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 the seasonal and annual trends of maximum temperature (Tmax), minimum temperature (Tmin), and mean temperature (Tavg) across the physiographic regions of the Koshi Basin (Himalaya, High Mountain, Middle Mountain, Siwalik, and Tarai) using observed data from 23 stations between 1962 and 2022. Missing temperature data were filled using the lapse rate method. The Mann-Kendall (M-K) test was employed to assess the consistency of the temperature dataset. The analysis revealed distinct regional and seasonal temperature trends in the Koshi Basin. In the Middle Mountain and High Mountain regions, Tmax increased significantly during the Pre-monsoon season, while Tmin decreased significantly during Monsoon and Winter. Conversely, the Siwalik and Tarai regions experienced more pronounced cooling trends, especially during Monsoon and Winter. Overall, the Himalaya and High Mountain regions exhibited a cooling trend until the late 1990s, followed by a warming trend. The Middle Mountain region demonstrated similar patterns, with a significant temperature increase after the 1990s. The Siwalik and Tarai regions experienced a general cooling trend, although the Siwalik region exhibited some fluctuations. The key findings are the significant regional variations in temperature trends were observed. The Tmax was increased in the Pre-monsoon season, while Tmin decreased in Monsoon and Winter in the Middle Mountain and High Mountain regions. The Siwalik and Tarai regions experienced cooling trends, particularly in Monsoon and Winter. Similarly, the Himalaya and High Mountains showed a cooling-warming shift in the late 1990s. The seasonal variations were prominent, especially in Monsoon and Winter. All these findings are underscoring the importance of considering both regional and seasonal factors when studying temperature trends in the Koshi Basin.

Keywords: Koshi Basin, temperature trends, spatial variation, physiographic regions, 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) (IPCC, 2021). 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 and 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 and Bhattarai, 2008; Yao et al., 2019; Shrestha et al., 1999).

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 and 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.Hingane et al. (1985); Shrestha et al. (2017); Sabin et al. (2020), Shrestha et al., (2017), Sabin et al. (2020) highlighted that while warming rates are generally consistent, they vary depending on altitude, commonly referred to as the elevation dependency of climate warming. 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. This finding underscores the persistent warming trend in Nepal, particularly in higher-altitude regions.

Recent studies further emphasize 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. 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 byPoudel 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 (Bajracharya 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 Materials and Methodology

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. 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.

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

For this research, the Department of Hydrology and Meteorology (DHM) in Nepal provided daily maximum and minimum temperature readings from synoptic, aero-synoptic, and agrometeorological stations across Koshi basin for a 30-year period (1962–2022). 23 temperature station 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 is used for data analysis, geopandas, matplotlib, shpely is used for representation. Study data did not show such inhomogeneity and had missing data. Missing data were filled by (equation 1) lapse rate formula:

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

Where,

$$\begin{aligned}
T_{\text{cal}} &= \text{High elevation calculating temperature} \\
T_{\text{obs}} &= \text{Low elevation observed temperature} \\
H_{\text{Elevation}} &= \text{High elevation (calculating temperature station's elevation)} \\
L_{\text{Elevation}} &= \text{Low elevation (Observed temperature station's elevation)}
\end{aligned}$$

Annual and seasonal averages were computed for each year across all stations. The four seasons were categorized 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 regions to analyze the spatial variation 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.

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

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 are provided according to the Department of Hydrology and Meteorology station index, with numbers increasing from west to east, and from north to south.
b Physiographic regions are denoted as follows: TAR for Terai, SW for Siwalik, MM for Middle Mountain, HM for High Mountains, and H for Himalaya.

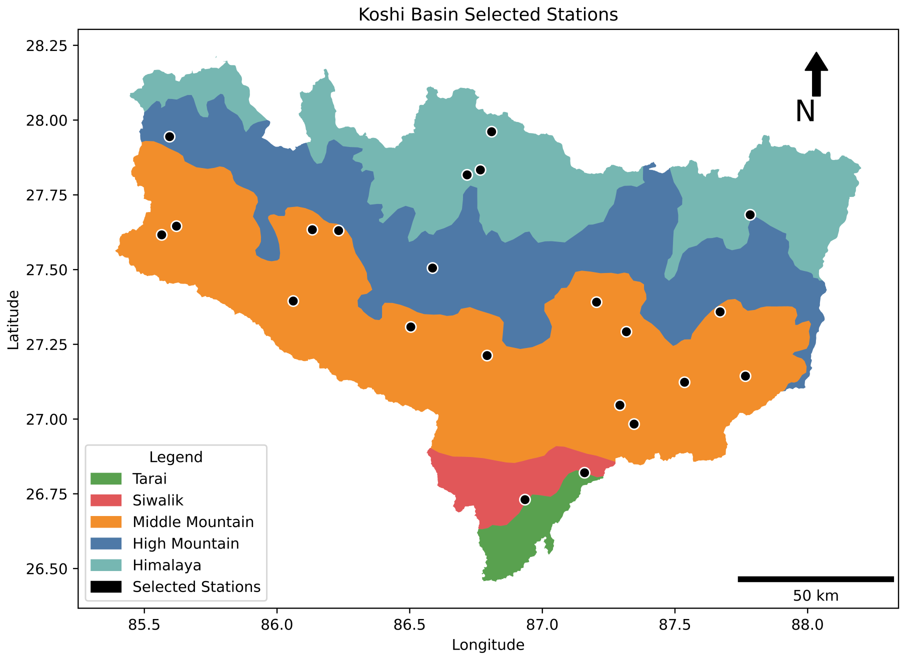

Figure 1: Study area, represents Koshi basin in Nepal, with selected stations.

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 Mann (1945); Kendall (1949) 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):

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

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

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

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:

$$y = a + bt \tag{4}$$

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 in rainfall and temperature data across the study period.

3 Results and Discussion

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

Table2 presents the regional and seasonal distribution of temperature trends across the Koshi Basin. In the Himalaya region, the Pre-monsoon season shows a statistically significant warming trend in Tmax (0.0186, p=0.0115), indicating potential shifts in climatic patterns that may affect the region's ecosystem. Conversely, the Monsoon season reflects slight cooling trends in Tmax (-0.0111, p=0.1672) and Tmin (-0.0160, p=0.2340). The High Mountain region exhibits diverse temperature trends, with the post-monsoon season showing a significant warming trend for Tmax (0.0233, p=0.0035) and Tavg (0.0181, p=0.0035). The Pre-monsoon season also indicates a notable warming trend in Tmax (0.0125, p=0.0845), while Tmin trends remain relatively stable. The Middle Mountain region presents a more mixed scenario. The Monsoon season reveals a significant cooling trend in Tmax (-0.0122, p=0.0338) and Tmin (-0.0128, p=0.0076). The other seasons show minimal or non-significant trends, indicating that temperature variability is more pronounced during the Monsoon. In the Siwalik region, stark cooling trends are evident across all seasons, particularly during the Monsoon (-0.0552, p=0.0000) and Winter (-0.0260, p=0.0030) seasons. The extreme cooling in Tmax (-0.0572, p=0.0000) and Tmin (-0.0592, p=0.0000). the Tarai region demonstrates notable cooling trends during the Monsoon (-0.0183, p=0.0005) and Winter (-0.0280, p=0.0000) seasons. The Tmin trends in the Monsoon are also significant (-0.0215, p=0.0000). These findings point to unique seasonal and regional differences in Nepal's temperature changes.

The study conducted by Shrestha and Aryal (2011) discovered regular warming trends in seasonal mean maximum temperatures in all of Nepal's regions during 1977 to 1994, with warming seen throughout the winter, pos-monsoon, pre-monsoon, and monsoon seasons. On the other hand, the present study's seasonal analysis reveals more diversified tendencies: the Hills and Middle Mountains show mixed trends, with major drops in Tmin during Monsoon and Winter, while the High Mountains show minimal changes with a significant Tmax rise mainly during Pre-monsoon. Significant seasonal cooling tendencies are visible in the Siwalik and Tarai areas, especially during the Monsoon and Winter, indicating different regional temperature behaviors from previous research.

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	Tavg p-value
Himalaya						
Monsoon	-0.0111	0.1672	-0.0160	0.2340	-0.0135	0.1964
Postmonsoon	0.0114	0.1412	-0.0011	0.9435	0.0051	0.6504
Premonsoon	**0.0186***	0.0115	0.0040	0.7977	0.0113	0.3058
Winter	0.0031	0.7077	-0.0177	0.0972	-0.0073	0.4334
High Mountain						
Monsoon	-0.0038	0.5811	**-0.023***	0.0019	**-0.01***	0.0062
Postmonsoon	**0.0233***	0.0035	0.0128	0.1022	**0.02***	0.0035
Premonsoon	0.0125	0.0845	**0.0164***	0.0103	**0.01***	0.0084
Winter	**0.0317***	0.0058	-0.0088	0.2583	0.0114	0.1407
Middle Mountain						
Monsoon	**-0.0122***	0.0338	**-0.013***	0.0076	**-0.01***	0.0157
Postmonsoon	0.0032	0.5873	0.0011	0.8304	0.0021	0.6808
Premonsoon	0.0071	0.2333	0.0074	0.1586	0.0072	0.1738
Winter	-0.0004	0.9422	**-0.021***	0.0002	**-0.01***	0.0466
Siwalik						
Monsoon	**-0.0552***	0.0000	**-0.06***	0.0000	**-0.06***	0.0000
Postmonsoon	-0.0135	0.0945	**-0.04***	0.0000	**-0.03***	0.0003
Premonsoon	-0.0106	0.1916	**-0.04***	0.0005	**-0.03***	0.0017
Winter	**-0.0260***	0.0030	**-0.10***	0.0000	**-0.06***	0.0000
Tarai						
Monsoon	**-0.0183***	0.0005	-0.0215	0.0000	-0.0199	0.0000
Postmonsoon	0.0027	0.5809	-0.0045	0.4620	-0.0009	0.8552
Premonsoon	0.0067	0.2577	0.0011	0.8275	0.0039	0.4280
Winter	-0.0006	0.9121	-0.0280	0.0000	-0.0143	0.0104

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

Shrestha et al. (2017) observed long-term trends (1975–2010) in seasonal maximum and minimum temperatures showed an overall increase at most stations, though some decreases were observed in winter and pre-monsoon. Seasonal minimum temperatures increased more than maximum temperatures. The findings indicated widespread significant warming, particularly in indices based on daily minimum temperatures, with stronger warming trends in more recent decades. Study by Nayava et al. (2017) for 1981–2010 shows varying seasonal temperature trends across Nepal. In the Terai, Valley, Hill, Mountain regions warming is presence across all season from 0.01-0.13°C/year, whereas the Trans-Himalaya shows 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) for 1977 to 1994, temperature trends across Nepal showed significant regional and seasonal variation, 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°C/year, and the post-monsoon season showing an overall national average warming rate of 0.059°C/year, while the Terai region exhibited a much lower warming rate of 0.006°C/year in winter and -0.004°C/year in pre-monsoon.

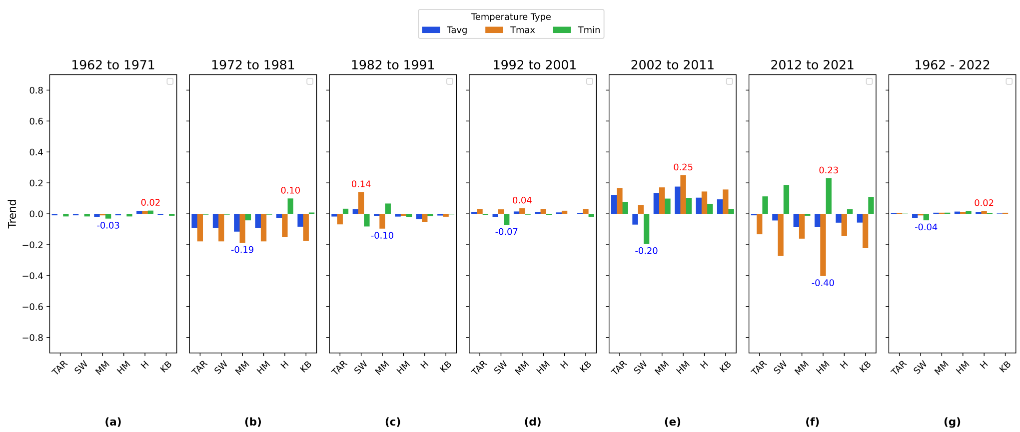

Figure 2: Pre-monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

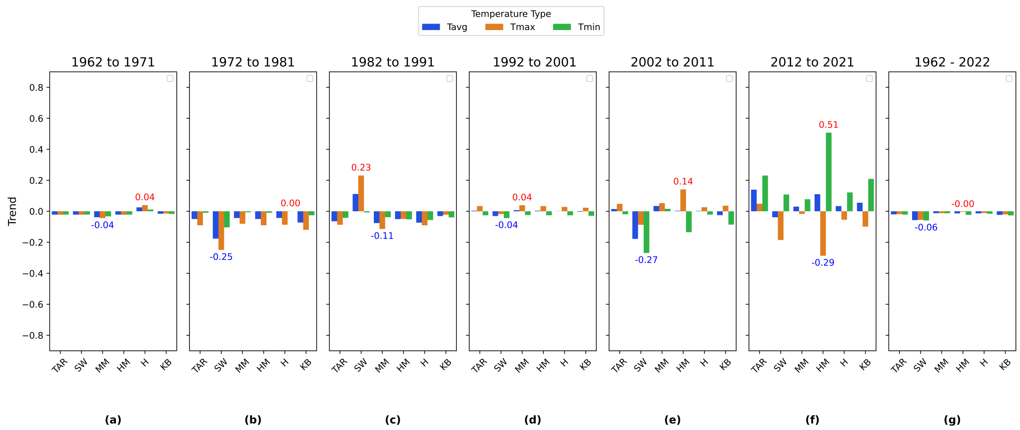

Figure 3: Monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

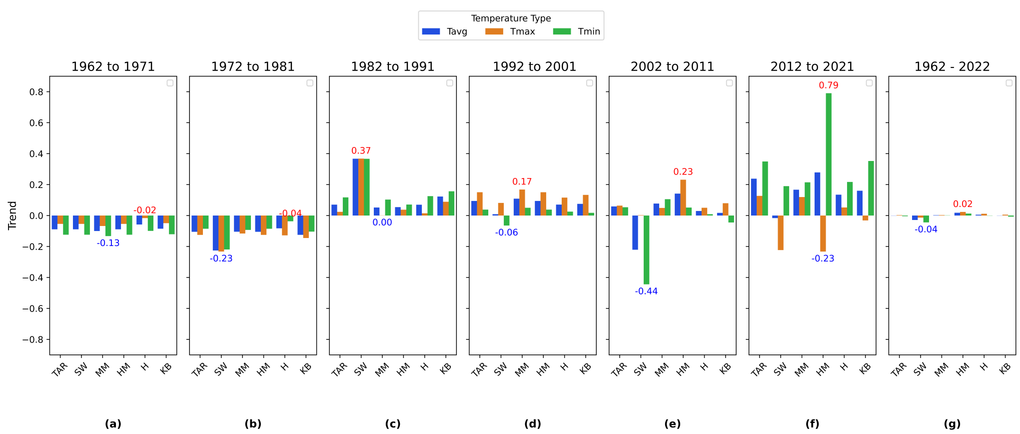

Figure 4: Post-monsoon temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

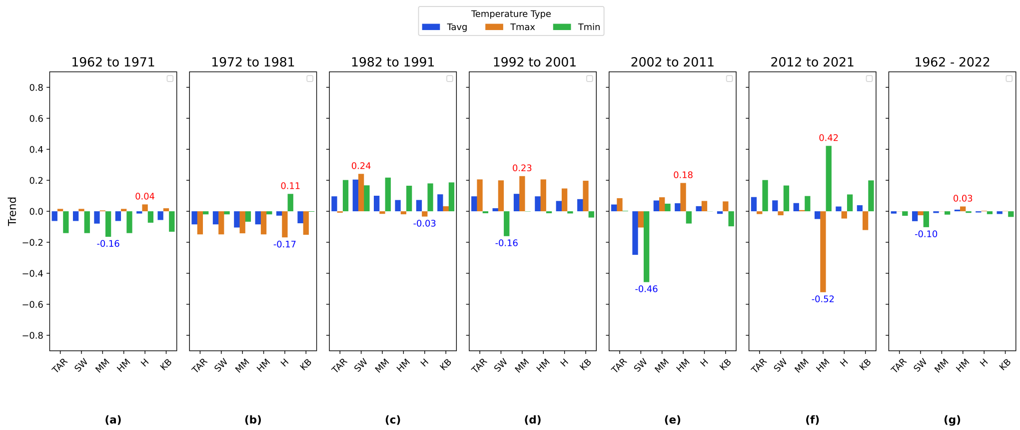

Figure 5: Winter temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

Figures**??** present an analysis of temperature trends based on three key factors: temperature type (Tavg, Tmax, Tmin), geographic regions (Himalayas, High Mountain, Middle Mountain, Siwalik, Tarai, and Koshi Basin), and seasonal classifications (Monsoon, Post-monsoon, Pre-monsoon, Winter, and annual trends) across different decades. The temperature trends exhibit considerable variability influenced by the decade, temperature type, physiographic regions, and seasonal characteristics.

Figure2, the 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. 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°C/year.

Figure3 illustrates that during the Monsoon season, 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.

Figure4 highlights a cooling trend in the Post-monsoon period from 1962 to 1981, followed by a notable warming trend that has intensified in recent decades.

Figure5 indicates distinct temperature trends during the Winter season across different regions and time periods. Minimum and average temperatures experienced warming between 1982-1991 and 2012-2021, while a cooling trend was observed from 1962 to 1971. Maximum temperatures warmed during the 1992-2001 and 2002-2011 decades, with a notable cooling trend of 0.52 degrees Celsius in the High Mountain region from 2012 to 2021. Overall, from 1962 to 2022, the Siwalik region shows a general cooling trend, whereas only the High Mountain region exhibits a warming trend.

Adhikari and Devkota (2016)Adhikari and Devkota (2016) studied temperature trends from 1988 to 2010 in the Annapurna, Langtang, and Khumbu basins. In the Khumbu region, moderate warming was observed across all seasons, with maximum temperatures rising by 0.0857°C/year in winter and 0.0628°C/year in pre-monsoon. Minimum temperatures showed slight changes, with a small increase of 0.0101°C/year in spring and a decrease of -0.0024°C/year during monsoon. Overall, mean temperatures increased by 0.0857°C/year in winter, with Khumbu showing lower trends compared to Langtang and Annapurna, particularly in minimum temperatures.

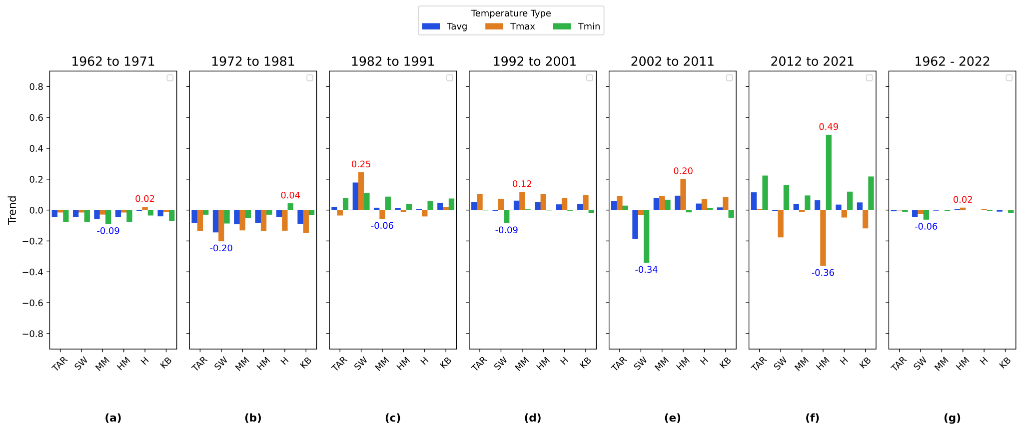

Figure 6: Annual temperature trends across the time intervals (a) 1962–1971, (b) 1972–1981, (c) 1982–1991, (d) 1992–2001, (e) 2002–2011, (f) 2012–2021, and (g) 1962–2022.

Figure6 illustrates the annual temperature trends across different regions of the Koshi Basin reveal 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. Study conducted by Bajracharya et al., (2023) indicates an increase in projected average temperature across Koshi basin, with higher rates in northern regions. Shrestha et al. (2017) 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 variation. Stations in the hills and mountains exhibited significant warming, while in the plains, maximum temperatures showed a decreasing trend. In the Koshi region, 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 leading up 1963 to 2009 (Nepal, 2016) (Nepal, 2016). Similar studies done by Chand et al. (2019) Chand et al., (2019) at Narayani Basin showed that, The annual average temperature is in a decreasing trend till 1972 and increasing order for later years. Study done by Nayava et al. (2017) Nayava et al., (2017) shows air temperature trends at different altitudinal zones of Nepal based on 30 years (1981–2010) annual mean temperatures increased at varying rates, with the Terai warming by 0.024°C/year, valley floors at 0.034°C/year, hill valleys at 0.063°C/year, mountain valleys at 0.033°C/year, hilltops at 0.072°C/year, mountain tops at 0.038°C/year, and the Trans-Himalaya at 0.029°C/year. Paudel et al. (2021)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 done by

Shrestha et al. (1999) 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) Adhikari and Devkota, (2016) observed annual temperature trends in the Khumbu region from 1988 to 2010. The maximum temperature increased by 0.0639°C/year, while the minimum temperature showed a slight rise of 0.0036°C/year. Overall, the mean annual temperature in Khumbu increased by 0.0639°C/year.

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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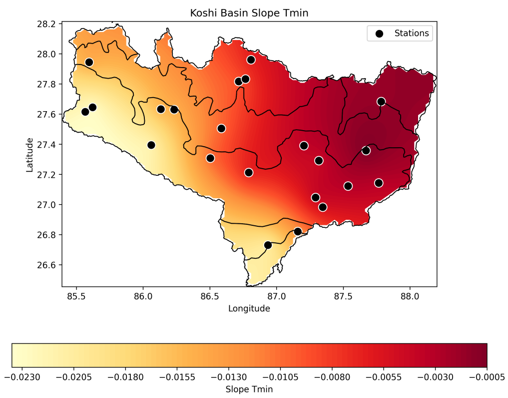
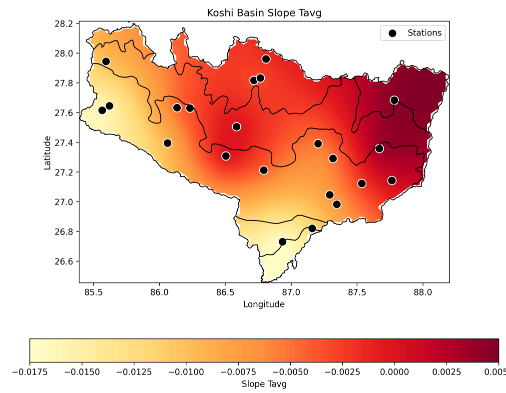
The Annual Regional Mann-Kendall test findings are shown in the table 4.

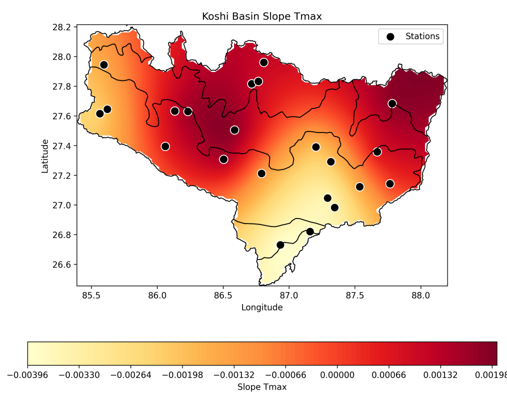
This test evaluates trends in minimum (T_{min}), maximum (T_{max}), and average (T_{avg}) temperatures in five regions: Tarai, Siwalik, Middle Mountains, High Mountains, and Himalaya. While T_{max} and T_{avg} show rising tendencies (0.005** and -0.000**, respectively) in the Himalaya, the T_{min} shows a decreasing trend (-0.009), and the latter two are not statistically significant ($p \geq 0.05$). T_{min} and T_{avg} (-0.008 and -0.003**) also exhibit declining patterns in the Middle Mountain region, although T_{max} (-0.001**) shows a relatively constant trend. The High Mountains, on the other hand, show an increasing trend in T_{min} (-0.016) and a more marked reduction in T_{max} and T_{avg} (0.008** and 0.002**). All temperature measurements exhibit similar declines in the Siwalik region: T_{min} (-0.063), T_{max} (-0.033), and T_{avg} (-0.05). Lastly, with T_{min} (-0.015), T_{max} (-0.003**), and T_{avg} (-0.006**) showing diminishing trends across all temperature parameters, the Tarai also shows declining trends, but T_{max} and T_{avg} are not statistically significant. Similarly, the Koshi region's maximum temperature grew at a rate of 0.058 °C/year, and its minimum temperature increased at a rate of 0.014 °C/year during the forty years leading up to 1963–-2009 (Nepal, 2016).



(a) Caption for subfigure (a)



(b) Caption for subfigure (b)



(c) Caption for subfigure (c)

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

Figure 7 illustrates a nonuniform temperature trend across the Koshi basin region. In Figure 7a, the annual average of daily minimum temperatures shows an overall cooling trend, ranging from -0.0005°C to -0.023°C, with higher elevations experiencing less cooling. 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 compared to the Tarai and Siwalik regions. Similarly, in Figure 7c, the annual average of daily maximum temperatures shows trends from cooling to slight warming, 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 data between 1980 and 2018, the mean annual temperature in the Koshi River Basin increased by 0.084°C/ year in the mountain region (p = 0.0005), 0.0975°C/year in the hill region (p = 0.0002), and 0.0187°C/year in the Tarai region (p = 0.0206), with significant correlations throughout. illustrates a nonuniform temperature trend across the Koshi basin region. In Figure 7a, the annual average of daily minimum temperatures shows an overall cooling trend, ranging from -0.0005°C to -0.023°C, with higher elevations experiencing less cooling. 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 compared to the Tarai and Siwalik regions. Similarly, in Figure 7c, the annual average of daily maximum temperatures shows trends from cooling to slight warming, 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 data between 1980 and 2018, the mean annual temperature in the Koshi River Basin increased by 0.084°C/ year in the mountain region (p = 0.0005), 0.0975°C/year in the hill region (p = 0.0002), and 0.0187°C/year in the Tarai region (p = 0.0206), with significant correlations throughout.

4 Conclusion

- The seasonal and annual temperature trends across the Koshi Basin reveal distinct patterns in each of the five physiographic regions. During the first two decades, seasonal and annual temperatures generally decreased, followed by a warming trend with occasional cooling periods. Minimum and average temperatures show consistent warming trends, while maximum temperatures experienced notable warming during the decade from 1982 to 2011.
- For the overall Koshi Basin from 1962 to 2022, the northeastern part shows stronger warming trends in average and maximum temperatures, along with less pronounced cooling in minimum temperatures. In contrast, maximum temperatures show cooling trends in the Tarai and Siwalik regions, similar to the patterns seen in minimum and average temperatures. The Himalaya and High Mountain regions exhibit significant warming trends for maximum temperatures, while average temperature shows no significant changes.
- This study highlights the changes in daily maximum, minimum, and average temperatures over different time frames and seasons. Temperature variations are influenced by factors such as elevation, slope, aspect, hilltops, valleys, solar radiation, and more. Therefore, to capture more precise temperature trends, it is crucial to establish a denser network of climate stations across the regions.
- The findings of this research indicate that decadal temperature analysis for physiographic regions is more effective compared to 30-year analysis. The temperature change has been identified in the Koshi Basin, characterized by an erratic pattern of temperature changes across regions, seasons, and time periods.

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