB represents the count of decreasing values. By employing the Men Kendall test on the IMD gridded rainfall data, we aimed to identify and analyze significant trends or changes in rainfall patterns in Ladakh. This test enhances the traditional MK test by considering trends in sequential and potentially evolving time segments.

3.2 Precipitation Concentration Index (PCI): PCI is given by Oliver (1980), for the estimation of rainfall data on annual scale. PCI is used to estimate the uniformity or non-uniformity in the rainfall over a period. Higher PCI value shows greater non-uniformity of rainfall and if the PCI is less than 10 then there is uniform distribution of the rainfall values. The annual PCI is estimated for this study to calculate the concentration and variation of rainfall (Nandargi et al. 2018). The PCI value give the information about distribution of rainfall on uniform, moderate, irregular and strong irregular category (Table 1). Linear regression trend line is applied to analyse the trend in the values of PCI.

3.3 Spatial Interpolation: Spatial Interpolation is a geospatial method to evaluate data at unobserved locations of the study area by using rainfall and meteorological variables which is used to plot a continuous map from discrete data points and helpful in filling the missing value and visualizing data across a spatial domain. In this study spatial interpolation is carried out using the Inverse Distance Weighted (IDW) method because it provides least mean error than other interpolation method, however the interpolation method is highly dependent on the resolution of meteorological stations therefore it may affect the resulting spatial pattern of the rainfall (Zhang & Liang 2020).

Table 1
Classification of PCI values.

PCI	*Description*
< 10	*Uniform precipitation distribution (that is, low precipitation concentration)*
11 to 15	*Moderate precipitation distribution*
16 to 20	**Irregular distribution**
> 20	**Strong irregularity of precipitation distribution (that is, high precipitation concentration)**
Source: Oliver (1980)**.**	

Spatial Interpolation is carried out to plot a continuous map from discrete data because this method gives a value for unobserved location also. However, gridded rainfall data of IMD has coarse resolution and thus may fail to capture small-scale variations in rainfall in the regions of the Himalayas because they have complex topography. The orography effects may not be captured well in which moist air is lifted up and cause increased precipitation on windward slopes. The accuracy of gridded data is dependent on the station data and Ladakh region has few stations therefore it may bring uncertainties. The data also fail to look into seasonal and diurnal variation and least accuracy in measuring extreme events like cloudburst whose effects are localized.

4. Results and Discussions

To study monthly rainfall distribution from 1932 to 2021, yearly accumulated rainfall and monthly mean rainfall is taken into consideration. For this time period total annual rainfall is range from 159.91mm in 1960 and 1361.31mm in 1996. For seasonal distribution of rainfall with respect to annual percentage, namely pre-monsoon, monsoon, post-monsoon and winter which cover 34.19%, 31.25%, 6.23% and 28.26% respectively (Table 2). The Table 2 provides detailed monthly mean precipitation data over 3 tricades and indicates the maximum rainfall is reported in Pre-monsoon season with march accounting maximum rainfall of 15.00% and minimum rainfall observed during post-monsoon season with November having only 3.08% of total annual ratio. It is found that total rainfall has abruptly increased from first tricade (T1 = 329.42mm) and get stabilized in next two tricade i.e., T2 accounts 578.15mm and T3 with 576.17mm respectively (Table 2). However, seasonal distribution of rainfall in all the three tricade having least rainfall in post monsoon season with T1 having 1.94% in November, T2 accounts 3.28% in December and again in November T3 is 2.83%. Decadal analysis is shown in Table 3. The results of the decadal mean analysis (Table 3) reveal significant variations in the total monthly mean rainfall over the nine decades in Ladakh. However, total rainfall trend of all four season shows increasing trend in which winter has least increase (Fig. 5), the rainfall levels in Ladakh show considerable inter-decadal variability. The analysis reveals that the winter rainfall in Ladakh ranges from 10.09 mm to 457.83 mm with considerable inter-annual variability, with no distinct long-term trend. Pre-monsoon rainfall shows fluctuations ranging from 32.08 mm to 479.58 mm and the data indicates inconsistent patterns, with no clear trend obtained over the years. Total Monsoon rainfall in Ladakh ranges from 21.22 mm to 559.65 mm. The analysis demonstrates significant inter-annual variability, with some years experiencing intense rainfall, while others show relatively lower rainfall. Post-monsoon rainfall varies from 2.89 mm to 267.96 mm. The highest rainfall levels are observed in the months of March, July, and August, while the lowest levels are recorded in October and November. The rainfall levels in January and February generally increase from the early to the late decades, with the highest values observed in the final decades. The months of March, April, May, and June exhibit varying rainfall patterns, with some decades experiencing higher levels than others. July and August show consistent rainfall increases throughout the decades, with notable spikes in the later decades. September experiences relatively stable rainfall levels, with slight fluctuations over the decades. November shows a gradual increase in rainfall from early to late decades. December displays significant variations in rainfall, with no clear trend over the decades.

Table 2
The amount of total monthly Mean Precipitation over 1932–2021, T1, T2 and T3 phases.

Months	**Total monthly Mean Precipitation over 1932–2021**		**Total Monthly Mean Precipitation over 1932–1961 (T1).**		*Total monthly Mean Precipitation over 1961–1991 (T2)*		*Total monthly Mean Precipitation over 1991–2021 (T3)*	
	Precipitation (mm)	*Ratio of Annual Precipitation (%)*	*Precipitation (mm)*	*Ratio of Annual Precipitation (%)*	*Precipitation (mm)*	*Ratio of Annual Precipitation (%)*	*Precipitation (mm)*	*Ratio of Annual Precipitation (%)*
January	*144.17*	9.72	*45.44*	*13.79*	46.77	8.09	51.96	9.02
February	190.95	12.87	45.00	13.66	74.85	12.95	71.10	12.34
March	222.49	15.00	49.93	15.16	95.74	16.56	76.83	13.33
April	161.93	10.91	32.88	9.98	70.45	12.19	58.60	10.17
May	122.90	8.28	27.08	8.22	52.76	9.13	43.05	7.47
June	77.98	5.26	16.21	4.92	28.26	4.89	33.51	5.82
July	136.33	9.19	26.23	7.96	50.20	8.68	59.89	10.40
August	141.21	9.52	25.03	7.60	48.14	8.33	68.04	11.81
September	108.05	7.28	23.64	7.18	33.70	5.83	50.71	8.80
October	48.00	3.24	11.50	3.49	20.22	3.50	16.29	2.83
November	45.65	3.08	6.38	1.94	18.96	3.28	20.31	3.53
December	84.08	5.67	20.09	6.10	38.11	6.59	25.88	4.49

Figure 6 illustrates the temporal variation of annual PCI from 1932 to 2021. The PCI values exhibit considerable interannual variability throughout the study period and it shows significant fluctuation. The PCI values ranged from a minimum of 9.527 in 1961 to a maximum of 25.385 in 1950. The highest PCI values indicate more concentrated rainfall, while lower values suggest a more dispersed rainfall pattern. To assess long-term trends, we calculated the linear regression for the PCI values over the study period. The regression analysis revealed a statistically significant ($p < 0.05$) decreasing trend in the PCI values over the analyzed years, indicating a more dispersed rainfall pattern. The average annual decrease in the PCI was estimated at -0.14 units per year. The first two decades exhibited relatively higher PCI values, indicating a more concentrated rainfall pattern. However, the PCI values decreased in the subsequent decades, reflecting a shift towards more dispersed rainfall events which may impact water availability and agricultural practices. The years having PCI more than 20 shows rainfall within a short period, which may lead to increased risk of flooding and erosion, while years with low PCI values suggest a more uniform distribution of rainfall, which is more favorable for agriculture and water resource management.

Based on the results obtained from the Mann-Kendall test (Table 4) for variables T1, T2, and T3, the corrected Zc values are negative, indicating a decreasing trend or a negative slope. The new p-values for all variables are extremely small, indicating a significant trend in the data. For T1 and T2, the original Z values are negative, supporting the evidence of a decreasing trend. However, for T3, the original Z value is also negative but less pronounced, suggesting a weaker decreasing trend compared to T1 and T2. The Tau values estimates the strength and direction of the correlation. In all cases, the Tau values are negative, indicating a negative correlation or a decreasing trend. T1 has the largest absolute Tau value, indicating a stronger negative correlation compared to T2 and T3. Sen's slope is a measure of the magnitude of the trend. T2 exhibits the largest negative Sen's slope, indicating a steeper decrease over time compared to T1 and T3. For all the 9 decades the Mann-Kendall test (Table 4) indicates a significant downward trend and the Sen's slope analysis shows a strong negative trend in D1, D2, D5, D6 and D9; moderate negative trends in D7 and D8, however the decades D3 and D4 having relatively weaker negative trend. This indicates a decreasing pattern over time. The application of the Mann-Kendall test to the monthly mean rainfall data in Ladakh has provided valuable insights into the decadal changes in rainfall patterns. The analysis revealed significant positive trends in January, February, March, April, June, July, and August, indicating an increasing pattern of rainfall in these months. On the other hand, months like May, September, October, November, and December exhibited no significant trends in rainfall. The Fig. 7 shows the Mann-Kendall statistic curve for annual and seasonal rainfall sequences and calculated UF and UB, were analyzed and interpreted to understand the direction and significance of the trends in rainfall patterns. The presence of UF and UB moving in opposite directions or exhibiting contrasting trends which indicate complex dynamics within the dataset. The curves cross the upper and lower bounds, indicating statistically significant trends at the 0.05 significance level for annual and seasonal rainfall sequences which suggest that the rainfall patterns in Ladakh are undergoing changes that are not merely random variations.

Table 4

The results of Mann-Kendall (MK) test for the annual decadal and tricadal precipitation over the Ladakh during 1932–2021. Z is the standardized MK test statistic.

Time	Corrected Zc	Tau	Sen's slope	P. Value
D1	-6.69	-0.696	-0.916	0.002
D2	-4.556	-0.666	-1.756	0.003
D3	-6.853	-0.545	-0.65	0.016
D4	-3.755	-0.393	-0.651	0.086
D5	-6.966	-0.606	-1.373	0.007
D6	-4.019	-0.484	-3.461	0.033
D7	-4.715	-0.454	-1.72	0.046
D8	-4.365	-0.363	-0.966	0.114
D9	-6.093	-0.545	-1.117	0.016
T1	-7.762	-0.757	-3.321	0.001
T2	-6.879	-0.575	-4.847	0.011
T3	-4.855	-0.454	-4.27	0.046

Table 5a. shows the IMD classification for rainfall categories but Ladakh is comes under rain shadow zone and average rainfall is 100 mm therefore, the IMD categories are redistributed (Table 5b.) to analyze the rainfall events and no. of rain days (Table. 6) for different decades. The categories are defined as *C1, C2, C3, C4* and *C5* to characterize No rainy day, light rain, moderate rain, heavy rain and exceptionally heavy rain respectively. First of all, we talk about monsoon month which is crucial for this region the total no of no rain days *C1* has been fluctuating from 715 in D1, then continues to decrease and reach to 430 days in D6 then again start increasing and reach to 521 in D9 however the events of extremely heavy rain have also been increased. In previous decades like D1 and D2 have zero event of *C5* however the Decades D3 and D4 have one extremely heavy rain event again D5 have but D6 have 3 and D7 have 12 *C5* category of rain events which again decreased in D8 and D9. The *C2* category of rain days has also been increasing from 445 in D1 to 479 in D2 and 520 in D3 which decreased to 447 days in D4 then 541 days in D5 and D6 then again decreases in D7, D8 and D9 with 418, 534 and 525 respectively. The *C3* and *C4* category of rain days have also increased in recent decades because it was 45 and 5 respectively in D1 now it reached to 118 and 45 respectively. The pre-monsoon months also receive rain days of *C5* category in D6 with 12 days and D7, D8 with 5 and 4 days. *C1* category of rain is more or less same in each decade except D3, D5 and D6 which having 369, 348 and 299 days. *C3* and *C4* have least no of variation seen in pre-monsoon months. Winter months have *C5* category of rain events since D2, D3, D5, D6, D7, D8 with 2,1,1,7,4 and 3 respectively and *C1* category have increased from 497 to 598

days in D1. C1 category have increased from 497 to 598 from D1 to D9. Winter months have fluctuation in *C2, C3* and *C4* categories of rain events. Post-monsoon month receive only one *C5* category of rain in D7, however the *C3* and *C4* categories have been increased in past few decades. But D9 have only one *C4* category of rain. *C3* category of the rain have increased from 11 in D1 to 46 in D6 then again start decreasing and reached to 29 in D9. *C1* and *C2* category of rain events also decreased slightly. Tricadal analysis for rainfall category (Table 7) shows increased no of *C5* in almost all season which is extremely high in monsoon with 15 days in T3 from 1 and 4 in T1 and T2. The pre-monsoon season receive zero *C5* in T1 and 13 and 9 in T2 and T3. Winter has 3, 8 and 7 in T1, T2 and T3 respectively. Post-Monsoon season also receive one extreme rain event *C5* in T3 and previously there is no *C5* in T1 and T2. No rainy days *(C1)* have decreased from 1903 to 1537 and then 1458 in consecutively T1, T2 and T3 respectively during Monsoon Months. *C1* category is decreased in T2 from 1450 to 1361 then again 1450 in T3 during post-monsoon season. Winter season have increased number of *C1* category of rain events from 1423 in T1 to 1667 in T3 and 1391 in T2. Pre-Monsoon season has decreased in *C1* from 1319 to 1113 then hike and reached to 1377 days. During Post-monsoon Season there is decrease in *C2* category from 322 in T1 to 260 in T3 which was increased during T2 and reached to 336 light rainy days. *C3* and *C4* categories of rain have drastic increase from 44 and 14 in T1 to 93 and 40 in T2 respectively which then reaches to 84 and 35 during T3. Winter month has decreased in *C2* category from 905 to 794 and then 600 in T1, T2 and T3 each. *C3* have increase from 276 to 363 and then decreased to 267 during T1, T2 and T3 in each. There is abrupt increase in *C4* category from 101 to 151 and 167 in T1, T2 and T3. Similarly, Pre-monsoon has decrease in *C2* and increase in *C4* category from 1039 to 824 and 93 to 198 respectively. *C3* increased from 93 to 235 and then decreased to 198. Monsoon season have increase in *C3* from 226 to 438 and reached to 496 days and *C4* having 56 to 184 from T1 to T3.

Table 5a
IMD Classification for rainfall categories.

Categories	*Daily Rainfall (mm)*
No Rainy Day	*0–0.1*
Very Light Rain	*0.1–2.4*
Light Rain	2.5–7.6
Moderate Rain	7.6–35.5
Rather Heavy Rain	35.6–64.4
Heavy Rain	64.5–124.4
Very Heavy Rain	124.5–244.4
Exceptionally Heavy Rain	> 244.5

Table 5b
Reclassification of IMD categories for Ladakh (Rain Shadow).

Categories	*Daily Rainfall (mm)*
C I (No Rainy Day)	*0–0.1*
C II	*0.1–2.4*
C III	2.5–7.6
C IV	7.6–35.5
C V	> 35.6

The analysis of total rainfall in Ladakh highlights the unique climatic characteristics of the region. The absence of a consistent long-term trend in winter, pre-monsoon, monsoon, and post-monsoon rainfall suggests the influence of multiple factors, such as local topography, atmospheric dynamics, and regional climate systems. The variability in rainfall patterns can be attributed to the complex interaction between these factors. The decreasing trend in the PCI implies a more dispersed rainfall distribution, which can have significant hydrological implications (Zamani et al. 2018). Higher PCI values indicate intense rainfall events, which may lead to increased runoff, soil erosion, and the risk of flash floods (Nunes et al. 2016). Conversely, lower PCI values suggest a more uniform distribution of rainfall, which can enhance groundwater recharge and promote sustainable water resource management. The decreasing trend in the PCI observed over the study period may be associated with climate change effects. Climate models predict altered rainfall patterns, including increased rainfall variability and more frequent extreme events. The decreasing PCI values may reflect changes in regional climate regimes, necessitating adaptation strategies for water resource management and agricultural practices.

The Decadal and Tricadal variability of rainfall in all the four seasons namely Pre-Monsoon, Monsoon, Post-Monsoon and winter season over Ladakh is elaborated by spatial interpolation method in Fig. 8, Fig. 9, Fig. 10 and Fig. 11 respectively. The pre-monsoon rain has increased in first two tricade and decreased in third tricade in most of the area (Fig. 8). The Pre-monsoon rain (Fig. 9) is spread over the larger area of Ladakh and central part is receiving intense rainfall. Among all the three tricade T2 is receiving higher rainfall over larger area and T3 get least rainfall. The decadal analysis shows D7 have higher rainfall over larger area and D8 is receiving least. The total decadal rain of D8 is decreased however, in other decades there is increased rainfall in most of the area. During monsoon season T2 is receiving more rain than the other two tricades. Central and Northwestern part of the Ladakh shows rainfall in larger area and southeastern part is rain deficient in T1 and T3 during this season. Among all decades D6 is receiving highest rain over larger area and D3 having least. Monsoon rain is also increase in larger area of Ladakh. Post-Monsoon rain (Fig. 10) has also increased in the past few decades and D7 receives highest amount among all decades. Surprisingly, the southeastern part which is rainfall sparse in other decades receive high rainfall during D8. D2 receives least rain and D7 and D5 having higher area extent of rainfall. Post-Monsoon rain is increasing in succession tricade and T3 receives highest rainfall over the whole region. In consecutive tricade the winter rain (Fig. 11) is increasing over the greater area extent. The South-Eastern part of Ladakh which receiving lesser rainfall have increased rain over larger area. D2 and D3 is showing, central part of North-Western part receiving more rain over larger area and in D5, D6, D7 and D8 have South-eastern part receiving more rain to larger area.

Understanding the decadal changes in rainfall over different seasons is vital for agricultural planning and water resource management. Higher rainfall levels during March, July, and August can support crop cultivation and provide water resources during critical periods. However, the fluctuating patterns in other months emphasize the need for adaptive agricultural practices and efficient water management strategies. The decadal changes in rainfall patterns have implications for infrastructure development and tourism. Increased rainfall during certain months may impact road conditions, leading to challenges in transportation and infrastructure maintenance. The tourism sector must consider these rainfall variations while planning travel itineraries and infrastructure development. The Mann-Kendall test results reveal interesting trends in monthly mean rainfall in Ladakh over the nine decades. Several months, such as January, February, March, April, June, July, and August, exhibit significant positive trends in rainfall. This indicates an increasing pattern of rainfall in these months. These findings suggest that Ladakh may be experiencing a shift towards wetter conditions during these specific months. On the other hand, months like May, September, October, November, and December show no significant trends in rainfall. These months have relatively stable rainfall patterns over the analyzed period. It is important to note that while these months do not exhibit significant trends, they still contribute to the overall climatic conditions in Ladakh. The positive trends observed in specific months can have significant implications for various sectors in the region. Increased rainfall in months like January and February can positively impact agricultural activities, as it provides ample moisture for crop growth during the winter season. Similarly, the rising trends in June, July, and August can contribute to water availability for irrigation and other purposes. Even stable rainfall patterns can play a crucial role in maintaining ecological balance and sustaining natural resources in Ladakh.

The seasonal rainfall anomaly plots for the Ladakh region are depicted in Figs. 12, 13 and 14 which providing a comprehensive view of how rainfall patterns have changed over 9 decades and 3 tricades. The Fig. 12 shows D1(1932–1941), D2(1942–1951) and D3(1952–1961) with a long-term average for 1932–1961 represented in T1, similarly for Fig. 13D4(1962–1971), D5(1972–1981), D6(1982–1991) and T2(1962–1991). The Fig. 14 covers the decades D7(1992–2001), D8(2002–2011), and D9 (2012–2021), with a long-term average for T3 (1992–2021). The pre-monsoon season shows significant variability across the decades. The earlier decades D1, D2, D3, D4 show a mix of positive and negative anomalies, with a tendency towards increased rainfall in the long-term average. There is no consistent pattern seems across the different decadal intervals which suggests variability in pre-monsoon rainfall from year to year or across the decades. However, the more recent decades (1992–2021) show a general trend of decreasing rainfall, with the long-term average indicating below-average rainfall. The monsoon season shows significant positive anomalies in D1 and D2 which indicate above-average rainfall during this season in these decades. There are also areas with negative anomalies which is prominently seen in D3, particularly in the northern parts of the region, which receive less rainfall than average during the monsoon and over the long term T1 the monsoon season exhibits a trend of decreasing rainfall. But the recent decades and the long-term average from 1992 to 2021 show predominantly negative anomalies which shows a reduction in monsoon rainfall. The post-monsoon season also displays variability, with no clear trend in the earlier decades (D1 to D6) generally show lower anomalies compared to the monsoon season, with a mix of positive and negative values. The anomalies are relatively small which shows the post-monsoon rainfall does not deviate as much from the average as the monsoon rainfall does. However, the recent decades (D6-D8) show a tendency towards reduced rainfall, with the long-term average indicating a decrease in post-monsoon rainfall. Winter rainfall anomalies are mixed across the decades, with some showing positive anomalies (D1, D3, D4 & D9) and others negative (D2, D5, D6, D7 & D8). The long-term trends indicate a shift in winter rainfall patterns, with the most recent decades showing a tendency towards reduced rainfall in the southern parts of the region.

There is considerable decadal variability in rainfall patterns across all seasons in Ladakh, which could be attributed to complex interactions between local topography, global atmospheric circulation patterns, and possibly climate change. The seasonal analysis indicates that pre-monsoon and monsoon seasons contribute the most to annual rainfall, with notable inter-decadal variability. The post-monsoon season consistently shows the least rainfall, which is a critical observation for water resource planning. The winter season, while variable, does not exhibit a distinct long-term trend, suggesting the influence of local topographical and atmospheric dynamics. The tricadal study reveals an abrupt increase in total precipitation from the first to the second tricade, followed by a stabilization in the third tricade. This pattern suggests a shift in climatic conditions, which may be attributed to broader environmental changes or natural climate variability. The decadal analysis further emphasizes the interannual variability and the absence of a consistent long-term trend in seasonal rainfall. However, the Mann-Kendall test results and Sen's slope analysis indicate a significant downward trend in precipitation over the nine decades, with varying degrees of decline across different periods. The Precipitation Concentration Index (PCI) analysis has shown a statistically significant decreasing trend, indicating a transition towards more evenly distributed rainfall events over the years. The overall trend suggests a decrease in rainfall during the monsoon and post-monsoon seasons in recent decades, which could have significant implications for water availability, agriculture, and the sustainability of ecosystems in the region. The variability and trends observed in the winter season and over spatial distribution, with shifts in rainfall patterns, may be influenced by topography, changes in Western Disturbances and other climatic factors that affect the region during this season. The long-term decrease in rainfall during the key monsoon season could be a cause for concern, as it may impact the region's water resources and agricultural productivity, which are already challenged by the arid climate of Ladakh. Certain areas seem to consistently show positive or negative anomalies, which could be indicative of microclimates or persistent climatic trends in those areas. The rainfall pattern of Ladakh is primarily dependent on the geographical location and topographic position as this region is nestled between the Karakoram Range and the Himalayas which significantly influence its climate. Moist air masses are forced to rise over mountains, they cool and precipitate on the windward side which leads to reduced rainfall on the leeward side (Barry & Chorley, 2009). One of the most significant factors affecting rainfall patterns is climate change, which is largely driven by the increase in greenhouse gases in the atmosphere due to human activities such as burning fossil fuels, deforestation, and industrial processes. Climate change can alter atmospheric circulation, temperature, and the distribution of moisture, leading to changes in precipitation patterns (IPCC, 2021). Beside these human activities have also increased which is responsible for higher emission and additionally change the land surface for urbanization, deforestation, and agriculture and these affect local and regional climate conditions which influence rainfall by altering surface albedo, evapotranspiration rates, and the formation of clouds (Pielke et al. 2002).

5. Conclusions

The comprehensive analysis of precipitation patterns in Ladakh from 1932 to 2021 has revealed significant insights into the climatic variability and trends in this high-altitude region. The findings highlight the significant inter-decadal and seasonal variability in rainfall patterns due to the influence of various factors on the region's hydro climatology and these have important implications for agriculture, water resource management, and infrastructure development in this region. The analysis of total rainfall in Ladakh during different seasons provides valuable insights into the local climate dynamics. These findings contribute to a better understanding of the climatic conditions in Ladakh and have implications for various sectors, including agriculture, water resource management, and infrastructure planning. More extreme rain events are occurring in last few decades during Monsoon, Pre-Monsoon and a few extents in winter also. These changes have significant implications for the region's water availability, agriculture practices, soil erosion control, flood risk management and overall ecosystem functioning. The observed trends suggest that certain areas of Ladakh are experiencing shifts in rainfall patterns, which could be linked to changes in regional climate regimes, possibly influenced by global climate change. The study of rainfall patterns in Ladakh over nearly a century presents a complex picture of climatic variability. The findings highlight the need for adaptive strategies to manage water resources and agricultural practices in response to changing precipitation patterns. It is important to continue monitoring and analyzing rainfall patterns in Ladakh to gain a more comprehensive understanding of long-term trends. However, the absence of clear long-term trends in rainfall patterns indicates the need for further research to better understand the underlying mechanisms governing rainfall in the region and while the Men Kendall test provides robust statistical analysis, it is essential to consider other factors such as local topography, atmospheric circulation patterns, and climate indices when interpreting the results. Further research could focus on investigating the underlying causes of the observed trends and their potential impacts on the region's socio-economic and ecological systems. This study serves as a foundation for future investigations and contribute to improved water resource management and climate change adaptation strategies in Ladakh. Future research should be focus on a more comprehensive analysis, considering additional climatic factors to improve our understanding of Ladakh's rainfall dynamics or overall area of the Western Himalayas.

Declarations

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Author Contribution

R Bhatla has developed the research idea, framed the manuscript and provided the flow in the manuscript and has subsequently supervised and modified the paper. Richa Singh has done the data collection, analysis, plotting and wrote the manuscript.

Data availability

The datasets used in the current work is freely available on IMD Web Site

Competing Interests

The authors declare that there is no competing interests.

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Conflict of Interest

Authors declare that there is no known competing financial interest or personal relationship that could have appeared to influence the work done in the paper and there is no conflict of interest associated with this publication.

References

1. Banerjee, D., & Singh, C. (2023). On the solid and liquid precipitation characteristics over the North-West Himalayan region around the turn of the century. Climate Dynamics, 60(3-4), 959-980.
2. Barry, R. G., & Chorley, R. J. (2009). Atmosphere, Weather and Climate. Routledge.
3. Basu, S. K. (2013). *Geology of Sikkim state and Darjeeling district of West Bengal*. Bangalore: Geological Society of India.
4. Brian, H. A. R. R. I. S. O. N. (2021). The Impact of a Tourism Boom in an Environmentally-Sensitive Region: A Case Study of Ladakh (Kashmir, India). Japanese Journal of Policy and Culture, 29, 21-41.
5. Dar, T., Rai, N., Kumar, S., & Bhat, M. A. (2022). Climate change impact on cryosphere and streamflow in the Upper Jhelum River Basin (UJRB) of north-western Himalayas. *Environmental Monitoring and Assessment*, *194*(3), 140.
6. Gauss, C. F. (1809). Theoria motus corporum coelestium in sectionibus conicis solem ambientium.
7. IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)].
8. IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press. DOI: 10.1017/9781009157896.001
9. IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647
10. Ji, Q., Yang, T. B., Li, M. Q., Dong, J., Qin, Y., & Liu, R. (2022). Variations in glacier coverage in the Himalayas based on optical satellite data over the past 25 years. Catena, 214, 106240.
11. Joshi, P., & Pant, P. (2023). "Drivers of rainfall variability in the Himalayan region: A synthesis of observational and modeling studies."
12. Kendall, M. G., & Mann, B. (1948). A New Measure of Rank Correlation. Biometrika, 35(1/2), 81-89.
13. Kumar, S., et al. (2023). "Assessment of future rainfall variability over India using climate models: A multi-model ensemble approach."
14. Liaqat, M. U., Grossi, G., Hasson, S. U., & Ranzi, R. (2022). Characterization of interannual and seasonal variability of hydro-climatic trends in the Upper Indus Basin. *Theoretical and Applied Climatology*, *147*(3-4), 1163-1184.
15. Mall, R. K., Kumar, R., & Bhatla, R. (2011). Climate change and disaster in India. *Journal of South Asian Disaster Studies*, *4*(1), 27-76.
16. Mall, R. K., Singh, N., Patel, S., Singh, S., Arora, A., Bhatla, R., ... & Srivastava, P. K. (2023). Climate Changes over the Indian Subcontinent: Scenarios and Impacts. In Science, Policies and Conflicts of Climate Change: An Indian Perspective (pp. 27-52). Cham: Springer International Publishing.
17. Nandargi, S. S., & Aman, K. (2018). Precipitation concentration changes over India during 1951 to 2015. Scientific Research and Essays, 13(3), 14-26.
18. Nunes, A. N., Lourenço, L., Vieira, A., & Bento-Gonçalves, A. (2016). Precipitation and erosivity in southern Portugal: seasonal variability and trends (1950–2008). *Land Degradation & Development*, *27*(2), 211-222.
19. Oliver JE (1980) Monthly precipitation distribution: a comparative index. Prof Geogr 32(3):300–309. https://doi.org/10.1111/j.0033-0124.1980.00300.x
20. Ougahi, J. H., Cutler, M. E., & Cook, S. J. (2022). Assessing the Karakoram Anomaly from long-term trends in earth observation and climate data. *Remote Sensing Applications: Society and Environment*, *28*, 100852.

21. Pielke, R. A., et al. (2002). The influence of land-use change and landscape dynamics on the climate system: Relevance to climate-change policy beyond the radiative effect of greenhouse gases. Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 360(1797), 1705-1719.
22. Rani, S., Kumar, R., & Maharana, P. (2022). Climate change, its impacts, and sbhustainability issues in the Indian Himalaya: an introduction. In *Climate Change: Impacts, Responses and Sustainability in the Indian Himalaya* (pp. 1-27). Cham: Springer International Publishing.
23. Reilly, B. (2022). *Disaster and human history: case studies in nature, society and catastrophe*. McFarland.
24. Schmidt, S., & Nüsser, M. (2017). Changes of high-altitude glaciers in the Trans-Himalaya of Ladakh over the past five decades (1969–2016). Geosciences, 7(2), 27.
25. Sen, M. B. (1968). Estimates of the Regression Coefficient Based on Kendall's Tau. Journal of the American Statistical Association, 63(324), 1379-1389.
26. Shafiq, M. U., Bhat, M. S., Rasool, R., Ahmed, P., Singh, H., & Hassan, H. (2016). Variability of precipitation regime in Ladakh region of India from 1901–2000. Journal of Climatology & Weather Forecasting, 4(2), 165.
27. Sharma, A., & Mishra, V. (2023). "Temporal trends and variability of rainfall in the Trans-Himalayan region: A comprehensive analysis."
28. Singh, G., Singh, A., Singh, P., & Mishra, V. K. (2021). Impact of climate change on freshwater ecosystem. In Water Conservation in the Era of Global Climate Change (pp. 73-98). Elsevier.
29. Singh, R., et al. (2022). "Impact of climate change on rainfall variability in India: A review."
30. Soheb, M., Ramanathan, A., Bhardwaj, A., Coleman, M., Rea, B. R., Spagnolo, M., ... & Sam, L. (2022). Multitemporal glacier inventory revealing four decades of glacier changes in the Ladakh region. *Earth System Science Data*, *14*(9), 4171-4185.
31. Tiwari, S., Kar, S. C., & Bhatla, R. (2016). Interannual variability of snow water equivalent (SWE) over Western Himalayas. *Pure and Applied Geophysics*, *173*, 1317-1335.
32. Tiwari, S., Kar, S. C., & Bhatla, R. (2018). Mid-21st century projections of hydroclimate in Western Himalayas and Satluj River basin. *Global and Planetary Change*, *161*, 10-27.
33. Tuladhar, S., Hussain, A., Baig, S., Ali, A., Soheb, M., Angchuk, T., ... & Shrestha, A. B. (2023). Climate change, water and agriculture linkages in the upper Indus basin: A field study from Gilgit-Baltistan and Leh-Ladakh. *Frontiers in Sustainable Food Systems*, *6*, 1012363.
34. WHO, U. N. I. C. E. F. (2023). Unfpa. Geneva: WHO, 2.
35. Zamani, R., Mirabbasi, R., Nazeri, M., Meshram, S. G., & Ahmadi, F. (2018). Spatio-temporal analysis of daily, seasonal and annual precipitation concentration in Jharkhand state, India. *Stochastic environmental research and risk assessment*, *32*, 1085-1097.
36. Zhang, Y., & Liang, C. (2020). Analysis of annual and seasonal precipitation variation in the Qinba Mountain area, China. *Scientific Reports*, *10*(1), 961.

Tables

Tables 3, 6 and 7 are available in the Supplementary Files section.

Figures

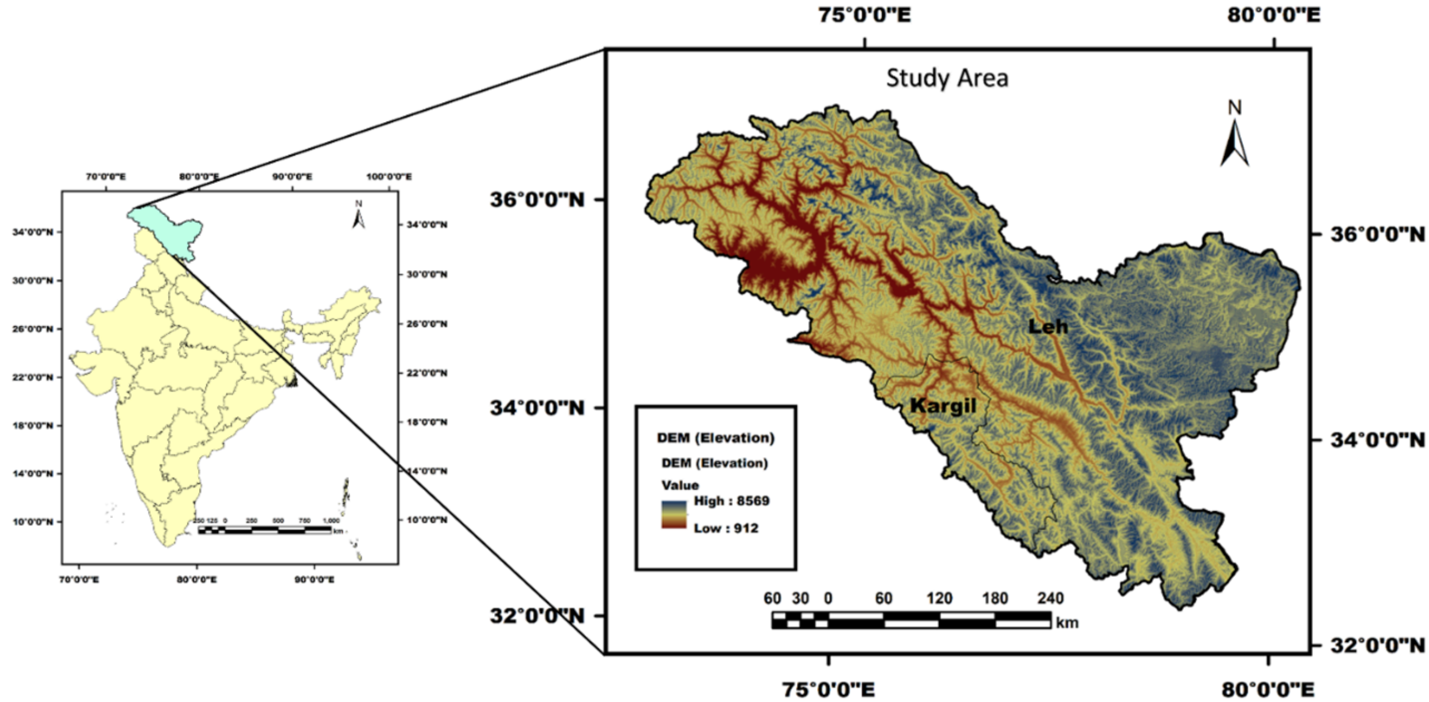

Figure 1

Study area map visualizing DEM image of Ladakh

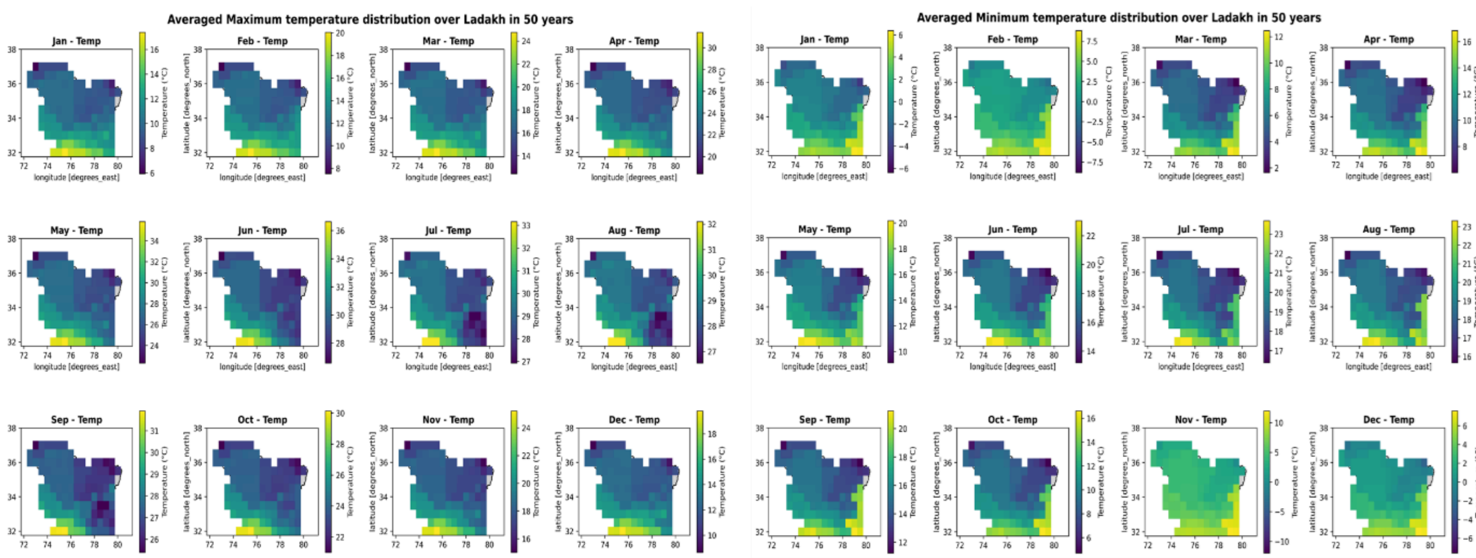

Figure 2

Maximum and Minimum temperature (°C) Climatology over Ladakh: A half Century overview

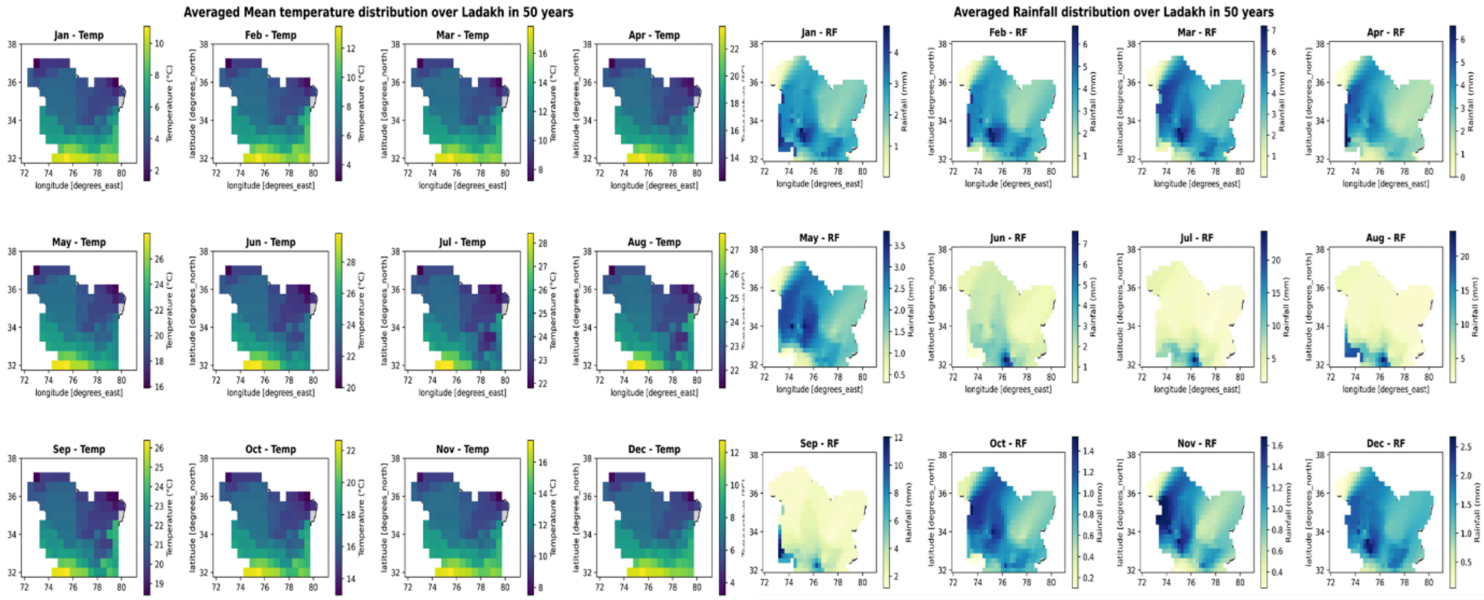

Figure 3

Monthly Mean Temperature (°C) and Rainfall Distribution (mm) over Ladakh (50 years averaged)

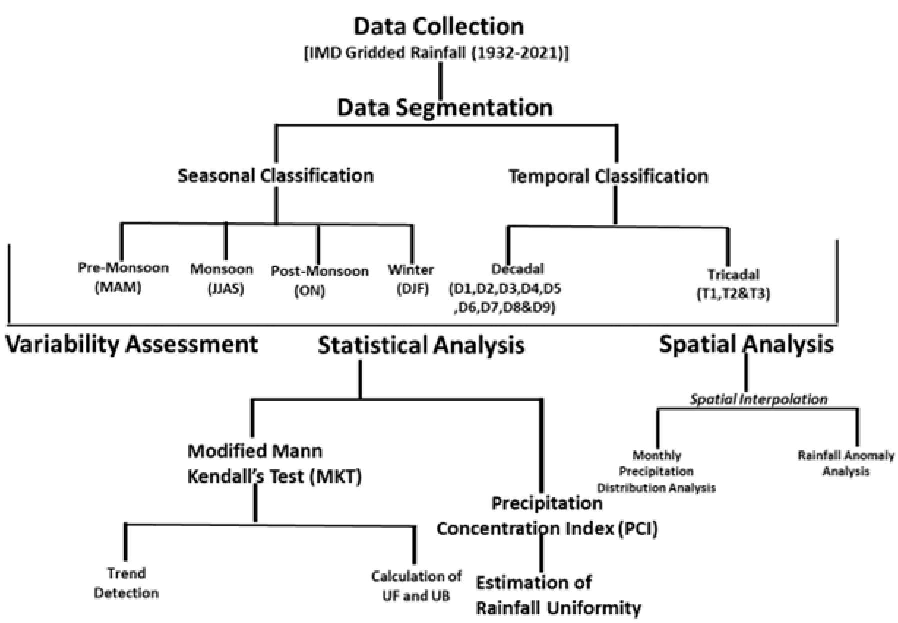

Figure 4

Flow Diagram of Methodology

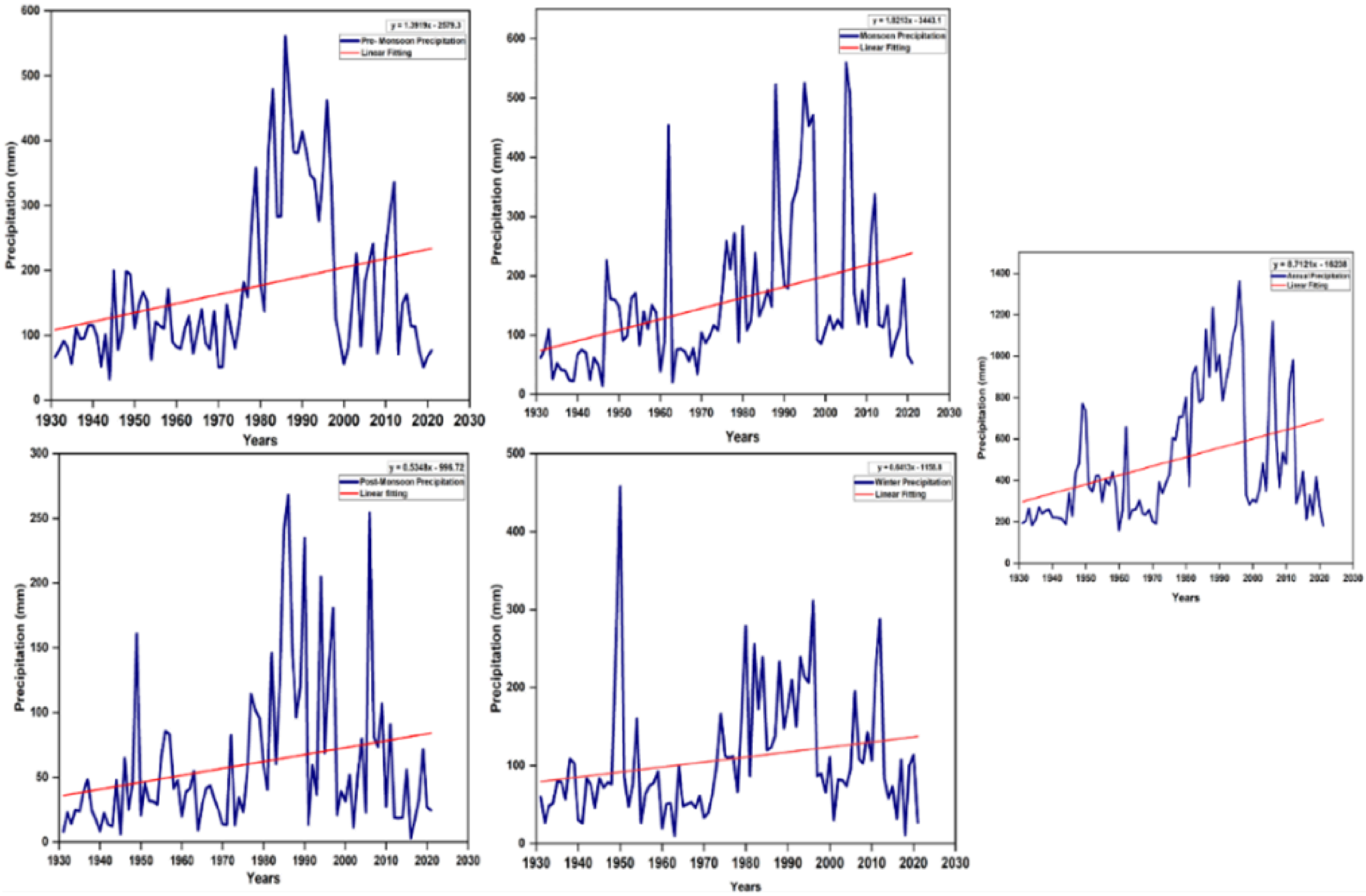

Figure 5

Seasonal and annual accumulated rainfall (mm) and its trend over 90 years.

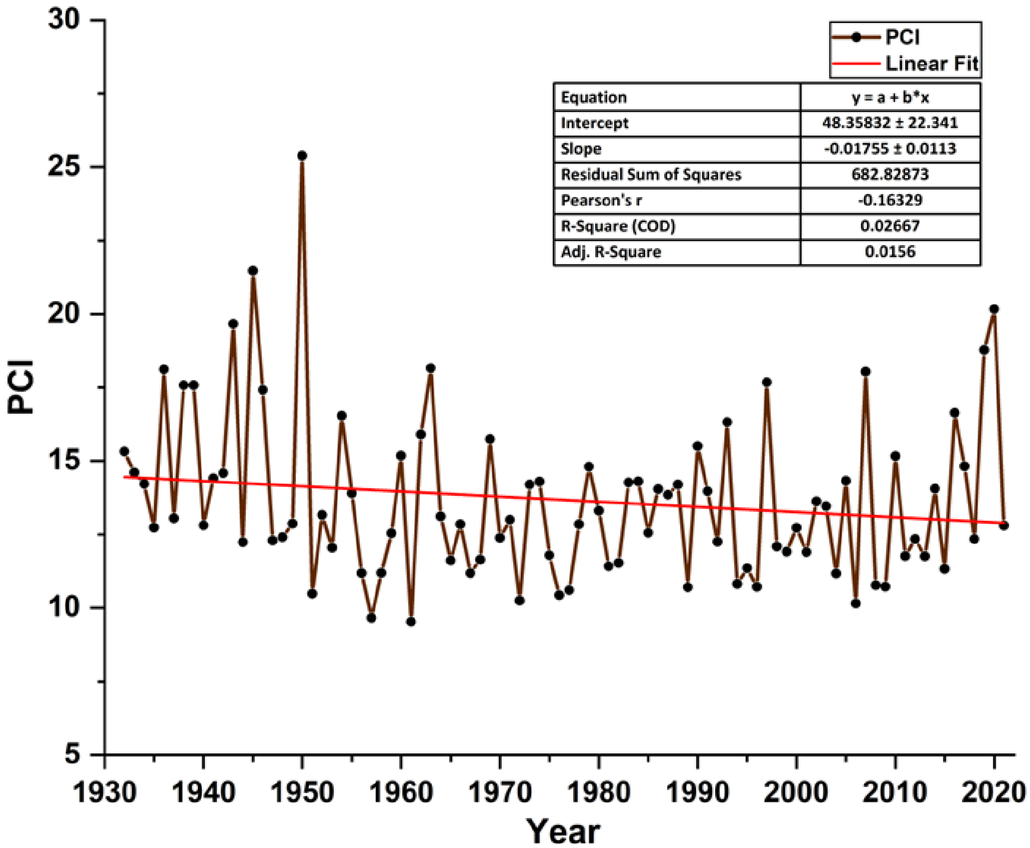

Figure 6

Showing the Precipitation Concentration Index from Year 1931 to 2021

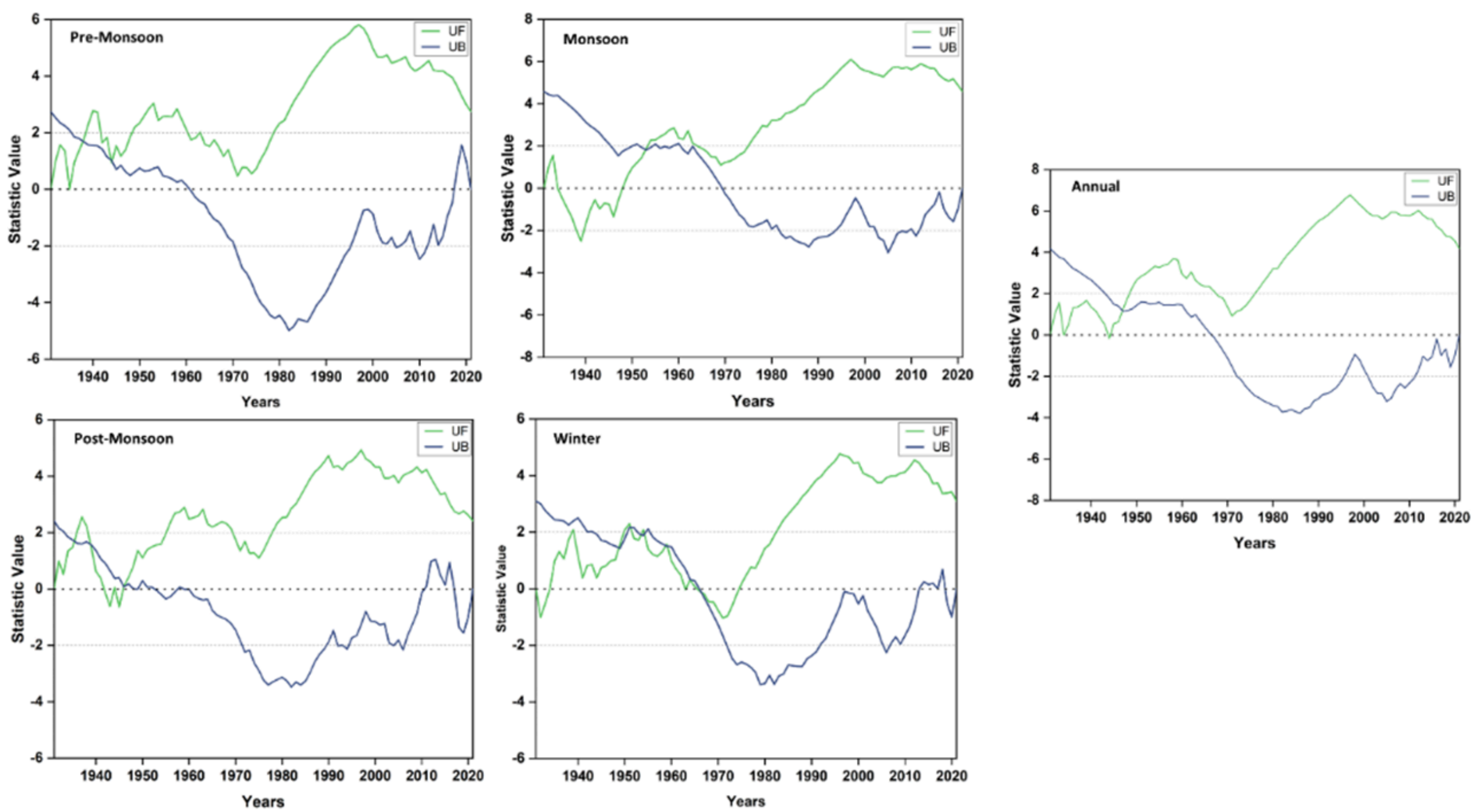

Figure 7

Mann-Kendall statistic curve of the annual and the seasonal rainfall sequence: Pre-Monsoon, Monsoon, Post-Monsoon, and winter at 0.05 significance level

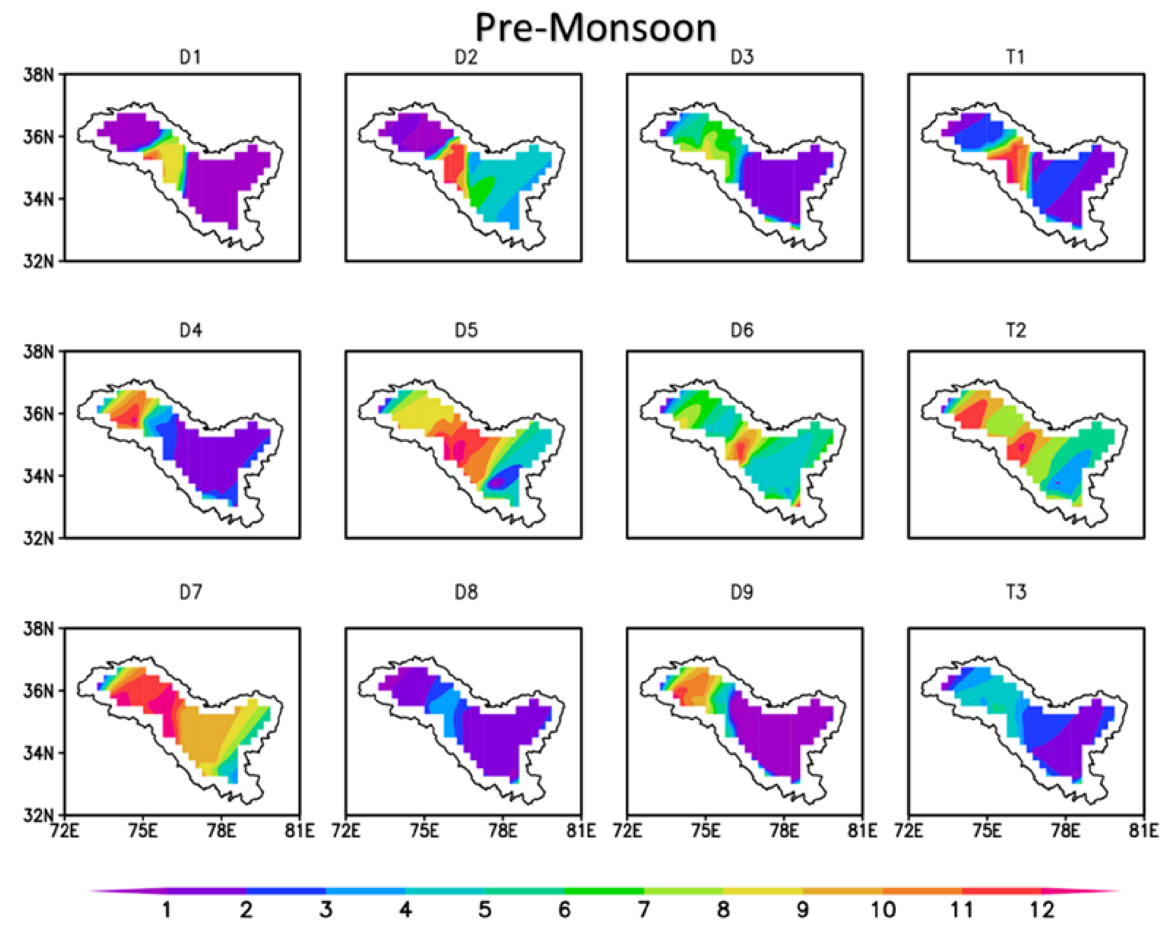

Figure 8

The Decadal and Tricadal variability of averaged rainfall (mm) in Pre-Monsoon season over Ladakh

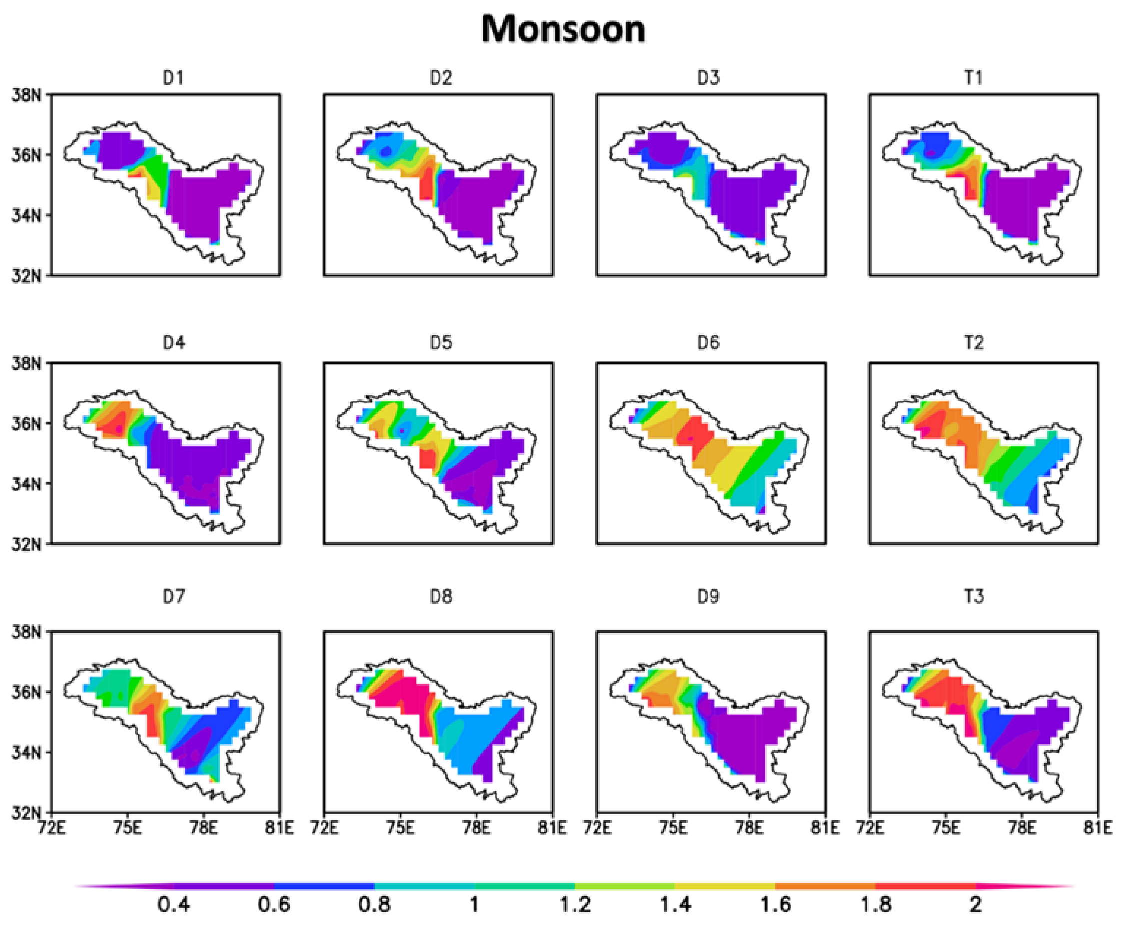

Figure 9

The Decadal and Tricadal variability of average rainfall (mm) in Monsoon season over Ladakh

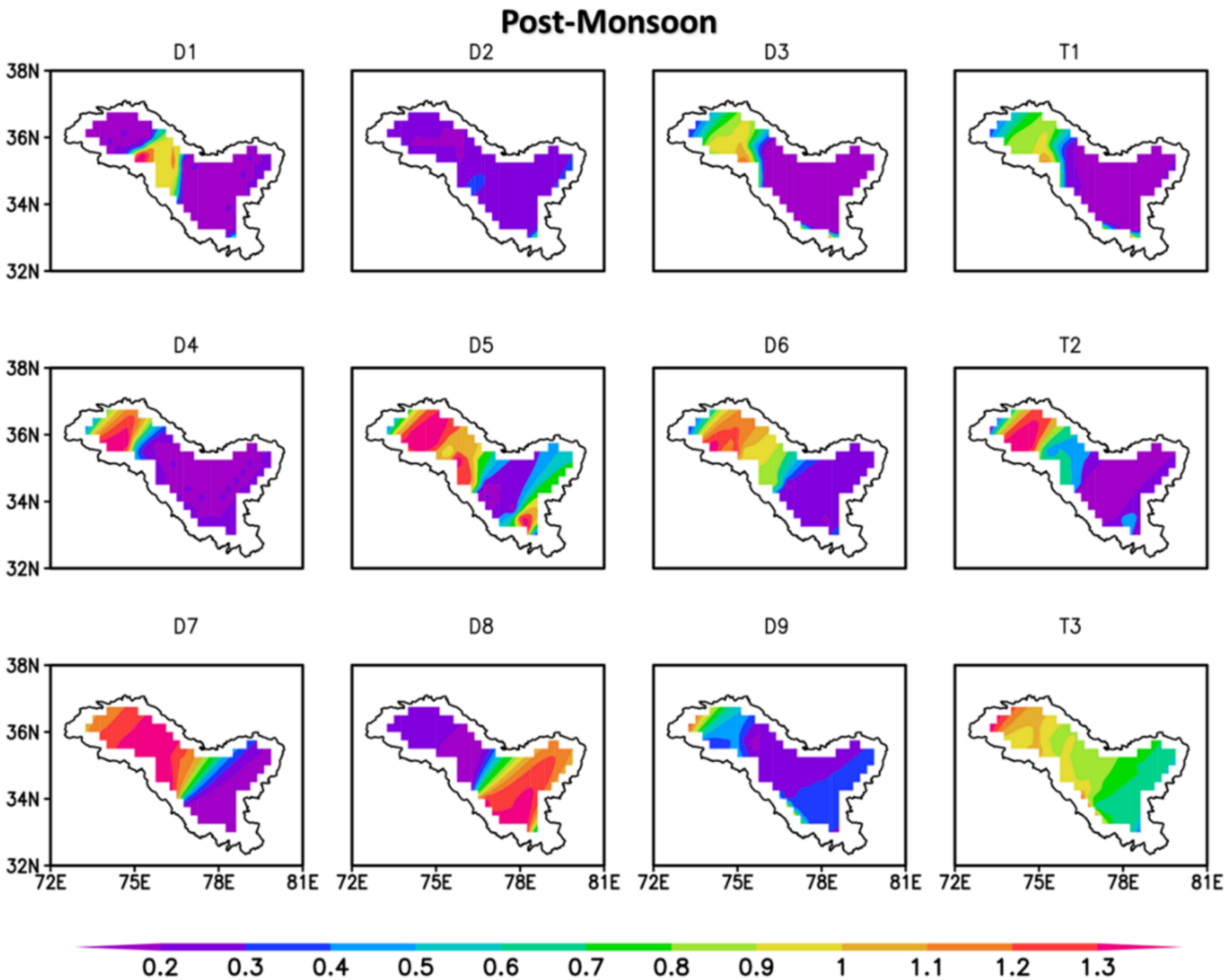

Figure 10

The Decadal and Tricadal variability of average rainfall (mm) in Post-Monsoon season over Ladakh

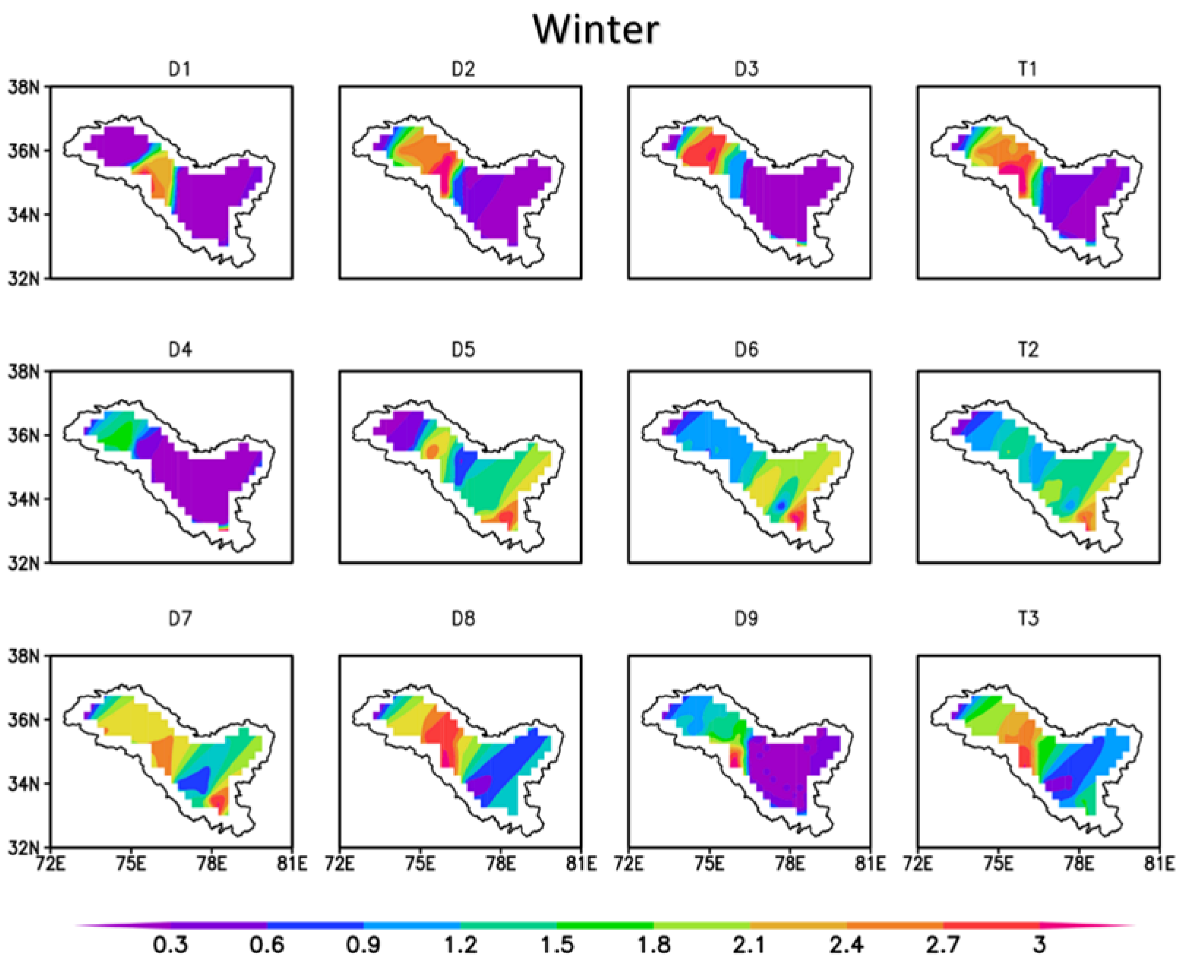

Figure 11

The Decadal and Tricadal variability of average rainfall (mm) in winter season over Ladakh

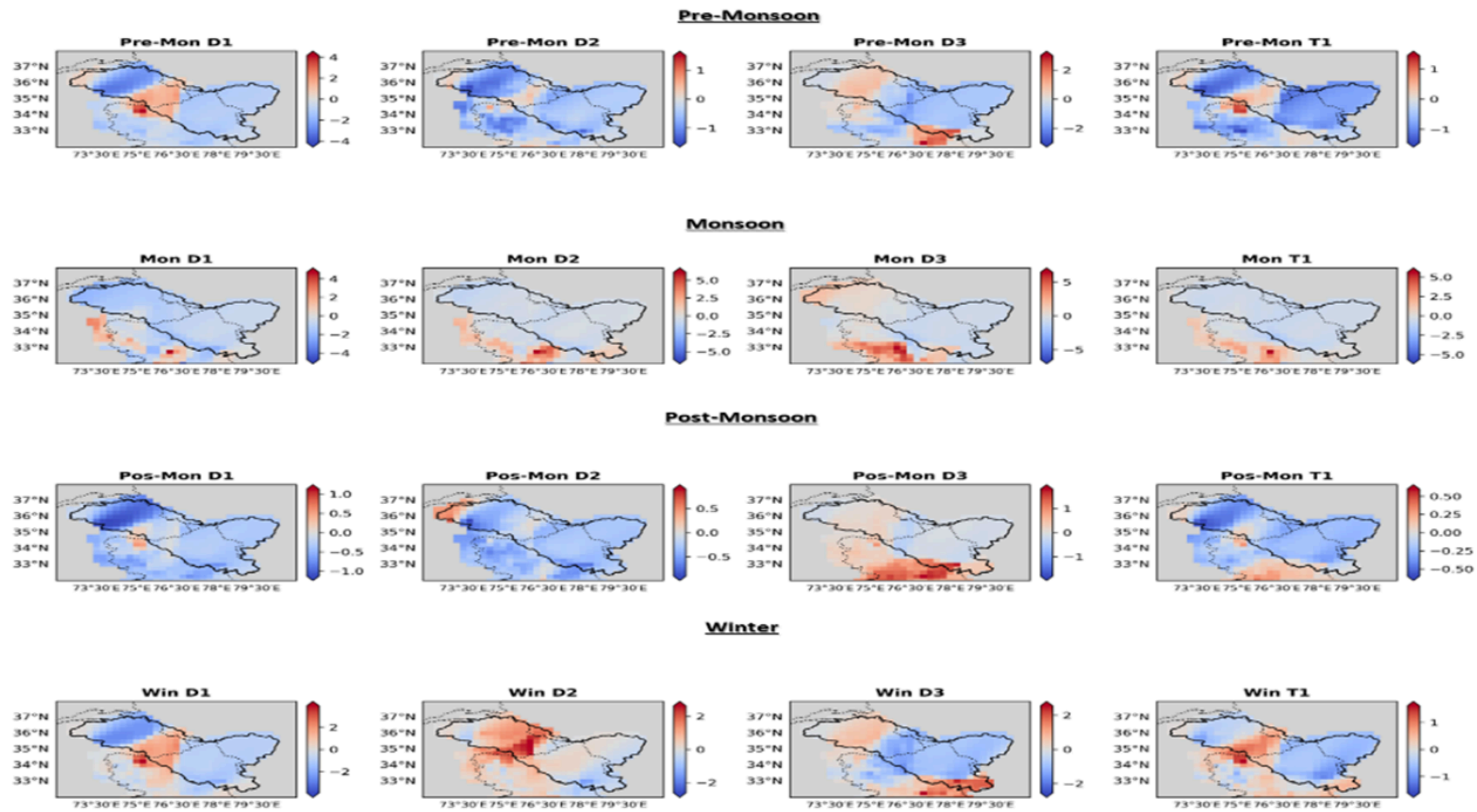

Figure 12

Seasonal Anomaly of Rainfall (mm) over Ladakh in 1st Tricade (1932-1961)

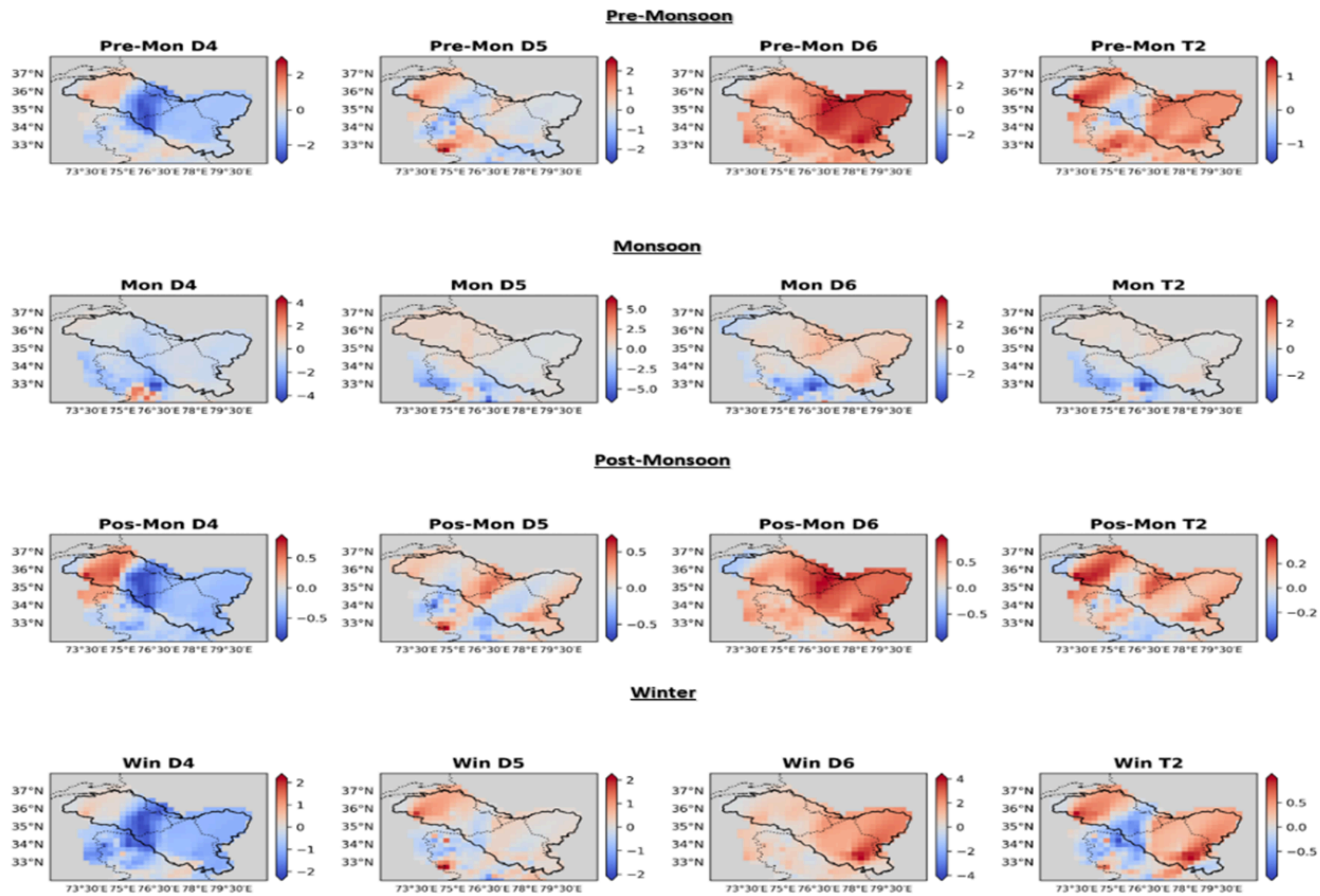

Figure 13

Seasonal Anomalies of Rainfall (mm) over Ladakh in 2nd Tricade (1962-1991)

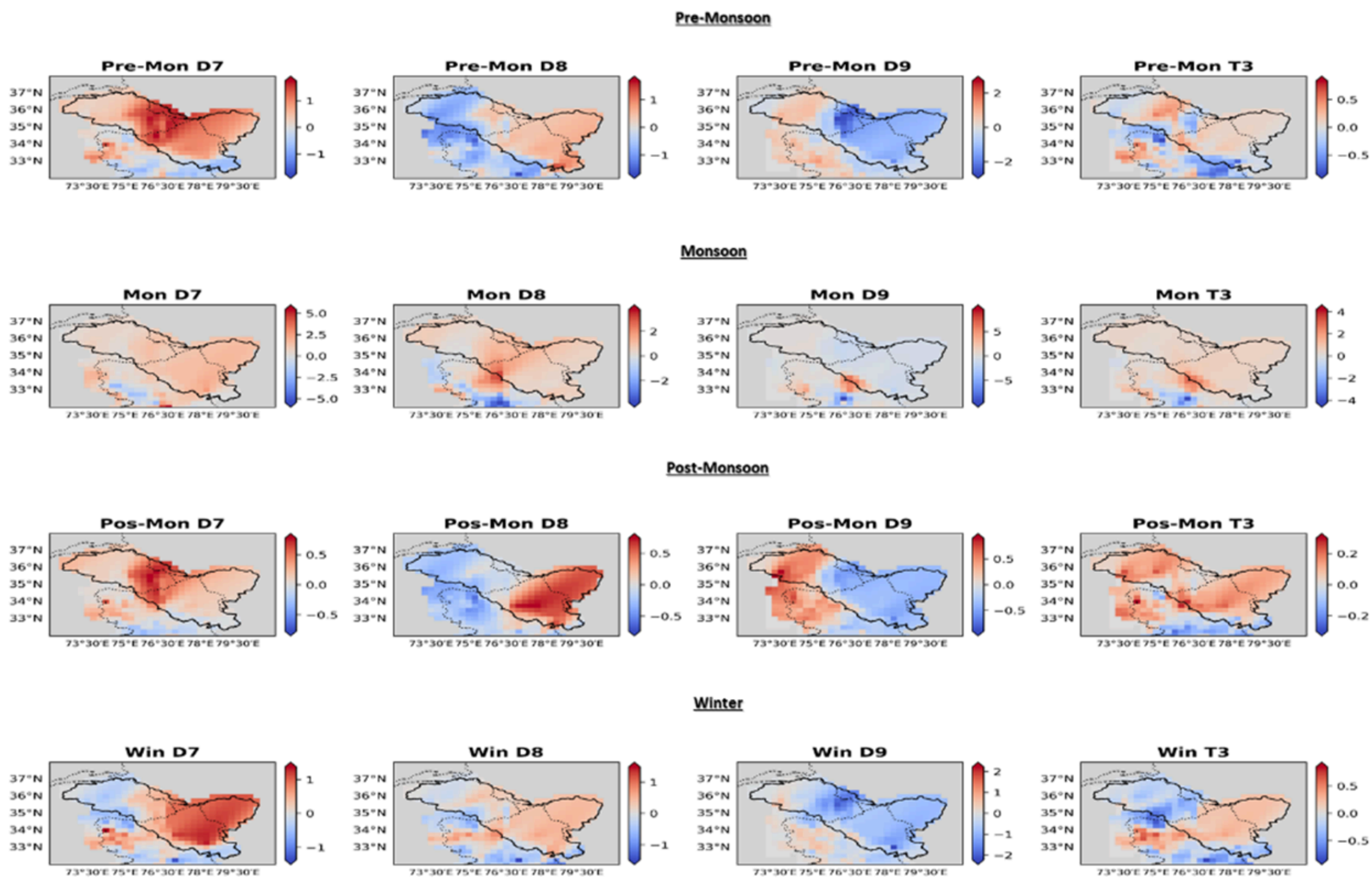

Figure 14

Seasonal Anomalies of Rainfall (mm) in Ladakh over 3rd Tricade (1992-2021)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.docx