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Climatic Trends in Different Bioclimatic Zones in the Chitwan Annapurna Landscape, Nepal

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Abstract: The Chitwan Annapurna Landscape (CHAL) is the central part of the Himalayas and covers all bioclimatic zones with major endemism of flora, unique agro-biodiversity, environmental, cultural and socio-economic importance. Not much is known about temperature and precipitation trends along the different bioclimatic zones nor how changes in these parameters might impact the whole natural process, including biodiversity and ecosystems, in the CHAL. Analysis of daily temperature and precipitation time series data (1970–2019) was carried out in seven bioclimatic zones extending from lowland Terai to the higher Himalayas. The non-parametric Mann-Kendall test was applied to determine the trends, which were quantified by Sen's slope. Annual and decade interval average temperature, precipitation trends, and lapse rate were analyzed in each bioclimatic zone. In the seven bioclimatic zones, precipitation showed a mixed pattern of decreasing and increasing trends (four bioclimatic zones showed a decreasing and three bioclimatic zones an increasing trend). Precipitation did not show any particular trend at decade intervals but the pattern of rainfall decreases after 2000AD. The average annual temperature at different bioclimatic zones clearly indicates that temperature at higher elevations is increasing significantly more than at lower elevations. In lower tropical bioclimatic zone (LTBZ), upper tropical bioclimatic zone (UTBZ), lower subtropical bioclimatic zone (LSBZ), upper subtropical bioclimatic zone (USBZ), and temperate bioclimatic zone (TBZ), the average temperature increased by 0.022, 0.030, 0.036, 0.042 and 0.051 °C/year, respectively. The decade level temperature scenario revealed that the hottest decade was from 1999–2009 and average decade level increases of temperature at different bioclimatic zones ranges from 0.2 to 0.27 °C /decade. The average temperature and precipitation was found clearly different from one bioclimatic zone to other. This is the first time that bioclimatic zone level precipitation and temperature trends have been analyzed for the CHAL. The rate of additional temperature rise at higher altitudes compared to lower elevations meets the requirements to mitigate climate change in different bioclimatic zones in a different ways. This information would be fundamental to safeguarding vulnerable communities, ecosystem and relevant climate-sensitive sectors from the impact of climate change through formulation of sector-wise climate change adaptation strategies and improving the livelihood of rural communities.

Keywords: climate change; lapse rate; precipitation; temperature; trend

1. Introduction

Elevation-dependent warming is higher in the Himalayas than any other part of the world [1,2]. Globally, the average yearly temperature is increasing by 0.02 °C [3], but the average maximum yearly temperature of Nepal has increased by 0.056 °C [2],varying in different areas and bioclimatic zones [4]. This indicates that the impact of climate change is severe and more rapid in both the upland and lowland areas of Nepal [5], which could lead to several erratic problems for livelihoods [6], ecosystem processes, biodiversity, and natural resources in general. Climate change is very likely to strongly impact the hydrological cycle, which is predicted to alter rainfall patterns and intensity as well as the frequency of extreme precipitation. Extreme precipitation is considered a trigger for mountain hazards which could threaten agricultural production and the livelihoods of millions of people.

The Chitwan-Annapurna Landscape (CHAL) area in Central Nepal extends from 164m to 8091m altitudes within a short north-south distance of about 185km. It covers 32,090 km^2, encompassing19 political districts that cover 22% of the land in Nepal. It is known that altitude and aspect along the latitude create a wide range of climatic conditions and that CHAL also features almost all types of bio-climate—from tropical to alpine—which makes it an appropriate landscape for climatic study. The climate change analysis and trend information would be useful for biodiversity analysis, biological invasion, natural disaster, and vulnerability and impact studies. Climate change and spread of invasive alien species are major drivers of change in many localities. The interactions and impacts of these and other parameters are often local, specific to the bioclimatic zones in the context of landscape as well as socio-economic and cultural environment. CHAL is a unique landscape in term of environmental, socioeconomic, cultural and livelihood settings. It includes biodiversity rich and provides innumerable ecosystem services to millions of Nepalese people and outsides.

The Nepalese government has prioritized climate change adaptation as an elemental tool to safeguard vulnerable communities, ecosystems and relevant climate sensitive sectors from the impact of climate change [5]. To formulate the adaptation plan at different bioclimatic zones an empirical data on trends of climatic parameter (temperature and precipitation) is crucial. Some of the temperature trends study for a localized place show that warming at higher elevations is more than lower altitudes [2], however temperature and precipitation trend analyses along the different bioclimatic zones in CHAL remain to be documented.

Since 1993, numerous analyses of climatic trends at the national and regional levels have been conducted in Nepal [2,7–20]. Most of these studies have been conducted thorough analyses of selected meteorological stations in Nepal and adjoining regions. However, systematic climatic trends from a complete set of meteorological stations at different bioclimatic zones of a landscape level have not been studied. Due to the topographic variation and orographic effects, the average temperature and precipitation assessment is a challenge in a region like CHAL. Simply averaging the data from stations at different altitudes cannot distinguish variations in trends among bioclimatic zones.

This study fulfils a gap in knowledge of the rate of warming in different elevation levels within CHAL by: (i) analyzing the trends of temperature and precipitation in the different bioclimatic zones, (ii) examining decade interval temperature and precipitation climate change patterns in the different bioclimatic zones, and (iii) determining the average temperature, precipitation, and lapse rate of temperature and precipitation in different bioclimatic zones of the area.

2. Materials and Methods

2.1. Study Area

The study area is the Chitwan Annapurna Landscape (CHAL), located in central Nepal between 27°35′ and 29°33′ N latitude and 82°88′ and 85°80′ E longitude [21]. The CHAL includes all or part of 19 districts (*Mustang, Manang, Gorkha, Rasuwa, Nuwakot, Dhading, Lamjung, Tanahu, Syangja, Kaski, Palpa, Parbat, Baglung, Myagdi, Gulmi, Arghkhachi, Makwanpur, Chitwan and Nawalparasi*, Figure 1). Based on altitude, topography, and climate, Nepal is generally divided into Terai (59–200 m), Siwaliks (200–1500 m), middle mountains (1000–2500 m), high mountains (2200–4000 m), and high Himalayas (>4000 masl). In this study, CHAL is categorized into seven bioclimatic zones [22,23] with slight modification, to evaluate the climatic trends: lower tropical bioclimatic zone (<500 m, LTBZ), upper tropical bioclimatic zone (500–1000 m, UTBZ), lower subtropical bioclimatic zone (1000–1500 m, LSBZ), upper subtropical bioclimatic zone (1500–2000 m, USBZ), temperate bioclimatic zone (TBZ), lower sub-alpine bioclimatic zone (3000–3500 m, LABZ) and upper sub-alpine bioclimatic zone (>3500 m asl, ABZ).

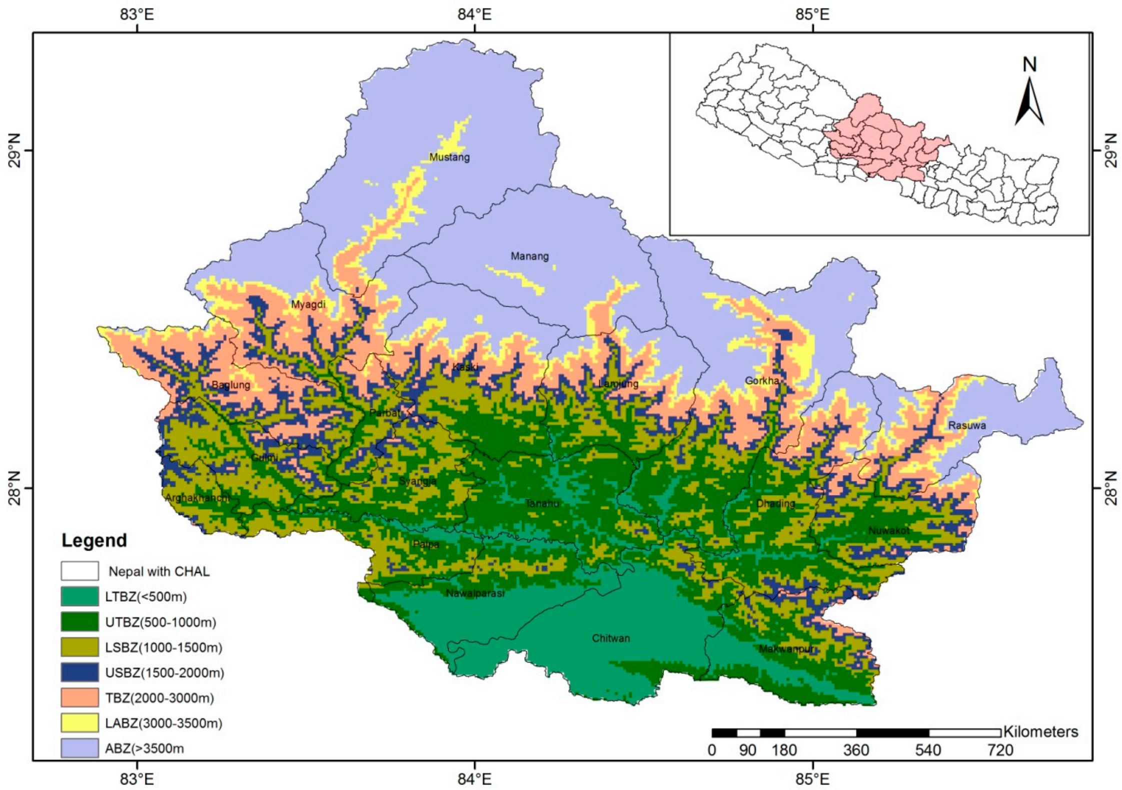

Figure 1. Map of CHAL area with different bioclimatic zones.

A wide range of climatic conditions exist in CHAL, including the tropical humid climate in the lowlands of the Chitwan and Nawalparasi districts, the alpine one in the high mountains and the cold dry climate in the trans-Himalaya in parts of Mustang and Manang districts. The mean temperature of Terai/Siwalik is more than 25 °C, about 20 °C in the middle hills, and in between 10 °C to 20 °C in the high mountains [24]. The average annual rainfall ranges from 165 mm at Lomanthang (Mustang) in the northern part to 5244 mm at Lumle (the highest rainfall in the country) in the mid-hills [2]. Orographic effects cause high spatial variation in precipitation in different zones of the landscape. Nearly 78% of the total annual precipitation occurs during the monsoon season between June and September [16]. Occasional winter rainfall is common, including brief rainfall in the Siwalik and mid-hills and snowfall is common in the high altitude regions.

The LTBZ lies below 500 m and experiences a tropical climate with dry winters and hot summers, a mean annual temperature is about 25 °C [24]. It covers major parts of the Terai (Chitwan and Nawalparasi) districts in CHAL. This is dominated by a tropical type of vegetation, mostly sal (*Shorea robusta*) forests. UTBZ, which covers a major part of the Churia region and has a tropical type of climate, a mean annual average temperature of about 22 °C [24], covers parts of the Chitwan and Nawalparasi districts and the low lying riverine valleys of the Tanahu, Palpa, Syangja, Arghakhanchi and Dhading districts. The vegetation of UTBZ is a mix of *Shorea robusta*, *Terminalia* species, *Acacia catechu* and *Dalbergia sisoo*.

LSBZ experiences a subtropical type of climate and covers the lower parts of the mid-hills, including large valleys like Pokhara within CHAL. The average annual mean temperature is about 20 °C [24]. This region is dominated by *Castanopsis indica* and *Schima wallichii* forests, however, depending on the altitude and slope of the mountains, forest is replaced by *Pinus ruxburgii* and *Alnus nepalensis* species. USBZ also experiences a subtropical type of climate with a maximum rainfall of about 5244 mm per year at Lumle and an average mean temperature is about 18 °C [24]. Subtropical broad-leaved forest is the main vegetation in this zone, which produces an important part of the non-timber forest products (NTFPs) in Nepal.

TBZ covers the main part of the mid-hills, with temperate climate of about 13 °C average annual temperature. Temperate forests are mainly comprised of lower temperate mixed broad-leaved forests dominated by *Quercus lamellosa, Castanopsis tribuloides*, and Lauraceae species and upper temperate broad-leaved forests of *Quercus semecarpifolia*, *Acer* species, and *Rhododendron* species

LABZ extends from 3000 to 3500 m altitudes with a subalpine climate. It covers the major part of the Annapurna conservation area, the largest conservation area with high endemism in Nepal. The subalpine forest mainly comprises *Abies spectabilis, Betula utilis*, and *Rhododendron* species. ABZ includes a broad area of high mountains including the cold and dry Trans-Himalayan region of Manang and Mustang districts where the high peaks exceed 8000 m. Subalpine vegetation exists up to 4000 m and alpine scrub and meadows occur up to the tree lines

2.2. Climate Analysis

Daily precipitation and temperature data for all available weather stations in CHAL were procured from the Department of Hydrology and Meteorology (DHM), Government of Nepal. There are 81 precipitation and 32 temperature stations that measure rainfall and temperature within CHAL (Table 1). However, time series data (1970–2019) of daily temperature and rainfall of only 52 precipitation and 26 temperature stations were used in this analysis due to the presence of complete data sets. The stations with incomplete data set were omitted in analysis. The total number of stations in CHAL with complete data set (functional stations) and with incomplete data set are presented in Table 1. The distribution scenarios of functional stations used to depict inferences along different bioclimatic zones are presented in Figures 2 and 3. The station details, including the data available date, are presented in Appendices A and B. The rainfall and temperature trends were calculated in spatial (seven bioclimatic zones based upon altitude, climate, and vegetation) and temporal (annual and decade) scales.

Table 1. Total number of precipitation and temperature stations in each bioclimatic zone in CHAL. Numbers in parentheses indicate stations having complete data sets.

Bioclimatic Zones	Precipitation Stations	Temperature Stations
LTBZ (<500 m)	14(11)	6(5)
UTBZ (500–1000 m)	16(11)	10(8)
LSBZ (1000–1500 m)	16(10)	4(4)
USBZ (1500–2000 m)	14(8)	5(4)
TBZ (2000–3000 m)	10(7)	7(5)
LABZ (3000–3500 m)	3(2)	-
ABZ (>3500 m)	8(3)	-
Total	81(52)	32(26)

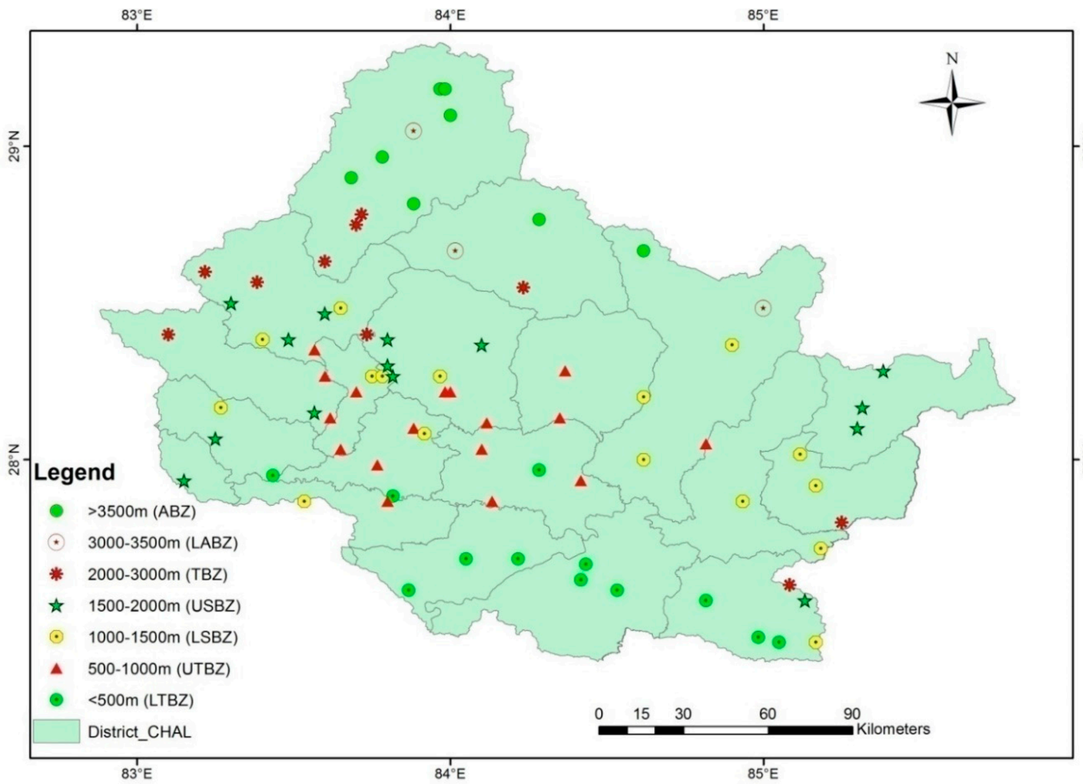

Figure 2. Stations recording precipitation at different bioclimatic zones in CHAL.

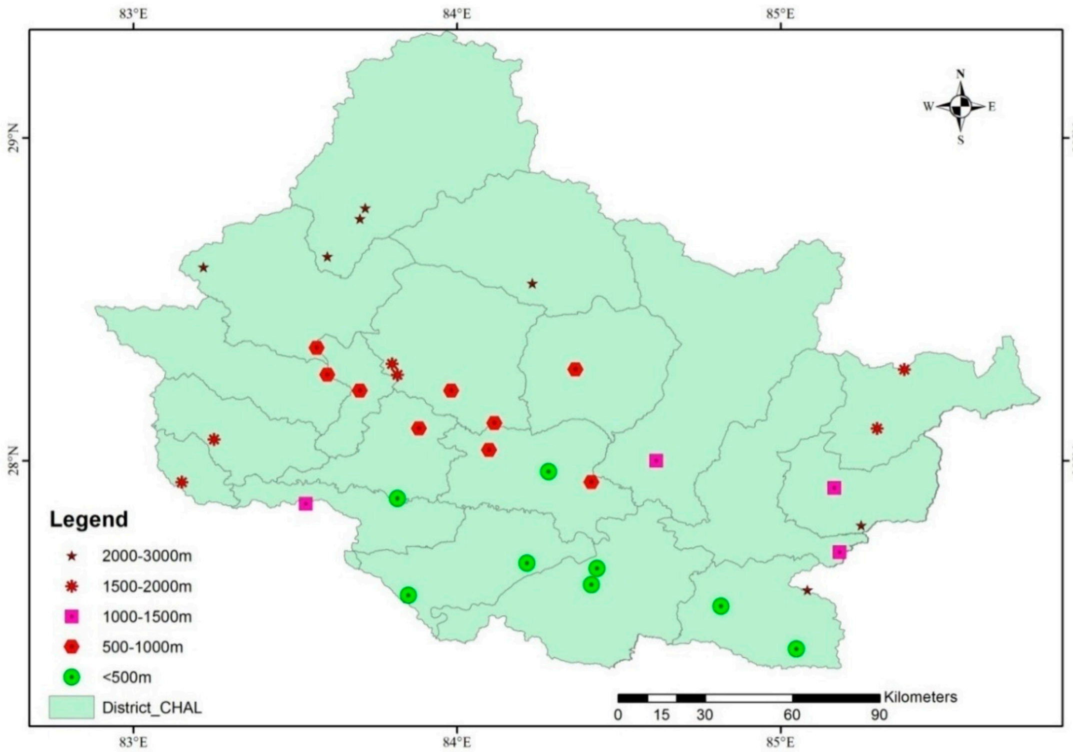

Figure 3. Temperature stations at different bioclimatic zones in CHAL.

The average temperatures of individual stations averaged and the average sum of precipitation from all stations in each bioclimatic zone was calculated. The temperature was analyzed only from LTBZ to TBZ in this study. Although two climatological stations, Jomsom and Thakmarpha (station Id

601 and 604), lie in between 2500 and 3000 m altitude in Mustang district of CHAL, the data of these stations cannot represent the temperature of all bioclimatic zones in upper temperate regions. Mustang lies within the Trans-Himalayan region, i.e., a rain shadow area. Therefore, stations of lower temperate and upper temperate bioclimatic zones were merged and averaged to calculate the trend.

2.3. Data Management

The stations level data were checked using the Microsoft Excel 2010 software to determine any odd and unusual patterns. The station data that showed outliers and unusual values were corrected for individual stations by replacing them with the average of the value from the previous day and the next day [2]. If there is an outlier or missing data for about a month or more, that particular year is omitted from the analysis.

2.4. Trend Analysis

A Mann-Kendall test and Sen's slope methods were used to analyze the climatic trend, magnitude, significance of temperature, and precipitation data in the bioclimatic zones. The Mann-Kendall test is a non-parametric tool and one of the best methods to analyze the presence and significance of monotonic positive or negative trend in time series climatic data [2,25,26]. Existence of positive or negative trend among the considered climatic variables was determined by using Mann-Kendall trend test, its quantification was done by using Sen's slope method, and significance by Mann-Kendall Methods in R package version 3.4.4 [27]. The Mann-Kendall method of significance test uses the hypothesis testing approach. In the testing mechanism null hypothesis (H_o) there is no monotonic trend in climatic data, and with alternative hypothesis (H_1), there is a monotonic trend in climatic data at significant level. Significance tests at 0.05 confidence levels were used.

2.5. Lapse Rate of Temperature and Precipitation

The lapse rate of temperature and precipitation in different bioclimatic zones along altitudinal gradient in CHAL were calculated following [28,29], with slight modifications. The lapse rate of precipitation was derived by analyzing annual average precipitation sums of the stations lying in each bioclimatic zone by using the following equation:

$$PPtLR = \frac{P_1 - P_2}{Z_1 - Z_2} \tag{1}$$

where PPt LR is the precipitation lapse rate, P_1 and P_2 are the precipitation sums of the highest and lowest bioclimatic zones (in mm) and Z_1 and Z_2 are their respective elevations of higher and lower bioclimatic zones. The value of Z_1-Z_2 considered 1 because our calculation is converted into 1 km along elevation change.

All temperature data were aggregated into yearly values for the period of 50 years. Temperature lapse rates were calculated through temperature difference between two successive bioclimatic zones i.e., temperature-elevation space [28]. Average temperature is normally assumed to decrease linearly with increasing elevation in CHAL, so Temp LR was calculated as:

$$TempLR = \frac{T_1 - T_2}{Z_1 - Z_2} \tag{2}$$

where Temp LR is Temperature lapse rate, T_1 and T_2 are the yearly average temperatures of the highest and lowest temperature in each bioclimatic zone (°C), and Z_1 and Z_2 are their average elevations (m). We calculated the lapse rates based on the strong relationship between ambient air temperature and elevation [28–30].

3. Result

3.1. Annual Trend of Precipitation

A mixed pattern of precipitation in different bioclimatic zones was noted in CHAL. Out of seven bioclimatic zones, four zones showed decreasing precipitation and three zones showed an increasing trend (Table 2). Except for UTBZ and LSBZ, the trend was statistically significant in these bioclimatic zones. At LTBZ (<500 m), the average precipitation significantly decreased at the rate of 1.8 mm/year. In UTBZ, the precipitation decreased at the rate of 1.98 mm/year. Precipitation in USBZ had a yearly increase of 0.45 mm, but at USBZ a decreasing rate of2.06 mm/year (Table 3 and Figure 4).

Table 2. Decade wise average precipitation (mm) trend in different bioclimatic zones in CHAL.

Bioclimatic Zones	1970–1979	1980–1989	1990–1999	2000–2009	2010–2019	Trends between 1970–2019		
						Sen's Slope Per Year	*p* Value (Mann-Kendall Test)	Significance
LTBZ	1964.4	2030.5	2022.3	2169.3	1823.6	−1.8	0.029	No
UTBZ	2620.8	2604.6	2665.7	2677.8	2496.3	−1.98	0.47	No
LSBZ	2145.8	2216.0	2362.1	2242.8	2152.8	0.45	0.89	No
USBZ	3222.5	3422.9	3066.9	3105.5	2913.79	−2.06	0.03	Yes
TBZ	1230.2	1558.1	1519.65	1498.75	1429.25	1.81	0.002	Yes
LABZ	886.2	854.8	992.1	971.1	1056.2	1.28	0.0001	Yes
ABZ	366.8	444.3	351.1	298.4	348.0	−1.80	0.05	Yes

Table 3. Average temperature trend (1970–2019) in different bioclimatic zones in CHAL.

Bioclimatic Zones	Sen's Slope	*p* Value (Mann-Kendall Test)	Significance
LTBZ	0.022	<0.001	Yes
UTBZ	0.030	<0.00001	Yes
LSBZ	0.036	<0.0001	Yes
USBZ	0.042	<0.00001	Yes
TBZ	0.051	<0.0001	Yes

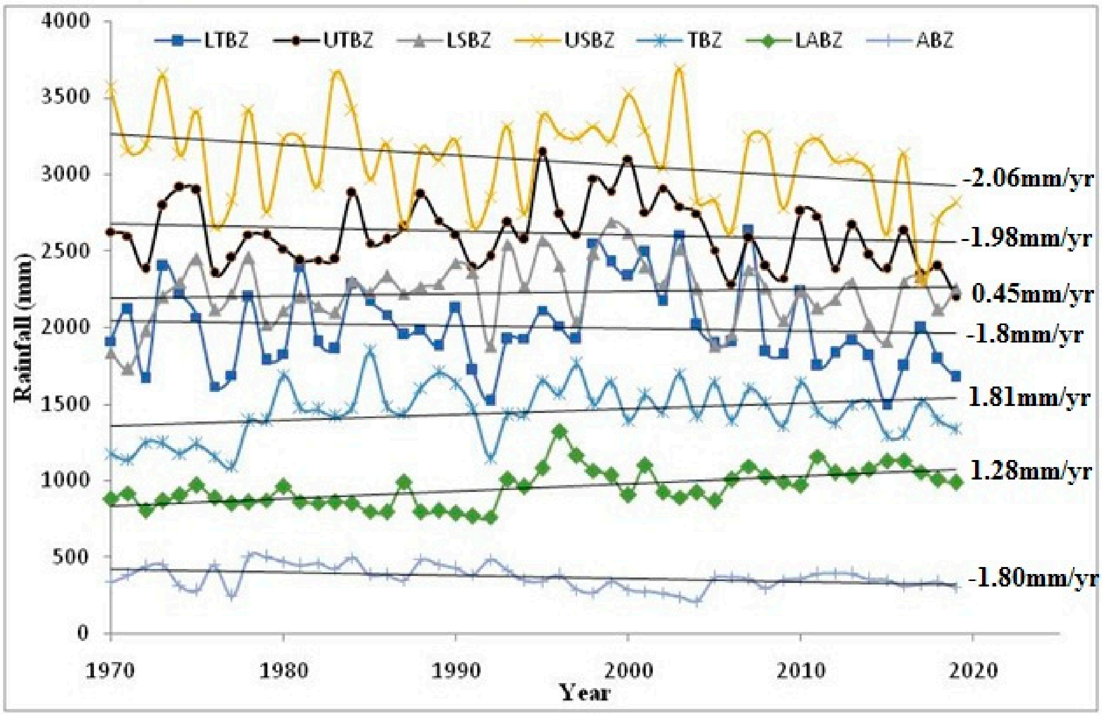

Figure 4. Average annual rainfall trends in different bioclimatic zones in CHAL.

Above 2000 m elevation, the precipitation showed an increasing trend up to 3500 m and then decreasing again. At TBZ (2000–3000 m), the precipitation increased at the rate of 1.81 mm/year and in LABZ (3000–3500 m) it also increased at the rate of 1.28 mm/year. At ABZ (>3500 m), precipitation had a decreasing trend at the rate of 1.80 mm/year (Table 3 and Figure 4).

3.2. Precipitation Trends in Different Decades

The average decade rainfall in the bioclimatic zones in CHAL was analyzed. In general, precipitation in all bioclimatic zones increased until 2000AD, but decreased after. In UTBZ, the average rainfall increased from 1970–1979 to 1980–1990 and again showed a decreasing and increasing pattern. In the last decade (2010–2019), the average rainfall was found to be decreasing from preceding decades. From Sen's slope value, the rainfall was found to be decreasing at the rate of 19.8 mm per decade.

USBZ received the maximum average rainfall in CHAL (Figure 5); however, its overall trend shows that average precipitation was decreasing at the rate of 20.6 mm/decade (Table 2).

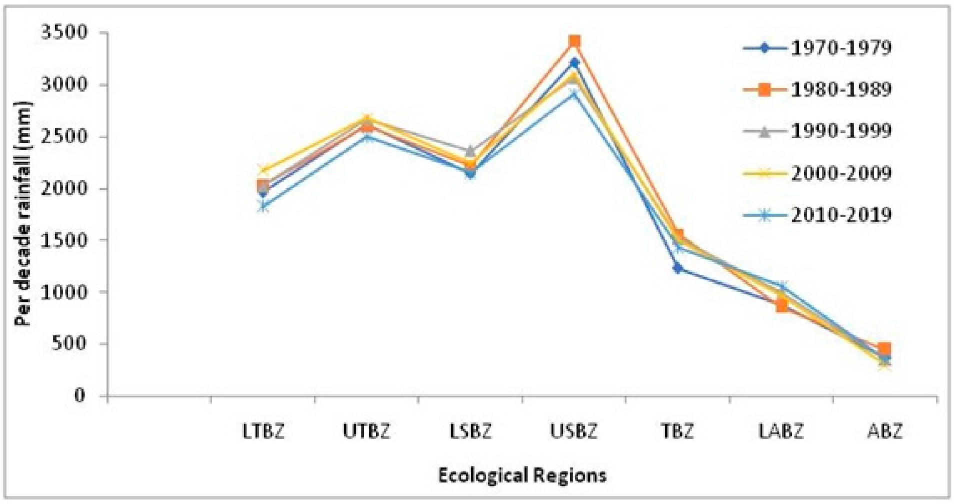

Figure 5. Decade-wise precipitation trends along different bioclimatic zones in CHAL.

In TBZ, from the first (1970–1979) to the second decade (1980–1989), the rainfall trend was found to be increasing and decreasing thereafter. However, overall decade level trend analysis showed increasing rainfall at the rate of 18.1mm/decade. Similarly, no particular trend was seen in LABZ, but the average decade rainfall was found to be increasing at the rate of 12.8 mm/decade.

3.3. Annual Trend of Temperature

The average temperature increased by 0.022 °C/year during 1970 to 2019 in LTBZ. However, in UTBZ, LSBZ, USBZ, and TBZ, the average annual temperature increased by 0.030, 0.036, 0.042, and 0.051 °C/year, respectively. This result clearly indicates that the temperature at higher elevations has been increasing significantly more than at lower elevations (Table 3 and Figure 6). Although the average temperature increased in all bioclimatic zones, the average annual temperature increase rate at higher elevations was high.

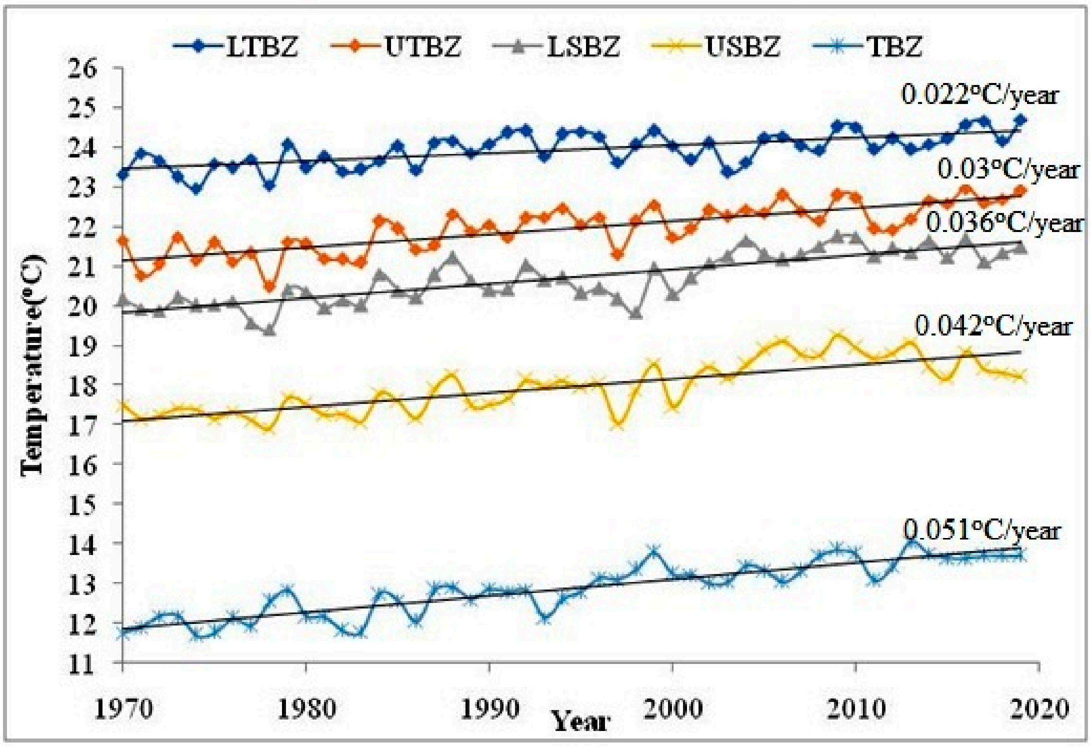

Figure 6. Average temperature trends in different bioclimatic zones of CHAL (1970–2019).

3.4. Temperatures in Different Decades

The average temperature in every bioclimatic zone of CHAL has been increasing over the past five decades (Table 4). On average, at a rate of 0.2 °C/decade, the temperature significantly increased at LTBZ of CHAL. At LTBZ, from 1989–1999, the highest average temperature increase was 0.27 °C/decade. From 1979–1989, the average temperature rose by 0.26 °C/decade, but during the last two decades it experienced a slightly low temperature gain (Table 4). Similarly, 1999–2009 was a comparatively hotter decade in higher altitudes above 1000 m (Table 4).

Table 4. Increased average temperature (°C) per decade in different bioclimatic zones of CHAL since 1979.

Bioclimatic Zones	1979–1989	1989–1999	1999–2009	2009–2019	1979–2019	
					Sen's Slope	Significance
LTBZ	0.26	0.27	0.16	0.19	0.022	Yes
UTBZ	0.28	0.28	0.33	0.32	0.030	Yes
LSBZ	0.17	0.39	0.44	0.42	0.036	Yes
USBZ	0.36	0.39	0.44	0.47	0.042	Yes
TBZ	0.48	0.51	0.56	0.52	0.051	Yes

3.5. Average Annual Temperature and Precipitation

The average temperature and precipitation values of all stations in each bioclimatic zone have been analyzed for 1970–2019(Table 5). The results show 24.1, 21.8, 19.7, 17.5, and 13.3 °C average annual temperatures at LTBZ, UTBZ, LSBZ, USBZ, and TBZ, respectively, in CHAL.

Table 5. Lapse rate and average temperature and precipitation along different bioclimatic zones in CHAL.

Bioclimatic Zones	AAT (°C)	TLR (°C/500 m)	TLR (°C/km)	ANR (mm)	PLR (mm/500 m)	PLR (mm/km)
Lower tropical bioclimatic zone (<500 m)	24.1		-	2002.1		-
Upper tropical bioclimatic zone (500–1000 m)	21.8	−2.3	−4.6	2613.1	611	1222
Lower subtropical bioclimatic zone (1000–1500 m)	19.7	−2.1	−4.2	2223.9	−389.2	−778.4
Upper subtropical bioclimatic zone (1500–2000 m)	17.5	−2.2	−4.4	3146.4	922.5	1845
Temperate bio- climatic zone (2000–3000 m)	13.3	−2.2	−4.4	1447.2	−849.6	−1699.2
Lower subalpine bioclimatic zone (3000–3500 m)				952.1	−495.1	−990.2
Alpine bioclimatic zone (>3500 m)				361.7	−590.4	−1180.8

Notes: AAT = Average annual temperature, TLR = Temperature lapse rate, PLR = precipitation lapse rate.

Similarly, average annual precipitation in LTBZ, UTBZ, LSBZ, USBZ, TBZ, LBZ, and ABZ was 2002.1, 2613.1, 2223.9, 3146.9, 1447.2, 952.1, and 361.7 mm/year, respectively. This result indicates that with increasing altitude from LTBZ to UTBZ, annual average precipitation increased, but in other BZ the precipitation successively decreased (Table 5).

3.6. Lapse Rate of Temperature and Precipitation Lapse Rate

The temperature lapse rate showed 2.1 to 2.3 °C decreases with every 500 m altitude increase along different bioclimatic zones in CHAL (Table 5). This implies that every one-kilometer that altitude rises, the temperature decreases by 4.2 to 4.6 °C/km in CHAL. Precipitation lapse rate analysis in CHAL does not show any specific pattern. However, greater PLA was found above from 2000 m elevation (Table 5).

4. Discussion

A mixed pattern of precipitation in different bioclimatic zones is in congruence with the precipitation pattern for the whole of Nepal [31]. Previous work in different parts of CHAL were localized to districts or whole regions involving small scale analysis based on some meteorological stations of Lamjung [32], Syangja [33], and other districts [2]. According to Poudel and Shaw [32], annual precipitation was increasing in the Khudi (855 m) and Kunchha (823 m) stations of Lamjung district at the rate of 0.063 mm/year and 4.42 mm/year, respectively. However, at the Gharedhunga (1120 m) station, in the same district over the course of 32 years (1980–2012), there was a decreasing trend at the rate of 3.48 mm/year within CHAL. Our findings in general conclude that for the whole CHAL, annual average precipitation varies because the precipitation amounts are varying in different years.

According to DHM [2], normal annual precipitation at a district level in CHAL showed that Mustang, a trans-Himalaya region, receives the lowest rainfall (<400 mm), whereas Kaski, Parbat, Tanahu, Lamjung, and Nuwakot receive more than 2000 mm of annual rain. Similarly, the High Himalayas (>4000 m) receive the least amount of rain and the remaining regions receive 1500–2000 mm, which is consistent with the present results. The annual precipitation trend of Nepal along different physiographic regions showed inconsistency. According to [2], in Terai, the annual average rainfall was found to be increasing at the rate of 0.49 mm/year, but Siwalik, Mid-mountain, High mountains, and High Himalayas showed decreases at rates of 1.48, 1.58, 3.17 and 1.46 mm/year, respectively. For the whole of Nepal, total annual precipitation since the 1960s has been decreasing at the rate of 3.7 mm per year [34]. District wise, annual precipitation trends in CHAL show a different pattern. Among the 19 districts, annual average rainfall significantly decreased in 10 districts and decreased in nine districts [2], which is consistent with the present study. There is no previous comparison at the bioclimatic zone level in CHAL.

In Nepal, the average annual rainfall is 1858.6 mm [35]; however, the spatial pattern of annual rainfall in the country depends on the topography. Altitude further affects rainfall patterns; total annual rainfall increases with altitude up to approximately 3000 m above sea level and then diminishes at higher elevations [36]. However, in CHAL, average annual rainfall was found to be inconsistently increasing and decreasing from lower to higher altitudes because of mountains blocking the monsoon wind. Seasonal analysis of station-based rainfall pattern in Gandaki river basin (major part of CHAL) revealed a significantly decreasing winter rainfall but increasing monsoon rainfall [16]. The precipitation was found to be significantly increasing in the high mountains of CHAL.

Precipitation in each bioclimatic zone in the mountains depends upon many factors such as topography, strength of moisture-bearing winds and the orientation of the mountain ranges with respect to the prevailing wind direction. Thus, precipitation processes and distribution in a region are influenced by the aforementioned factors, including steep altitudinal contrast [37]. Variation in elevation within a very short distance of about 185km creates dissimilarity in precipitation within particular regions in Nepal [31,38]. In this study, we found that the rainfall in LTBZ and UTBZ is decreasing annually, but in LSBZ it is increasing, and again significantly decreasing in USBZ. This unusual pattern of precipitation along different bioclimatic zones of CHAL is therefore due to orography and the spatial arrangement of topographic gradients, which control the precipitation patterns [37]. These spatial arrangements of topographic gradients, wind direction, aspects and slopes of mountain may alter consistency in precipitation along different ecological zones within a short distance in CHAL.

In the higher elevations above 2000 m, annual precipitation was found to be much lower than precipitation at lower elevations. Increases in annual precipitation from LTBZ to higher elevations up to 2000 m at USBZ, and decreases in precipitation above TBZ were well noted. The highest annual rainfall was found in USBZ in CHAL. The Lumle station in CHAL received the highest amount of annual precipitation in Nepal of about 5500 mm [35,39] as it lies on the windward side of the Annapurna-Machhapuchhre mountain range. The lowest precipitation site was recorded in Upper Mustang Dhiee, Lomanthang area of Mustang district within CHAL, with a mean annual precipitation of less than 200 mm. Both of these highest and lowest precipitation sites of the country are in the Annapurna area of present study site.

According to [15], there are two high monsoonal rainfall zones in Nepal, one around 600 m and another around 2100 m, with different rain patterns. This record of gradual increasing precipitation from LTBZ to USBZ, with highest at around 2000 m altitude, may be due to presence of high monsoonal rainfall zones. From the comprehensive precipitation observations in the Annapurna range [40], showed that the annual precipitation gradually increases from lowland and had a strong peak at about 3000 m altitude, then decreases as elevation increases. However, the present analysis showed that strong peak of precipitation at 2000 m then decreases as elevation increases in CHAL, which is inconsistent with the results of [40].

According to the precipitation trend analyzed from data of 80 stations in Nepal, most of the Terai area and Western Nepal observe a negative trend [41]. The hills and mountains of Western Nepal and the northern part of Eastern Nepal have a positive trend. Based on data from 1947 to 1993, [42] found that the precipitation trend in the Koshi Basin (Eastern Nepal) showed an increasing trend. The overall average trend for Nepal indicates that the annual average precipitation is decreasing at the rate of 9.8mm/decade [5]. Our findings on decade level precipitation trends in different bioclimatic zones of CHAL showed consistency with previous findings from Nepal.

According to [43], the global mean surface temperature has increased on average by 0.8 °C in the 20th century and by 0.6 °C from1975 to 2005. Reference [9] reported the maximum temperature increased in mountains of Nepal during 1971–1994 by 0.06 to 0.12 °C/year, while the southern plains increased by less than 0.03 °C/year, and during 1970–2015 the maximum temperature increased by

0.056 °C/year in Nepal [2]. In the CHAL, the rise in average temperature was found to be considerably higher than the global average.

At the district level, the highest significant positive trend was observed in Manang district (0.12 °C/yr) [2]. The average annual temperature increased in Terai (<200 m), Siwalik (200–1500 m), Middle mountain (1500–2500 m), High mountain (2200–4000 m), and High Himalayas at the rate of 0.020, 0.023, 0.031,0.032, and 0.035 °C/year, respectively, which is a similar pattern as in the present study. The temperature increase was noted higher in our study than DHM (2017). This speedy warming trend in high elevation zones compared to lower altitudes is due to melting of snow and ice [44] and cold air pooling along local heating by combination of topography and synoptic conditions [45].

In Nepal, the average temperature and precipitation analysis for different bioclimatic zones in particular areas has not been assessed before. However, average temperature and precipitation analysis along different physiographic regions had been done. The range of temperature in Terai and Siwalik, mid-hills, and mountain physiographic regions is 20–25, 15–20, 10–20, <3–10 °C, respectively [24,36]. Reference [20] analyzed the variation in temperature by increasing every two hundred meters altitudes and found that temperature at <200 m was 24.8 °C. The temperature at <3800 m was 7.8 °C without any consistency pattern of increasing temperature in between the lowest to higher elevation.

Thus, these reasonable elevation-dependent temperature and precipitation trends vary due to elevation-based differential changes in climate drivers, such as snow/ice cover, clouds, water vapor, aerosols and soil moisture, or differential sensitivities of surface warming due to changes in these drivers at different elevations. However, mountain systems are inherently difficult to understand as a result of their complex topography, which leads to a high level of spatial and temporal variability in their climatic responses [4].

According to [29], the annual average TLR on the southern slope of the central Himalayas is −5.2 °C/km, which is −0.4 to 0.8 °C/km higher than lapse rate at different bioclimatic zones of CHAL. The lapse rate of temperature depends on surface air temperature on elevation and varies due to different seasonality, interplay of radiation, slope and aspect of the mountains, and several local factors [46].

However, the precipitation lapse rate shows irregular patterns in different bioclimatic zones in CHAL. When altitudes rise from LTBZ to UTBZ, PLR shows positive trends of 611 mm/500 m elevation i.e. 1222 mm/km. However, moving upwards from UTBZ to LSBZ, the precipitation lapse rate (PLR) shows negative rate of 778.4 mm/km, and then again shows the rate of 1845 mm/km up to 3000 m. Then, PLR continuously decreases as altitude increases. The rate of decrease is higher at the uppermost elevation (Table 5). This unusual pattern of increasing and decreasing PLR is consistent with [47] in Langtang valley within CHAL. The difference in PLR between different bioclimatic zones may be due to the local effects of topography, slope, and aspects of mountain as well as the direction of wind and many other local factors.

5. Conclusions

The geological position of a place plays a crucial role in the distribution of temperature and precipitation. This study elaborates this notion to understand the spatial and temporal patterns of temperature and precipitation and its trends across different bioclimatic zones of CHAL. Annual and decade level precipitation and temperature trend analysis was carried out from time series daily data (1970–2019) obtained from weather stations in seven bioclimatic zones extending from lowland Terai to the higher Himalayas in CHAL. Precipitation and temperature lapse rates and average precipitation and temperature in each bioclimatic zone was also analyzed. A mixed pattern of precipitation in different bioclimatic zones was noted in CHAL. Out of seven bioclimatic zones, four zones showed decreasing and three zones showed increasing precipitation trends. Within the CHAL, the alpine bioclimatic zone gets the lowest amount of precipitation whereas the upper subtropical bioclimatic zone receives the most annual precipitation. However, the precipitation trend at higher altitudes showed a greater decrease. Average decade level rainfall in all bioclimatic zones increased until 2000AD, but decreased thereafter.

Bioclimatic zone level trend analysis showed a robust significant positive trend in annual temperature. Annual temperature trends clearly indicated that the temperature at upper elevations has been increasing significantly and more than at lower elevations. The temperature trends showed progressive increases from lower to higher elevations. This clearly indicates a significant increasing temperature on both spatial and temporal scales in CHAL. The temperate climatic zone of CHAL(altitudes in between 2000–3000 m) become 0.051 °C hotter every year but the average temperature increased by 0.022 °C/year in LTBZ(below 500 m). The significant successive annual temperature in UTBZ, LSBZ and USBZ is increasing at the rate of 0.030, 0.036 and 0.042 °C/year, respectively. The average temperature in every bioclimatic zone of CHAL has been increasing over the past five decades and 1999-2009 was a comparatively hotter decade at higher altitudes above 1000 m. On average, the temperature increased at a rate of 0.2 °C to 0.27 °C/decade in different bioclimatic zones in CHAL between 1970–2019.

This average precipitation and temperature study of each bioclimatic zones in CHAL contributes to understanding the variation of spatial patterns of climatic parameters with increasing altitudes. The average temperature and precipitation in lower tropical bioclimatic zone was 24.1 °C and 2002.1 mm, respectively. The average temperature and precipitation of the upper tropical bioclimatic zone was 21.8 °C and 2613.1 mm, and the average temperature in LSBZ, USBZ and TBZ was 19.7, 17.5, and 13.6 °C, respectively. This study identified a 2.1–2.3 °C temperature lapse rate. i.e., a 2.1–2.3 °C temperature decrease for every 500 m of altitude increase in CHAL. The average annual precipitation in LSBZ was 2223.9 mm and 3146.9 mm in the upper subtropical bioclimatic zones with the highest rainfall in CHAL. TBZ, LBZ, and ABZ receive 1447.2, 952.1, and 361.7 mm precipitation annually, respectively. These findings of temperature and precipitation trends in every bioclimatic zones might have numerous implications to the local people in each bioclimatic zone. The result should be useful for the planning of mitigation and adaptation strategies for climate change impacts indifferent bioclimatic zone in special ways.

Author Contributions: D.R.L., primary researcher, designed concept collected data, gathering and processing of all data source, and prepared manuscript. P.K.J., M.S., M.L.S. participate in its design, supervised the works and edited the manuscript. R.M. was involved in interpretation of results and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Stations used to analyze the temperature trends in CHAL, 1970–2019.

Station Name	Station ID	Station Type	District	Latitude	Longitude	Altitude (m)	Data Available
Lower tropical bioclimatic zone (<500 m)							
Dumkauli	706	Agro-meteorology	Nawalparasi	28.1	84.22	154	1976
Simari	728	Climatology	Nawalparasi	28.12	83.75	154	1981
Chapakot	810	Climatology	Syangja	27.88	83.82	460	1979
Rampur	902	Agro-meteorology	Chitwan	28.02	84.42	256	1970
Hetauda NFI	906	Climatology	Makawanpur	27.68	85.05	474	1971
Upper tropical bioclimatic zone (500–1000 m)							
Baglung	605	Climatology	Baglung	27.93	83.6	984	1978
Beni bazar	609	Climatology	Myagdi	27.53	83.57	835	1989
Kusma	614	Climatology	Parbat	28.28	83.7	891	1989
Khudi bazar	802	Climatology	Lamjung	28.3	84.37	823	1970
Pokhara airport	804	aeronautical	Kaski	28.03	84.0	827	1970
Syangja	805	Climatology	Syangja	27.62	83.88	868	1976
Malepatan	811	Agro-meteorology	Kaski	27.92	84.12	856	1970
Khairenitar	815	Climatology	Tanahu	28.1	84.1	500	1970
Lower subtropical bioclimatic zone (1000–1500 m)							
Tansen	702	Climatology	Palpa	28.22	83.53	1067	1972
Gorkha	809	Agro-meteorology	Gorkha	28	84.62	1097	1970
Nuwakot	1004	Climatology	Nuwakot	27.93	85.02	1003	1970
Pensayakhola	1057	Climatology	Nuwakot	28.28	85.12	1240	1975
Upper subtropical bioclimatic zone (1500–2000 m)							
Khachikot	715	Climatology	Arghakhanchi	28	83.15	1760	1977
Tamghas	725	Climatology	Gulmi	27.88	83.25	1530	1981
Lumle	814	Agro-meteorology	Kaski	27.8	83.8	1740	1970
Dhunche	1055	Climatology	Rasuwa	28.1	85.3	1982	1989
Temperate bio climatic zone (2000–2500 m)							
Jomsom	601	Climatology	Mustang	27.87	83.72	2744	1970
Thakmarpha	604	Agro-meteorology	Mustang	27.68	83.7	2566	1970
Daman	905	Climatology	Makawanpur	27.87	85.08	2314	1972
Lete	607	Climatology	Mustang	28.07	83.6	2384	1998
Kakani	1007	Agro-meteorology	Nuwakot	28.07	85.25	2064	1972

Source: Department of Hydrology and Meteorology.

Appendix B

Table A2. Stations used to analyze the precipitation trends in CHAL.

Station Name	Station ID	Station Type	District	Latitude	Longitude	Altitude
Lower tropical bioclimatic zone (<500 m)						
Ridi bazar	701	Precipitation	Gulmi	27.95	83.43	442
Beluwa (girwari)	704	Precipitation	Nawalparasi	27.68	84.05	150
Dumkauli	706	Agrometeorology	Nawalparasi	27.68	84.22	154
Dumkibas	710	Precipitation	Nawalparasi	27.58	83.87	164
Chapkot	810	Climatology	Syangja	27.88	83.82	460
Damauli	817	Climatology	Tanahun	27.97	84.28	358
Rampur	902	Agrometeorology	Chitawan	27.62	84.42	256
Jhawani	903	Precipitation	Chitawan	27.58	84.53	270
Hetaundan.f.i.	906	Climatology	Makwanpur	27.42	85.05	474
Beluwa(manahari)	920	Precipitation	Makwanpur	27.55	84.82	274
Bharatpur	927	Climatology	Chitawan	27.67	84.43	205

Table A2. *Cont.*

Station Name	Station ID	Station Type	District	Latitude	Longitude	Altitude
Upper tropical bioclimatic zone (500–1000 m)						
Baglung	605	Climatology	Baglung	28.27	83.60	984
Beni bazar	609	Climatology	Myagdi	28.35	83.57	835
Kushma	614	Climatology	Parbat	28.22	83.70	891
Garakot	726	Precipitation	Palpa	27.87	83.80	500
Khudi bazar	802	Climatology	Lamjung	28.28	84.37	823
Pokhara airport	804	Aeronatical	Kaski	28.22	84.00	827
Syangja	805	Climatology	Syangia	28.10	83.88	868
Kunchha	807	Precipitation	Lamiung	28.13	84.35	855
Bandipur	808	Climatology	Tanahun	27.93	84.42	965
Malepatan	811	Agrometeorology	Kaski	28.12	84.12	856
Khairinitar	815	Agrometeorology	Tanahun	28.03	84.10	500
Arughatbazar	1002	Precipitation	Dhading	28.05	84.82	518
Lower subtropical bioclimatic zone (1000–1500 m)						
Tatopani	606	Precipitation	Myagdi	28.48	83.65	1243
Tansen	702	Climatology	Palpa	27.87	83.53	1067
Musikot	722	Precipitation	Gulmi	28.17	83.27	1280
Jagat (setibas)	801	Precipitation	Gorkha	28.37	84.90	1334
Gorkha	809	Agrometeorology	Gorkha	28.00	84.62	1097
Lamachaur	818	Precipitation	Kaski	28.27	83.97	1070
Pamdur	830	Precipitation	Kaski	28.27	84.78	1160
Makwanpurgadhi	919	Precipitation	Makwanpur	27.42	85.17	1030
Nuwakot	1004	Climatology	Nuwakot	27.92	85.17	1003
Dhading	1005	Precipitation	Dhading	27.87	84.93	1420
Pansayakhola	1057	Precipitation	Nuwakot	28.02	85.12	1240
Upper subtropical bioclimatic zone (1500–2000 m)						
Karki neta	613	Precipitation	Parbat	28.18	83.75	1720
Khanchikot	715	Climatology	Arghakhanchi	27.93	83.15	1760
Tamghas	725	Climatology	Gulmi	28.07	83.25	1530
Lumle	814	Agrometeorology	Kaski	28.30	83.80	1740
Ghandruk	821	Precipitation	Kaski	28.38	83.80	1960
Chisapanigadhi	904	Precipitation	Makwanpur	27.55	85.13	1706
Markhugaun	915	Precipitation	Makwanpur	27.62	85.15	1530
Timure	1001	Climatology	Rasuwa	28.28	85.38	1900
Thamachit	1054	Precipitation	Rasuwa	28.17	85.32	1847
Dhunche	1055	Climatology	Rasuwa	28.10	85.30	1982
Lower temperate bioclimatic zone (2000–2500 m)						
Lete	607	Climatology	Mustang	28.63	83.60	2384
Bobang	615	Precipitation	Baglung	28.40	83.10	2273
Daman	905	Climatology	Makwanpur	27.60	85.08	2314
Kakani	1007	Agrometeorology	Nuwakot	27.80	85.25	2064
Upper temperate bioclimatic zone (2500–3000 m)						
Jomsom	601	Climatology	Mustang	28.78	83.72	2744
Thakmarpha	604	Agrometeorology	Mustang	28.75	83.70	2566
Gurjakhani	616	Climatology	Myagdi	28.60	83.22	2530
Chame	816	Climatology	Manang	28.55	84.23	2680
Lower subalpine bioclimatic zone (3000–3500 m)						
Ghami (mustang)	610	Precipitation	Mustang	29.05	83.88	3465
Manangbhot	820	Climatology	Manang	28.67	84.02	3420
Alpine bioclimatic zone (3500–4000 m)						
Ranipauwa (m.nath)	608	Precipitation	Mustang	28.82	83.88	3609
Mustang(lomangthang	612	Climatology	Mustang	29.18	83.97	3705
Larkesamdo	806	Precipitation	Gorkha	28.67	84.62	3650

Source: Department of Hydrology and Meteorology.

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