

Spatial and Temporal Variations of Surface Air Temperature (1962–2022) across Physiographic Regions in the Koshi Basin, Nepal

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Abstract

This study analyzed

Keywords: seasonal changes.

1 Introduction

Climate change (CC) contributes to increased greenhouse gas emissions, which will cause a global temperature rise of 1.40 to 5.8°C by the year 2100 compared to 1990 levels (McCarthy et al., 2001). The ongoing warming process is expected to significantly affect atmospheric and ecological processes, with wide-reaching consequences for ecosystems and human communities. The threat posed by climate change to mankind is growing, yet many of the most vulnerable individuals are still ignorant of the full effects of global warming (Maharjan et al., 2010). Globally, there has been an increase in the frequency and intensity of severe weather and climate events associated with human-induced climate change since the 1950s. These occurrences are predicted to get worse as long as global warming continues (IPCC, 2023).

The effects of climate change can particularly threaten small, developing nations whose economies and means of subsistence mostly rely on natural resources.

One of these nations is Nepal, which is distinguished by its landlocked location, diverse physiographic features within a small region, and difficult hilly terrain (Shrestha & Aryal, 2011). Nepal, recognized as the fourth most climate-vulnerable nation, exemplifies the challenges posed by climate change (Manandhar et al., 2011; Reilly et al., 2001). Notably, the warming rate in Nepal's Himalayan regions is expected to be greater than the global average, particularly in high-altitude areas (Leduc & Bhattacharai, 2008; Shrestha et al., 1999; Yao et al., 2019).

Seasonal shifts, such as heavy rainfall during the monsoon season and accelerated glacier melt, contribute to a range of climate-induced hazards, including landslides, floods, and droughts. The effects of these changes are becoming more apparent, and they present a significant challenge to the country's infrastructure and future development (Pokhrel & Pandey, 2013). Climate-related disasters are now the primary cause of natural disaster deaths in Nepal, with their frequency increasing in recent years. Because of its sensitivity and lack of preparation, Nepal is regarded as one of the country's most susceptible to catastrophic weather occurrences (Aksha et al., 2018). Environmental changes in the Koshi Basin, one of the significant subbasins of the Ganges River, have led to multiple challenges. Rising temperatures and changing precipitation patterns have increased the frequency and intensity of floods and droughts, leading to increased vulnerability in this region (Bastakoti et al., 2017). The Koshi Basin spans a wide geographical area, ranging from elevations near 100 meters to over 8,000 meters, including the highest point on Earth, Mount Everest. This varied topography results in significant temperature differences within the basin (Bhatt et al., 2014).

Multiple studies have demonstrated that the Himalayan region is warming at a faster rate than the global average, with temperature trends showing significant variability across altitudes and seasons. While warming rates are generally consistent, they vary depending on altitude, commonly referred to as the elevation dependency of climate warming Hingane et al. (1985), Sabin et al. (2020), and Shrestha et al. (2017) Their studies revealed an increase in mean annual temperatures, with some areas experiencing a rise of 0.4 degrees Celsius over the past century. Shrestha et al. (1999) investigated maximum temperature trends in Nepal from 1971 to 1994, reporting an average annual temperature increase of 0.06 °C/year. Shrestha et al. (2017) observed a clear warming trend in maximum and minimum temperatures over the Transboundary Koshi basin from 1975 to 2010, with notable spatial variations. Stations in the hills and mountains exhibited significant warming, while in the plains, maximum temperatures showed a decreasing trend. In the Koshi Basin, the maximum temperature rose at a rate of 0.058 °C per year, while the minimum temperature increased by 0.014 °C per year over the forty years during 1963 to 2009 (Nepal, 2016). Study conducted by Nayava et al. (2017) on air temperature trends at different altitudinal zones of Nepal for 30 years (1981-2010) shows

annual mean temperatures increase at varying rates, with the Terai warming by 0.024°C/year, valley floors by 0.034°C/year, hill valleys by 0.063°C/year, mountain valleys by 0.033°C/year, hilltops by 0.072°C/year, mountain tops by 0.038°C/year, and the Trans-Himalaya by 0.029°C/year. Paudel et al. (2021) found that between 1980 and 2018, the mean annual temperature in the transboundary Koshi River Basin increased by 0.084°C/year in the mountains, 0.0975°C/year in the hills, and 0.0187°C/year in the Tarai. Study conducted by Shrestha et al. (1999) for annual temperature trends from 1977 to 1994 revealed that the Trans-Himalaya experienced the most significant warming at 0.090°C/year. The Himalaya and Middle Mountains also showed substantial warming, with trends of 0.057°C/year and 0.075°C/year, respectively. Siwalik and Terai regions had the lowest annual temperature trends, both at 0.041°C/year. The all-Nepal average annual warming rate was 0.059°C/year, showing widespread temperature increases across the country. Adhikari and Devkota (2016) studied annual temperature trends in the Khumbu region from 1988 to 2010 and observed maximum temperature increasing by 0.0639°C/year, while the minimum temperature showing a slight rise of 0.0036°C/year. Overall, the mean annual temperature in Khumbu increased by 0.0639°C/year. This finding underscores the persistent warming trend in Nepal, particularly in higher-altitude regions.

Recent studies further emphasized that the warming rates in the Himalayas are not uniform. Some regions, particularly in the western and central parts of Nepal, have experienced more rapid warming than others. The seasonal patterns also vary, with significant temperature increases noted during winter, followed by spring, autumn, and summer (Agarwal et al., 2016). In the Koshi Basin, Shrestha et al. (2017) found that hill and mountain areas experienced warming between 1975 and 2010, while the plains showed minimal warming or even declines. Bastakoti et al. (2017) observed an increasing variability in minimum temperatures and a narrowing of the range of maximum temperatures. Study conducted by Bajracharya et al. (2023) indicates an increase in projected average temperature across Koshi basin, with higher rates in northern regions. These findings highlight the critical importance of understanding the specific temperature trends in regions like the Koshi Basin to assess their impact on ecosystems and communities. Additionally, studies such as those by Poudel et al. (2020) emphasize the growing complexity of climate impacts, particularly in regions with varying elevations and climatic conditions.

Nepal's climate ranges from subtropical in the Tarai to arctic in the high Himalayas due to its unique physiographic and topographic diversity within a short north-south span. The mean maximum temperature in the Tarai exceeds 30°C, gradually decreasing with altitude to below 22°C in the high mountains. Similarly, the mean minimum temperature ranges from above 18°C in the Tarai to below 6°C

in the northwest, reflecting a distinct temperature gradient across the country's varied altitudes (Marahatta et al., 2009). Study of temperature is integral part of climate change studies, those changes can vary based on space and time (Barjacharya et al., 2023), temperature varies largely with altitude (Chand et al., 2019). Research in Nepal demonstrates the urgency of addressing climate change, as the country faces heightened vulnerability to extreme weather events and significant challenges in preparedness (Chapagain et al., 2021). This research aims to contribute to the growing body of knowledge on climate trends in the Himalayas and their implications for environmental and social resilience in vulnerable regions like the Koshi Basin.

2 Study area, Data and Methods

2.1 Study Area

Koshi Basin is situated in the eastern part of Nepal and constitutes one of the five major river basins in the country, recognized as the largest. This transboundary river, known as the Koshi River, meanders through China, Nepal, and India, with its origin in China before flowing southward into Nepal and on% in China, 45% in Nepal, and 23% in India (Bastakoti et al., 2017). The study area was delineated by creating a basin map, with Chatara assumed as the river's outlet point. The elevation ranges from 65 m MSL in the Terai to over 8848 m MSL in the High Himalaya.

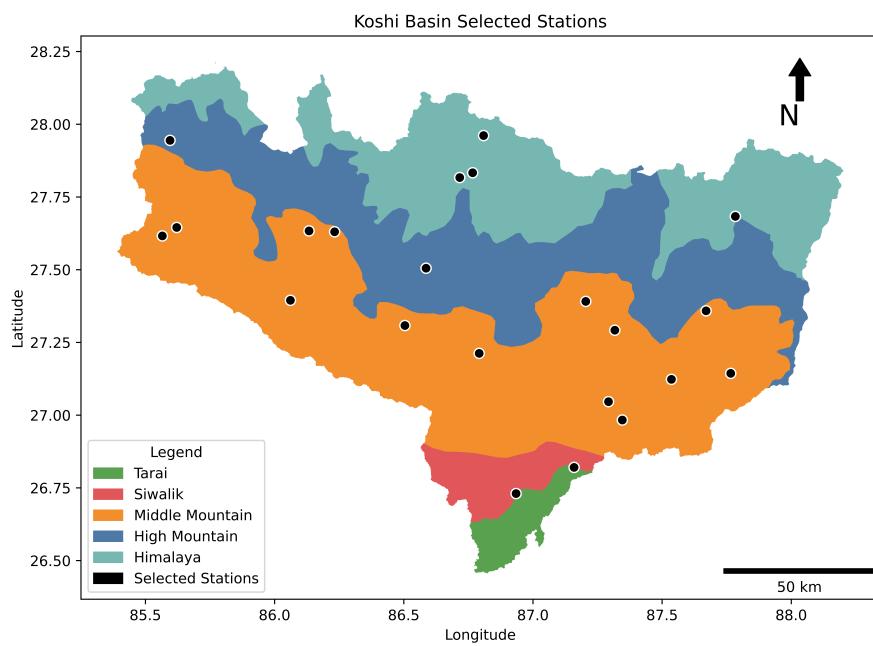


Figure 1: Selected stations for the study in the Koshi basin of Nepal

Table 1: Descriptions of the selected stations included in this study

Station No.	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)	Physiographic Regions
1316	Chatara	26.82044	87.15917	105	TAR
1201	Namche Bazar	27.81667	86.71667	3450	H
1401	Olangchuhg G	27.68333	87.78333	3119	H
1225	Syangboche	27.81667	86.71667	3700	H
1218	Tengboche	27.83333	86.76667	3857	H
1206	Okhaldhunga	27.30812	86.50423	1731	MM
1405	Taplejung	27.35861	87.67	1744	MM
1103	Jiri	27.63045	86.23211	1877	MM
1036	Panchkhal	27.64513	85.62088	857	MM
1016	Sarmathang	27.94456	85.59514	2574	HM
1123	Manthali	27.3947	86.06123	497	MM
1124	Kabre	27.63333	86.13333	1755	MM
1212	Phatepur	26.73054	86.93481	101	TAR
1219	Salleri	27.50512	86.58622	2383	HM
1222	Diktel	27.21252	86.79189	1612	MM
1304	Pakhribas	27.04632	87.29247	1720	MM
1327	Khadbari	27.39106	87.20438	1064	MM
1303	Chainpur (East)	27.2921	87.31697	1277	MM
1307	Dhankuta	26.98322	87.34596	1192	MM
1024	Dhulikhel	27.61612	85.5655	1543	MM
1419	Phidim (Panchther)	27.14367	87.7656	1157	MM
1314	Terhathum	27.12304	87.53619	1525	MM
XXXX	Lubuche	27.96111	86.80889	5200	H

a Station numbers correspond to Department of Hydrology and Meteorology station index numbers. Numbers increase from west to east, and north to south.

b TAR stands for Terai, SW stands for Siwalik, MM represents Middle Mountain, HM stands for High Mountains, and H stands for Himalaya regions

2.2 Data and Methods

Daily maximum and minimum temperature measurements from synoptic, aero-synoptic, and agrometeorological stations throughout the Koshi basin for a 30-year period (1962–2022) were provided for this research by the Department of Hydrology and Meteorology (DHM) in Nepal. Twenty-three temperature stations from 101 m asl to 5200 m asl (Table 1) were selected for this study. Python version 3.12 is used for the data analysis. Pandas, Numpy, sklearn, pymannkendall, scipy, pykrig are used for data analysis; geopandas, matplotlib, shpely are used for graphical representation. The study data exhibited no significant inhomogeneity, although some data points were missing. Missing data were calculated and filled by lapse rate formula:

$$T_{\text{cal}} = T_{\text{obs}} + (H_{\text{Elevation}} - L_{\text{Elevation}}) \cdot (-0.0065) \quad (1)$$

Where,

T_{cal} = High elevation calculating temperature

T_{obs} = Low elevation observed temperature

$H_{\text{Elevation}}$ = High elevation (calculating temperature station's elevation)

$L_{\text{Elevation}}$ = Low elevation (Observed temperature station's elevation)

Annual and seasonal averages were computed for each year across all stations. The seasonal categorization was as follows: winter (including December of the previous year, January, and February), pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October and November). Physiographically, Nepal is divided into five regions: Terai, Siwalik, Middle Mountains, High Mountains, and Himalayas (Nayava et al., 2017). In line with this classification, this study also considers five physiographic regions to analyze the spatial variations of temperatures in the Koshi Basin. Seasonal and annual temperature trends for all stations were analyzed using linear regression. The spatial distribution of these temperature trends was mapped through interpolation, utilizing Kriging based on the station trends.

Chand et al. (2019) calculated a lapse rate of $0.006 \text{ }^{\circ}\text{C m}^{-1}$ in the Narayani River Basin, while Nayava et al. (2017) found a lapse rate of $0.0058 \text{ }^{\circ}\text{C m}^{-1}$ for eastern Nepal and $0.0057 \text{ }^{\circ}\text{C m}^{-1}$ for the entire country. This research utilized a theoretical lapse rate value of $0.0065 \text{ }^{\circ}\text{C m}^{-1}$.

Spatial and temporal variations in air temperature are influenced by factors such as physiography (e.g., slope, aspect, hilltops, and valleys), land cover characteristics, and incoming solar radiation therefore Quantification of the contribution of each factor is complicated. This study has focused solely on temperature variations based on altitude, specifically within physiographic regions. Three types

of temperature data were analyzed: Tmax, the mean of daily maximum temperature; Tmin, the mean of daily minimum temperature; and Tavg, the daily average temperature. To compare the relative magnitudes of the temperature data, the Kendall (1949) and Mann (1945) test was employed to estimate monotonic trends—whether positive or negative—and their statistical significance. This analysis was conducted using (equation 1) and (equation 2), with the variance determined through (equation 3):

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

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases} \quad (2)$$

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (3)$$

Where n is the number of data points, m is the number of tied groups, and t_i is the number of observations in the i^{th} tied group.

The collected data were thoroughly checked and screened for quality and consistency. To analyze the temporal and spatial variations of temperature, linear regression was employed. A time series analysis was conducted. This technique allowed the fitting of a linear trend between the time series data (y) and time (t), as described by the equation 4:

$$y = a + bt \quad (4)$$

Where:

- y : represents the temperature or rainfall,
- t : represents time (in years),
- a and b are constants estimated using the least squares method, which minimizes the sum of the squared differences between the observed and predicted values.

This method provides an accurate and reliable estimation of the overall trend of temperature data across the study period.

3 Results and Discussion

3.1 Seasonal Temperature Trends

Figures?? display temperature trend analyses based on three primary factors: temperature categories (Tavg, Tmax, Tmin), geographic regions (Himalayas, High Mountain, Middle Mountain, Siwalik, Tarai, and the entire Koshi Basin), and seasonal classifications (Monsoon, Post-monsoon, Pre-monsoon, Winter, and annual trends) across various decades. The trends reveal substantial variability influenced by decade, temperature type, physiographic region, and seasonal attributes.

Pre-monsoon

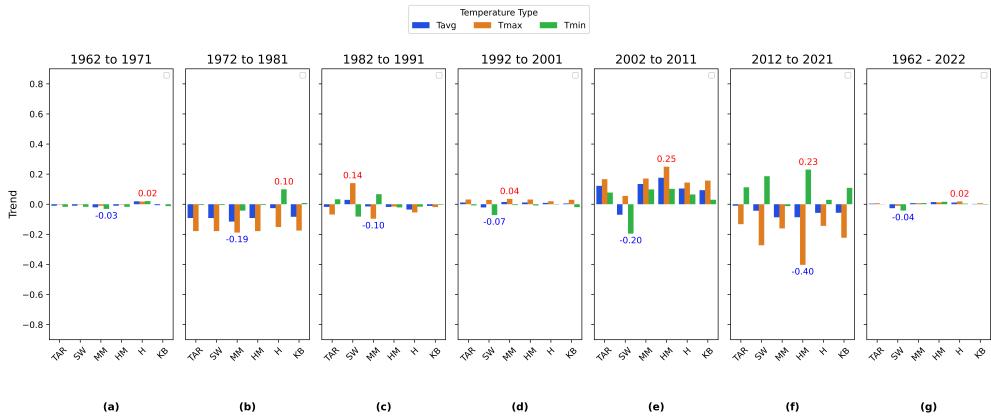


Figure 2: Pre-monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

Pre-monsoon season reveals overall cooling trends in the 1962–1971 decade except in Himalaya regions, similar cooling trend from 1972 to 1981, and later decade experience a warming trend except maximum and average temperature shows cooling trend in 2012–2021 (Figure 2). For the overall period from 1962 to 2022, only the Siwalik region demonstrates a cooling trend; all other regions display warming trends, particularly the Himalayan region, which shows a higher rate of warming at $0.02^{\circ}\text{C}/\text{year}$.

Monsoon

During the Monsoon season (Figure 3), temperature fluctuations have accelerated in recent decades, particularly from 2012 to 2021, with significant warming

observed in average and minimum temperatures, while maximum temperatures predominantly show a cooling trend. Overall, from 1962 to 2022, the Monsoon season reflects a cooling trend across the various regions.

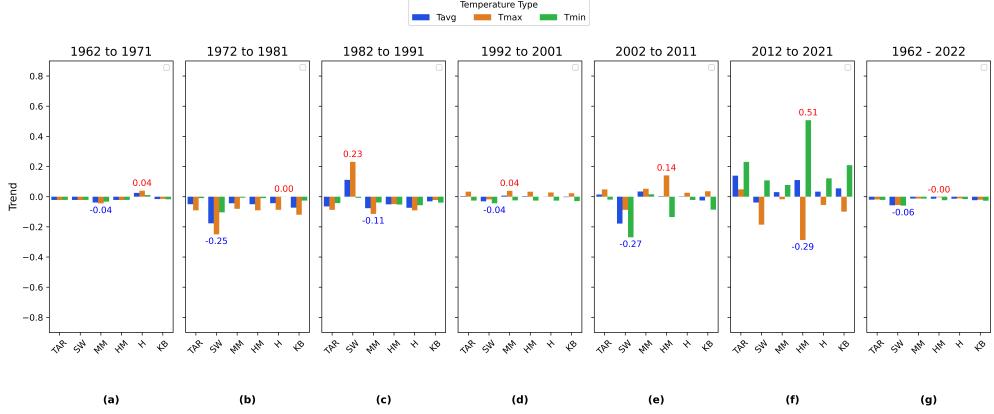


Figure 3: Monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

Post-monsoon

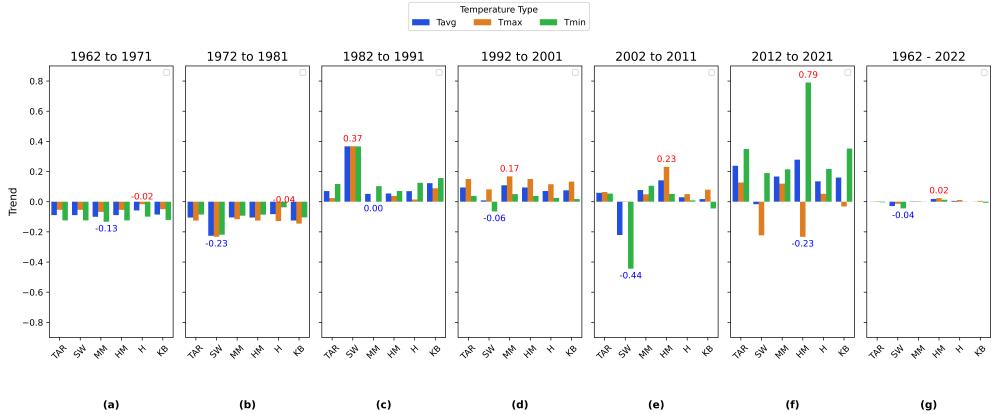


Figure 4: Post-monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

A cooling trend is evident in the post-monsoon period from 1962 to 1981 (Figure 4), followed by a notable warming trend that has intensified in recent decades.

Winter

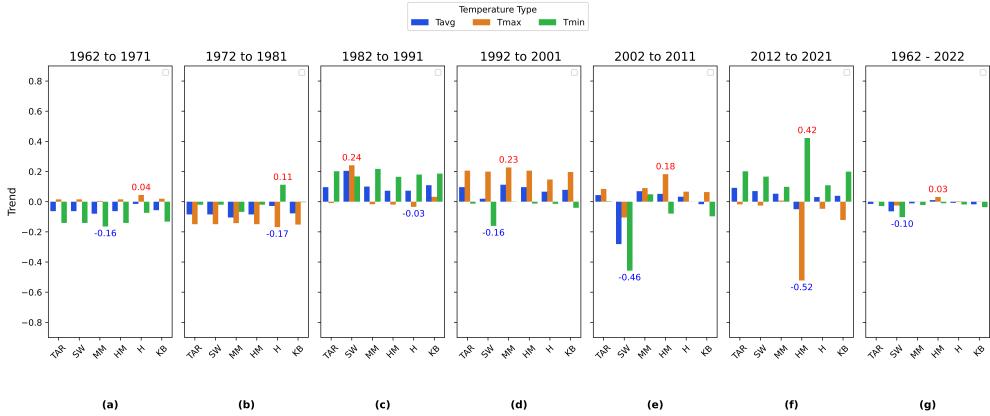


Figure 5: Winter temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

Distinct temperature trends are observed during the Winter season (Figure 5) across different regions and time periods. Minimum and average temperatures showed warming between 1982–1991 and 2012–2021, while a cooling trend occurred from 1962–1971. Maximum temperatures increased during the 1992–2001 and 2002–2011 decades, with a notable cooling of 0.52°C in the High Mountain region from 2012 to 2021. Overall, from 1962 to 2022, the Siwalik region experienced a general cooling trend, while only the High Mountain region exhibited a warming trend.

Annual

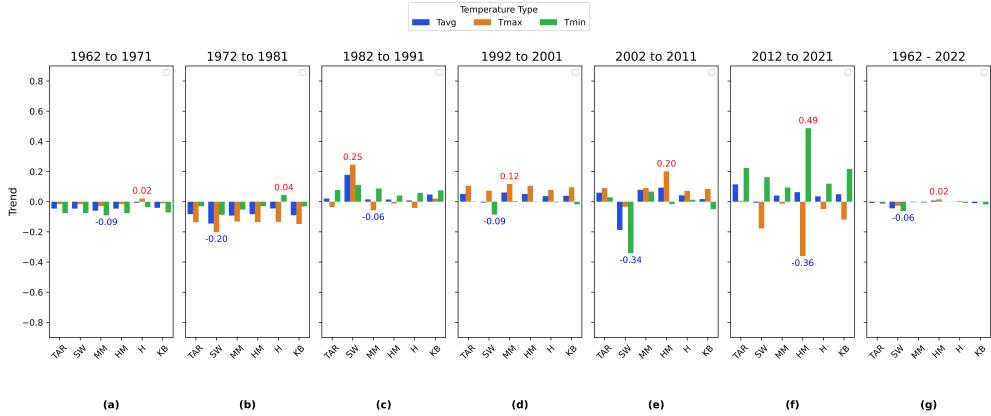


Figure 6: Annual temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

Figure 6 illustrates the annual temperature trends across different regions of the Koshi Basin revealing significant variations over the decades. The first two decades (1962-1981) exhibit an overall cooling trend, with the exception of warming observed in the Himalayan regions, where maximum temperatures increased by 0.02 °C and minimum temperatures rose by 0.04 °C in later decades. The period from 1982 to 2021 predominantly shows a warming trend; however, from 2002 to 2011, the Siwalik region experienced a cooling trend, and in 2012 to 2021, maximum temperatures again exhibited a cooling trend. In overall annual temperature trends in Koshi Basin showed decreasing trend followed by increasing trend similar to study conducted by Chand et al. (2019) at Narayani Basin Nepal.

Temporal and spatial analysis of five physiographic regions- Tarai, Siwalik, Middle-mountain, and High-mountain and Himalayas of Koshi Basin presented via Table 2.

In the five physiographic regions of Koshi Basin, temperature trends display distinct seasonal variations across physiographic regions (Table 2).

In the Himalaya region, a significant warming trend is observed during the pre-monsoon season in Tmax (0.0186 , $p=0.0115$), while other trends remain largely non-significant, including slight cooling in the monsoon (Tmax: -0.0111 , $p=0.1672$; Tmin: -0.0160 , $p=0.2340$) and winter seasons (Tmin: -0.0177 , $p=0.0972$). The High Mountain region exhibits significant temperature changes across multiple seasons. In the post-monsoon, Tmax and Tavg show strong warming trends (Tmax: 0.0233 , $p=0.0035$; Tavg: 0.0200 , $p=0.0035$), while the monsoon season shows a

Table 2: Spatial distribution of temporal trends of temperature for 1962-2022

Region	Tmax Trend	Tmax p-value	Tmin Trend	Tmin p-value	Tavg Trend	T
Himalaya						
Monsoon	-0.0111	0.1672	-0.0160	0.2340	-0.0135	
Postmonsoon	0.0114	0.1412	-0.0011	0.9435	0.0051	
Premonsoon	0.0186*	0.0115	0.0040	0.7977	0.0113	
Winter	0.0031	0.7077	-0.0177	0.0972	-0.0073	
High Mountain						
Monsoon	-0.0038	0.5811	-0.023*	0.0019	-0.01*	
Postmonsoon	0.0233*	0.0035	0.0128	0.1022	0.02*	
Premonsoon	0.0125	0.0845	0.0164*	0.0103	0.01*	
Winter	0.0317*	0.0058	-0.0088	0.2583	0.0114	
Middle Mountain						
Monsoon	-0.0122*	0.0338	-0.013*	0.0076	-0.01*	
Postmonsoon	0.0032	0.5873	0.0011	0.8304	0.0021	
Premonsoon	0.0071	0.2333	0.0074	0.1586	0.0072	
Winter	-0.0004	0.9422	-0.021*	0.0002	-0.01*	
Siwalik						
Monsoon	-0.0552*	0.0000	-0.06*	0.0000	-0.06*	
Postmonsoon	-0.0135	0.0945	-0.04*	0.0000	-0.03*	
Premonsoon	-0.0106	0.1916	-0.04*	0.0005	-0.03*	
Winter	-0.0260*	0.0030	-0.10*	0.0000	-0.06*	
Tarai						
Monsoon	-0.0183*	0.0005	-0.0215	0.0000	-0.0199	
Postmonsoon	0.0027	0.5809	-0.0045	0.4620	-0.0009	
Premonsoon	0.0067	0.2577	0.0011	0.8275	0.0039	
Winter	-0.0006	0.9121	-0.0280	0.0000	-0.0143	

* Indicates $p \leq 0.05$ which denotes significant changes

significant cooling trend in T_{min} (-0.0230, $p=0.0019$). The pre-monsoon season also reflects a notable warming in T_{min} (0.0164, $p=0.0103$) and T_{avg} (0.0100, $p=0.0084$), with additional warming in T_{max} during winter (0.0317, $p=0.0058$). In the Middle Mountain region, a significant cooling trend is observed in the monsoon for both T_{max} (-0.0122, $p=0.0338$) and T_{min} (-0.0130, $p=0.0076$). The winter season also displays significant cooling in T_{min} (-0.0210, $p=0.0002$) and T_{avg} (-0.0100, $p=0.0466$), while other seasons show minimal changes. The Siwalik region experiences substantial cooling across all seasons, particularly in the monsoon, where strong cooling trends are present in T_{max} (-0.0552, $p=0.0000$), T_{min} (-0.0600, $p=0.0000$), and T_{avg} (-0.0600, $p=0.0000$). Similarly, significant cooling trends persist in the winter season (T_{max} : -0.0260, $p=0.0030$; T_{min} : -0.1000, $p=0.0000$; T_{avg} : -0.0600, $p=0.0000$). In the Tarai region, notable cooling is observed during the monsoon in T_{max} (-0.0183, $p=0.0005$), T_{min} (-0.0215, $p=0.0000$), and T_{avg} (-0.0199, $p=0.0000$). Additionally, the winter season shows a marked cooling trend in T_{min} (-0.0280, $p=0.0000$) and T_{avg} (-0.0143, $p=0.0104$), while other seasons display minimal trends. Seasonal analysis reveals more diverse trends across regions. In the Hills and Middle Mountains, mixed patterns are evident, with significant declines in T_{min} during the monsoon and winter seasons. In contrast, the High Mountains display minimal seasonal variation, aside from a notable increase in T_{max} primarily during the pre-monsoon season. Significant seasonal cooling tendencies are visible in the Siwalik and Tarai areas, especially during the Monsoon and Winter, indicating different regional temperature behaviors.

Shrestha et al. (2017) analyzed long-term trends in seasonal maximum and minimum temperatures from 1975 to 2010, finding widespread significant warming, particularly in minimum temperature indices, with stronger warming trends in recent decades; however, some stations showed declines in winter and pre-monsoon temperatures, and seasonal minimum temperatures generally increased more than maximum temperatures.

The study conducted by Shrestha and Aryal (2011) identified consistent warming trends in seasonal mean maximum temperatures across all regions of Nepal from 1977 to 1994. Their study observed warming during the winter, post-monsoon, pre-monsoon, and monsoon seasons. Study by Nayava et al. (2017) for 1981–2010 showed varying seasonal temperature trends across Nepal. There is warming in the Terai, Valley, Hill and Mountain regions across all seasons from 0.01–0.13°C/year, with the Trans-Himalaya showing 0.03°C in pre-monsoon, -0.02°C in post-monsoon, 0.01°C in monsoon, and 0.08°C in winter. Similarly, Shrestha et al. (1999) showed significant regional and seasonal variations for 1977 to 1994 in temperature trends across Nepal, with the Trans-Himalaya experiencing the highest winter warming at 0.124°C/year, the Middle Mountains seeing the largest

monsoon increase at $0.094^{\circ}\text{C}/\text{year}$, and the post-monsoon season showing an overall national average warming rate of $0.059^{\circ}\text{C}/\text{year}$, while the Terai region exhibited a much lower warming rate of $0.006^{\circ}\text{C}/\text{year}$ in winter and $-0.004^{\circ}\text{C}/\text{year}$ in pre-monsoon.

3.2 Regional Temperature Trends

Table 3: Regional temperature regression equations

Region	Tmin Equation	Tmax Equation	Tavg Equation
Himalaya	$y = -0.01x + 15.46$	$y = 0.00x + 2.58$	$y = -0.00x + 9.02$
High Mountain	$y = -0.00x + 13.97$	$y = 0.01x - 9.35$	$y = 0.00x + 2.31$
Middle Mountain	$y = -0.01x + 27.88$	$y = -0.00x + 27.81$	$y = -0.00x + 27.85$
Siwalik	$y = -0.06x + 145.24$	$y = -0.03x + 91.55$	$y = -0.05x + 118.40$
Tarai	$y = -0.01x + 50.79$	$y = -0.00x + 41.15$	$y = -0.01x + 45.97$

Table 4: Nonparametric (Mann-Kendall Test) tests for annual regional trends for the period 1962–2022

Regions	Tmin Slope	Tmax Slope	Tavg Slope
Himalaya	-0.009	0.005**	-0.000**
High Mountains	-0.016	0.008**	0.002**
Middle Mountains	-0.008	-0.001**	-0.003**
Siwalik	-0.063	-0.033	-0.05
Tarai	-0.015	-0.003**	-0.006**

** indicates $p \geq 0.05$ which denotes no significant changes.

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The Annual Regional Mann-Kendall test findings are shown in the table 4. This test evaluates trends in minimum (Tmin), maximum (Tmax), and average (Tavg) temperatures in five regions: Tarai, Siwalik, Middle Mountains, High Mountains, and Himalaya. While Tmax and Tavg show rising tendencies (0.005^{**} and -0.000^{**} , respectively) in the Himalaya, the Tmin shows a decreasing trend (-0.009), and the latter two are not statistically significant ($p \geq 0.05$). Tmin and Tavg (-0.008 and -0.003^{**}) also exhibit declining patterns in the Middle-mountain, although Tmax (-0.001^{**}) shows a rather constant trend. The High Mountains, on

the other hand, show an increasing trend in Tmin (-0.016) and a more marked reduction in Tmax and Tavg (0.008** and 0.002**). All temperature measurements exhibit similar declines in the Siwalik region: Tmin (-0.063), Tmax (-0.033), and Tavg (-0.05). Lastly, with Tmin (-0.015), Tmax (-0.003**), and Tavg (-0.006**) showing diminishing trends across all temperature parameters; the Tarai likewise shows declining trends, but Tmax and Tavg are not statistically significant. In similar vein, the Koshi region's maximum temperature grew at a rate of 0.058 °C/year and its lowest temperature increased at a rate of 0.014 °C/year during the forty years leading up 1963 to 2009 (Nepal, 2016).

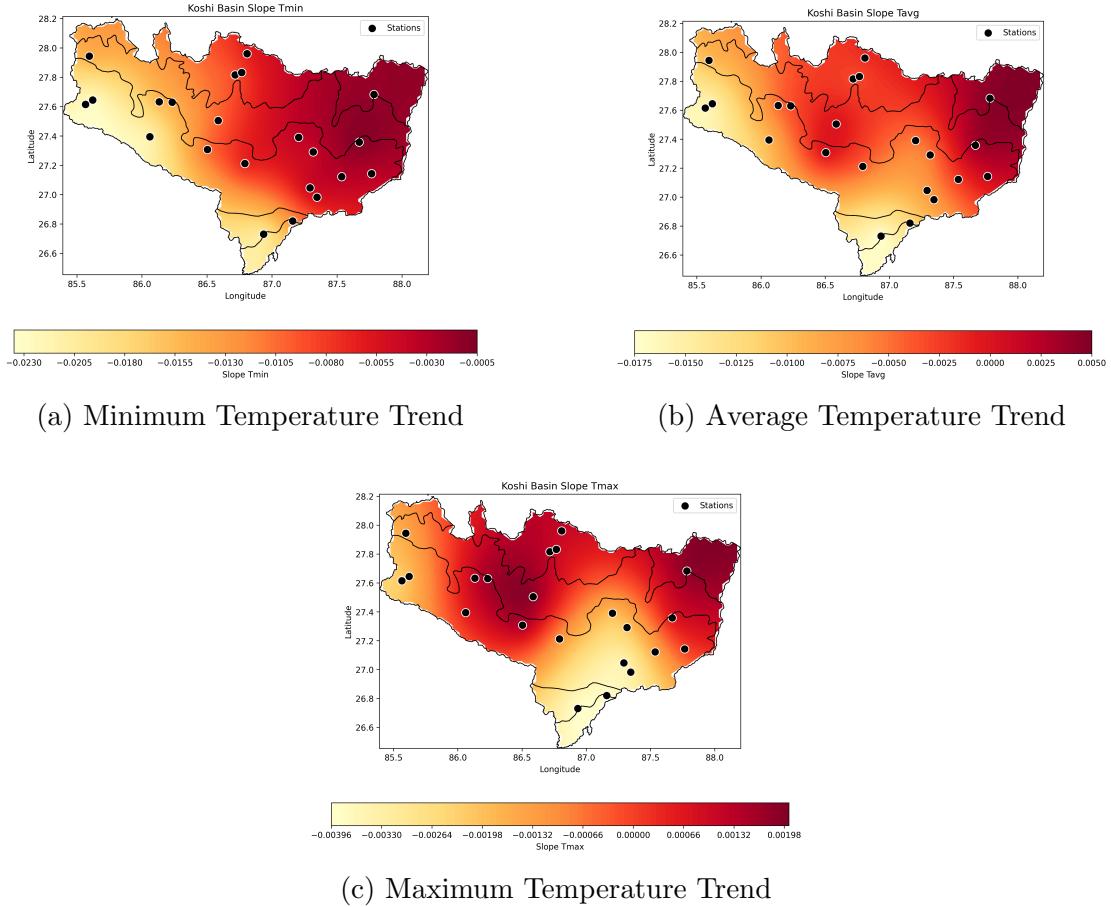


Figure 7: Spatial distributions of annual temperature trends for the period 1962–2022 for (a) Tmin, (b) Tavg, (c) Tmax

The results obtained from the analysis reveal a heterogeneous temperature trend across the Koshi basin region, as illustrated in Figure 7. An annual average of daily minimum temperatures shows an overall cooling trend, as shown in Figure 7a, ranging from -0.0005°C to -0.023°C, with higher elevations experiencing

less cooling. As shown in Figure 7b, the annual average temperatures reveal both warming and cooling trends, ranging from -0.0175°C to 0.005°C , where higher elevations tend to warm or cool less, when compared to the Tarai and Siwalik regions. Similarly, the annual average of daily maximum temperatures shows trends from cooling to slight warming (Figure 7c), ranging from -0.00396°C to 0.00198°C , with Tmax exhibiting a warming trend in higher elevation areas. Study conducted by Paudel et al. (2021) in transboundary Koshi basin for the years between 1980 and 2018, revealed an increase in the mean annual temperature by $0.084^{\circ}\text{C}/\text{year}$ in the mountain region ($p = 0.0005$), by $0.0975^{\circ}\text{C}/\text{year}$ in the hill region ($p = 0.0002$), and by $0.0187^{\circ}\text{C}/\text{year}$ in the Tarai region ($p = 0.0206$), with significant correlations throughout.

Adhikari and Devkota (2016) studied temperature trends from 1988 to 2010 in the Annapurna, Langtang, and Khumbu regions of Nepal. In the Khumbu region, moderate warming was observed across all seasons, with maximum temperatures rising by $0.0857^{\circ}\text{C}/\text{year}$ in winter and $0.0628^{\circ}\text{C}/\text{year}$ in pre-monsoon. The trend in the change of minimum temperatures was slightly different with a small increase of $0.0101^{\circ}\text{C}/\text{year}$ in spring and a decrease of $-0.0024^{\circ}\text{C}/\text{year}$ during monsoon. Overall, mean temperatures increased by $0.0857^{\circ}\text{C}/\text{year}$ in winter, with Khumbu showing lower trends compared to Langtang and Annapurna, particularly in minimum temperatures.

4 Summary

- Temperature trends across the Koshi Basin show regional variations. The Himalaya region shows warming in pre-monsoon, while the High Mountain region exhibits significant seasonal temperature changes. The Middle Mountain region shows cooling in monsoon and winter. The Siwalik and Tarai regions experience consistent cooling across seasons, particularly in Tmin and Tavg.
- Seasonal temperatures show heterogeneous trends across decades, temperature categories, and physiographic regions. In overall observed seasonal and annual temperatures trends decreases in starting decades and increase in later decades.
- The Mann-Kendall Test for annual regional trends from 1962 to 2022 revealed varied temperature patterns across the Koshi Basin. In the Himalaya region, Tmax and Tavg slightly increases, while Tmin decreased, though the changes in Tmax and Tavg were not statistically significant. The Middle Mountains exhibited a cooling trend in Tmin and Tavg, with Tmax remaining constant. In the High Mountains, Tmin increased significantly, while

Tmax and Tavg experienced notable decrease. The Siwalik region showed consistent declines in all temperature parameters, and the Tarai region also displayed decreasing trends in Tmin, Tmax, and Tavg, though Tmax and Tavg were not statistically significant.

- Temperatures trends in Koshi Basin exhibits heterogeneous patterns across regions, seasons and time periods.

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