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ARTICLE

Snowfall Shift and Precipitation Variability over Sikkim Himalaya Attributed to Elevation-Dependent Warming

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ABSTRACT

Sikkim Himalaya hosts critical water resources such as glacial, rain, and snow-fed springs and lakes. Climate change is adversely affecting these resources in various ways, and elevation-dependent warming is prominent among them. This study is a discussion of the elevation-dependent warming (EDW), snowfall shift, and precipitation variability over Sikkim Himalaya using a high-resolution ERA5-land dataset. Furthermore, the findings show that the Sikkim Himalaya region is experiencing a warming trend from south to north. The majority of the Sikkim Himalayan region shows a declining trend in snowfall. A positive advancement in snowfall trend (at a rate of 1 mm per decade) has been noticed above 4500 meters. The S/P ratio indicates a shift in snowfall patterns, moving from lower elevations to much higher regions. This suggests that snowfall has also transitioned from Lachung and Lachen (3600 m) to higher elevated areas. Moreover, the seasonal shifting of snowfall in the recent decade is seen from January-March (JFM) to February-April (FMA). Subsequently, the preceding 21 years are being marked by a significant spatiotemporal change in temperature, precipitation, and snowfall. The potent negative correlation coefficient between temperature and snowfall (–0.9), temperature and S/P ratio (–0.5) suggested the changing nature of snowfall from solid to liquid, which further resulted in increased lower elevation precipitation. The entire Sikkim region is transitioning from a cold-dry to a warm-wet weather pattern. In the climate change scenario, a drop in the S/P ratio with altitude will continue to explain the rise in temperature over mountainous regions.

***Keywords*:** Sikkim Himalaya; EDW; Snowfall; Seasonal shift; Precipitation variability; S/P ratio; ERA5-land

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1. Introduction

In recent years, the scientific community and society have begun devoting significant attention to global warming and climate change. Though scientific organizations all over the world have extensively conveyed global climate change studies, the repercussions of these effects on regional climate need more attention and to be addressed. Regional landform processes, as well as land-use profiles, influence the costs of climate change. The Himalayan region has complex landform inadequacy. These landforms are changing in recent times as developmental and anthropogenic activities are rising, which is triggering erratic climate change consequences over the Himalayan region. The warming of the Himalayan region is inadequately reported in several researches [1-4]. Scientists observed that the highest temperature increase occurred across the northern slope of the central Himalayas during the cold season. However, winter season precipitation also has a significant influence on glacier simulation [5-7]. Furthermore, the majority of research focuses on the western and central Himalayas [5,6,8-14]. There is a knowledge gap about the eastern Himalaya's climate change impact behaviour and pattern. Therefore, this study focuses on the snowfall and precipitation variability and changes over the Sikkim Himalayan region. The mountain region's snowfall pattern has been altered as the global average temperature is rising [15]. During the seasonal accumulation period, a variety of climatological factors that affect snowfall distribution and accumulation (such as wind-gust, precipitable water, circulation systems, frontal behaviour, surface temperature, adiabatic lapse rate, as well as atmospheric boundary layer stability) have an impact on snowfall, either directly or indirectly [16]. The North Atlantic Oscillation (NAO), El Nio Southern Oscillation (ENSO), Jet Stream, Indian Ocean Dipole (IOD) and other monsoons teleconnection climatic factors also influence precipitation distribution and amount over the Himalayan region [5,17-19]. By utilizing Weather Research Forecast simulation, Norris et al. (2015) addressed extreme snowfall events over the entire Himalayan region [14,20-29]. The amount of snowfall and resulting snow accumulation are recommended as key indicators of climatic change [11,30-34].

The temperature and precipitation have a very peculiar and complex relationship. The changing temperature is affecting various meteorological variables, which are directly or indirectly linked with the cryosphere, and biosphere. Snowfall is one of the major sources of water over Sikkim. Snow and rain-fed springs are the major sources of Sikkim's potable water [26,35]. Agrawal et al. (2014) found that declining air quality is causing regional climate changes in Sikkim [36]. This is evidenced by an increase in temperature at higher altitudes, less snowfall/precipitation, decreased water availability, and rapid loss of glacierized landscape [37]. Airborne aerosols, such as pollutants, can act as cloud condensation nuclei (CCN), which can change snowflake formation and snowfall patterns [38]. Poor air quality, often linked to greenhouse gas emissions, can cause black carbon and dust particles to settle on snow and glaciers, reducing their reflectivity [39-41]. This causes them to absorb more heat and melt faster, intensifying the impact of poor air quality [10]. As glaciers retreat due to climate change, they expose more terrain, which can release additional dust and debris into the atmosphere, worsening air quality and further accelerating glacial melting and retreat [42,43]. Air quality indirectly affects snowfall and glaciers by influencing aerosols, black carbon, dust deposition, precipitation patterns, and the broader climate system [40,41]. These factors collectively lead to observable changes in snowfall and glacier dynamics in regions with poor air quality and ongoing climate change. The impact of climate change on air quality is also a concern, as it can contribute to air pollution and further exacerbate the effects of poor air quality on snowfall and glaciers. This study of Sikkim Himalaya highlights the importance of understanding the region's climate, which is still underrated due to limited research.

The elevation-dependent warming (EDW) in the Himalayan region has a different signature than any other region. EDW is affecting precipitation and snowfall, which are the key sources of water [44,45]. The warming in the Eastern Himalayan region is inducing more convective precipitation during the summer season and suppressing orographic rain. The researchers [46] synthesized several studies' results on climate change in Sikkim, which suggested the various impacts of climate change on Sikkim's Himalayan indigenous population [47-51]. Viste and Sorteberg (2015) suggested that the uppermost western Brahmaputra basins have the greatest relative variability in snowfall [28]. The majority of this basin will experience temperatures above freezing, particularly in the summer season, under the highest forcing scenario. The yearly average snowfall is expected to decrease by 65-75% [28]. The rise in temperature reduces the portion of precipitation that occurs as snowfall, greatly reduces the period of snowpack during the winter season, causes thawing to occur during the spring, and enhances the intensity of melting [52]. On the basis of reanalysis data, the unequal distribution of snowfall has mostly been investigated statistically. Moreover, the data from observations (including the gridded data from the analysis of in-situ observation by IMD) somehow doesn't adequately describe the actual regional climate feature and neither provides spatiotemporally relevant information of snowfall over the study region, particularly in higher elevations at which stations are ill-equipped, due to the limitation of weather stations owing to geographic variation and the multifaceted topography in Sikkim Himalaya [26,53-56]. The accurate assessment of the shift in snowfall with respect to precipitation in a warming climate is very intricate. Summer snowfall has reduced while winter snowfall has increased over the Tibetan Plateau [57]. Berghuijs et al. (2014) addressed how increasing temperatures promote conversion from snowfall to rain [58]. According to scientists [59], changes in the snowfall/precipitation (S/P) ratio throughout time were established to be accurate markers of changing climate. Warming has reduced snowfall in the cold season, causing snowmelt to occur earlier [60,61]. However, the significant decline in snowpack and snowfall is not uniform. Sikkim's high altitudes receive a large majority of its yearly precipitation in the form of snowfall during the winter and spring seasons with a major contribution from monsoon and summer seasons rainfall. However, the habitat of the region primarily depends on water accessibility from snowmelt [36,56]. Significant variations in the S/P ratio may be essential for understanding other hydrometeorological patterns because there may be an impact on the timing of spring drainage, the freezing point of streams, and delayed winter snow accumulation [62]. Dubey et al. (2022) suggest that the warm and wet days have risen from 1951 to 2018 [53]. Therefore, it would be sensible to adequately monitor the S/P ratio and snowfall in order to manage regional climate crises and natural resources.

Concerning the Sikkim Himalaya, the present research attempts to succeed in the following particular objectives. (1) To carry out a long-term investigation of the snowfall and precipitation using high-resolution datasets available. (2) To accurately describe the seasonal shift and regional variability in precipitation, the S/P ratio, and snowfall over Sikkim with challenging topography as well as elevation gradient. (3) To investigate the use of the findings to understand whether regional climatic change is affecting snowfall over Sikkim Himalaya.

2. Study area

Figure 1 shows the land use cover (LUC) for the year 2021 from sentinel-2 classifications focusing on built-up, glaciated regions, water bodies, vegetation cover, cropland, and fallow land. The study region has a very typical landscape, and for a better understanding of atmospheric processes, the LUC has been applied in the context of natural and anthropogenic influences on temperature, snowfall, and total precipitation variability over Sikkim. LUC of the southern part of Sikkim reveals a high sprawl of built-up regions, which is a strong sign of anthropogenic activity over the region. Gangtok Municipal Corporation (GMC) region has an enormous built-up area compared to the rest of Sikkim. This indicates that the surface radiation and 2-meter temperature change are greater in the build-up region than in the forest cover area [56].

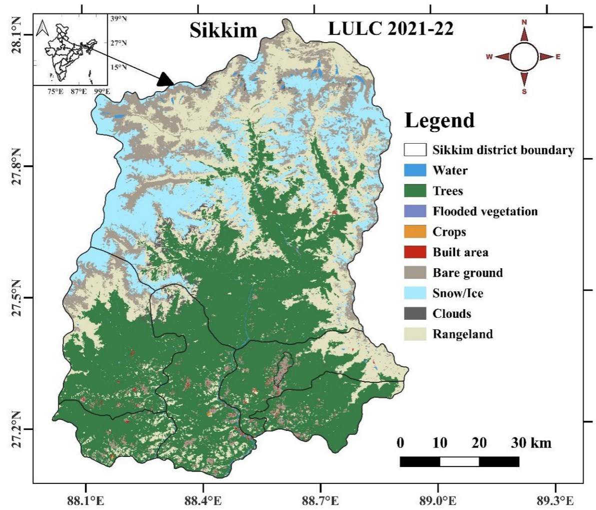

Figure 1. The study region and its land cover for the year 2021 using Sentinel-2 LULC classification. Here, a small boundary represents Gangtok Municipal Corporation (GMC).

3. Dataset and methodology

The present study used various basic as well as advanced statistical techniques to analyze the temperature, precipitation, snowfall changes, and seasonal shifts in four decades (1980-2021) for the Sikkim Himalaya (**Figure 1**). The climatology, anomaly, significant change, linear trend, and Theil-Sen estimator trend analysis [59,63,64] for snowfall and total precipitation ratio [(S/P) ratio] have been computed. The seasonal shifts of temperature, snowfall, and total precipitation are examined. The seasons have been classified as abjointed twelve seasons (DJF: December, January, February; JFM: January, February, March; FMA: February, March, April; MAM: March, April, May; AMJ: April, May, June; MJJ: May, June, July; JJA: June, July, August; JAS: July, August, September; ASO: August, September, October; SON: September, October, November; OND: October, November, December; NDJ: November, December, January) to understand the shift of snowfall, temperature and precipitation temporal regimes. The steps of the seasonality computation are discussed in Supplementary Method SM6 and **Figures S1-S5b**.

The anomaly is also analysed to quantify the abnormal change in the time series (from 1980 to 2021) from the long-term average of the time series as Equation (1):

$$\text{Anomaly}\ (A) = (X - \overline{X}) \quad (1)$$

where X is the time series of the yearly dataset, and $\overline{X} = \frac{\sum_{i=1}^{n=42} X}{n}$, i is the initial, n last number of the time series.

Percentage precipitation change is calculated to see the wetness, and dryness [65] as Equation (2):

$$Precipitation\ Change(\%) = \Delta P\% = \left(\frac{A}{\overline{X}}\right) * 100 \quad (2)$$

where A, and $\overline{X}$ are the anomaly, and long-term average, respectively as Equation (1).

Theil-Sen estimator trend analysis is calculated [64] as Equation (3):

$$trend = \frac{\partial S}{\partial P} = \frac{(\partial S * P - S * \partial P)}{P^2} \quad or \quad \frac{\partial S}{\partial P} = \frac{\overline{S}}{\overline{P}}[(\partial lnS) - (\partial lnP)] \quad (3)$$

where $\overline{S}$, $\overline{P}$ are long-term averages over the study region. And, (lnS), (lnP) are logarithms of snowfall and total precipitation. However, (∂lnS) and (∂lnP) are the linear trend of logarithmic terms for the study period (1980-2021). The details of the methodology can be seen in the supplementary method section SM6.

The t-test [66] has been applied for the significant difference and trend values as Equation (4).

$$t\ test = \frac{(\overline{Y_1} - \overline{Y_2})}{\sqrt[2]{\left(\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}\right)}} \quad (4)$$

where $(\overline{Y}_1)$, $(\overline{Y}_2)$, σ_1, σ_2, and $n_1 = n_2 = 21$ are mean of first time series slice (from 1980 to 2000) of the variables, the mean of the second time series slice (from 2001 to 2021), standard deviation for the first time slice, standard deviation for the second time slice, total number years for the first time slice 1980 to 2000 (21 years), and total number of years for the second time slice 2001 to 2021 (21 years), respectively. This is used to find the p-values and significant investigation with a p-value table [67].

The present study used the high-resolution reanalysis open-source dataset ERA5-land (**Table 1**). Reanalysis is a process that combines model data with observations from around the world to create a globally complete and consistent dataset [68]. ERA5 is the fifth generation of atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and is the latest climate reanalysis [68,69]. It provides hourly data on many atmospheric, land-surface, and sea-state parameters, along with estimates of uncertainty. ERA5-Land is a reanalysis dataset that provides a consistent view of the evolution of land variables over several decades at an enhanced resolution [70,71]. The products of the reanalysis are available to the public through the Climate Data Store. ERA5 has several benefits, including the ability to provide spatiotemporally consistent data, which is useful for climate studies [72,73]. It also allows for the study of long-term trends in temperature and precipitation, which can help understand the physical atmospheric system and assess the influence of any climatic change on the biophysical and socio-economic setup of a region [68-71,74]. Station data from the India Meteorological Department (IMD) have been used for the primary result analysis. However, as the result was absurd in the case of snowfall, we visited the nearby locations for cross-checking of IMD stations and found that there was a lack of maintenance. Only five of the IMD-installed automatic weather stations (AWS) are working. Additionally, IMD observation standards measure quality issues in time series data as well and facilities measurement uncertainty during traditional meteorological observation is significant, especially in the winter season over northern Sikkim. At higher elevations, errors due to lack of maintenance of precipitation gauge measurements may range from 10 to 100%. The above factors invoked the present research work to choose the ERA5-land reanalysis dataset for Sikkim (see **Table 1**). Some of the studies are reported in detail about the ERA5 dataset and Its performance for the Himalayan region [20,43,56,72,75,76].

Sentinel-2 bands 3 (green, 10 m), 4 (red, 10 m), 8 (near-infrared, 10 m), 11 (SWIR, 20 m), and 12 (SWIR, 20 m) are utilized for land cover classification. Band 2 is beneficial for distinguishing soil and plants, charting forest types, and detecting man-made objects. It is absorbed by the atmosphere, illuminates things in shadows more effectively than longer wavelengths, and penetrates clear water better than other colours. Chlorophyll absorbs it, resulting in darker plants. Band 8 is helpful for identifying water vapour, while band 9 is good for distinguishing plants. Cirrus band 10 is excluded since it has no surface information [77,78]. LULC Classes are discussed in detail in the supplementary section SM7.

4. Results

According to **Figure 2a**, the climatology (i.e., long-term annual average) of temperature over southern Sikkim is much higher than the rest of Sikkim. The temperature ranges from 15 °C to –6 °C from south to north, resulting in a wide gradient. **Figures 2a and 2b** show the long-term annual average pattern of the temperature and snowfall. And peak of the snowfall can be seen at the isothermal line of 0 °C and –3 °C, from **Figures 2a and 2b**. The snowfall over the north-central (27.7°N) is found to be the highest, whereas to the south (27.3°N) there is

Table 1. Details of the data sets used for the study.

Variables	Temporal resolution	Horizontal resolution	Source	Reference
Temperature (2m air mean) Snowfall Total precipitation	1980-2021 (daily)	0.1^{O} x 0.1^{O} Or (9 km.)	ERA5-Land (ECMWF)	Muñoz-Sabater et al., 2021
LULC	December 2021-2022	Band-2 (blue), Band-3 (green), Band-4 (red), Band-8 (near-infrared), 10 m resolution.	Esri Inc. Sentinel-2 (https://www.arcgis.com/home/item.html?id=fc92d38533d440078f17678ebc20e8e2)	Karra et al., 2021

almost no snowfall (**Figure 2b**). However, the total precipitation follows an almost similar pattern to that of temperature. In **Figure 2c**, the climatology of total precipitation shows that most of the Sikkim region receives precipitation > 110 mm per day. However, the northernmost part of Sikkim is receiving 30 to 50 mm/day. **Figure 2d** depicts the decadal temperature trend in Sikkim, ranging from –0.05 °C to 0.4 °C, with a peak (0.4 □/decade) over central and the lowest (–0.05 □/decade) over southwest Sikkim. The snowfall trend shows negative values over most of the regions with the lowest (–4 mm/decade) over central Sikkim. In **Figure 2e**, a positive trend value of snowfall has been observed over the northernmost part of Sikkim with a peak value of 2 mm/decade. The strong decreasing trend of snowfall over the central part of Sikkim has a resemblance with a strong warming trend in the same region (**Figures 2d and 2e**). In **Figure 2f**, the decadal trend of total precipitation has a positive value over the entire Sikkim, ranging from 2 to > 5 mm/decade with the highest measure over the central part of Sikkim (i.e., > 5 mm/decade). **Figures 2g, 2h, and 2i** are anomalies with respect to the 1980-2021 long-term mean for temperature, snowfall, and total precipitation at 27.6°N along with longitudinal cross-section. The temperature anomaly suggests that the nonstop abnormal warming has been stirring since 2002 and in the year 2021 attained a 1.5 °C above average value. The snowfall anomaly shows unusually intense and frequently occurring positive values against the long-term average before 2015. However, since 2015, there has been an anomalous negative shift of snowfall relative to the long-term average over 88.2°E-88.8°E (**Figure 2h**). Nevertheless, the total precipitation anomaly indicates anomalous high precipitation from 2009 to 2021 and intense low precipitation from 2000 to 2001. **Figures 2g, 2h, and 2i** reveal the snowfall reduction from 2000 to 2021. The anomalous temperature rise causes massive precipitation, signifying that the snowfall has been altered to liquid precipitation as a result of the anomalous warming.

4.1 Elevation dependent warming (EDW)

The elevation-dependent variations in temperature, snowfall, and total precipitation have been depicted in **Figure 3**. The climatology of temperature along with elevation ranges from –8 °C to 20 °C. The elevation zones above 3500 m elevation show negative annual long-term average temperature and below 3500 m elevation values are positive (**Figure 3a**). The annual long-term average of snowfall ranges from 1 to 140 mm/day for all the grids from lower to higher elevations. At the elevation of 1500 m, three grids show snowfall ranging from 5 mm to 55 mm/day, with no snowfall received below 1400 m (**Figure 3b**). The majority of elevation zones up to 3500 m elevation are clustered to minimal snowfall. However, above 4500 m elevation, the majority of the elevation zones are scattered from 10 mm to 140 mm/day (**Figure 3b**). In **Figure 3c**, the decadal temperature trend is observed between –0.1 °C to 0.5 °C/decade over all the grids from lower to higher elevation. Only three elevation points indicate a negative temperature trend from 1400 m to 2000 m elevation. The majority of elevation zones > 4500 m elevation are clustered around 0.2 °C to 0.3 °C/decade warming rate (**Figure 3c**). In **Figure 3d**, above 4000 m elevation, snowfall shows an increasing trend and is clustered near 1 mm/decade. On the other hand, below 4000 m all elevation zones show a decreasing trend and are scattered from –1 mm to –2.5 mm/decade (**Figure 3d**). Hence, the warming is increasing, and corresponding to this, the snowfall is decreasing along the elevation. **Figure 3e** shows the total precipitation climatology along the elevation. This ranges from 30 mm to 255 mm/day. The total amount of precipitation that elevation zones receive decreases with elevation. Most of the elevation zones are clustered together to a total precipitation rate of 50 mm/day above 4500 meters (**Figure 3e**). The trend of the total precipitation shows an increase, which is highest at lower elevations and minimum at higher elevations (ranging from 1 mm to 14 mm/decade rate). Above 4000 m elevation, there is a clear margin which suggests the total precipitation is clustered above this height (**Figure 3f**). At elevations

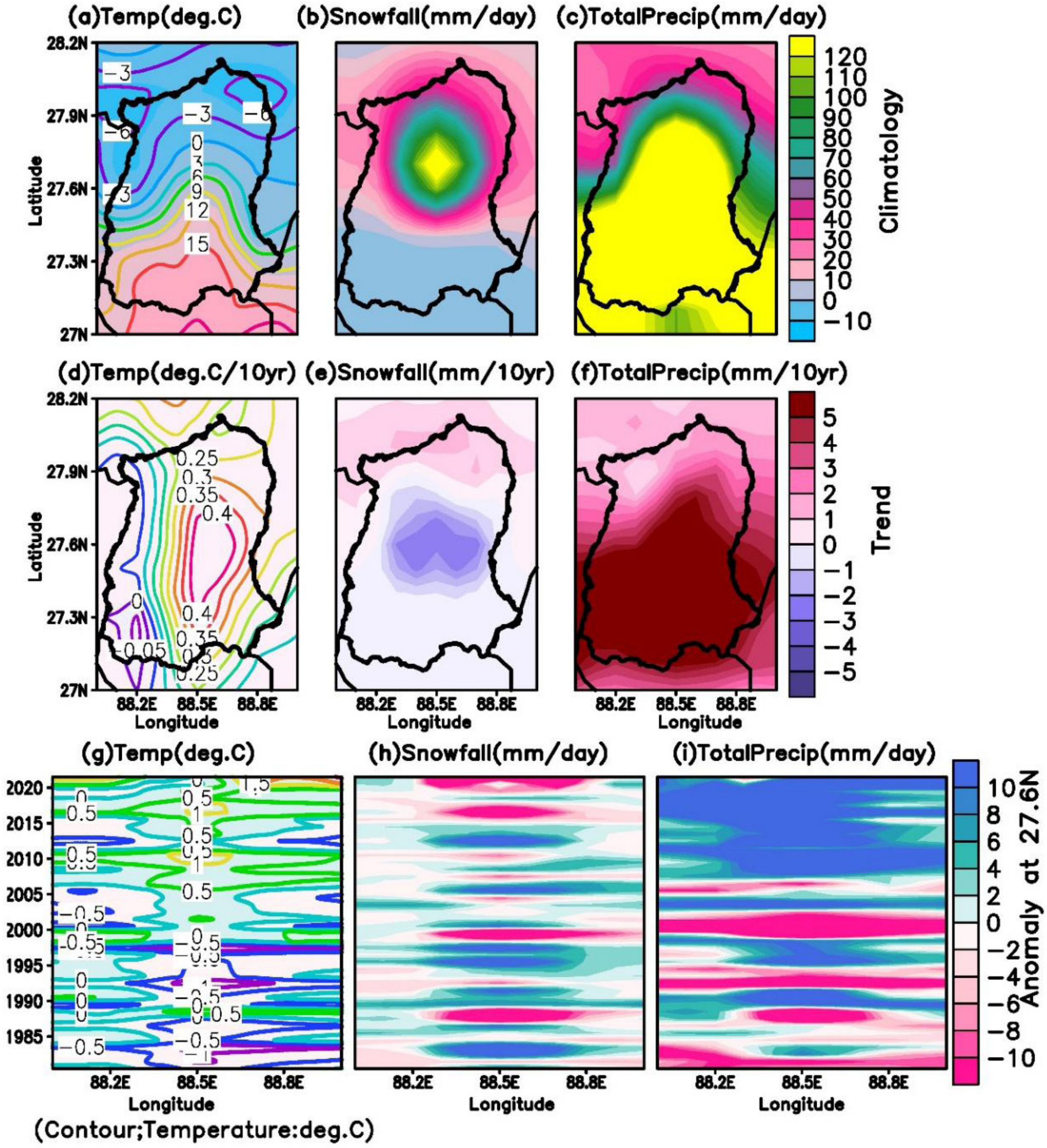

Figure 2. The climatology (long-term annual average), linear trend (decadal), and anomalies at 27.6°N latitude along with longitudinal cross-section are shown as climatology: (a) for temperature, (b) for snowfall, and (c) for total precipitation; linear trend: (d) for temperature, (e) for snowfall, and (f) for total precipitation; respectively, for anomalies: (g) temperature, (h) snowfall, and (i) total precipitation.

below 1500 m, the highest variability in precipitation trend is observed. There are three elevation zones between 1500 m to 1400 m that receive total precipitation with the highest rate of 12 to 15 mm per decade. However, the snowfall shows a negative inclination at the same elevation zones, and the warmer temperature trend explains that accordingly more liquid precipitation has been raising the total precipitation trend. This can be understood by the S/P ratio along with elevation.

4.2 S/P ratio analysis

To see the spatiotemporal variability of snowfall, the S/P ratio has been described in **Figure 4**. **Figure 4a** shows the spatial distribution of the long-term average of snowfall to total precipitation ratio (S/P ratio). The S/P ratio suggests a higher chance of

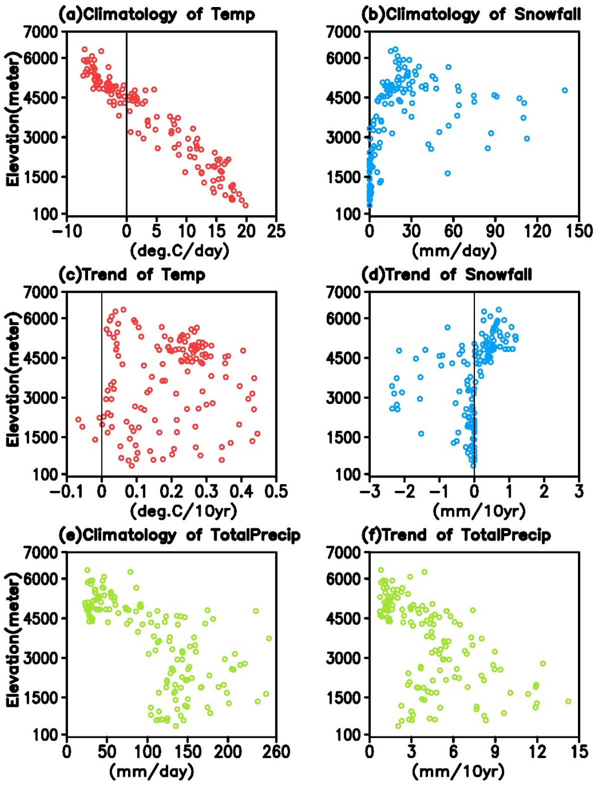

Figure 3. Elevation-dependent variation in temperature, snowfall, and total precipitation. The long-term annual average (climatology) (a) for temperature, (b) for snowfall, and (e) for total precipitation. The linear trend (decadal) is shown in (c) for temperature, (d) for snowfall, and (f) for total precipitation along with elevation over Sikkim.

snowfall when the percentage of the S/P ratio is higher. The region beyond the 27.6°N shows more snowfall region in Sikkim, with maxima over the northernmost part of Sikkim. Theil-Sen estimator is utilized to calculate linear trends [84] for these variables over 42 years. The decadal trend of the S/P ratio suggests a negative trend over the entire Sikkim (except the northernmost of Sikkim) (**Figure 4b**). The S/P ratio decadal trend values are most negative over central Sikkim (i.e., –2% per decade), which suggests drastic snowfall reduction over this region in 42 years of the study period (**Figure 4b**). For temporal variability of the S/P ratio, the anomaly has been assessed to explain the annual deviation from the long-term average over Sikkim. Prior to 2000, the majority of the years had anomalously positive values of the S/P ratio (**Figure 4c**). Afterwards, the S/P ratio is found to be more anomalously negative. The S/P ratio has shifted towards abnormal negative years in recent times. The elevation-dependent S/P ratio decadal trend shows that the majority of the elevation zones have negative trend values ranging from –3.5 to –0.01. Some of the grids are showing positive trend values from 0.01 to 0.5% per decade for elevation > 4000 m, while the rest of the grids are scattered in a negative trend, suggestive of the snowfall reduction in the majority of the grids. The trend of the S/P ratio also explains the seasonal shifting during the study period over Sikkim (**Table 2** and **Figure S4**).

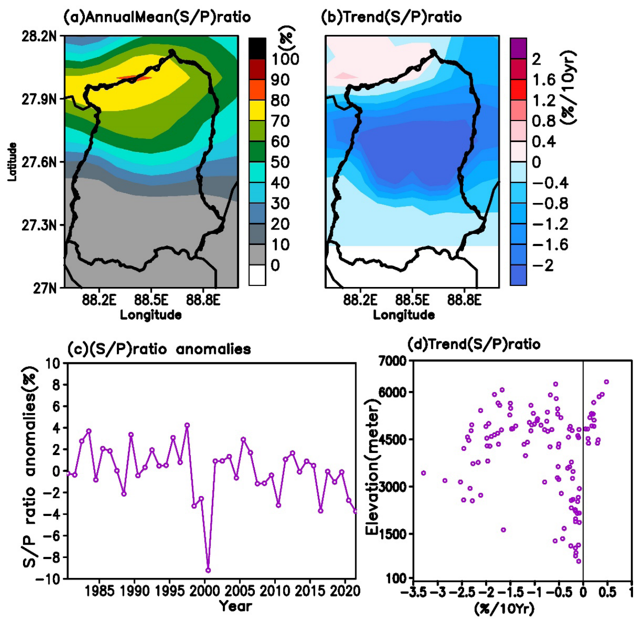

Figure 4. S/P ratio and its features for snowfall change over the region are shown in (a) for annual long-term average, (b) linear trend, (c) anomalies, and (d) decadal trend along with elevation over Sikkim.

4.3 Seasonal shift

In **Figure 5a**, the seasonal variation of long-term averaged temperature, snowfall, total precipitation, and S/P ratio show the peaks and troughs with respective seasons. The temperature is the lowest in NDJ followed by JFM. However, the warmest seasons are observed to be JJA, and JAS followed by MJJ, ASO, AMJ, and SON. Total precipitation has a similar pattern, with a significant fall particularly compared to temperature. The peak of snowfall has been observed in JFM and NDJ followed by DJF, FMA, MAM, and OND. A similar paradigm is observed in the case of S/P ratio. **Figures 5b, 5c, 5d, and 5e** are the annual averaged seasonal variation of temperature, snowfall, total precipitation, and S/P ratio. **Figure 5b** shows temperature incident escalation especially in OND, NDJ, and DJF from 1980 to 2021. The extension of high temperature is found to be expanding from seasons AMJ, MJJ, JJA, JAS, ASO to MAM, AMJ, MJJ, JJA, JAS, ASO, and SON in 42 years. A significant surging trend of temperature has been observed in seasons DJF, JFM, JAS, SON, OND, and NDJ (**Table 2** and **Figure S1**). **Figure 5c** shows that the magnitude of snowfall has declined throughout the peak seasons NDJ, DJF, JFM, and FMA. In addition to this, seasons MAM, AMJ, and MJJ have evidenced a significant rise in snowfall in recent decades (**Table 2** and **Figure S2**). In **Figure 5d**, total precipitation shows the seasonal widening to ASO after the year 2007. A significantly increasing trend of total precipitation is detected in seasons DJF, FMA, MAM, AMJ, MJJ, JJA, JAS, and ASO (**Table 2** and **Figure S3**) which is attributed to the warming as temperature patterns have a similarity. In **Figure 5e**, S/P ratio shows the seasonal shift in snowfall from JFM to FMA after the year 2001. The values of snowfall have dropped, and this occurs frequently during NDJ season. A significant decreasing trend in the S/P ratio has been observed in the seasons DJF, JFM, and NDJ over the entire Sikkim (**Table 2** and **Figure S4**).

4.4 Climate change attribution

Temperature and S/P ratio have a linear relation with a negative slope, which helps to understand the seasonal temperature change affecting snowfall. Thereafter, the S/P ratio decreases with temperature rise for seasons as well as annually (see supplementary **Figures S5a and S5b**). The significant change in temperature and precipitation observed after the year 2000 encourages the further study of deferential change in the two time periods (i.e., 1980-2000 and 2001-2021). Temperature is a controlling factor of snowfall and total precipitation. The significant change has been compared from the past 21 years (1980-2000) to the recent 21 years (2001-2021). Temperature change has been noted to be significantly positive over most of the region. The highest magnitude of temperature change (1 °C) has been found in the central part of Sikkim (**Figure 6a**). West Sikkim has undergone cooling in the recent two decades (–0.2 °C). The snowfall has been reduced significantly (–4 mm/day) from the central to southern part of Sikkim (**Figure 6b**). The northernmost part of Sikkim has shown a significant

Table 2. Seasonal variation trend of temperature, snowfall, total precipitation and S/P ratio. The stars (***) indicate 95% significant confidence, the upward arrow (▲) indicates an increasing trend, and the downward arrow (▼) indicates a decreasing trend.

Seasons \ Variables	Temperature	Snowfall	Total precipitation	S/P ratio
DJF	▲***	▲	▲***	▼***
JFM	▲***	▼	▲	▼***
FMA	▲	▲	▲***	▼
MAM	▲	▲***	▲***	▼
AMJ	▲	▲***	▲***	▲
MJJ	▲	▲***	▲***	▲
JJA	▲	▲	▲***	▼
JAS	▲***	▼	▲***	▼
ASO	▲	▲	▲***	▼
SON	▲***	▼	▲	▼
OND	▲***	▼	▲	▼
NDJ	▲***	▼	▼	▼***

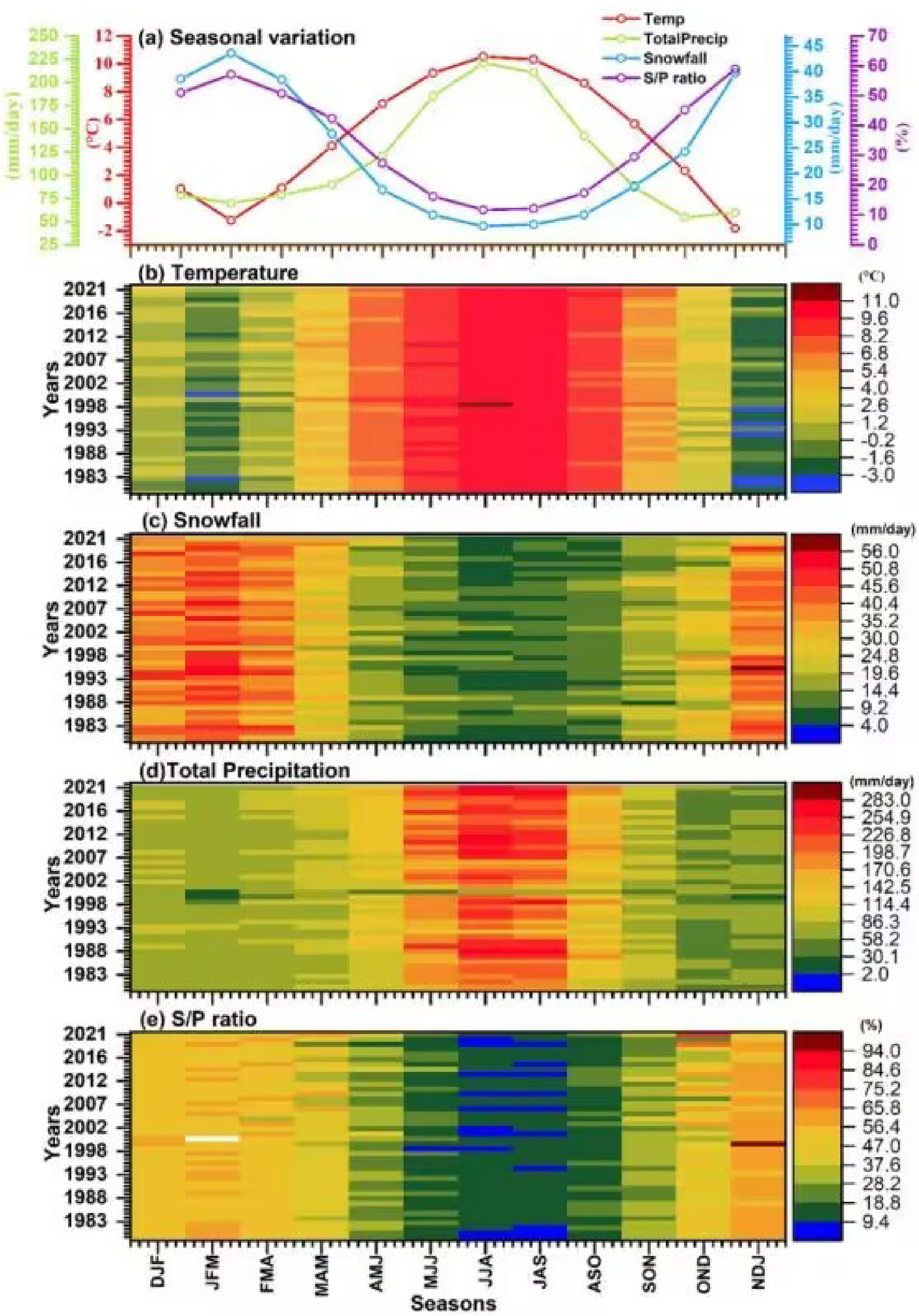

Figure 5. Seasonal variation in temperature, snowfall, total precipitation, and S/P ratio over Sikkim, (a) for long-term average, but (b), (c), (d), and (e) for time series for the study period 1980-2021 over Sikkim. Figures (b), (c), (d), and (e) show each year's seasonal variation for the corresponding variables such as temperature, snowfall, total precipitation and the S/P ratio. This heatmap clearly shows the pragmatic shifting in the snowfall season from 1980 to 2021.

positive change in snowfall in recent decades (3 mm/day). Total precipitation has been elevated significantly over the entire Sikkim with a peak at central Sikkim (30 mm/day). These changes in the snowfall may be attributed to significant warming over the entire Sikkim (and at the same place rise in total precipitation reveals the rise in warming and liquid form of precipitation).

The correlation among temperature vs. snowfall, total precipitation, and the S/P ratio explains the

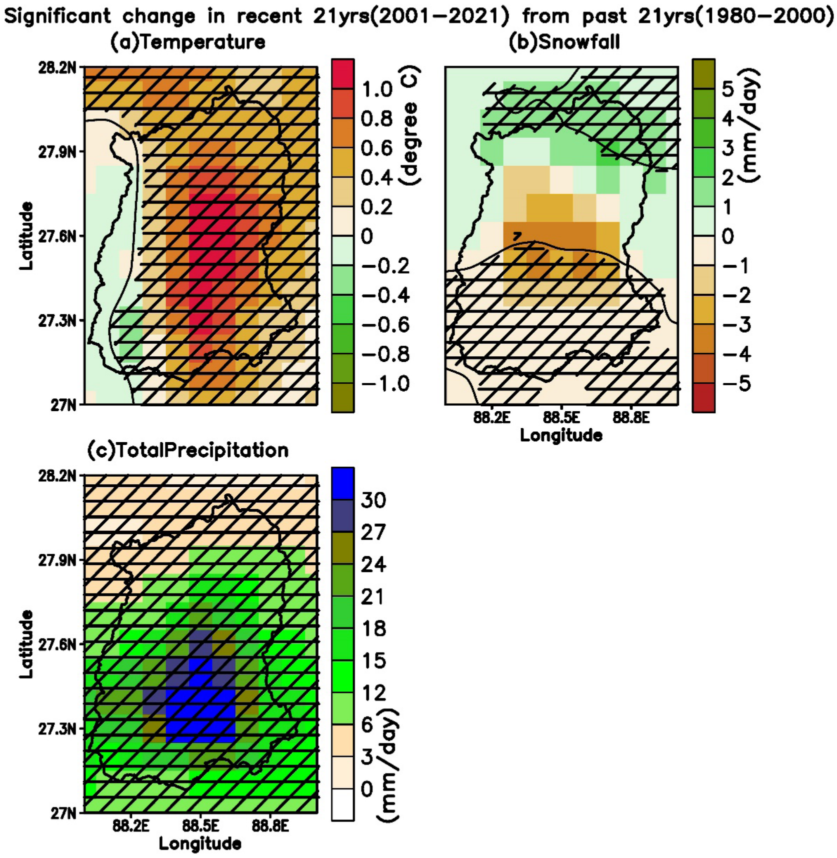

Figure 6. The changes from the past 21 years (1980-2000) to the recent 21 years (2001-2021) are at a 95% significant level over the Sikkim. The shading shows the change in magnitude for corresponding variables, and hatching shows the significance at 95% confidence.

dependency of snowfall on the temperature. As the temperature rises, the snowfall is reduced along with a corresponding total precipitation rise; as higher temperature favours convective rain and liquid precipitation as well. **Figure 7a** shows a strong negative correlation between temperature and snowfall over the entire Sikkim. However, **Figure 7b** suggests a good positive correlation between temperature and total precipitation. **Figure 7c** discusses the correlation between temperature and S/P ratio. The spatial distribution of correlation explains the regional features playing an important role in controlling temperature, snowfall, and total precipitation dependency. **Figure 7d** shows the temporal variation of correlation among the variables. The temperature vs. total precipitation correlation coefficient varies from 0.6 to 0.8 (except in 2000). Similarly, temperature vs. snowfall has a strong negative correlation coefficient varying from –0.82 to –0.88 (except 2000) followed by an S/P ratio. **Figure 8** suggests the dryness and wetness conditions of the region. **Figure 8a** shows the majority of the grids indicating the cold-dry, a few warm-dry, a few cold-wet, and one warm-wet weather system during the first decade (1980-1990) of the study period. However, in **Figure 8b** i.e., during the second decade (1991-2000), the majority of grids are pointing towards cold-dry and warm-dry weather systems. In addition to this, the third and fourth decades are prioritizing warm-wet, and cold-wet weather systems (**Figures 8c and 8d**). Decades 1 and 3 have less precipitation change variance (–4 to 1%). However, decades 2 and 4 have more precipitation change variance (–17 to 17%), respectively (**Figure 8**).

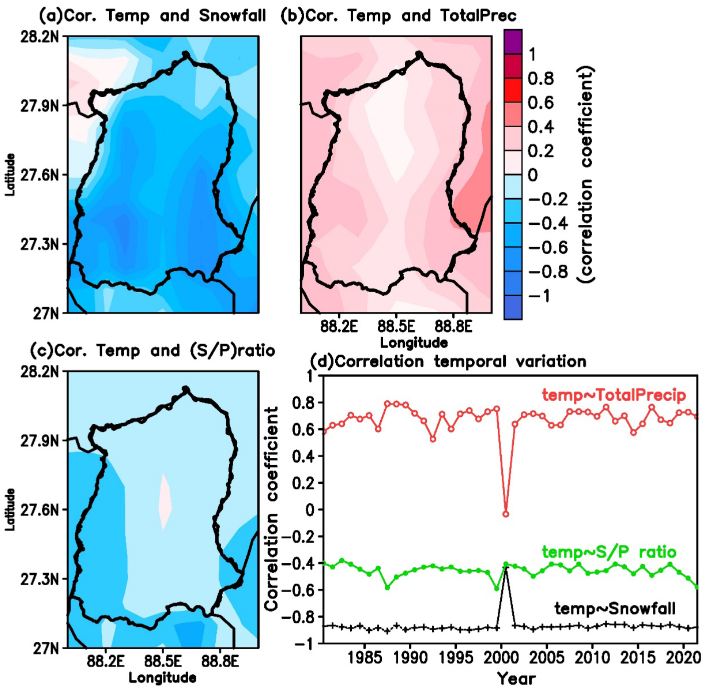

Figure 7. The spatiotemporal variation in correlation for temperature versus snowfall, total precipitation, and S/P ratio. The spatial variation in correlation (i.e., correlation over time) is shown for (a) temperature vs. snowfall, (b) Temperature vs. total precipitation, and (c) temperature vs. S/P ratio. The temporal variation in correlation (i.e., correlation in grid space) is shown for (d) temperature vs. snowfall, total precipitation, and S/P ratio over Sikkim.

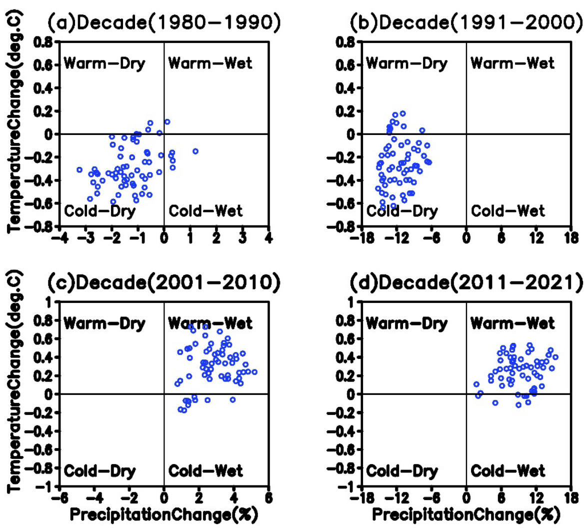

Figure 8. Decadal temperature-precipitation changes, dryness, and wetness extent for the Sikkim Himalaya. Figure shows four weather patterns warm-dry, warm-wet, cold-dry, and cold-wet.

5. Discussion

In recent decades, the land use of Sikkim has changed considerably [79]. The settlement is replacing the green vegetation regions as well making more anthropogenic contributions to the regional warming and emissions that are adversely impacting the microclimatic region [56]. This study tries to establish the fact that warming is the major accountable behind the changing snowfall pattern over the Sikkim Himalayan region. The rate of warming over the Himalayan Mountains is increasing rapidly, making them more vulnerable to disasters [3,40,80,81]. The snowfall is closely connected with warming; as the temperature rises, the snowfall reduces [16,82-85]. In addition to this, total precipitation is positively connected with warming; as temperature rises, total precipitation intensifies following the Clausius-Clapeyron relationship [86]. The anomalous warming over Sikkim has resulted in anomalously high total precipitation every year [53]. The warming trend over higher elevations is much faster than at lower elevations. However, the lower elevation is suffering a significant decline in snowfall due to significant anomalous warming [5]. The enormous variability in snowfall and total precipitation below 1500 m elevation highlights the lower elevation warming significance and precipitation extreme. Total precipitation is increasing along the elevation and following the temperature trend over the entire Sikkim, which is also addressed by some studies [46,87]. Subsequently, EDW is greatly affecting the precipitation as well as snowfall over the entire Sikkim Himalaya. Some elevation zones over 1300 to 2000 m have a negative warming trend that is possibly the west Sikkim region which includes dense forest region and less human disturbances. However, an insignificant cooling change has been found in western Sikkim as well.

The S/P ratio suggests a decline in snowfall over 1500 m elevation and above. A strong declining trend in the S/P ratio over central Sikkim caused by warming indicates an increase in liquid precipitation, which eventually stimulates an increase in total precipitation with an anomalous low annual S/P ratio. The temperature and S/P ratio relationship justifies the variation of snowfall with warming. The fraction of precipitation in the region that occurs in the form of snow, as reported by Sharma and Goyal (2020), is declining as a result of the region's rising temperature [87]. Some of the research articles also suggest the subsequent trends in Sikkim Himalayas due to climate change [35,46,87,88]. The decadal trend of the S/P ratio suggests a negative trend over the entire Sikkim (except the northernmost of Sikkim) [46]. The S/P ratio decadal trend values are most negative over central Sikkim, which suggests drastic snowfall reduction over this region in 42 years of the study period [46]. The S/P ratio has shifted towards abnormal negative years in recent times [35,46,87,88]. These trends indicate that climate change and rapid warming are affecting snowfall patterns in the Sikkim Himalayas, which can have significant impacts on the region's ecology, economy, and society.

Seasonal shift of the snowfall has been found over the central part of Sikkim. It is seen that the snowfall has been shifting from NDJ, and DJF to JFM, and FMA respectively. In fact, the seasons MAM, AMJ, and MJJ have seen a significant upsurge in snowfall in the last decade [82,84,85,89]. Climate change is directly influencing snowfall, as the global average temperature rises at a faster rate [90]. In recent decades, higher warming has significantly declined the winter season (NDJ, and DJF) snowfall (–4 mm/day) from the central to southern parts of Sikkim. In the analyzed results spanning from 1980 to 2021, a significant rise in temperatures was observed during the OND, NDJ, and DJF seasons, with this warming trend extending to encompass additional seasons. Conversely, snowfall has decreased notably during peak seasons (NDJ, DJF, JFM, FMA) but has shown a significant increase in MAM, AMJ, and MJJ. Moreover, total precipitation has exhibited a seasonal expansion, particularly post-2007, with a noticeable increase in various seasons, including DJF, FMA, MAM, AMJ, MJJ, JJA, JAS, and ASO. These patterns align with the effects of climate change and warming on seasonal weather [91-93]. Le et al. (2023) also support climate-driven changes in the amounts of precipitation and their seasonal variability [91]. The seasonal shift is going to make it more difficult for farming and crop production. As Wang et al. (2021) also suggested that summer and winter have become longer and hotter, while spring and autumn have become shorter and warmer [93].

Snowfall drop is justified by a strong inverse relationship between temperature and snowfall. The two-tailed Student's t-test is employed to assess significant differences. Climatic change and differences are only presented if they are statistically significant at the 95% significance level (**Figure 6** and **Table 2**). This emphasizes the significant seasonal change as well as the alteration in the spatial distribution of snowfall. Temperature versus total precipitation for four decades indicates that most of the elevation zones are tending from cold-dry towards warm-wet weather systems of the Sikkim Himalaya. Dubey et al. (2022) have also reported that Sikkim has witnessed warm and wet days from 1951 to 2018 [53]. The result examined the correlation between temperature, total precipitation, and snowfall using correlation coefficients [94]. The correlation coefficient between temperature and total precipitation varied from 0.6 to 0.8, while the correlation coefficient between temperature and snowfall was strongly negative, ranging from –0.82 to –0.88. This suggests the major cause of the snowfall change and precipitation variability [52,94]. The changing pattern of the precipitation and snowfall along with the temperature rise influences the weather system of the mountainous region [90]. Thereafter, the dryness and wetness conditions of the study region are observed to be altered, which showed that the majority of elevation zones indicated cold-dry during the first and second decades (1980-1990, 1991-2000) and warm-wet weather systems during the third and fourth decade (2001-2010, 2011-2021) of the study period.

Henceforth, Climate change and EDW are affecting vegetation, and shifting it to higher elevations due to temperature and precipitation changes. These shifts affect the ecosystems and biodiversity of the mountainous region [95]. Thereafter, interactions with hydrological factors like evapotranspiration and soil moisture anomalies also influence regional precipitation patterns [95]. However, some researchers have suggested that EDW and climate change are affecting vegetation and other hydrometeorological parameters over the Himalayan region at a faster rate, and collectively altering snowfall patterns in the Sikkim Himalayas. Furthermore, recent studies have highlighted those human activities, such as deforestation and urbanization, emissions, contribute to the intricacy of regional climate dynamics [18,52,94,95].

6. Conclusions

The temperature is rising across the entire region, with maxima over the central part of Sikkim. As temperature and snowfall have an inverse relation, the snowfall has been dropping throughout the entire region, with a negative peak over the central part of Sikkim Himalaya. Across Sikkim's zonal cross-section, anomalous warming since 2000, abnormally low snowfall since 2015, and contrastively heavy precipitation since 2007 have been observed. The snowfall seasons are shifting from NDJ, and DJF to JFM, and FMA [96]. Snowfall is declining along elevations up to 4500 m with huge variance. Snowfall is slowly rising above 5000 m elevation with minimal variance. The precipitation is rising over the entire Sikkim from lower elevation (with greater variability) to higher elevation (with least variability). The rise in temperature, which boosted rainfall while cutting down snowfall, was precisely explained by a drop in the S/P ratio with altitude. Temperature, snowfall, and precipitation have changed significantly from the previous two decades (1980 to 2000) to the most recent two decades (2001 to 2021). The weather system of the entire Sikkim is also shifting from cold-dry to warm-wet weather. Essentially, the Sikkim Himalaya is undergoing significant snowfall shifts and precipitation variability caused by EDW in recent decades. The findings of this study will be helpful for policymakers and the scientific community in better comprehending the long-term implications of climate change.

People's perceptions

People believe that such non-climatic issues (like land degradation, land use, urbanization, and air pollution) make it particularly challenging for them to mitigate the hazards created by climatic changes, and act as obstacles for them to escape from it. The present study concludes that programs must be designed in a way that addresses the region's multidimensional problems since achieving this will improve the community's innate ability to adapt to both present and future climate-related risks.

The majority of people think and consider that the weather system over the entire Sikkim is changing, which is the root cause for snowfall pattern change as per the survey response of 51 people of the entire Sikkim region.

Author Contributions

Pramod Kumar: Formulated the concept, plotted the figures, drafted the original work, and wrote the manuscript.Khushboo Sharma: Created seasonal analysis figures, and conducted the local people's perception survey and manuscript editing.

Conflict of Interest

The authors declare that there is no conflict of interest.

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Appendix

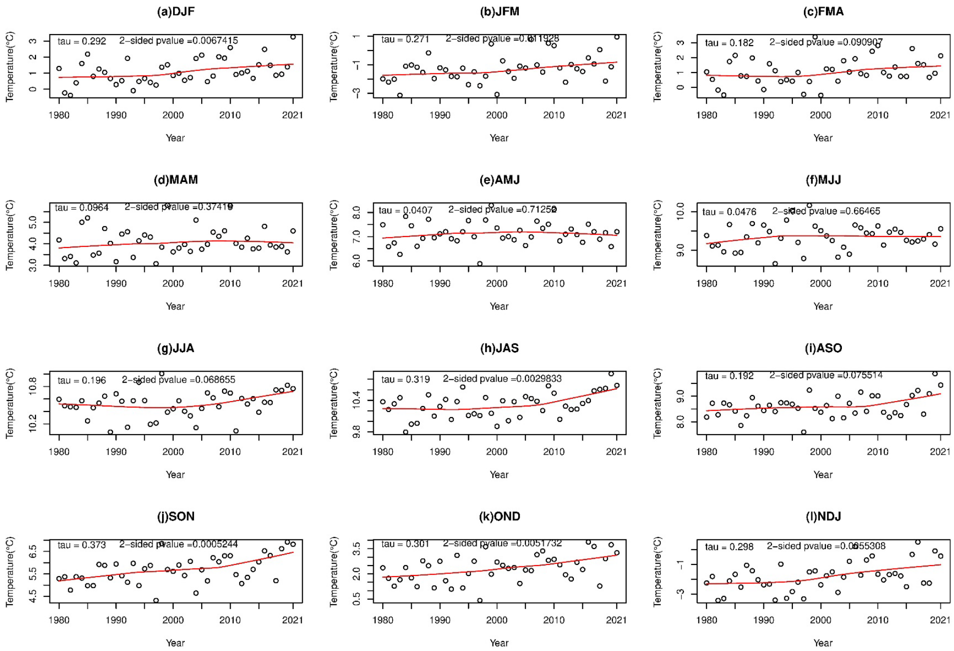

Figure S1. Mann-Kendall trend of temperature with significant t-test analysis; if the p-value is less than 0.05 the trend is significant, p-value greater than 0.05 shows the insignificant trend. The tau value suggests that the trend is negative or positive based on the sign of the tau values [(a) DJF, (b) JFM, (h) JAS, (i) ASO, (j) SON, (k) OND, and (l) NDJ are significant, remaining are insignificant].

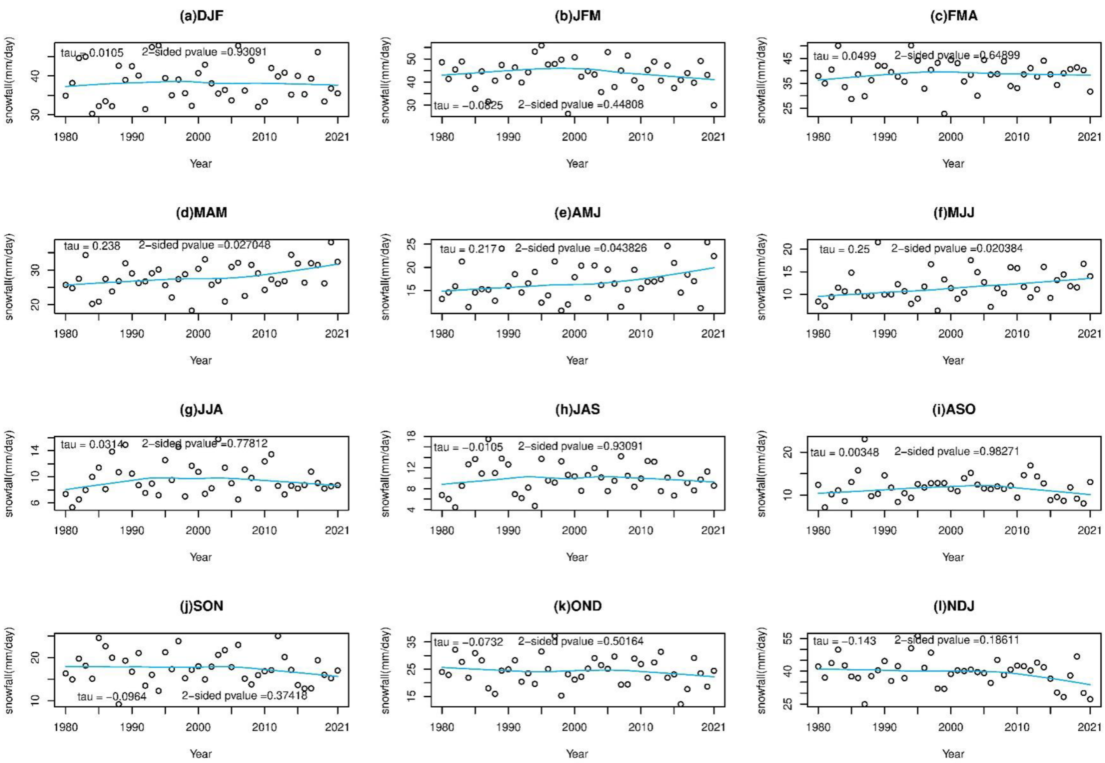

Figure S2. The Mann-Kendall trend of snowfall with significant t-test analysis; if the p-value is less than 0.05 the trend is significant. The tau value suggests that the trend is negative or positive based on the sign of the tau values [(d) MAM, (e) AMJ, and (f) MJJ are significant, remaining are insignificant].

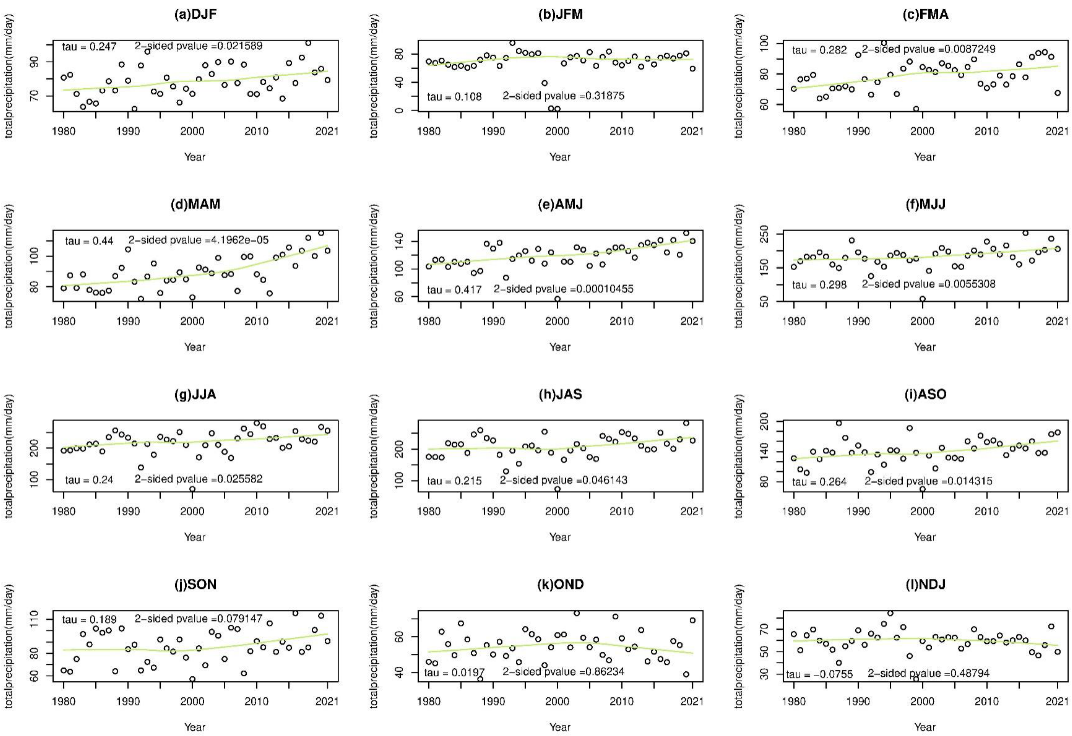

Figure S3. The Mann-Kendall trend of total precipitation with significant t-test analysis; if the p-value is less than 0.05 the trend is significant. The tau value suggests that the trend is negative or positive based on the sign of the tau values [(a) DJF, (c) FMA, (d) MAM, (e) AMJ, (f) MJJ, (g)JJA, (h) JAS, and (i) ASO, are significant, remaining are insignificant].

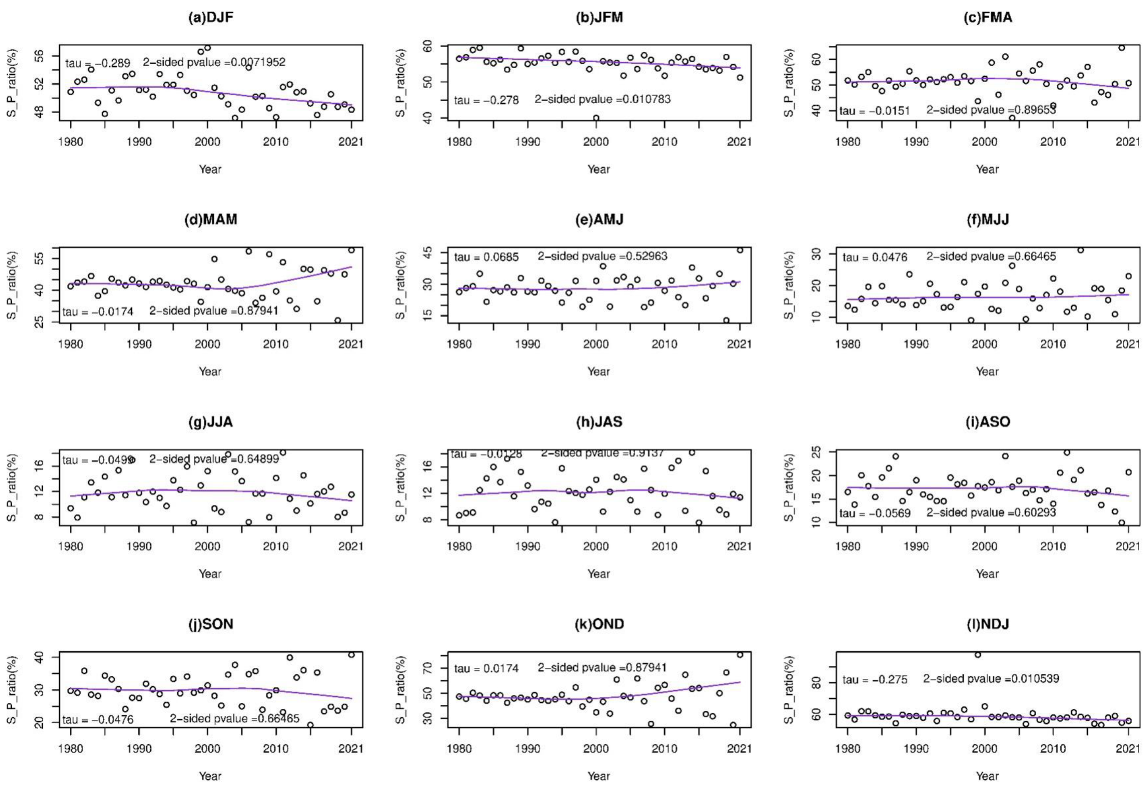

Figure S4. The Mann-Kendall trend of S/P ratio with significant t-test analysis; if the p-value is less than 0.05 the trend is significant. The tau value suggests that the trend is negative or positive based on the sign of the tau values [(a) DJF, (b) JFM, and (l) NDJ are significant, remaining are insignificant].

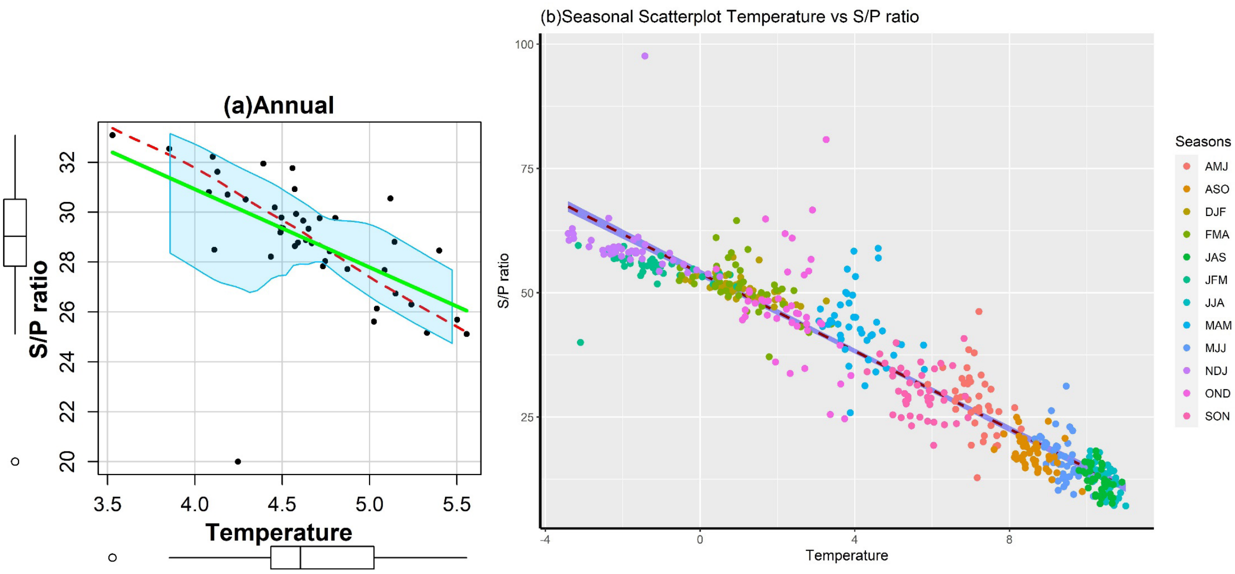

Figure S5. Scatterplot (a) annual, and (b) seasonal variations in temperature versus S/P ratio over Sikkim Himalaya for 1980 to 2021. Shading along the lines shows 95% significance confidence level.

Supplementary Material

Method SM6

They suggested outlining the methodology for conducting the seasonal analysis and investigating the shifts in temperature, snowfall, and total precipitation. (1) Data Preparation: Organized the collected data into a suitable format for analysis, ensuring proper labelling and data integrity. Verify the accuracy and consistency of the data, checking for any missing values or outliers that may require handling. (2) Seasonal Classification: Defined the twelve seasons based on the chosen seasonal classification (DJF, JFM, FMA, MAM, AMJ, MJJ, JJA, JAS, ASO, SON, OND, NDJ) as described in the manuscript's methodology section. Group the data into these defined seasons by extracting the respective months' data for each season. (3) Seasonal Analysis: Calculate the seasonal means or sums for temperature, snowfall, and total precipitation within each defined season. Compare the seasonal values across different years to identify any temporal shifts or trends. (4) Visualization: Created visual representations such as line plots or bar graphs to depict the seasonal variations of temperature, snowfall, and total precipitation (**Figures 5, S1, S2, S3, S4, and S5b**). Overlayed the data from different years or seasons to visualize the shifts and identified notable patterns. (5) Statistical Analysis: Applied statistical methods (e.g., t-tests, regression analysis, and time series analysis) to quantitatively analyze the data and determine the significance of the observed shifts and trends.

A non-parametric method 'Theil-Sen estimator' is used for estimating the slope of a linear trend between snowfall and total precipitation. The present study opted for this method because it is easy to compute, can control outliers well, and doesn't make any conventions regarding the data's distribution. The steps have been used for the calculation of the Theil-Sen estimator trend analysis: (1) Sorted the data in ascending order based on the values of the independent variable (e.g., snowfall and total precipitation for 1981 to 2021). (2) For each pair of observations (x1, y1) and (x2, y2), compute the slope of the line connecting the two points as (y2 – y1)/(x2 – x1). (3) Stored all of the slopes computed in previous step in a list. (4). Computed the median of the list of slopes computed in previous step. Now we found the Theil-Sen estimator for the slope of the linear trend for snowfall and total precipitation. (5) Computed the intercept of the line using the median slope and the median values of the independent (snowfall) and dependent (total precipitation) variables.

Equation (3) provided in the methodology section shows the calculation of the slope of a linear trend using the long-term averages of two variables (snowfall and total precipitation), and their logarithms. The first expression of Equation (3) is the derivative of the ratio of the partial derivatives of the variables S (snowfall) and P (total precipitation) with respect to P. This expression calculates the slope of the linear trend between S and P using the partial derivatives of the variables. The second expression of Equation (3) is a simplified version of the first expression, using the long-term averages of S and P, and their logarithms. It calculates the slope of the linear trend using the average values and the partial derivatives of the logarithms of S and P over the study period (1980-2021). The terms (∂lnS) and (∂lnP) represent the linear trends of the logarithms of snowfall and total precipitation, respectively, over the study period. These terms are calculated using the Theil-Sen estimator method explained earlier, as applied to the logarithms of the variables.

Method SM6

LULC Class

Water: Areas where water was predominantly present throughout the year; may not cover areas with sporadic or ephemeral water; contains little to no sparse vegetation, no rock outcrop nor built up features like docks; examples: rivers, ponds, lakes, oceans, flooded salt plains.

Trees: Any significant clustering of tall (~15-m or higher) dense vegetation, typically with a closed or dense canopy; examples: wooded vegetation, clusters of dense tall vegetation within savannas, plantations, swamp or mangroves (dense/tall vegetation with ephemeral water or canopy too thick to detect water underneath).

Flooded vegetation: Areas of any type of vegetation with obvious intermixing of water throughout a majority of the year; seasonally flooded area that is a mix of grass/shrub/trees/bare ground; examples: flooded mangroves, emergent vegetation, rice paddies and other heavily irrigated and inundated agriculture.

Crops: Humans planted/plotted cereals, grasses, and crops not at tree height; examples: corn, wheat, soy, fallow plots of structured land.

Built Area: Human made structures; major road and rail networks; large homogenous impervious surfaces including parking structures, office buildings and residential housing; examples: houses, dense villages/towns/cities, paved roads, asphalt.

Bare ground: Areas of rock or soil with very sparse to no vegetation for the entire year; large areas of sand and deserts with no to little vegetation; examples: exposed rock or soil, desert and sand dunes, dry salt flats/pans, dried lake beds, mines.

Snow/Ice: Large homogenous areas of permanent snow or ice, typically only in mountain areas or the highest latitudes; examples: glaciers, permanent snowpack, snow fields.

Clouds: No land cover information due to persistent cloud cover.

Rangeland: Open areas covered in homogenous grasses with little to no taller vegetation; wild cereals and grasses with no obvious human plotting (i.e., not a plotted field); examples: natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures. A mix of small clusters of plants or single plants dispersed on a landscape that shows exposed soil or rock; scrub-filled clearings within dense forests that are clearly not taller than trees; examples: moderate to sparse cover of bushes, shrubs and tufts of grass, savannas with very sparse grasses, trees or other plants.