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# Observed temperature trends and projected changes under CMIP6 climate scenarios in North Shewa Zone of Amhara Region Ethiopia

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**Research Article**

**Keywords:** Climate change, CMIP6, Mann–Kendall test, North Shewa, SSP2-4.5, SSP5-8.5, temperature trends

**Posted Date:** September 3rd, 2026

**DOI:** https://doi.org/10.21203/rs.3.rs-10728089/v1

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**Additional Declarations:** No competing interests reported.

## Abstract

Understanding temperature dynamics across complex topographic environments is important for designing effective climate adaptation strategies for smallholder agricultural systems. This study assessed historical temperature trends during 1992–2022 and projected future temperature changes for the mid-century (2031–2060; hereafter 2050) and end-century (2071–2100; hereafter 2100) periods in the North Shewa Zone of Ethiopia's Central Highlands. Historical records were analyzed using the non-parametric Mann–Kendall test and Sen's slope estimator, while future projections under SSP2-4.5 and SSP5-8.5 were derived from a multi-model ensemble of five downscaled CMIP6 global climate models processed in Google Earth Engine and R (version 4.5.3). Results revealed statistically significant increasing trends in annual mean minimum temperature ($T_{min}$; Z = 3.195, p = 0.0014) and annual mean maximum temperature ($T_{max}$; Z = 3.807, p = 0.00014). $T_{max}$ increased slightly faster than $T_{min}$ during the historical period, with substantial spatial variability across the zone. Future projections indicate continued warming, with approximately 1–2°C increases by mid-century and substantially greater warming under SSP5-8.5 by the end of the century. Under SSP5-8.5, projected $T_{max}$ ranges from 24.90 to 38.74°C and $T_{min}$ from 11.25 to 25.06°C, indicating substantial warming across both daytime and nighttime temperatures. These thermal shifts pose significant agricultural challenges, including increased crop respiration, contraction of cold-adapted highland crop zones, and intensified heat stress in lowland livestock systems in the zone. Although mean temperatures are projected to increase, localized radiative cooling and microclimatic conditions may allow frost events to persist in susceptible highland areas. This study provides critical climatic evidence to guide specific agricultural adaptation, crop suitability planning, and hazard management across North Shewa Zone specifically, and highland ecosystems in general.

## 1. INTRODUCTION

Climate change is a major global challenge, with profound impacts on ecological and socioeconomic systems across spatial and temporal scales [1, 2]. Similarly, East Africa, characterized by immense ecological diversity and socio-economic vulnerability, is among the regions most exposed to climate-related risks [3]. Its impact, however, is often more severe in developing countries than in developed countries [4]. While developed countries have established institutional frameworks and technological tools to mitigate current and emerging climate impacts, developing nations often face constraints in designing and implementing appropriate adaptation mechanisms [5]. This disparity underscores the urgent need for context-specific strategies to enhance resilience [6].

Ethiopia, as part of East Africa, is highly vulnerable to climate change impacts [7]. The country is characterized by diverse microclimatic, physical, and topographic conditions [8, 2]. However, the availability of high-resolution observational climatic data at local scales remains limited [4]. Therefore, the use of climate models to generate climatic information for planning agricultural management and decisions is quite important [9]. CMIP6 provides an updated framework for evaluating climate-model simulations and projecting future climate under different socioeconomic and emissions pathways [10, 11].

Temperature is one of the most important climate variables influencing ecosystem processes and agricultural productivity [12]. Consistent with findings from previous studies [13, 14], long-term climate records in Ethiopia indicate an overall increasing trend in temperature [15]. However, climate change in the country is not only characterized by gradual warming but is also associated with increased climate variability and a rising frequency of extreme weather events [16, 17]. In the Ethiopian highlands, this variability is manifested not only through rising temperatures but also through unseasonal cold spells and frost events [18–20]. Such hazards can damage or destroy crops at sensitive growth stages, reduce yields, and threaten the livelihoods of smallholder farmers [21, 22]. Consequently, changes in temperature patterns and the increasing occurrence of temperature extremes present significant challenges for agricultural production, food security, and the design of effective climate change adaptation and risk management strategies [19, 23, 24].

The North Shewa Zone, located in the Amhara Regional State of central Ethiopia, is characterized by substantial altitudinal variation and diverse agro-ecological zones, making it particularly vulnerable to climate variability and change [25, 26]. Temperature variations influence crop growth and phenology, livestock productivity, water resources, and the occurrence of climate-related hazards, with significant implications for agricultural production and rural livelihoods [27]. Therefore, understanding both historical and future temperature patterns is essential for supporting evidence-based climate adaptation and sustainable resource management in the region [6].

Building on this need, the present study examines historical temperature trends in North Shewa Zone using observed climate data from 1992 to 2022 and projects future temperature changes under the SSP2-4.5 and SSP5-8.5 emission scenarios using CMIP6 climate models. Future changes are assessed for the mid-century and end-century periods to characterize the magnitude and spatial patterns of projected warming across the region. The findings provide a scientific basis for understanding future temperature dynamics and their potential implications for agricultural productivity and climate change adaptation planning in North Shewa Zone.

## 2. MATERIALS AND METHODS

## 2.1. Study area description

Geographically, the study was conducted in the North Shewa Zone, Amhara National Regional State of Federal Democratic Republic of Ethiopia, which is one of the eleven administrative zones found in Amhara National Regional State. It is about 130 kilometers North of Addis Ababa to the administrative town of the Zone, Debre Birhan. The study area is located between 8°43'06" and 10°43'58" N latitude and 38°39'50" and 40°06'32" E longitude. It covers an area of 15,936 $km^2$ [25].

The North Shewa Zone is characterized by a diverse agro-climatic profile comprising four distinct zones: the predominant Midland (*Woinadega*) and Highland *(Dega)*, which account for 45.58% and 32.02% of the area respectively, followed by Lowland *(Kola)* at 21.95% and a minimal Cold/Alpine *(Wurch)* belt at 0.46% [54]. With a mean annual temperature of 12.3°C, the area is defined by mild days and cold nights, where temperatures can range from 21°C during dry season days to as low as 3°C during wet season nights, accompanied by significant seasonal fluctuations in humidity [2].

## 2.2. Study design and data processing environment

This study adopted a quantitative geospatial modelling approach to analyze historical and projected climate variability over the North Shewa Zone, Ethiopia. The analysis of minimum temperature (Tmin) and maximum temperature (Tmax) was conducted using a combination of reanalysis datasets and multi-model climate projections, implemented within Google Earth Engine and R (version 4.5.3).

## 2.3. Climate data sources and scenario selection

In this study, historical daily minimum and maximum air temperature data for 1992–2022 were obtained from the ERA5-Land reanalysis dataset. The daily data were aggregated to annual mean minimum temperature ($T_{min}$) and annual mean maximum temperature ($T_{max}$) for trend analysis. Future temperature projections were obtained from the NASA Global Daily Downscaled Projections for CMIP6 (NEX-GDDP-CMIP6) dataset under SSP2-4.5 and SSP5-8.5. Projections were summarized for the mid-century period (2031–2060, hereafter 2050) and end-century period (2071–2100, hereafter 2100). To improve understanding of past, present, and future climate conditions, the World Climate Research Programme (WCRP) established the Climate Model Intercomparison Project (CMIP) in 1995, providing a coordinated framework for evaluating and comparing global climate models [28]. The latest phase, CMIP6, incorporates the Shared Socioeconomic Pathways (SSPs), including SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0, and SSP5-8.5, which represent alternative future socioeconomic development and greenhouse gas emission trajectories [29]. These scenarios were developed to provide continuity with the Representative Concentration Pathways (RCPs) used in CMIP5 while incorporating updated socioeconomic assumptions and producing comparable radiative forcing levels by the end of the twenty-first century [30]. SSP2-4.5 and SSP5-8.5 were selected to represent contrasting future greenhouse-gas emission pathways. SSP2-4.5 represents an intermediate-emission pathway, whereas SSP5-8.5 represents a high-emission pathway with substantially greater radiative forcing. The use of both scenarios enables comparison of projected temperature changes under moderate and high-emission futures and provides a broader basis for assessing potential climate-related risks and adaptation needs in the North Shewa Zone.

Table 1
Summary of climate datasets and processing used in the study

| Data source/product | Data type | Spatial resolution | Temporal resolution | Available period | Period used | Variables | Processing | Application |
|---|---|---|---|---|---|---|---|---|
| ERA5-Land Daily Aggregated (ECMWF/Copernicus) | Reanalysis | ~ 9 km | Daily | 1950–present | 1992–2022 | Tmin, Tmax | Daily data aggregated to annual mean Tmin and Tmax | Historical temperature trend analysis |
| NASA NEX-GDDP-CMIP6 | Downscaled climate projections | ~ 0.25° | Daily | Product-dependent | 2031–2060 and 2071–2100 | Tmin, Tmax | Daily projections aggregated over 30-year periods | Future temperature projections |
| ACCESS-CM2, MPI-ESM1-2-HR, MRI-ESM2-0, NorESM2-MM, and UKESM1-0-LL | CMIP6 GCMs | ~ 0.25° after downscaling | Daily | Product-dependent | 2031–2100 | Tmin, Tmax | Five-model arithmetic ensemble mean | Multi-model future projections |
| SSP2-4.5 | Intermediate-emission pathway | ~ 0.25° | Daily | 2015–2100 | 2031–2060; 2071–2100 | Tmin, Tmax | Five-model arithmetic ensemble mean | Moderate-emission scenario |
| SSP5-8.5 | High-emission pathway | ~ 0.25° | Daily | 2015–2100 | 2031–2060; 2071–2100 | Tmin, Tmax | Five-model arithmetic ensemble mean | High-emission scenario |

## 2.4. Multi-Model Ensemble Approach

To reduce dependence on any individual climate model, a multi-model ensemble mean approach was used. The ensemble comprised five CMIP6 models: ACCESS-CM2, MPI-ESM1-2-HR, MRI-ESM2-0, NorESM2-MM, and UKESM1-0-LL. These are selected based on their availability of daily minimum and maximum temperature projections under both SSP2-4.5 and SSP5-8.5. For each scenario and projection period, outputs from the five selected models were aggregated and their arithmetic mean was calculated to obtain the multi-model ensemble mean [31, 32]. The multi-model ensemble mean has better performance with observations than individual models and can therefore be used reliably for assessing future climate scenarios [33].

## 2.5. Trend Analysis

The Mann–Kendall test and Sen's slope estimator were used to detect monotonic trends in the temperature time series and estimate the magnitude of change [34, 35]. It is preferred due to its robustness against non-normal data distributions and missing values [36, 37].

# 3. RESULTS

## 3.1. Historical Temperature Trends (1992–2022)

The non-parametric Mann–Kendall test and Sen's slope estimator (Table 2) indicated statistically significant monotonic increasing trends in both annual mean minimum and maximum temperatures across the North Shewa Zone during 1992–2022.

Table 2
Mann-Kendall trend test and Sen's slope results (1992–2022)

| Statistic | Value | |
|---|---|---|
| | $T_{min}$ | $T_{max}$ |
| Z-value | 3.195 | 3.807 |
| p-value | 0.0014 | 0.00014 |
| Kendall's $\tau$ | 0.406 | 0.484 |
| S | 189 | 225 |
| Sen's slope (°C year$^{-1}$) | 0.0208 | 0.0237 |

The Mann–Kendall trend analysis revealed statistically significant increasing trends in both annual mean minimum temperature ($T_{min}$) and annual mean maximum temperature ($T_{max}$) in North Shewa during 1992–2022. For Tmin, the test yielded a positive Z-value of 3.195 and a p-value of 0.0014, indicating a significant upward trend at the 1% significance level. Similarly, Tmax exhibited a stronger increasing trend with a Z-value of 3.807 and a p-value of 0.00014. The positive Kendall's tau coefficients (0.406 for Tmin and 0.484 for Tmax) further confirmed the increasing temperature trends over time [6].

Sen's slope estimator indicated that $T_{min}$ increased at a rate of approximately 0.0208°C per year, while $T_{max}$ increased at a rate of 0.0237°C per year. Over the entire study period, these rates correspond to total increases of approximately 0.65°C and 0.74°C for $T_{min}$ and $T_{max}$, respectively. The results suggest a clear warming tendency in North Shewa, with maximum temperature increasing slightly faster than minimum temperature.

During the baseline period (1992–2022), the North Shewa Zone exhibited a wide spatial variability in temperature (Fig. 4). The maximum temperature ranged from 20.01°C in cooler highland areas to 34.89°C in warmer lowland regions. Similarly, the minimum temperature varied between 6.76°C in cold pockets and 21.11°C in relatively warmer valleys. This broad range reflects the strong influence of elevation and topography on local climate, with significant spatial and seasonal temperature contrasts across the zone [38].

## 3.2. Projected Spatial and Temporal Climate Change Scenarios

The multi-model ensemble projects a continuous, heterogeneous warming trend across North Shewa under both the intermediate (SSP2-4.5) and pessimistic (SSP5-8.5) emission pathways.

**Mid-century Projections (2050)**

By mid-century (2050), both scenarios project a modest but consistent warming trend. Under SSP2-4.5, maximum temperatures are expected to range between 22.09°C and 35.86°C, while minimums will range from 7.90°C to 21.75°C. Under SSP5-8.5, maximums shift slightly higher, ranging from 22.31°C to 36.09°C, with minimums between 8.22°C and 21.98°C. These projections indicate increases of approximately 1–2°C compared to the baseline, with the lower bounds of both maximum and minimum temperatures rising more sharply than the upper bounds. This suggests that traditionally cooler areas will experience more pronounced warming [13, 15].

**End-century Projections (2100)**

By the end of the century (2100), the divergence between scenarios becomes more pronounced. Under SSP2-4.5, maximum temperatures are projected to range between 23.10°C and 36.87°C, while minimums will range from 8.99°C to 22.82°C. In contrast, SSP5-8.5 projects a much stronger warming signal, with maximums ranging from 24.90°C to 38.74°C and minimums from 11.25°C to 25.06°C. This indicates that even the coolest areas of the zone may approach 25°C in maximum temperature and exceed 11°C in minimum temperature under SSP5-8.5. These projections indicate substantially higher temperatures across the zone by the end of the century, particularly under SSP5-8.5. Both minimum and maximum temperatures increase relative to the baseline, with the magnitude of warming varying spatially across the zone [6]. Such changes have critical implications for heat stress, agricultural resilience, and ecosystem stability, as reduced nighttime cooling can exacerbate physiological stress in humans, crops, and livestock [2, 7]

Table 3
Simulated Climate Scenarios and Temperature Ranges

| Period | Scenario | $T_{max}$ range (°C) | $T_{min}$ range (°C) |
|---|---|---|---|
| 1992–2022 | Baseline | 20.01– 34.89 | 6.76–21.11 |
| 2050 | SSP2– 4.5 | 22.09–35.86 | 7.90–21.75 |
| | SSP5– 8.5 | 22.31– 36.09 | 8.22–21.98 |
| 2100 | SSP2– 4.5 | 23.10–36.87 | 8.99–22.82 |
| | SSP5– 8.5 | 24.90– 38.74 | 11.25– 25.06 |

Overall, the analysis reveals a consistent warming trajectory across the North Shewa Zone, with spatial heterogeneity persisting but shifting upward in both maximum and minimum values. The SSP5-8.5 scenario projects substantially higher warming by 2100 compared to SSP2-4.5, underscoring the importance of mitigation efforts [6]. The rise in temperatures suggests that warming will be a defining feature of future climate in the region, with wide-ranging consequences for heatwave risks, agricultural productivity, and climate-driven hazard interactions [8].

## 4. DISCUSSION

# 4.1 Observed Historical Warming and Regional Context

The significant warming trend detected in North Shewa over 1992–2022 aligns with broader patterns observed across East Africa and Ethiopia [6]. The region's mean annual temperatures have increased at a rate faster than the global average, particularly in recent decades, depending on global emissions scenarios. According to many studies [6, 27, 28, 30, 31], the spatial differences in temperature between lowland and highland areas highlight the strong influence of elevation and topography on the magnitude and distribution of warming across the zone [15].

The slightly faster warming of Tmax compared to Tmin in the historical period (0.0237°C/year vs. 0.0208°C/year) differs from the global diurnal asymmetric warming phenomenon observed in earlier decades but aligns with emerging research [9, 32]. Recent episodes of global brightening and regional droughts and heatwaves have brought notable alterations to the diurnal warming asymmetry, resulting in a reversal of the diurnal warming trend with a substantial increase in the warming rates of daily maximum temperatures, while daily minimum temperatures have remained relatively stable [14]. This shift in North Shewa may reflect regional changes in cloud cover, precipitation, and surface energy balance; however, these mechanisms were not directly investigated in the present study.

# 4.2 Future Temperature Projections and Climate Impacts

The projected warming under both SSPs (SSP2-4.5 and SSP5-8.5) scenarios for mid-century and end-of-century periods is consistent with recent multi-model ensemble studies in Ethiopia and broader East Africa [6, 30]. During the mid-century horizon (2050), both radiative forcing scenarios project a consistent warming shift [13]. By the end of the century (2100), thermal profiles under SSP2-4.5 and SSP5-8.5 diverge significantly due to cumulative radiative forcing differences [28, 30]. In contrast, the high-emission SSP5-8.5 pathway exhibits severe end-century warming, pushing maximum temperatures up in lowland areas and elevating the lowest minimum temperature threshold to 11.25°C. This upward shift signifies that even the historically coldest highland pockets of North Shewa will no longer experience nighttime temperatures below 11.25°C under high-emission conditions [6, 15].

# 4.3 Agricultural Implications

The observed and projected warming trends in the North Shewa Zone carry significant consequences for local agricultural systems [9]. Statistically significant increases in both minimum ( $T_{\min}$) and maximum ( $T_{\max}$) temperatures indicate a progressive intensification of thermal stress on crop production [8]. Elevated minimum temperatures limit nighttime recovery and elevate respiration losses, whereas rising maximum temperatures exacerbate daytime heat stress, potentially abbreviating grain-filling periods and depressing yields of heat-sensitive staple crops [39–42].

The projections indicate an overall warming across the zone, with both minimum and maximum temperatures increasing relative to the baseline period [43]. Higher nighttime temperatures have been shown to disrupt flowering and pollination processes in crops, while also increasing pest and disease pressure [44, 45]. Livestock systems are similarly affected; as reduced nighttime cooling may exacerbate physiological stress, lower milk yields, and increase mortality risks during heatwaves [46–48].

The spatially heterogeneous warming pattern suggests that traditionally cooler highland areas will also experience substantial temperature increases [49]. This may shift agro-ecological zones upward, reducing the suitability of highland niches and threatening local food security [50, 51]. Conversely, warmer lowland regions face accelerated evapotranspiration, which increases irrigation demand and strains already limited water resources [38, 52, 53].

## 5. CONCLUSIONS

Analysis of historical reanalysis temperature data for 1992–2022 revealed statistically significant warming trends in both $T_{min}$ and $T_{max}$, with Sen's slope estimates indicating increases of 0.0208°C/year and 0.0237°C/year, respectively. These warming rates correspond to total increases of approximately 0.65°C for minimum temperature and 0.74°C for maximum temperature over the study period, highlighting a clear warming tendency with maximum temperatures rising slightly faster than minimums.

The multi-model ensemble projections for the North Shewa Zone reveal a continuous, spatially heterogeneous warming trajectory across both mid-century (2050) and end-century (2100). Spatial variability remains pronounced, reflecting the influence of elevation and topography. Importantly, while mean temperatures are increasing, this does not eliminate the probability of frost occurrence, as localized radiative cooling and microclimatic conditions can still generate frost events in highland pockets.

Future projections under SSP2-4.5 and SSP5-8.5 scenarios reinforce the persistence of heterogeneous warming across the zone, with end-century outcomes diverging sharply depending on emission pathways. Under the high-emission scenario, minimum temperatures are projected to rise above 11°C even in historically cold areas, while maximums may exceed 38°C in lowlands. These shifts imply heightened risks of heat stress for crops, livestock, and ecosystems, alongside the possibility of residual frost hazards in susceptible highland microclimates. The dual challenge of managing both warming-induced stress and residual frost risk underscores the need for integrated adaptation strategies, including crop diversification, climate-informed planting calendars, improved water management, and strengthened climate advisory and extension services to sustain agricultural productivity and resilience in North Shewa.

## DECLARATIONS

## Declaration of Competing Interest

The authors declare that they have no competing interests.

**Ethics approval:**

Not applicable.

**Consent to participate:**

Not applicable.

**Consent for publication:**

Not applicable.


## Funding statement

No funding was received for this study.


## Author Contribution

Baykedagn Taye Shenkut: Conceptualization, formal analysis, software, validation, writing original drafts, review and editing, and data curation. Solomon Tekalegn Demissie: Writing—review & editing, validation, supervision, methodology, and conceptualization. Solomon Asfaw Beza: Writing—review & editing, validation, supervision, methodology, and conceptualization. Sitotaw Haile Erena: Writing – review & editing, supervision, methodology, and conceptualization. Ashenafı Yimam Kassaye: Writing – review & editing, validation, supervision, methodology, and conceptualization.

# Data Availability

The code and workflow scripts used in this study are publicly available in Zenodo at https://doi.org/10.5281/zenodo.21918876. Administrative boundary shapefiles were retrieved from the Humanitarian Data Exchange (https://data.humdata.org/), and basemap tiles were sourced from Esri. The climate datasets used in the analysis are publicly available from their respective data providers.

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## Figures

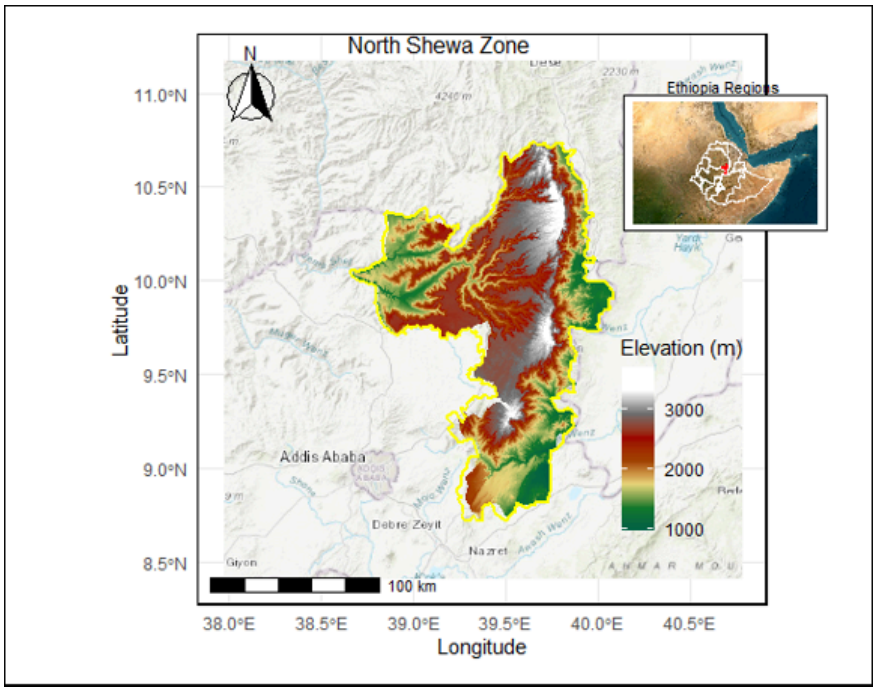



**Figure 1**

Location of North Shewa Zone, Ethiopia

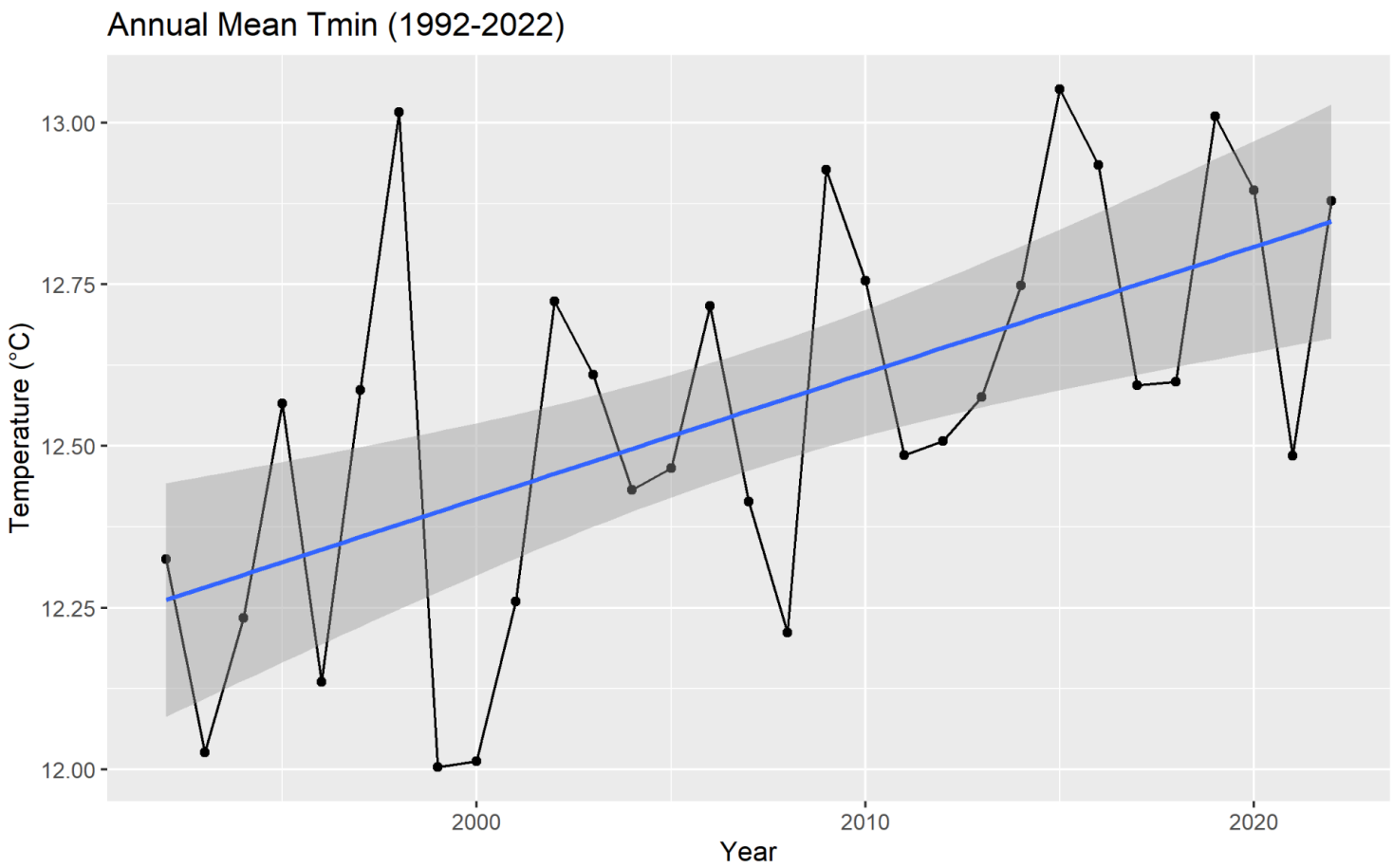



**Figure 2**

Trend of Mean Minimum Temperature ($T_{min}$)

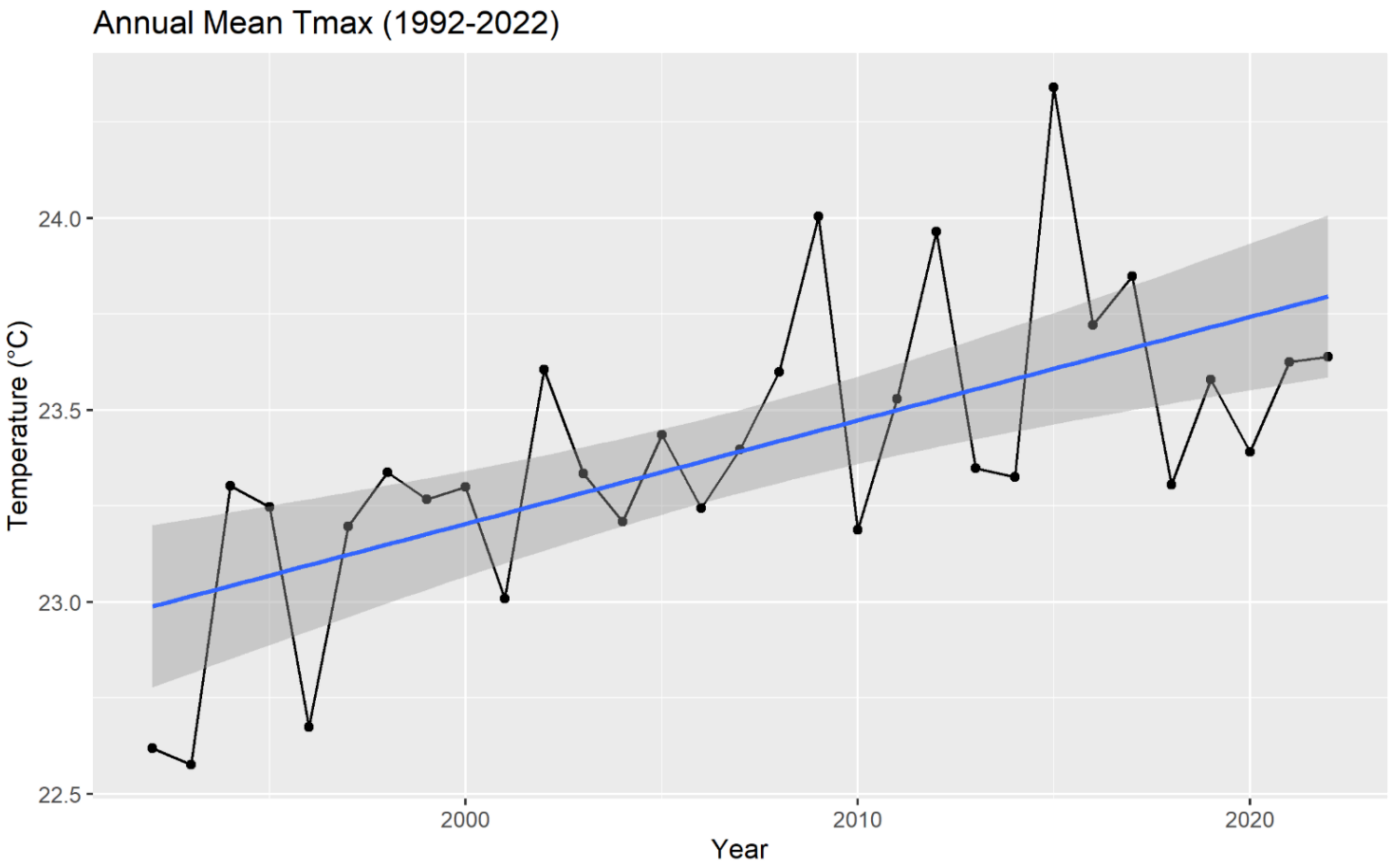



**Figure 3**

Trend of Mean Maximum Temperature ($T_{max}$)

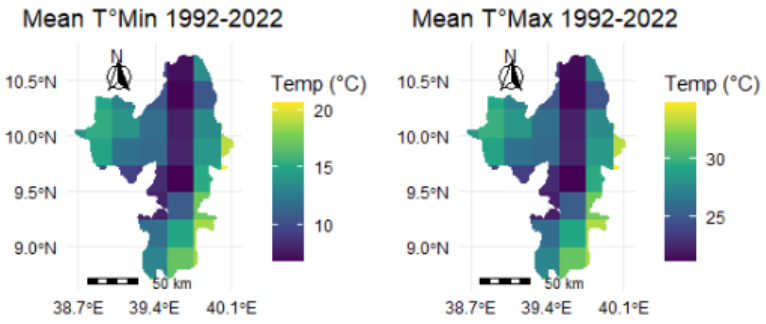



**Figure 4**

Spatial variability of $T_{max}$ and $T_{min}$

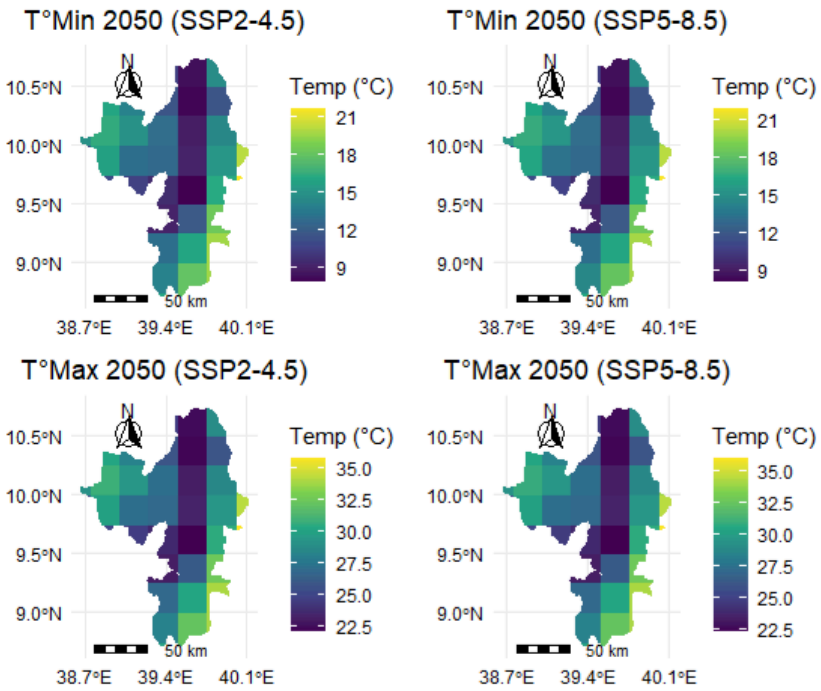



**Figure 5**

Projected Minimum and Maximum Temperature in 2050

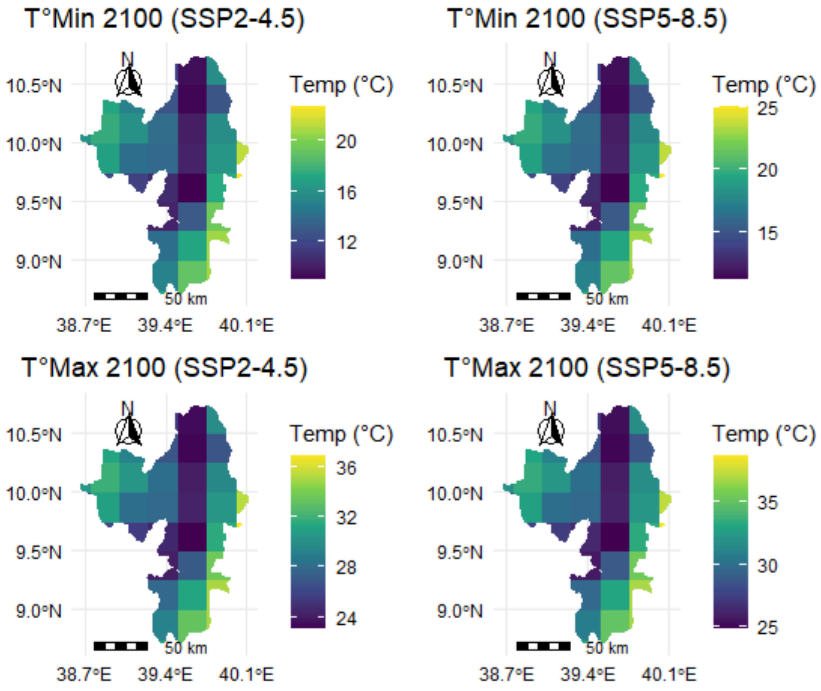



**Figure 6**

Projected Minimum and Maximum Temperature in 2100