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31 **Abstract**

32 Outside of the polar areas, the Himalayan ranges have far more snow. Approximately 17% of the Himalayas and
33 37% of the Karakoram Mountains are covered in snow. Fluctuations in glacier advancement or retreat are
34 considered sensitive indicators of climatic variations in the earth system. The present study deals with daily gridded
35 ($0.25^\circ \times 0.25^\circ$) data of extracted variables and investigates the recent trends in temperature and precipitation over
36 severe cold regions of Ladakh, Kargil, and Zaskar. Trends were calculated using parametric (simple linear
37 regression) and non-parametric (Mann- Kendall and Sen's Slope) tests. Abrupt change point detection in a dataset is
38 also calculated using Pettitt's test and is detected after 2010. The result shows that both rainfall and snowfall show
39 an increasing trend in all the regions but the intensity of the increase is different. It is high over Zaskar at the rate of
40 5.153 mm/year (rainfall) and 0.702 mm/year (snowfall) at a 99.99% confidence level, while precipitation has also
41 increased throughout the study area. Also, the trend of average temperature shows an increasing trend. This recent
42 shift in climatic trends and patterns could have irreversible implications across the study area, resulting in
43 catastrophic outcomes.

44 **Keywords:** Trends, Mann-Kendall, Sen's slope, Pettitt's test, Precipitation

45 **1 Introduction**

46 The nature of environmental risks is influenced primarily by a variety of circumstances, which leads to increased
47 exposure and repercussions to different type of disasters like floods, droughts, avalanches, extreme events and many
48 more (Liu et al., 2006). Worldwide susceptibility has already been rising as a result of different human-induced
49 challenges like encroachment in flood-prone areas, haphazard growth of urbanization, ablation of mountain glaciers
50 etc. (Chang et al., 2009; Yang et al., 2022). As stated in the fourth Assessment Report of the Intergovernmental
51 Panel on Climate Change (IPCC), the average temperature all around the world has increased by 0.74°C during the
52 past century (IPCC, 2007). Owing to the fact that extreme events are more susceptible to climate change, substantial
53 emphasis has been placed on the fluctuations and trends of these occurrences (Vose et al., 2005; You et al., 2008a).

54 Precipitation and temperature extremes have been studied in many parts of the world (Frich et al., 2002;
55 Alexander et al., 2006), including the Asia-Pacific region (Manton et al., 2001; Griffiths et al., 2005; Tian et al.,
56 2006), southern and West Africa (New et al., 2006), Caribbean region (Peterson et al., 2002), South America
57 (Vincent et al., 2005; Haylock et al., 2006), Central America and northern South American (Aguilar et al., 2005),
58 and Middle East (Zhang et al., 2005). These investigations discovered that significant increases in temperature
59 extremes are connected with global warming, despite the fact that changes in precipitation extremes are significantly
60 less coherent than temperature (Arya, 2011; Gupta et al., 2012). Growing susceptibility on the flood plains of big
61 continental rivers has gotten a lot of attention because of the potentially disastrous economic consequences
62 (Bhutiyan et al., 2010; Rasmussen & Houze, 2012).

63 The study area i.e. Ladakh is India's highest and largest highland plateau, with an average elevation of about
64 3000 mt. above sea level (asl), and its thermal forcing mechanism have a significant impact on regional and global
65 climate (Yeh & Gao, 1979; Yanai et al., 1992; Duan & Wu, 2005). The study area is one of the most severely
66 affected locations on the planet as a result of global environment change (Chen et al., 2003; Duan et al., 2006).

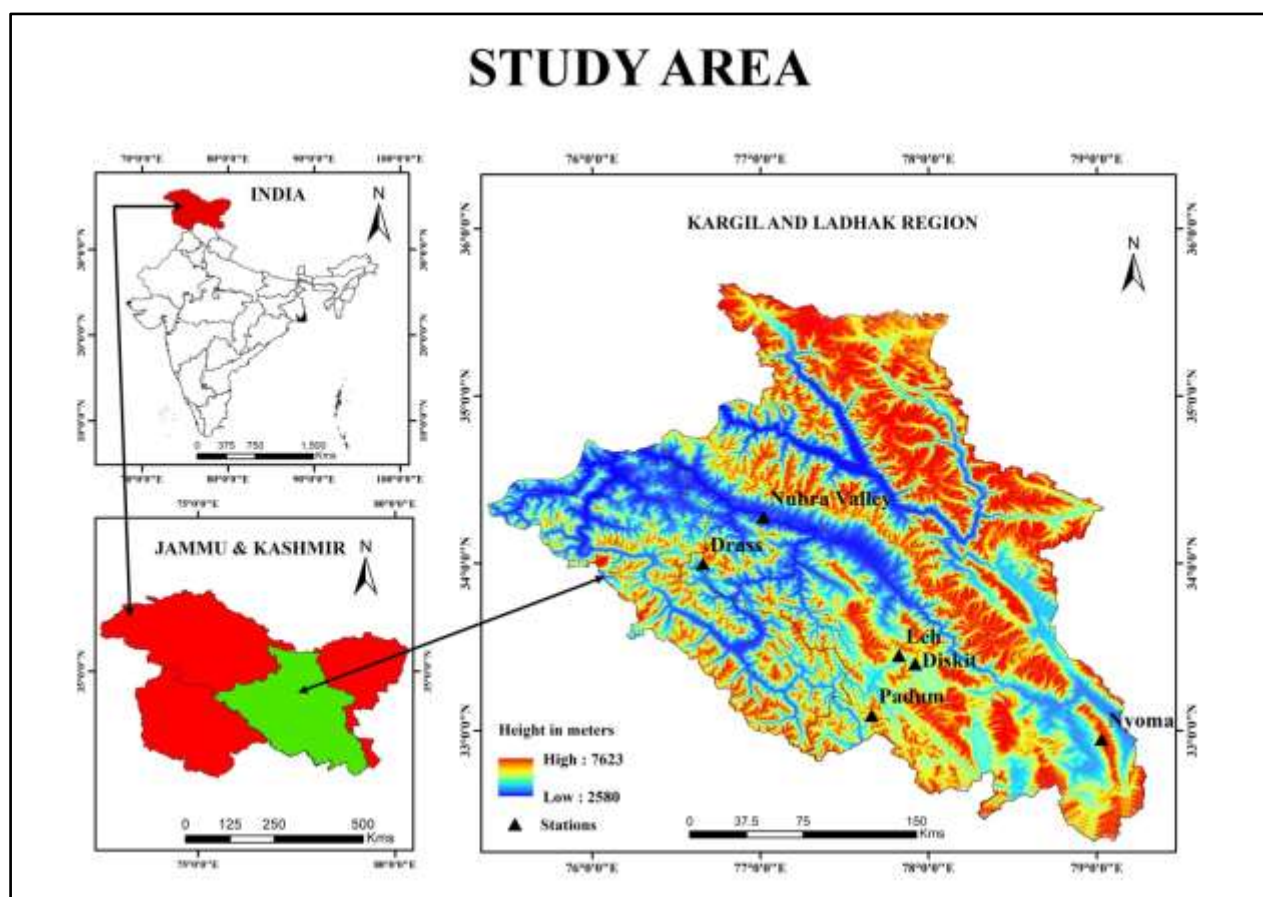
67 Furthermore, owing to a dearth of publicly available data for the region, there has been little research on
68 precipitation and temperature extremes. A definite regional precipitation signal has yet to be discovered due to the
69 difficult terrain and lack of meteorological stations (Lin & Zhao, 1996; Liu & Yin, 2001; Du & Ma, 2004). Our
70 research work is centred on Ladakh, India, where the climatic conditions are extremely harsh, and the risk of disaster
71 continues to rise as the rate of temperature increase has accelerated in recent decades (Chen et al., 2003; Geneletti &
72 Dawa, 2009; Hobley et al., 2012). Ladakh is an example of an area where vulnerability is increasing as a result of a
73 rapidly growing economy, strong tourism industry, rising population, infrastructure challenges, and a lack of
74 government reaction (Bharti, 2015) (Fig. 1). Ladakh is situated between the Great Himalayas and the Karakoram
75 Range in the Trans-Himalayan Region, and is surrounded by the Zaskar and Ladakh Mountain ranges. The harsh
76 high altitude desert climate that exists at elevations ranging from 3300 to 6120 meters has proven resilient to Ladakh
77 settlements. The average annual precipitation is 115mm, with extreme temperatures ranging from -28°C to 33°C
78 (Thayyen et al., 2013; Kumar et al., 2014). Leh and its surrounding areas are located in one of the broadest segments
79 of the Indus River valley, which is flanked on the south by the severely deformed sedimentary rocks of the Zaskar
80 Range and on the north by a foliated granite batholith. The Indus River is flanked on both sides by the Zaskar
81 Range's huge and steeply sloping alluvial and colluvial fans, funnel-shaped fans coming from the batholith, and
82 fluvial terraces (Santi et al., 2010). In certain spots, sand ramps run along the valley walls. All of these geomorphic
83 variables combine to create huge bare surfaces with semi-consolidated sediments beneath them, which could
84 become clastic debris sources carried by floodwaters. Finally, when minor debris dams in streams break, they can
85 cause massive floods and sediment flows (Juyal, 2010; Arya, 2011).

86 The study area (i.e. the union territory of Ladakh) is now a popular base for mountaineering, environmentalism,
87 contemplation, and religious activities in the mountains and valleys, and is now considered as a tourist hotspot
88 (Ziegler et al., 2016). Four decades after the region was opened to outsiders in 1974, tourist industry has become one
89 of the fastest growing sectors in the country (Pellicciardi, 2013). Environmental dangers like floods appear to have
90 been managed in the past via millennia of adaptation. However, due to a recent surge in fast urbanisation,
91 particularly in response to a burgeoning tourism sector, this position has shifted (Dolkar, 2015). The present study
92 investigates the recent trends in precipitation and temperature over the union territory of Ladakh which is the
93 primary triggering factors behind the devastating floods and debris flows generated by brief and intense rainfall
94 events.

95 **2 Database and methodology**

96 Daily gridded data for both precipitation ($0.25^\circ \times 0.25^\circ$) and temperature ($31^\circ \times 31^\circ$) from six meteorological
97 stations which are well distributed over the Union territory of Ladakh were utilized in the present study (Fig. 1).
98 Also, dataset for both rainfall and snowfall were collected from the portal of NASA data access viewer
99 (<https://power.larc.nasa.gov/data-access-viewer>) a widget provide access to climatology dataset for the entire globe.
100 The duration of the dataset for the precipitation, rainfall, snowfall is the same which is 1980-2021 (42 years) and for
101 temperature, it is 1981-2020 (40 years). The discontinuity in the time series data is the reason of this variation in
102 dataset duration. Data for the said parameters (i.e. precipitation and temperature) are collected from National Data
103 Centre (NDC), Indian Meteorological Department (IMD), Pune. The authenticity of the dataset was analyzed in

104 accordance with the procedure followed in the study of Pai et al. (2014). Pai et al. (2014) used daily rainfall data for
 105 the period 1901–2010 from all the rain gauge stations across the nation that were stored in the archive of the NDC,
 106 IMD, Pune, to create the new daily (0.25° x 0.25°) gridded rainfall dataset. He observed that the broad scale
 107 climatological and variable characteristics of rainfall data over India acquired from the portal of IMD were
 108 consistent with the data-sets already in existence. Furthermore, owing to the current data properties of higher spatial
 109 resolution and density of rain gauge stations that are used in the study of Pai et al. (2014), the spatial distribution of
 110 rainfall, particularly the heavy and very heavy rainfall areas over the orographic locations of the west coast and
 111 north-east, low rainfall in the leeward side of the western Ghats, etc. were much more pragmatic and better
 112 explained. After the collection of the IMD gridded data, it is converted into CSV or excel file in IMDLIB-Python
 113 software.



114 **Figure. 1** Map of the study area

115 Table 1 shows the geographical location (latitude and longitude) and height of all six stations. Data quality
 116 assessment begins with evaluating the quality of the data, since the said parameters trends and patterns have a big
 117 impact on deviation trends (You et al., 2008b; Shahid et. al., 2016). For the time series data of the said parameters,
 118 an objective student t-test was used to establish dataset consistency. The Student's t-test identified no break point or
 119 statistically significant difference in the time series at the 95 percent confidence level. Apart from that, monthly,

120 seasonal, and annual values have been calculated using the daily dataset. Seasonal analysis was carried out for all
121 four seasons, namely, early winter (November–January), late winter (February–April), early summer (May–July),
122 and late summer (August–September) in accordance with the weather conditions in the study area.

Station	Latitude	Longitude	Altitude (mt.)	Mean Precipitation (mm)	Maximum Precipitation (mm)		Minimum Precipitation (mm)		SD (mm)	CV (%)	Maximum Temperature (° C) (1981-2020)		Minimum Temperature (° C) (1981-2020)	
					Precipitation	Year	Precipitation	Year			Temperature	Year	Temperature	Year
Drass	33.998	76.660	4452	302.84	639	2015	145.97	2009	118.84	39.24	17.19	2001	-45.06	2019
Padum	33.147	77.627	4985	259.50	547.45	2015	65.68	1991	117.61	45.32	18.83	2001	-37.43	2019
Leh	33.450	77.825	5058	174.44	378.05	2015	39.78	1991	82.06	47.04	21.24	1999	-39.48	2019
Nyoma	32.949	79.029	5011	150.47	341.24	2017	50.32	1982	77.97	51.82	21.52	1999	-38.95	2019
Diskit (Nubra)	33.450	77.825	4452	208.17	443.89	2015	95.27	1991	81.01	38.92	23.85	2001	-37.37	2019
Nubra Valley	34.275	77.017	4559	222.17	428.05	2015	114.62	2009	79.53	35.81	23.51	2001	-37.68	2019

123 **Table. 1** Basic information of selected stations and station-wise precipitation and temperature characteristics over severe cold region of Ladakh (1980–2021).

124 2.1 Methodology

125 Data from Nyoma, Leh, Diskit and Nubra stations is combined to create the dataset for the entire Ladakh region. Both Zaskar and Kargil each have one
 126 meteorological station which is situated in Padum and Drass respectively. After organizing the entire dataset of different locations, suitable statistical analyses
 127 such as sum, percent, average, standard deviation (SD), and coefficient of variation (CV) were done for each region over the period (1980–2021). The following
 128 methodology was adopted in calculation of years with deficits and excesses in precipitation:

129 2.1.1 Recognition of excess and deficit precipitation years

130 In this study, a year is classified as surplus or deficit precipitation if precipitation differs by more than one standard deviation from the mean (Pant & Kumar,
 131 1997). An excess precipitation year can be calculated as follows

$$132 R_i \geq R_m + S_d \quad (1)$$

133 And a deficit year can be expressed as:

$$134 R_i \leq R_m - S_d \quad (2)$$

135 Where R_i = precipitation amount in a year i , R_m = mean precipitation and S_d = SD of precipitation.

136 2.1.2 Trend Detection

137 To find trends in rainfall, snowfall, precipitation and temperature, the non-parametric Mann–Kendall (MK) test
 138 (Mann, 1945; Kendall, 1948) was utilized. While looking for noteworthy patterns in the time series at various levels
 139 of significance, this MK test is a suitable example (Mayowa et al., 2015). The standard variable Z is utilized to
 140 detect trends and their significance level. Positive or negative Z values in time series data imply an increasing or
 141 declining trend. In this investigation, the presence of a statistically significant positive or negative trend was
 142 assessed at confidence levels of 90%, 95%, 99%, and 99.99%. If the lag-1 serial coefficients of the data were not
 143 statistically significant, the MK test was performed without any alterations to the original time series (Karpouzou et
 144 al., 2010). When an autocorrelation is present, the chance of spotting a significant trend increases (Bayazit & Onoz,
 145 2009). To remove the autocorrelation effect from the data series, the MK test was used in the current study after pre-
 146 whitening (Bayazit & Onoz, 2009) for all regions (Partal & Kahya, 2006). Sen's Slope estimator has been used to
 147 estimate the magnitude of change in the trend in non-parametric statistics (Sen, 1968). In addition, parametric simple
 148 linear regression was also used to evaluate the trend in the time series in this study. In various hydro-meteorological
 149 researches, all three approaches have been frequently used for this purpose. These tests were carried out using the
 150 XLSTAT 2017 software.

151 2.1.3 Homogeneity Analysis using Pettitt's test

152 In a time series, detecting abrupt change in point is essential for establishing the period during which
 153 considerable change has occurred. The specifics of Pettitt's for detecting abrupt change points is given below:-

154 Pettitt's test

155 The Pettitt's test is a useful non-parametric method for detecting abrupt changes in a time series (Winingaard et
 156 al., 2003). Furthermore, it detects a large change in a time series' mean when the actual timing of the change is
 157 uncertain. Pettitt's (1979) test states that if $x_1, x_2, x_3, \dots \dots \dots x_n$ is indeed a series of observable data with a
 158 deviation at t such that $x_1, x_2, x_3, \dots \dots \dots x_t$ have a distribution function $F_1(x)$ that differs from the distribution
 159 function $F_2(x)$ of the second segment of the series $x_{t+1}, x_{t+2}, x_{t+3}, \dots \dots \dots x_n$. This test statistic (U_t) can be stated
 160 mathematically as:

161

$$162 U_t = \sum_{i=1}^t \sum_{j=t+1}^n \text{sgn}(x_i - x_j) \quad (3)$$

163

$$164 \text{sgn}(x_i - x_j) = \begin{cases} +1, & \text{if } (x_i - x_j) > 0 \\ 0, & \text{if } (x_i - x_j) = 0 \\ -1, & \text{if } (x_i - x_j) < 0 \end{cases} \quad (4)$$

165 Where x_i signify date value at time i .

166 For the sample length (n), the test statistic K and the accompanying confidence level (q) can be defined as:

167

$$168 K = \text{Max}|U_t| \quad (5)$$

$$169 \quad p = \exp\left(\frac{-K}{n^2 - n^3}\right) \quad (6)$$

170 The rejection of the null hypothesis when q is less than the specified confidence level. For a change point, the
 171 estimated significance probability (P) is defined as:

$$172 \quad P = 1 - p \quad (7)$$

173 It is clear that where there is a substantial abrupt change point, the series is split into two sub-series at the
 174 change point. The test statistic K can be compared to the corresponding statistic for detecting a transition point in a
 175 time series at various confidence levels. This test is widely used in both hydrological and climatological studies for
 176 change detection (Zhang et al., 2008; Guerreiro et al., 2014).

177 **3 Results and discussion**

178 **3.1 Annual analysis**

179 The average annual trends in rainfall, snowfall and mean minimum, maximum and average temperature over
 180 severe cold regions of Ladakh, Kargil and Zaskar are shown in fig. 2. The time series dataset revealed a high degree
 181 of inter-regional variability in average annual precipitation, with the highest ($SD = 118.84$) in Kargil and the highest
 182 CV (51.82) over Nyoma station in Ladakh region, as well as varying degree of precipitation ranging from 39.78 mm
 183 (in 1991 over Leh) to 639 mm (in 2015 over Kargil) and average annual precipitation is high over Kargil region
 184 (302.84 mm) (table. 1). Similarly, maximum temperature which is 23.85°C is experienced in Diskit station of
 185 Ladakh region in the year 2001 and lowest temperature (-45.06°C) is experienced in 2019 over Drass station of
 186 Kargil region (table. 1). Trends in precipitation in all over the study area shows an increasing trend after the year
 187 2000 (Fig. 3a). It has been observed from the table 3 that most of the excess precipitation years such as 2013, 2015,
 188 2016, 2017, 2018 and 2019 have occurred after 2013 and most of the precipitation deficit year lies before 1992 i.e.
 189 increasing in precipitation trends starts fluctuating due to rise in temperature in the end of 20th century and second
 190 decade of 21st century. The majority of the rainfall deficit years, such as 1982, 1987, 2002, and 2009, have coincided
 191 with El-Nino years (table. 4). However results obtained from the pettitt's test reveal 2010 as the abrupt change
 192 detection year for all station stations except Nyoma. Besides after 2005, it is experienced in Nyoma only in case of
 193 rainfall (Fig. 3b). The results are in agreement with a heavy storm event of 2010 that is experienced over Leh led to
 194 devastating flash floods and debris flows, due to which, Leh and its adjoining areas were struck causing at least 234
 195 fatalities. However, as per the Army medical records, 800 more people were listed as missing (Gupta et al., 2012).
 196 Roads, schools, bridges, and innumerable cattle were all, also lost. Over 1450 dwellings were entirely destroyed,
 197 approximately belongs to 71 different communities, making Leh the worst-affected area (Disket, 2014). The
 198 majority of these dwellings were situated in perilous locations, mostly along the stream banks and flood plains. After
 199 the event an increase in both rainfall and snowfall was observed due to rise in temperature as a result of climate
 200 change. Thus, we can conclude from the history of floods over the severe cold regions of Ladakh that with the rise in
 201 temperature such extreme type of flood events will occur more in future.

202 Both rainfall and snowfall shows increasing trend in all the regions but the intensity of increase is different. The
 203 rate of increase in both rainfall and snowfall is high over Zaskar region which is 5.153 mm/year and 0.702 mm/year
 204 (table. 5) respectively which is at 99.99% confidence level while the average temperature is increasing all over the
 205 study area with no significant trend and minimum temperature is decreases in all over the study area. In case of

206 maximum temperature it is increases over Kargil and Ladakh and decreases over Zaskar (-0.031° C at 90%
 207 confidence level) (table. 5). Furthermore, increase in both rainfall and snowfall along with their rate and level of
 208 significant trend is shown in table 5. The dataset of both rainfall and snowfall imply that there has been a greater
 209 than average increase in both rainfall and snowfall over the study area. Also, the results of precipitation reveals that
 210 the rate of increase in precipitation is high over Zaskar region (5.74 mm/year at 99.99% confidence level) and it is
 211 also increases in rest of the regions i.e. over Kargil and Ladakh (table. 6). Precipitation trends over the union
 212 territory of Ladakh are affected by a variety of factors like terrain, altitude, rain shadow effect of the mountains and
 213 warming of Tibetan plateau. Over the upper Himalaya and Tibetan Plateau, a gigantic (meso-scale) rain-producing
 214 cloud structure was formed; (Rasmussen & Houze, 2012) and moisture was contributed to the system by monsoon
 215 air masses moving northward from the Arabian Sea and the Bay of Bengal. This diurnal heating of the Tibetan
 216 Plateau culminated in isolated convective cells forming over the steep terrain in the afternoon and easterly 500-mb
 217 jet, which was diurnally enhanced, propelled the cells west and southwestward to the edge of Tibetan Plateau, where
 218 a mass of heavy clouds accessed the moist air-flow associated with circulation around a mid-level vortex and soared
 219 above the Himalayan wall. This moist air pump-up the meso-scale convective system crossing the plateau and
 220 increased in precipitation-producing nimbostratus and cumulonimbus clouds that are culminating in 3 to 4 days of
 221 discrete, spatially discontinuous and heavy rain occur in the valley (Duan & Wu, 2006). Moreover, thunderstorms
 222 over desert and mountainous regions, as well as the interior portions of continental landmasses, are frequently
 223 associated with intense events during the rainy season (Kashmir Observer, 2015).

224 The sophisticated landform setup, altitude variation from region to region, the influence or impact of monsoon in
 225 high altitudes, imbalance in various micro-climate parameters (Sicard et al. 2013), increase or decrease in cloud
 226 cover, and human encroachment in the higher reaches of Karakorum Himalaya (Koul & Ganjoo, 2009) are some of
 227 the important phenomena's that can control the climatic conditions of the study area. Owing to recent changes or
 228 developments in horticulture, agricultural, and hydropower sectors have all suffered due to the newly induced
 229 phenomenon of global warming (Owen & Dortch, 2014). Temperature is a second important hydro-meteorological
 230 variable after precipitation. Rise in temperature of a region poses a major threat to the agriculture, vegetation,
 231 habitat, and biodiversity (Mishra, 2018). As a result, the current study also studied the temporal distribution of
 232 average annual, maximum and minimum temperature, which revealed that average temperature, was rises in the
 233 recent decades (Fig. 2b).

234 These results found true with some existing studies that are reported by different researchers such as Shaheen et
 235 al. (2013), Ziegler et al. (2016) and Chevuturi et at. (2018). These warming trends, according to Roy (2015), are due
 236 to an increase in anthropogenic activity, such as land use/cover changes, industrialization, and urbanisation. Heavy
 237 rains in Ladakh often results in disastrous flash floods and debris flows.

238 **3.2 Seasonal analysis**

239 Recent trends in seasonal snowfall, rainfall (Fig. 4) and precipitation (table. 2) over the study area during
 240 different seasons shows deviations. Approximately, 92% of seasonal precipitation over the Ladakh region has
 241 occurred during summer season (i.e., early summer and late summer). The remaining precipitation (less than 10%)
 242 fell over two seasons, namely early (2.5%) and late (5.31%) winter. The values of SD is found very less in late

243 winter (SD = 3.92 (Kargil), 2.69 (Zaskar), 2.76 (Ladakh)), and high in late summer season (highest region 99.60
244 mm) (table. 2). Also, it is observed from the table 3 which shows season wise excess and deficit precipitation years,
245 it shows that 2013 was the year of excess precipitation in all three seasons. It is clearly seen in fig. 4 that both
246 rainfall and snowfall is increases in all four seasons over the entire study area. Further, increase in both rainfall and
247 snowfall is significant only in early and late summer season. The rate of increase in rainfall (4.387 mm/year) and
248 snowfall (0.280 mm/year) is high in late summer season over Zaskar region (99.99% confidence level), rainfall
249 (3.479 mm/year) and snowfall (0.046 mm/year) over Kargil (99% confidence level), rainfall (2.532 mm/year at 99%
250 confidence level) and snowfall (0.060 mm/year at 95% confidence level) over the Ladakh region (table. 5). In early
251 winter season, highest increase in rainfall is noticed over Kargil region which is 0.025 mm/year (99% confidence
252 level) and the rate of increase in rainfall and snowfall for rest of the season over different regions is shown in table
253 5. Due to the retreat in north-east monsoon, Leh receives very little precipitation in the late winters. These instances
254 of precipitation are linked to western disturbances that bring rain to northern India in the winter (Dimri & Dash,
255 2012; Dimri & Chevuturi, 2014; Ziegler et al., 2014). Furthermore, some major western disturbances may have an
256 impact on the region during the late summer season. Tourism is a major driver of economic development,
257 uncontrolled urbanisation, and rural-to-urban migration in the region (Fewkes, 2008). Currently, the industry has not
258 built contingency plans for visitors or the long-term viability of firms in the event of a catastrophic incident. As a
259 result, one such event was observed in 2010 and a total of one hundred foreign nationals or non-local visitors were
260 killed in that event region (Gupta et al., 2012).

261 The temperature graphs in fig. 5 and values in table 5 shows that temperature is raising in all regions of the study
262 area, which is not a good indicator for the glacier ecosystem. Many buildings are being erected on fans in the Leh
263 area, which were themselves produced primarily by debris flows. As urban centers extend outward from the city
264 centre, many fields have been replaced with houses, and encroachment was done in the area that was originally used
265 in agriculture. The owners, fresh immigrants from nearby Kargil, built the dwellings with no knowledge of the
266 stream's recent deadly history. In 2015, a reminder was issued, but its modest size may not have been enough of a
267 deterrent to prevent construction in such hazardous regions (Santi et al., 2010). As a consequence of these activities
268 average temperature in the study area is increases in all the seasons except early winter. However, significant
269 increase in average temperature over the time period (1980-2020) is observed only in late summer season which is
270 highest over Ladakh (0.026° C/year at 99% significant level). Furthermore, it is clearly observed in table 5 that
271 maximum temperature is increases in all seasons except early summer. In early summer it is decreasing over the
272 entire study area with highest decrease in Zaskar (-0.054° C/year at 95% confidence level). However, in case of
273 minimum temperature it is increase in all seasons except early winter. The significant increase is observed in both
274 early and late summer season. Highest rate of increase in temperature over Kargil region (0.043° C/year at 95%
275 confidence level) was observed in early summer and over Zaskar (0.052° C/year at 99% confidence level) in late
276 summer (table. 5). As a result of increase in minimum, maximum and average temperature in early and late summer
277 season in all over the study area would lead to increase in melting or ablation of glaciers which in turn affects the
278 frequency of rainfall events i.e., increase in heavy storm events in the summer season.

Time	Kargil				Zaskar				Ladakh			
	M (mm)	SD (mm)	CV (%)	Regression (R)	Mean (mm)	SD (mm)	CV (%)	Regression (R)	Mean (mm)	SD (mm)	CV (%)	Regression (R)
January	2.93	1.61	54.94	0.04	1.79	0.98	54.74	0.03	1.97	0.98	49.74	0.06
February	3.83	1.88	49.09	0.00	2.75	1.43	52	0.03	2.59	1.24	47.88	0.00
March	5.25	2.16	41.14	0.01	3.47	1.49	43.94	0.04	3.49	1.46	41.83	0.01
April	7.02	2.21	31.48	0.02	4.7	1.52	32.34	0.04	4.85	1.5	30.92	0.02
May	9.83	3.07	31.23	0.25	5.59	2.29	40.96	0.16	7.18	2.42	33.70	0.16
June	21.15	9.51	44.96	0.33	9.75	5.34	54.96	0.28	16.34	7.29	44.61	0.23
July	39.68	21.84	55.04	0.33	24.11	19.43	80.58	0.41	29.57	16.97	57.39	0.34
August	94.65	60.56	63.98	0.10	94.98	57.25	60.27	0.22	60.59	38.9	64.20	0.08
September	88.74	47.86	53.93	0.22	89.54	51.04	57	0.25	58.42	33.1	56.65	0.25
October	25.07	19.87	79.26	0.08	19.99	16.43	82.19	0.26	19.83	17.15	86.48	0.64
November	2.85	2.62	91.92	0.15	1.53	1.93	126.14	0.04	2	2	100	0.13
December	1.84	1.37	74.47	0.07	1.3	1.48	113.84	0.08	1.33	1.01	76	0.05
Early Winter (Nov-Jan)	7.62	3.46	45.43	.1697	4.62	2.69	58.3	.0631	5.30	2.57	48.48	.0915
Late Winter (Feb-April)	16.09	3.92	24.38	.007	10.92	2.69	24.66	.0081	10.94	2.76	25.25	.084
Early Summer (May-July)	70.67	30.3	42.88	.3661	39.45	24.77	63.30	.3805	53.09	53.70	50.42	.2107
Late Summer (Aug-Sept)	208.46	96.97	46.52	.2532	204.51	99.60	48.70	.3694	138.84	64.38	46.37	.2482
Annual	302.84	118.84	39.23	0.33	259.5	117.61	45.32	0.44	208.17	81.01	38.92	0.34

294 **Table. 2** Mean (M), Standard Deviation (SD), Coefficient of Variation (CV), and Regression (R) of Monthly, Seasonal and Annual Precipitation over severe cold
295 regions of Ladakh, Kargil and Zaskar (1980-2021).

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Annual		Early Winter (November – January)		Early Summer (May – July)		Late Summer (August – September)	
Excess	Deficit	Excess	Deficit	Excess	Deficit	Excess	Deficit
2013	1982	1992	1982	1996	1989	2013	1987
2015	1987	1998	1987	2005	1997	2015	1991
2016	1991	2011	1989	2013	1999	2016	2009
2017	1992	2012	1996	2014	2004	2017	-
2018	2002	2013	1999	2015	2007	2018	-
2019	2009	2014	2000	2016	2018	2019	-
-	-	2018	2001	2017	-	-	-
-	-	-	-	2019	-	-	-

300 **Table. 3** Excess and deficient precipitation years over the union territory of Ladakh (1980-2021).

El-Nino and La-Nina Years								
	Categories							
Sr. No.	Very Strong El-Nino	Strong El-Nino	Moderate El-Nino	Weak El-Nino	Neutral	Weak La-Nina	Moderate La-Nina	Strong La-Nina
1	1982	1997	1986	2005	1980	1984	1989	1988
2	2002	-	1987	2009	1981	1985	2011	1998
3	2015	-	-	2018	1990	1993	2020	2007
4	2016	-	-	2019	1992	1995	2021	2010
5	-	-	-	-	1994	1999	-	-
6	-	-	-	-	1996	2000	-	-
7	-	-	-	-	2003	2001	-	-
8	-	-	-	-	2006	2008	-	-

9	-	-	-	-	2012	2017	-	-
10	-	-	-	-	2013	-	-	-
11	-	-	-	-	2014	-	-	-

301 **Table. 4** List of El-Nino and La-Nina Years (1982-2021).

Sr. No.	Temperature	Region	Test	Season				
				Early Winter	Late Winter	Early Summer	Late Summer	Annual
1	Average	Ladakh	Z	-1.01	0.76	0.94	3.24**	0.34
			Q	-0.028	0.017	0.013	0.026	0.007
		Kargil	Z	-0.80	0.97	0.94	3.44***	0.50
			Q	-0.025	0.023	0.014	0.025	0.009
		Zaskar	Z	-0.73	0.66	0.90	2.97**	0.72
			Q	-0.015	0.013	0.012	0.025	0.008
2	Maximum	Ladakh	Z	0.41	0.06	-1.29	0.50	0.07
			Q	0.004	0.001	-0.032	0.011	0.001
		Kargil	Z	0.06	0.08	-1.25	0.50	0.21
			Q	0.002	0.003	-0.026	0.011	0.003
		Zaskar	Z	0.13	-0.01	-2.38*	-0.64	-1.84+
			Q	0.004	0.000	-0.054	-0.012	-0.031
3	Minimum	Ladakh	Z	-1.19	0.87	1.78+	2.83**	-1.04
			Q	-0.061	0.041	0.059	0.044	-0.061
		Kargil	Z	-1.11	0.98	2.25*	2.88**	-0.69
			Q	-0.061	0.042	0.043	0.050	-0.036
		Zaskar	Z	-1.34	0.45	1.76+	2.78**	-0.85
			Q	-0.044	0.012	0.035	0.052	-0.035
4	Rainfall	Ladakh	Z	1.78+	-1.11	4.01***	3.10**	3.47***
			Q	0.008	0.000	0.759	2.532	3.120
		Kargil	Z	2.72**	1.07	3.74***	3.02**	3.46***
			Q	0.025	0.001	1.019	3.479	4.439
		Zaskar	Z	1.08	0.00	4.38***	3.66***	3.92***
			Q	0.000	0.000	0.732	4.387	5.153
5	Snowfall	Ladakh	Z	0.63	-0.22	2.95**	2.41*	2.73**
			Q	0.020	-0.003	0.180	0.060	0.258
		Kargil	Z	0.69	0.11	2.77**	1.26	2.30*
			Q	0.028	0.010	0.204	0.046	0.291
		Zaskar	Z	1.34	0.26	3.92***	3.49***	4.25***
			Q	0.033	0.011	0.323	0.280	0.702

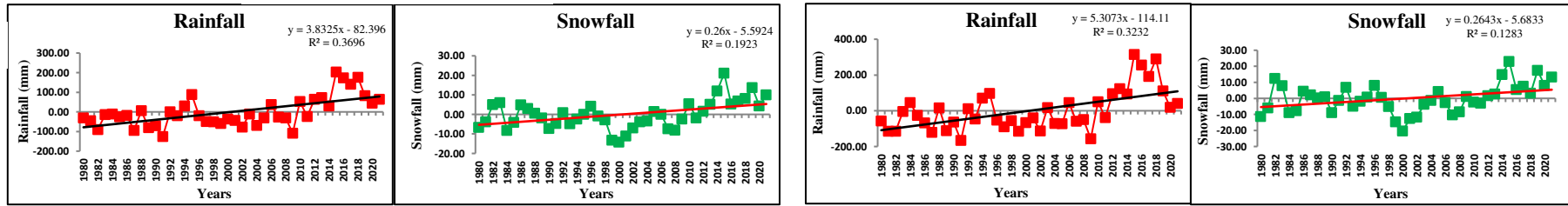
302 + Significant at 90% Confidence Level, * Significant at 95% Confidence Level, ** Significant at 99% Significant Level, *** 99.99% Significant Level

303 **Table. 5** Mann-Kendall Test (Z) and Sen's Slope Estimator (Q) of temperature (1981-2020), rainfall and snowfall (1980-2021) on seasonal and annual basis over severe cold region of Ladakh, Kargil and Zaskar.

Ladakh

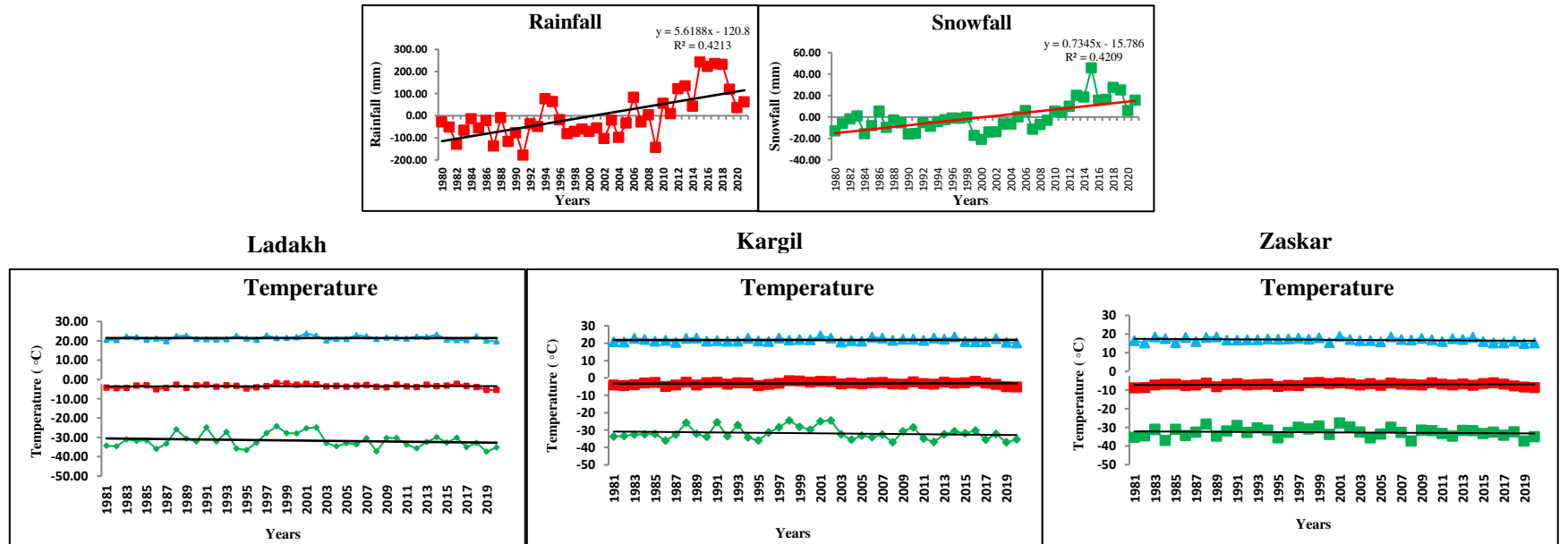
Kargil

(a)



Zaskar

(b)



Minimum Maximum Average

Fig. 2 (a) Annual Rainfall and Snowfall (1980-2021), (b) Maximum, Minimum and Average Temperature (1981-2020) over the study area.

Annual Precipitation

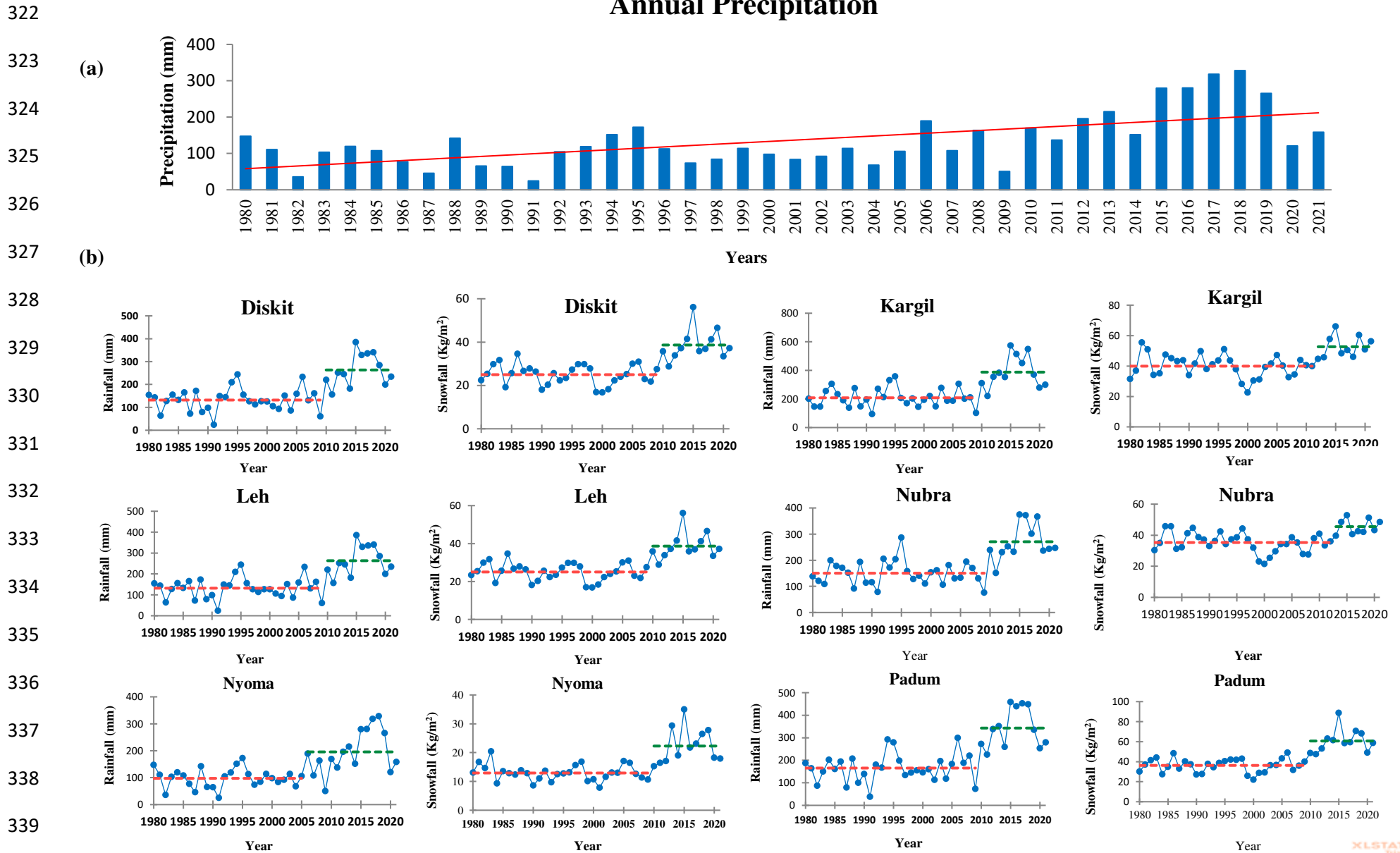


Fig. 3 (a) Annual Precipitation (b) Station-wise abrupt change point detection of rainfall and snowfall using Pettitt's test over the study area (1980-2021).

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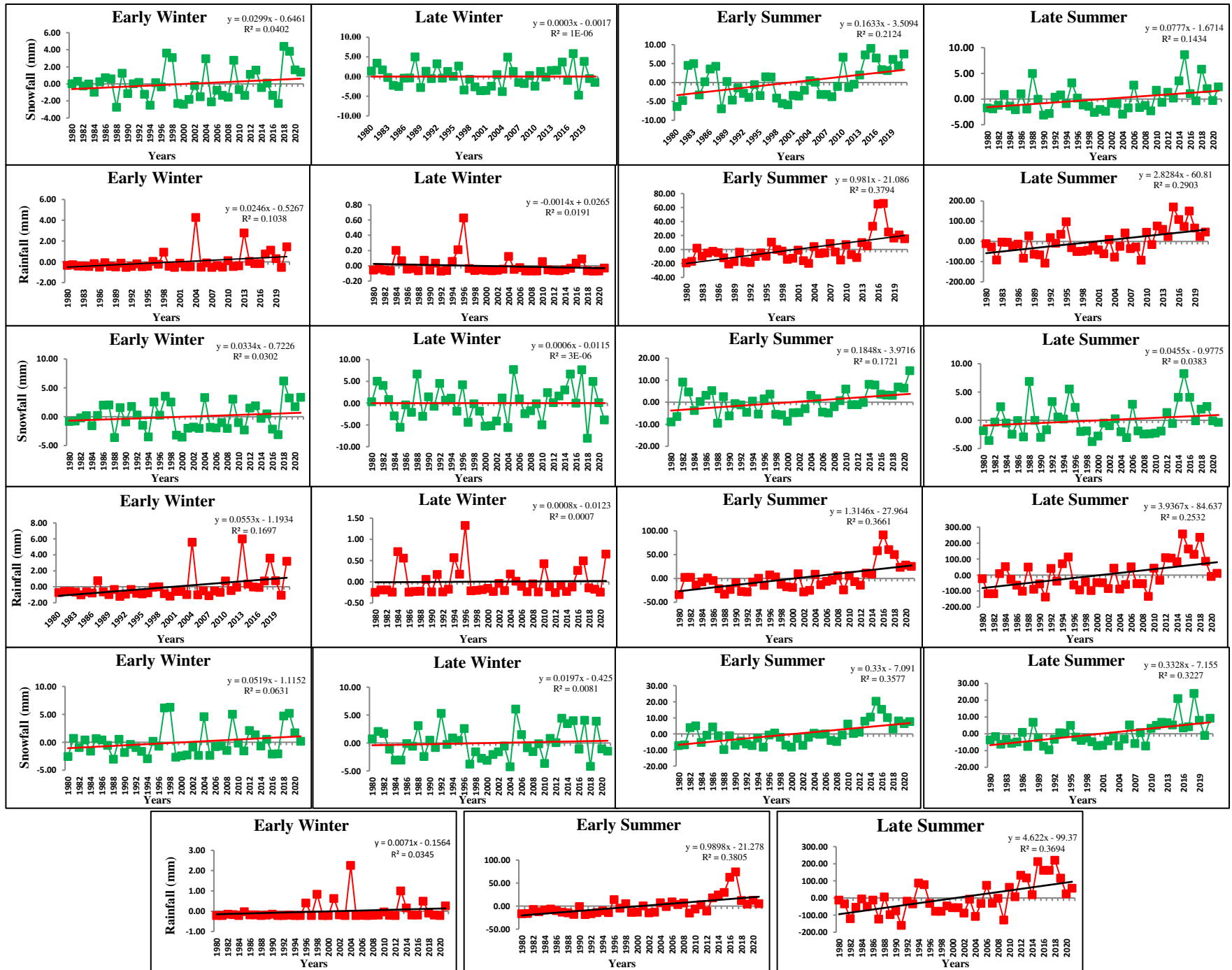
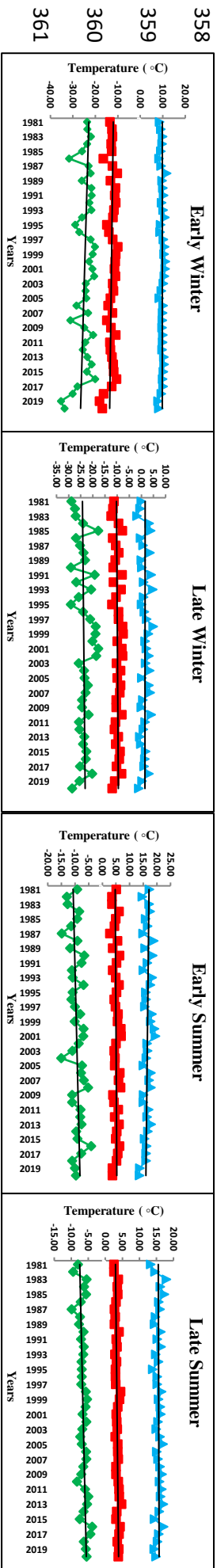
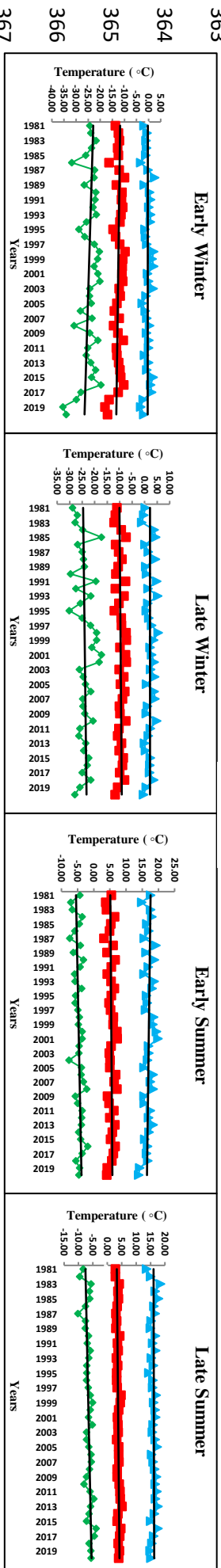


Fig. 4 Seasonal Snowfall and Rainfall over (a) Ladakh, (b) Kargil and (c) Zaskar Region over the study area (1981-2021).

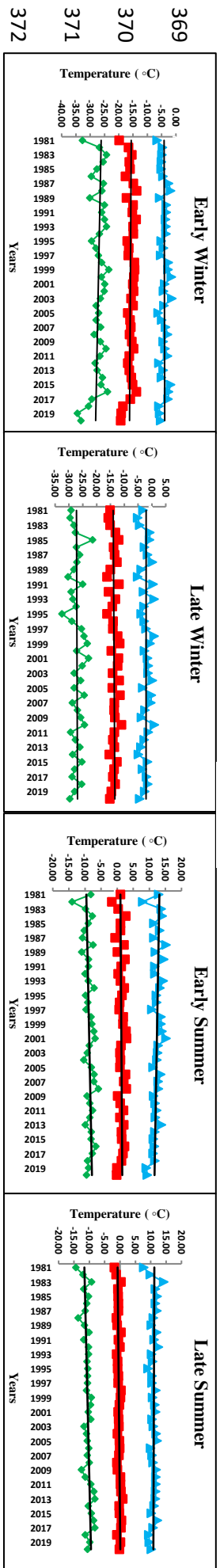
(a)



(b)

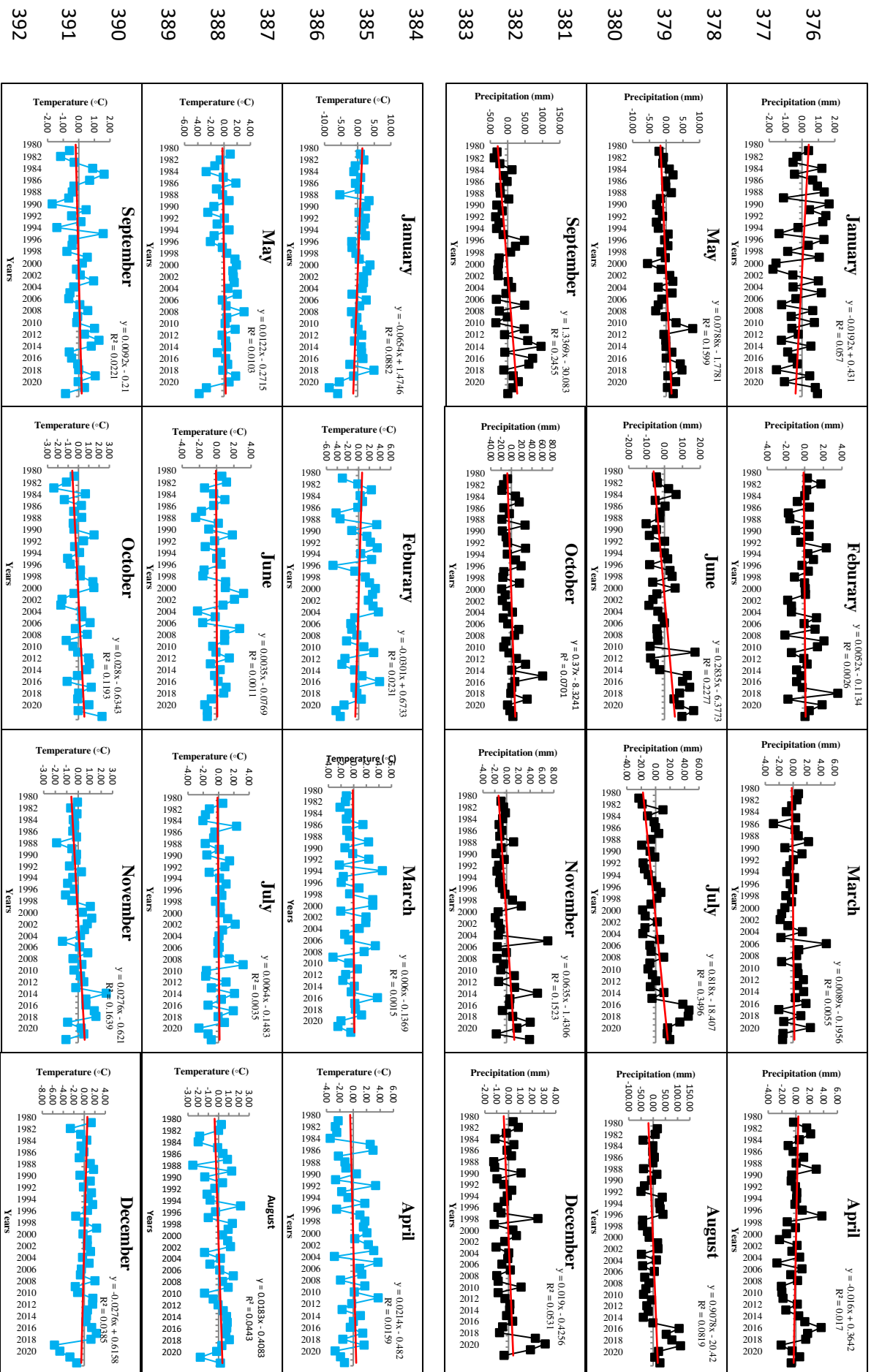


(c)

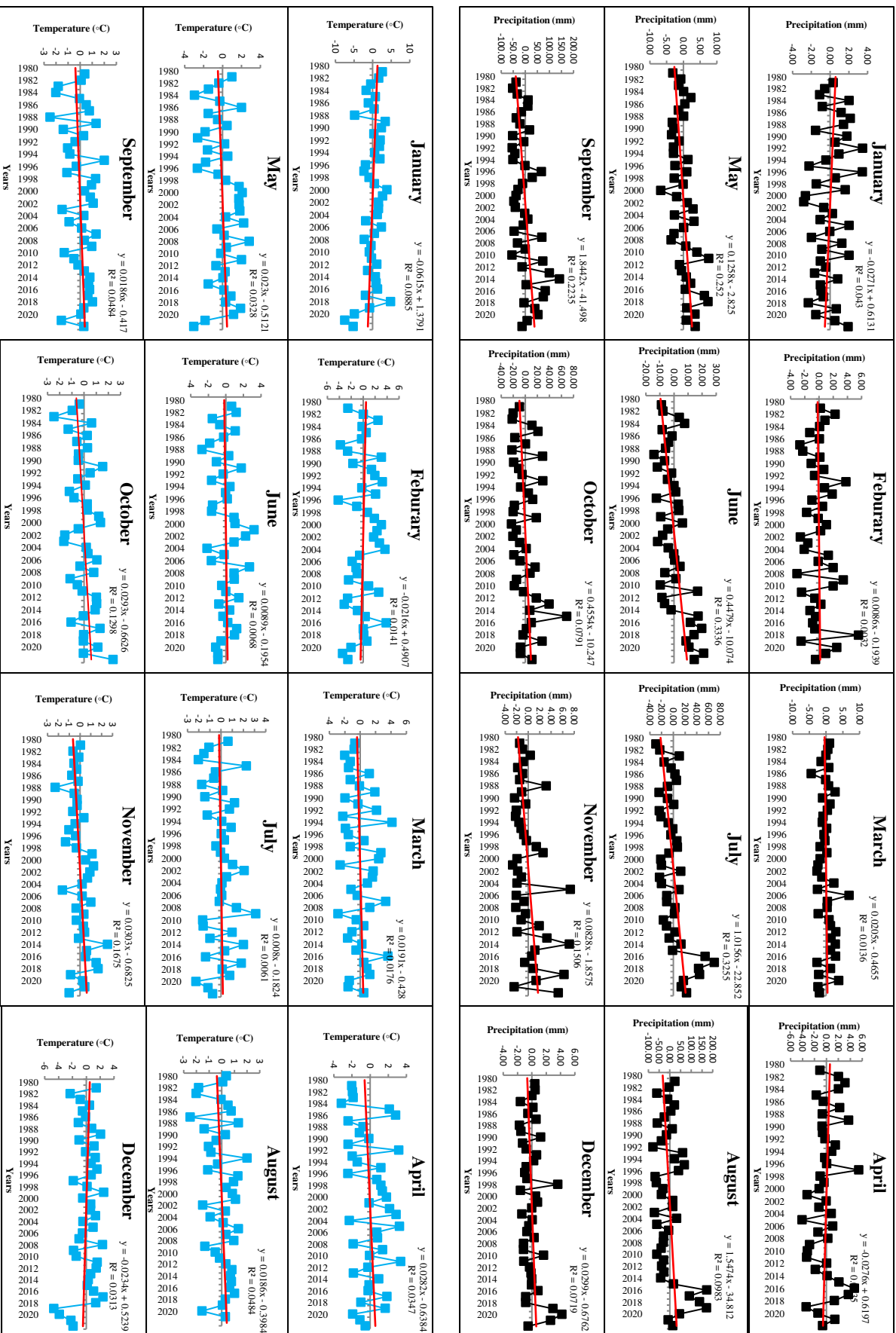


—■ Minimum
 —▲ Maximum
 —■ Average

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374 **Fig. 5** Season Wise Mean Maximum, Minimum and Average Temperature over (a) Ladakh, (b) Kargil, and (c) Zaskar (1981-2020).
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393 Fig. 6 Monthly Precipitation (1980-2021) and Temperature (1981-2020) trends over Ladakh Region.



411 **Fig. 7** Monthly Precipitation (1980-2021) and Temperature (1981-2020) trends over Kargil Region.

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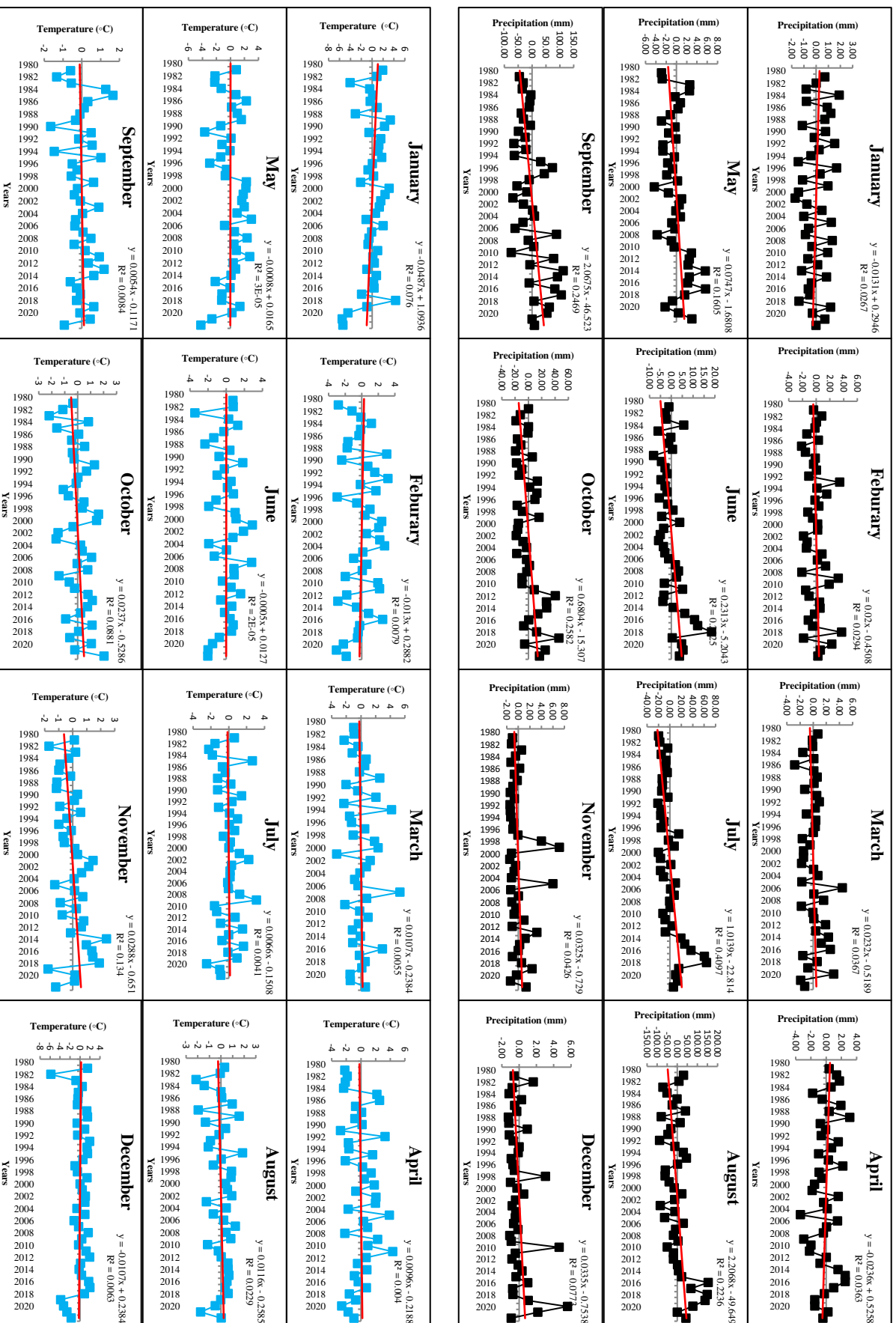


Fig. 8 Monthly Precipitation (1980-2021) and Temperature (1981-2020) trends over Zaskar Region.

Station	Ladakh		Kargil		Zaskar	
	Z	Q	Z	Q	Z	Q
January	-1.54	-0.018	-1.24	-0.029	-0.74	-0.012
February	-0.17	-0.003	0.07	0.002	1.02	0.016
March	0.17	0.005	0.46	0.013	0.76	0.01
April	-0.63	-0.013	-0.95	-0.03	-1.3	-0.024
May	2.58**	0.07	3.29***	0.113	2.3*	0.077
June	2.34*	0.258	3.38***	0.452	2.93**	0.196
July	3.6***	0.673	3.53***	0.809	4.36***	0.778
August	1.26	0.557	1.11	0.812	2.51*	1.83
September	2.9**	1.022	2.73**	1.375	3.12**	1.64
October	1.91 ⁺	0.347	1.93 ⁺	0.389	3.19**	0.58
November	1.76 ⁺	0.038	1.84 ⁺	0.051	1.8 ⁺	0.021
December	0.85	0.01	1.06	0.018	1.56	0.015
Annual	3.32***	3.244	3.47***	4.518	3.99***	5.744

431 + Significant at 90% Confidence Level, * Significant at 95% Confidence Level, ** Significant at 99% Significant Level, *** 99.99% Significant
432 Level

433 **Table. 6** Mann-Kendall Test (Z) and Sen's Slope Estimator (Q) of Monthly and Annual Precipitation in the Study
434 area (1980-2021).

Station	Ladakh		Kargil		Zaskar	
	Z	Q	Z	Q	Z	Q
January	-1.58	-0.05	-1.76 ⁺	-0.054	-1.89 ⁺	-0.049
February	-0.94	-0.038	-0.73	-0.027	-0.74	-0.015
March	0.35	0.012	0.76	0.018	0.66	0.01
April	0.7	0.024	1.34	0.028	0.4	0.011
May	0.91	0.02	1.01	0.023	-0.11	-0.001
June	-0.02	0	0.16	0.003	-0.37	-0.007
July	0.36	0.008	0.55	0.01	0.37	0.008
August	1.08	0.016	1.04	0.014	0.86	0.009
September	1.02	0.011	1.16	0.011	0.77	0.008
October	2.02*	0.027	1.96*	0.026	1.72 ⁺	0.024
November	2.38*	0.027	2.57*	0.028	2.5*	0.035
December	-0.37	-0.009	-0.37	-0.01	-0.17	-0.005

435 + Significant at 90% Confidence Level, * Significant at 95% Confidence Level, ** Significant at 99% Significant Level, *** 99.99% Significant
436 Level

437 **Table. 7** Mann-Kendall Test (Z) and Sen's Slope Estimator (Q) of Mean Monthly Temperature in the Study area
438 (1981-2020).

439 It is also noted in all figures that both rainfall and temperature suddenly rises after the year 2000. The principle
440 reason behind these trends is not yet known; may be it is because of recent phenomena of climate change or some
441 anthropogenic factors (Devika & Pillai, 2019). Seasonal precipitation analysis shows that it is also affected by

442 ENSO phenomena. In early winter, precipitation deficit year (1982, 1987) lies with El-nino events and excess years
 443 (1998, 2011) lies with La-nina events. The same phenomena are also observed in early summer {(Deficit 1997,
 444 2018), (excess 2017)} and late summer season {(deficit 1987), (excess 2017)} (table. 3, 4).

445 3.3 Monthly analysis

446 Mean monthly temperature and precipitation trends over Ladakh region is shown in fig. 6, and their monthly
 447 values in table 2. Although highest precipitation is experienced in august month (60.59 mm) yet it is highly erratic
 448 and fluctuating over Ladakh region. Monthly precipitation trends of Ladakh region shows the same trends as the
 449 trends of other two regions, precipitation is increased in all months except in January and April (Fig. 6). The trends
 450 of both Mann-Kendall and Sen's slope test shows that a significant increase in precipitation in the months of May,
 451 June, July, September, October and November was observed (table. 6). Highest increase in precipitation was
 452 observed in the month of September which is at the rate of 1.022 mm/year (99% confidence level). Also,
 453 temperature trends of Ladakh region shows increasing trends in all months except January, February and December
 454 (Fig. 6). Table 7 shows that temperature increase is significant only in the months of October and November at the
 455 same rate that is 0.027° C/year (95% confidence level).

456 The mean monthly trends of precipitation and temperature over Kargil region is shown in fig. 7 and their
 457 monthly values in table 2. Drass station is located in Kargil region known as the coldest place in India experienced
 458 highest precipitation in the month of august (94.65 mm) (table. 2). Monthly trends show significant change in
 459 precipitation only in the month of May, June, July, September, October and November. The trends are significant at
 460 99.99% confidence level in the month May, June and July (table. 6). However, highest increase is noticed in the
 461 month of September which is at the rate of 1.375 mm/year (at 99% confidence level) (table. 6). However, trends in
 462 temperature dataset over Kargil region follow the same pattern that existed over Ladakh region. Temperatures
 463 dropped in the month of January which is at the rate of -0.054° C/year (at 90% confidence level) and increased in
 464 the month of October (0.026° C/year) and November (0.028° C/year) at 95% confidence level (**table. 7**).

465 Monthly deviation trends over Zaskar region is shown in fig. 8 and their monthly values in table 2. The values of
 466 SD and CV were found to be high in month of August and September because these two months received a large
 467 amount of precipitation with a high degree of variability, but precipitation occurrence was extremely low in the
 468 remaining months (table. 2). Table 6 shows that increase in precipitation is significant only in the months of May,
 469 June, July, august, September and October and highest increase is noticed in the month of August which is at the
 470 rate of 1.83 mm/year (at 95% confidence level). Temperature decrease is detected only in the months of January and
 471 February. It declined at a rate of -0.049° C/year in January (with a 90% confidence level) and increased at a rate of
 472 0.035° C/year in November (at 95 percent confidence level) (**table. 7**). The same phenomena are also observed in
 473 case of precipitation trends. There is sudden rise in the peaks of monthly precipitation data after the year 2000. The
 474 current situation in Ladakh is frightening, as evidenced by the trends in precipitation and temperature depicted in the
 475 above diagrams. Small defensive retention walls being built along the streams, such as the Sabu Stream in

476 Choglamsar, to hold back flood waters from the next cloudburst will almost probably increase vulnerability by
477 providing a false sense of security to people (Newell & Wasson, 2002).

478 **4 Conclusion**

479 The Ladakh region in the south of the Karakorum Range is unusual due to its cold, arid temperature and vast
480 bleak scenery. People in this region rely on limited natural resources, and even modest changes in the ecosystem can
481 bring hardship. The characteristics of the changing climate in this region are not well understood due to insufficient
482 monitoring facilities in this region. As a result, the current research focuses on gaining a better knowledge of the
483 region's overall climatic trends and how it has changed during the recent phenomena of global warming.

484 Ladakh, at 3500 metres above sea level, has a wide annual temperature range, ranging from 23.85 degrees
485 Celsius (Nubra station) in the summer to -45.06° C (Drass station) in the winter, with an average annual temperature
486 of 7.3 degrees Celsius. The summer season brings the most precipitation to Drass (302.84mm), with extreme
487 precipitation events (cloudbursts) also occurring during this time. Due to the effect of western disturbances,
488 substantial precipitation falls over the entire study area throughout the winters. As a result of these elements, the
489 climate in the study area is cold and arid (dry).

490 It is elucidated from the required data that amidst 1980's and 1990's, there was enormous precipitation over the
491 dry region of Ladakh which outcome in form of lower temperature consequently. Temperature and precipitation
492 seems to be increasing since mid-1990s. Despite a recent decrease in precipitation amounts in the region, the study
493 area has experienced an overall increase in precipitation and rising temperature over the years. Our findings, which
494 demonstrate a rapid rise in temperature and a wide range of precipitation patterns in recent decades, pointing
495 towards changing climate in the Ladakh region in the coming years, with a higher likelihood of unexpected events.
496 The recent shift in the climatic trends possibly has irreversible implications across the region, resulting in
497 catastrophic outcomes.

498 Changing climate and precipitation patterns will have a significant impact on the ecosystem, flora, fauna,
499 hydrology, ice cover, and even human civilization in Ladakh. Despite the fact that it is a cold and desert region,
500 increased precipitation may benefit an arid region from an anthropogenic standpoint, but it will have a little impact
501 on the environment. Furthermore, this rise in the form of catastrophic occurrences or cloudbursts causes even more
502 devastation, with little potential for water surplus to be saved for the future. As a result, the region's changing
503 climate will have a severe and possibly irreversible detrimental impact. Deep investigations in the region are
504 hampered by a scarcity of historical data archives and a thin network of current data stations. Not only are there gaps
505 in the datasets, but also inherent diversity among observational datasets. Leading to a greater shift in climatic
506 patterns, this substantial body of climatic research from all over the region can be used to build successful climate
507 change mitigation and adaptation strategies.

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