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Research Article

Temporal Analysis of CMIP6 Historical and Projection Emission Scenarios

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Abstract

Globally, impacts of climate change observed across the sources of water, agricultural planning, and socio-economic factors. Objectives of the study are to analyze historical climate data, focusing on rainfall and temperature trends over the period 1981–2014 and to project future climate scenarios under SSP2-4.5 and SSP5-8.5 for the periods 2015–2040 (near term), 2041–2070 (mid-term), and 2071–2100 (end term), assessing changes in seasonal and annual rainfall and temperature. This study investigates historical and projected climate trends in Tiyo Woreda, Arsi Zone, Ethiopia, using data sources Copernicus and ECMWF and CMIP6 climate models under SSP2-4.5 and SSP5-8.5 scenarios. Ensembles global climate models selected from the five Coupled Model Intercomparison Project (CMIP6) are considered under SSP2-4.5 and SSP5-8.5 socio-economic pathways. The research conducted using multiple software tools, such as Excel for data entry and manipulation, Python for data processing, visualization, Heatmaps and plotting, and ArcGIS and GeoCLIM for location of study area and spatial analysis. The result demonstrated historical climate rainfall is highest during the Kiremt, moderate during Belg, and lowest during Bega. Projections both SSP2-4.5 and SSP5-8.5 scenarios suggest that rainfall will generally increase in the mid- and long term, though slight reductions are observed in the near term compared to the historical baseline. Seasonal trends of Bega and Belg rainfall show small near-term declines and slight increase respectively but recover and increase in later periods. Kiremt rainfall exhibits modest but consistent increases, with higher values under SSP5-8.5. Annual rainfall follows a similar trajectory, with gradual increases across the projection horizon. Scenario comparison across SSP5-8.5 consistently projects greater increases in rainfall than SSP2-4.5, particularly in the mid- to long-term. In general historical analysis show mixed rainfall trends with increases in Kiremt and decreases in Bega and Belg, while minimum and maximum temperatures exhibit a warming trend across all seasons. CMIP6 projections indicate an overall increase in seasonal rainfall and temperature, with more pronounced warming under SSP5-8.5. Projections SSP2-4.5 and SSP5-8.5 scenarios of maximum temperature show an increment across the periods of near-, mid- and end-term with the magnitude of 0.7 ℃, 1.6 ℃, 2.1 ℃ and 0.8 ℃, 1.9 ℃, 3.6 ℃ respectively. These results highlight the need for adaptive strategies in agricultural planning and water resource management to mitigate the impacts of climate change in the Tiyo Woreda.

Keywords

Temporal Analysis, Rainfall, Temperature, CMIP6, Historical, Projection, Climate Change

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) assessment reports and numerous studies have highlighted the impacts of increasing Greenhouse Gas (GHG) concentrations on the climate at both global and regional scales [1, 2]. In East Africa, several investigations have assessed future climate changes under different emission scenarios [3-6]. These studies largely emphasize evaluating CMIP model performance for present-day climate [7, 8], projecting changes in mean climate variables [9] or employing earlier generations of global models [10, 11]. However, limited attention has been directed toward detailed regional analysis of livestock-relevant extreme climate indices in both historical and future contexts using the latest CMIP6 simulations.

The Scenario Model Intercomparison Project (ScenarioMIP), which provides multi-model climate simulations based on alternative scenarios that are directly relevant to societal concerns regarding climate change mitigation, adaptation, or impacts, is the primary activity within theCMIP6 [12, 13]. The comprehensive set of the latest CMIP6 climate models is considered, and four future scenarios [12] are covered, namely, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 [13-15]. SSPs of ScenarioMIP describe different societal development paths without considering climate change or policy [12]. SSP1 and SSP5 represent optimistic trends, with SSP1 focusing on sustainability and SSP5 on fossil fuels. SSP3 and SSP4 depict pessimistic scenarios, withregional security concerns in SSP3 and inequalities in SSP4. SSP2 follows a moderate path continuing historical trends. These scenarios ensure continuity with CMIP6 historical simulations.

Ethiopia's climate is characterized by significant variability, with distinct seasonal patterns influencing rainfall and temperature regimes. The country experiences three primary seasons: Bega (October–January), Belg (February–May), and Kiremt (June–September), each with unique climatic characteristics. Understanding these seasonal variations is crucial for agricultural planning and water resource management [16-18].

The Coupled Model Intercomparison Project Phase 6 (CMIP6) provides a comprehensive framework for evaluating climate models under various Shared Socioeconomic Pathways (SSPs). These models offer valuable insights into potential future climatic conditions, aiding in the development of adaptation strategies. However, regional studies focusing on specific areas like Ethiopia Arsi Zone are limited, necessitating localized analysis to inform effective climate adaptation policies [17].

The Arsi Zone, located in the Oromia Region, is a critical area for agricultural production, particularly in TiyoWoreda. This region is heavily dependent on seasonal rainfall for crop cultivation, making it vulnerable to climate variability and change. Recent studies have highlighted increasing temperature trends and variable rainfall patterns across Ethiopia, with projections indicating more extreme climatic events in the future [18].

Accordingly, this study aims to analyze historical climate data, focusing on rainfall and temperature trends over the period 1981–2014 and to project future climate scenarios under SSP2-4.5 and SSP5-8.5 for the periods 2015–2040 (near-term), 2041–2070 (mid-term), and 2071–2100 (end-term), assessing changes in seasonal and annual rainfall and temperature. To improve understand of current and future extreme climate hazards and their implications for climate-sensitive sectors. We evaluate sector-specific extreme indices over TiyoWoreda using an ensemble of seven CMIP6 global climate models under two future emission scenarios (SSP2-4.5 and SSP5-8.5).

Despite this progress, limited emphasis has been placed on localized analysis that captures seasonal and interannual climate variability at the sub-regional scale. In particular, the Arsi Zone of Ethiopia, which is highly dependent on rain-fed agriculture and livestock, remains under, studied in terms of its exposure to extreme climate events under future scenarios. This study therefore seeks to address this gap by conducting a temporal analysis of rainfall, maximum temperature, and minimum temperature in Tiyo Woreda using ensembles of CMIP6 global climate models under two emission pathways (SSP2-4.5 and SSP5-8.5). The results are intended to enhance understanding of localized climate risks and to inform adaptation strategies for climate-sensitive sectors in the Woreda.

2. Study Area

Tiyo is a Woreda found in Arsi Zone, Oromia Regional State, Ethiopia. TiyoWoreda is a part of the Arsi Zone, Tiyo bordered on the south by Munesa, on the west by Batu Dugda, on the northeast by Hitosa, and on the southeast by DigelunaTijo. The administrative center of the Woreda and Zone is Asella; other towns in Tiyo include Gonde. Tiyo Woreda is located in Arsi Zone, Oromia regional state at latitude between 7.7552 up to 8.042 degree, longitude between 38.94 up to 39.33 degree and with elevation varies from 1655 meter up to 3870 meter; as average 2726.5 meter.

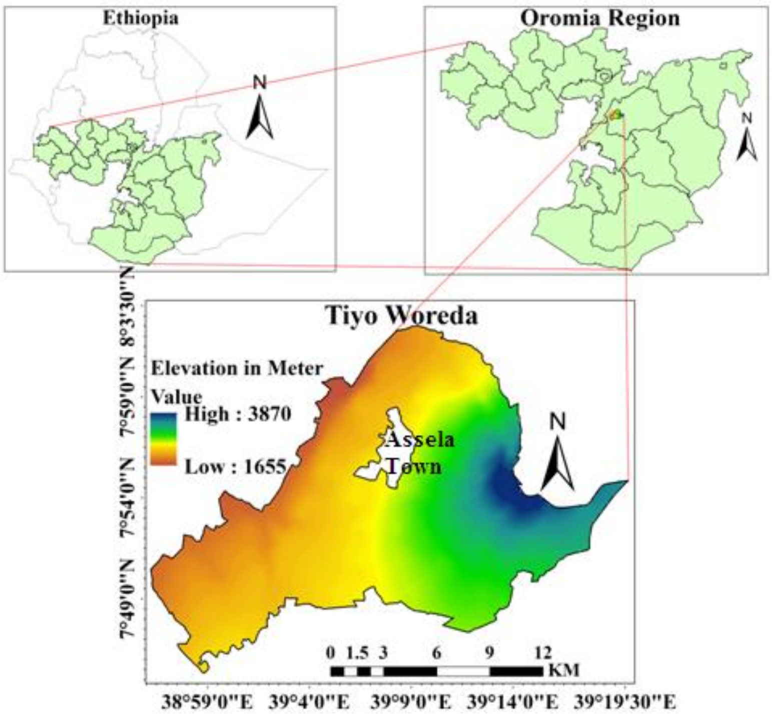


Figure 1. Study area with elevation for Arsi Zone Tiyo Woreda.

3. Data and Methodology

In this study, selected and analyzed seasonal Bega (ONDJ), Belg (FMAM) and Kiremt (JJAS), and Annual CHIRPS for rainfall spatial climatology data and coefficient of variation data from 1991-2024 were acquired from GeoCLIM tool by importing CHIRPS -Prelim in the format of ire_ppt_dekad.climdata.

The Coupled Model Intercomparison Project Phase 6 (CMIP6) provides standardized climate model simulations to assess historical and future climate changes globally. CMIP6 includes multiple climate models from international research institutions, offering a range of projections under different Shared Socioeconomic Pathways (SSPs), such as SSP2-4.5 and SSP5-8.5. These models simulate key climate variables, including rainfall, minimum and maximum temperatures, and extreme events, across past, present, and future periods.

3.1. Copernicus Climate Change Service (C3S)

The Copernicus Climate Change Service (C3S), coordinated by the European Centre for Medium-Range Weather Forecasts (ECMWF), provides high-resolution climate datasets derived from CMIP6 simulations and observational products. Copernicus integrates historical data, reanalysis datasets, and model projections, enabling robust climate trend analysis at global, regional, and local scales. Its products include: Downscaled CMIP6 projections for regional climate assessment. C3S ensures data quality, accessibility, and reproducibility, which is critical for regional climate studies like Arsi Zone, Ethiopia [19].

3.2. European Centre for Medium-range Weather Forecasts (ECMWF)

ECMWF is the primary center managing Copernicus data and provides global climate reanalysis and seasonal forecasts. ECMWF data sources for CMIP6 studies include: Reanalysis datasets (ERA5, ERA6) offering consistent historical climate records with high spatial (~0.25°) and temporal (hourly/daily) resolution. Model simulations from participating CMIP6 models, including global circulation models (GCMs) and earth system models (ESMs).

ECMWF datasets are widely used forevaluating historical climate trends and validating climate models due to their high accuracy and comprehensive spatial coverage [20].

3.3. Integration in This Study

In this study, CMIP6 model outputs obtained via Copernicus and ECMWF platforms were used to:

Evaluate historical rainfall and temperature trends (1981–2014).

Assess future projections under SSP2-4.5 and SSP5-8.5 scenarios (2015–2100).

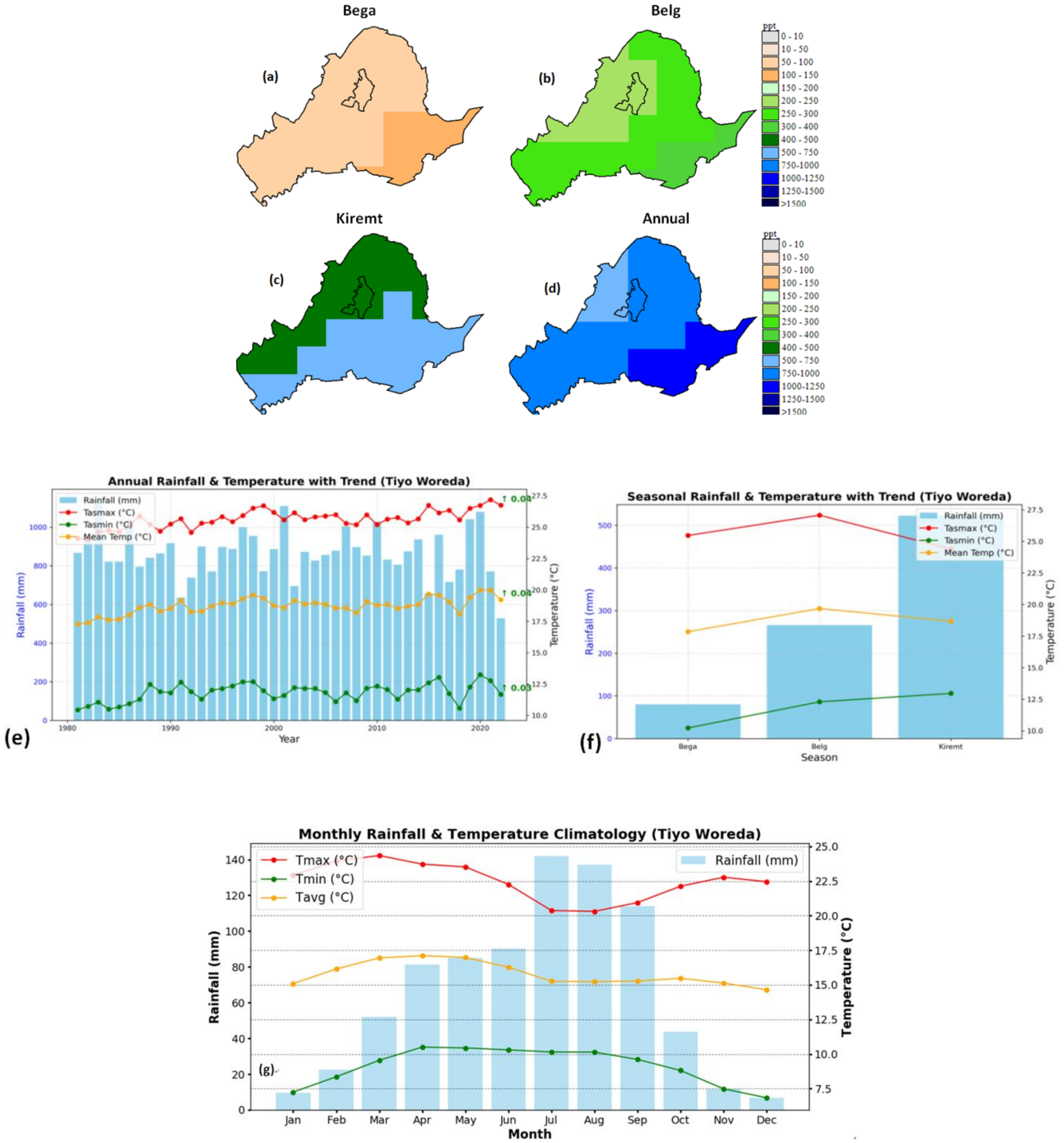
Generate seasonal (Bega, Belg, Kiremt) and annual climate analysis for Tiyo Woreda.

3.4. Tools

The research conducted using multiple software tools, such as Excel for data entry and manipulation, Python for data processing, visualization, Heatmaps and plotting, and ArcGIS and GeoCLIM for location of study area and spatial analysis.

4. Result and Discussions

4.1. Rainfall Climatology



(g)

Figure 2. Spatial and temporal analysis of (e) annual, (f) seasonal and (g) monthly climatology trends across rainfall and temperature with trends over Tiyo woreda.

From the results of the study area, Bega season average rainfall in most areas of north, west, central, east and south ranges up to 100 mm, in south east up to 150 mm. The Belg season climatologically rainfalldistribution (FMAM) showsthat in the (Figure 2b) the rainfall amount ranges from 200 mm to 400 mm. Similarly, climatologically distribution of rainfall in Kiremt season (JJAS) indicated in the (Figure 2c) 400 mm to 750 mm (high spatial rainfall coverage) fell in relation to Kiremt season in TiyoWoreda. Spatial Annual rainfall climatology ranges between 750 mm up to 1250 mm in different rainfall distribution from location to location over Tiyo Woreda.

Coefficient of variation indicated across seasonal and annual with high variable over Bega season than Belg, Kiremt and annual. Bega coefficient of variation indicated high with the magnitude of greater than 50 respects to other; in case of Belg coefficient variation ranges between 31 up to 40 in most parts of Tiyo Woreda except few parts of central and west. Kiremt season ranges between 21 up to 30 in all of TiyoWoreda; in case of annual less coefficient of variation than others with the magnitude of 11 up to 15 in most parts of study area (Figure 3h, i, j, k).

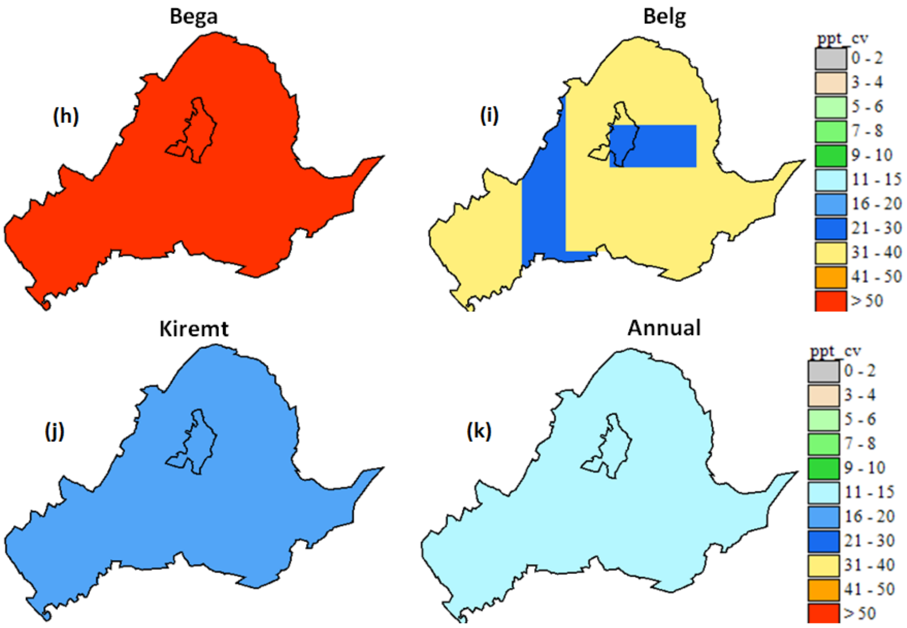


Figure 3. *Seasonal and annual coefficient of variation (CV) over Arsi zone Tiyo Woreda.*

4.2. Temporal Analysis of CMIP6 Historical and Projection

Based on the results of CMIP6, projected shifts in rainfall and temperatures are analyzed across seasonal and annual. The Multi-Model Ensemble (MME) mean of these adjusted datasets assessed changes under SSP2-4.5 and SSP5-8.5 scenarios for near, mid, and end term periods compared to historical rainfall and temperature simulations.

Historical rainfall during the Bega season ranges between 100 mm and 220 mm, with an average of about 160 mm. CMIP6 models under the SSP2-4.5 and SSP5-8.5 emission scenarios project an overall slightly increase in Bega rainfall. In the near-term, a slight decrease is followed by an increase in both scenarios. In the mid-term, rainfall shows a slightly increase, while in the end-term; both scenarios indicate an increments in rainfall than near and mid-term (Figure 4a). However, the projected rainfall for SSP2-4.5 and SSP5-8.5 (2015–2100) is slightly increase compared to the historical period (1981–2014).

Historical rainfall during the Belg season ranges between 140 mm and 240 mm, with an average of about 190 mm. Projections from SSP2-4.5 and SSP5-8.5 indicate an overall slight increase in Belg rainfall. In the near-term, a slight increase is followed by an increase under both scenarios. In the mid-term, rainfall shows a modest increase, with overlapping values between SSP2-4.5 and SSP5-8.5. In the end-term, both scenarios indicate an increase, with SSP2-4.5 projecting a smaller rise compared to SSP5-8.5 (Figure 4b). Similar to the Belg season, the long-term projections (2015–2100) show a slightly enhanced with rainfall compared to the historical baseline (1981–2014).

Historical rainfall during the Kiremt season (1981–2014) ranges between 580 mm and 770 mm, with an average of about 675 mm. Projections under SSP2-4.5 and SSP5-8.5 suggest a slight increase across the near- (slight decrease), mid-, and end-term periods, with the maximum rainfall values occurring under SSP5-8.5 (Figure 4c). Historical annual rainfall ranges between 850 mm and 1150 mm. Projections under SSP2-4.5 and SSP5-8.5 indicate an overall increase in Annual rainfall. In the near term, rainfall shows a slight decrease followed by an increase under both scenarios. Mid- and end-term projections suggest a modest increase in annual rainfall under both SSP2-4.5 and SSP5-8.5 (Figure 4d). Generalized Findings on Historical and Projected Rainfall, Analysis of CMIP6 model historical rainfall data (1981–2014) and CMIP6 model simulations under SSP2-4.5 and SSP5-8.5 scenarios (2015–2100) shows that rainfall patterns vary across seasons but share consistent long-term trends.

1) Historical climate: Rainfall is highest during the Kiremt season (June–September), moderate during Belg (March–May), and lowest during Bega (October–February). Annual totals range from ~580 to 770 mm.
2) Projections: Both SSP2-4.5 and SSP5-8.5 scenarios suggest that rainfall will generally increase in the mid- and long term, though slight reductions are observed in the near term compared to the historical baseline.
3) Seasonal trends:
   a) Bega and Belg rainfall show small near-term declines and slight increase respectivelybut recover and increase in later periods.
   b) Kiremt rainfall exhibits modest but consistent increases, with higher values under SSP5-8.5.
   c) Annual rainfall follows a similar trajectory, with gradual increases across the projection horizon.
4) Scenario comparison: SSP5-8.5 consistently projects greater increases in rainfall than SSP2-4.5, particularly in the mid- to long-term.

Overall, while short-term variability may include slight declines, long-term projections point toward increasing rainfall across seasons and annually, with stronger intensification under the high-emission scenario (SSP5-8.5).

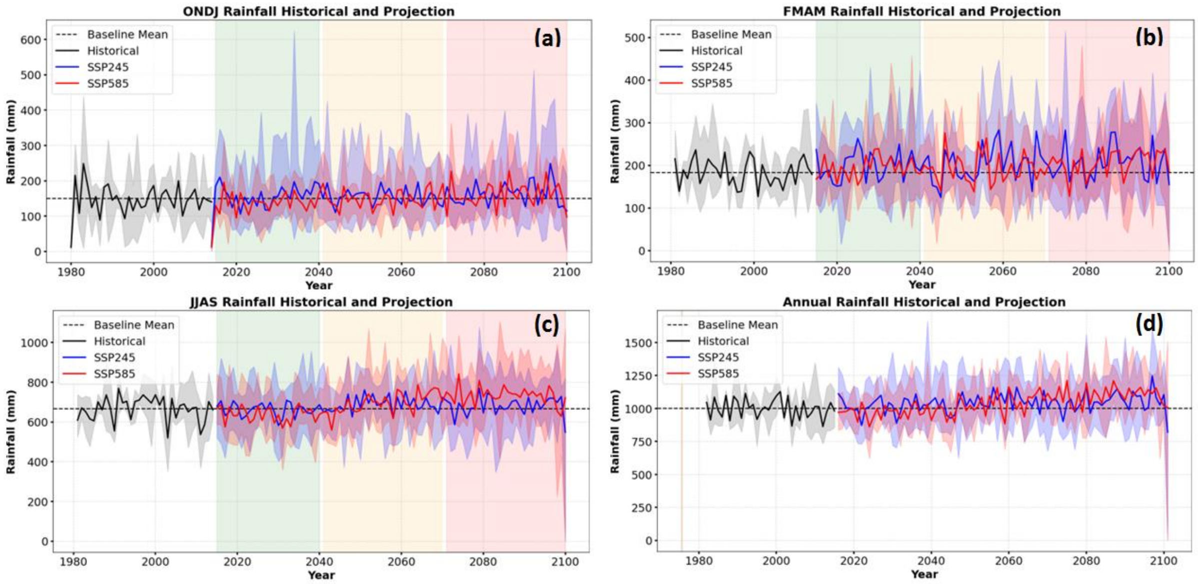
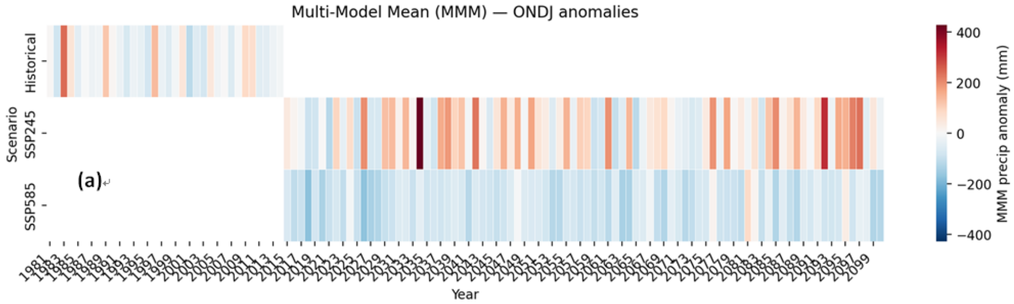


Figure 4. Temporal rainfall analysis of Bega [historical-black line (1981-2014) and projection (SSP2-4.5-blue line and SSP4-8.5-red line) trends], Belg [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends], Kiremt [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends] season and annual [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends] with baseline mean over Tiyo Woreda.



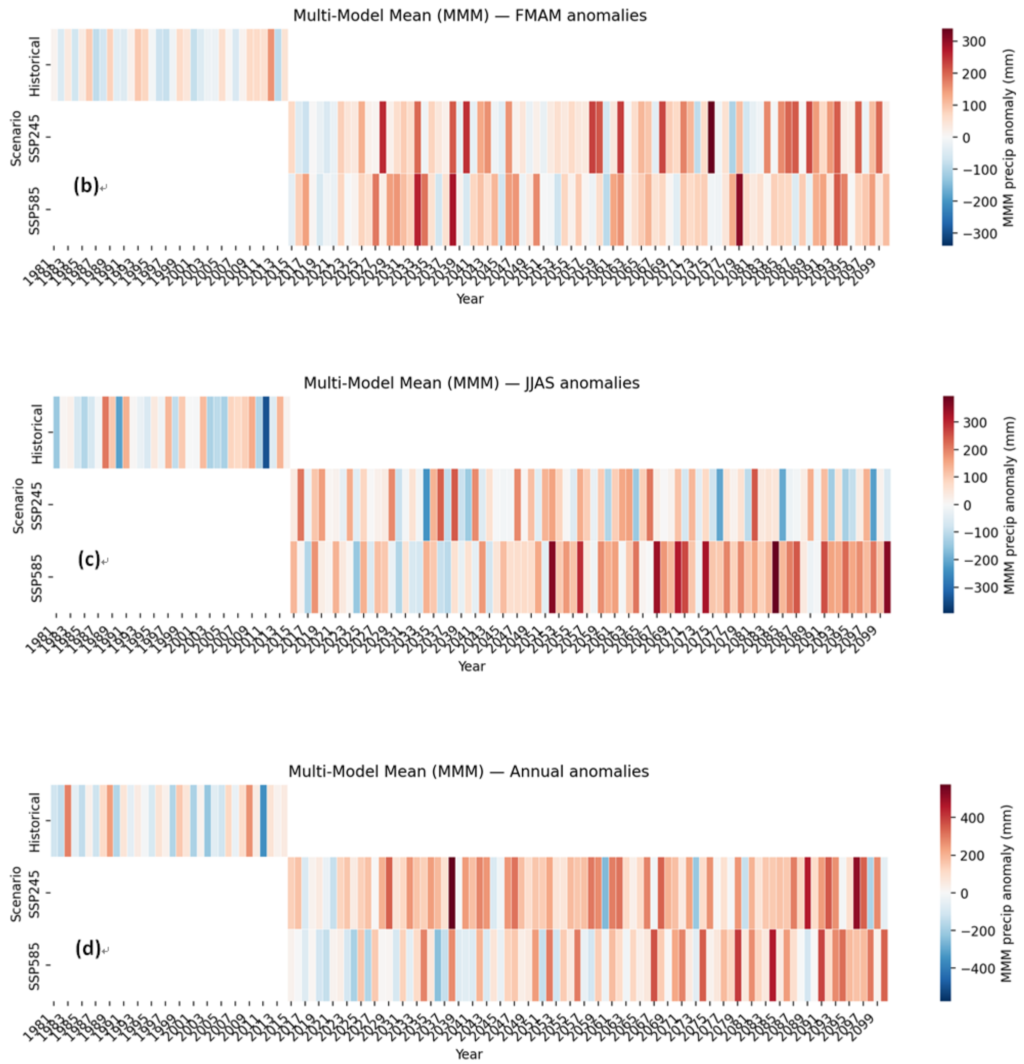


Figure 5. *Seasonal (a) Bega, (b) Belg, (c) Kiremt) and (d) annual rainfall anomaly Heatmap for Historical, SSP2-4.5 and SSP5-8.5 scenarios.*

4.3. Temporal Maximum and Minimum Temperature Analysis for Historical, SSP2-4.5 and SSP5-8.5 Scenarios

4.3.1. Historical and Projected Maximum Temperature

Historical maximum temperature of Bega oscillates between the ranges 22 ℃ up to 23 ℃; averagely increase up to 22.5 ℃. CMIP6 models of SSP2-4.5 and SSP5-8.5 projection emission scenarios show that an increase across Bega season. Near term indicate slightly increase across SSP2-4.5 and SSP5-8.5 projection emission scenarios. Mid-term indicate linearly increase, similarly end-term also show that an increment through corresponding maximum temperature values across SSP2-4.5 and SSP5-8.5 projection emission scenarios (Figure 6a). The projection of SSP2-4.5 and SSP5-8.5 (2015-2100) rainfall simulation show that a linearly increase at the maximum of the magnitudes 24 ℃ and 26 ℃ respectively.

Belg Historical maximum temperature of Bega oscillates between the ranges 24 ℃ up to 25.5 ℃; averagely increase up to 24.75 ℃. CMIP6 models of SSP2-4.5 and SSP5-8.5 projection emission scenarios show that an increase across Belg season. Near term indicate slightly increase across SSP2-4.5 and SSP5-8.5 projection emission scenarios. Mid-term indicate linearly increase, similarly end term also show that an increment through corresponding maximum temperature values across SSP2-4.5 and SSP5-8.5 projection emission scenarios (Figure 6b). The projection of SSP2-4.5 and SSP5-8.5 (2015-2100) rainfall simulation show that a linearly increase at the maximum of the magnitudes 27 ℃ and 30 ℃ respectively.

Kiremt Historical (1981-2014) maximum temperature of Kiremt oscillates between the ranges 20.5 ℃ up to 21.5 ℃; averagely increase up to 21 ℃. CMIP6 models of SSP2-4.5 and SSP5-8.5 projection emission scenarios show that an increase across Kiremt season. Near-term indicate slightly increase across SSP2-4.5 and SSP5-8.5 projection emission scenarios. Mid-term indicate linearly increase, similarly end term also show that an increment through corresponding maximum temperature values across SSP2-4.5 and SSP5-8.5 projection emission scenarios. The projection of SSP2-4.5 and SSP5-8.5 (2015-2100) maximum temperature simulation show that a linearly increase at the maximum of the magnitudes 23 ℃ and 26 ℃ respectively (Figure 6c).

Annual Historical (1981-2014) maximum temperature oscillates between the ranges 22.5 ℃ up to 23.5 ℃; averagely increase up to 23 ℃. CMIP6 models of SSP2-4.5 and SSP5-8.5 projection emission scenarios show that an increase across annual. Near term indicate slightly increase across SSP2-4.5 and SSP5-8.5 projection emission scenarios. Mid-term indicate linearly increase, similarly end term also show that an increment through corresponding maximum temperature values across SSP2-4.5 and SSP5-8.5 projection emission scenarios. The projection of SSP2-4.5 and SSP5-8.5 (2015-2100) annual maximum temperature simulation show that a linearly increase atthe maximum of the magnitudes 24 ℃ and 27.5 ℃ respectively (Figure 6d).

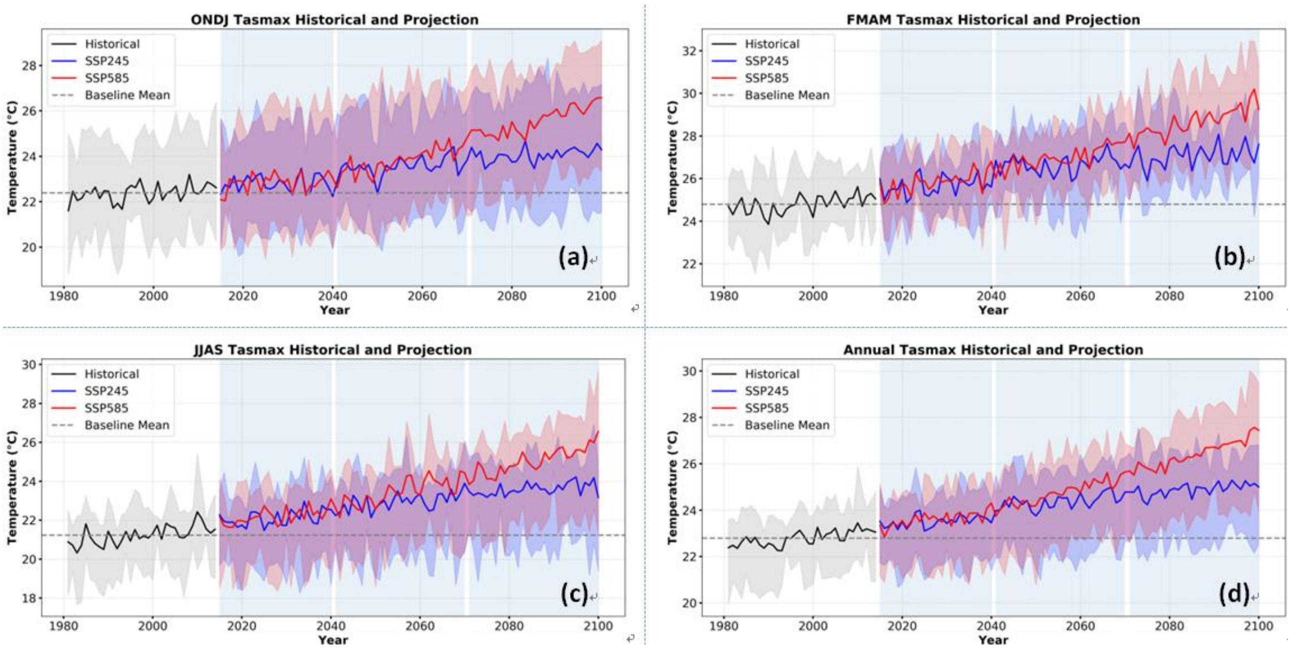


Figure 6. *Temporal maximum temperature analysis of Bega [historical-black line (1981-2014) and projection (SSP2-4.5-blue line and SSP4-8.5-red line) trends], Belg [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends], Kiremt [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends] seasons and annual [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends (2015-2100)] with baseline mean over Tiyo Woreda.*

Table 1. *CMIP6 models maximum temperature simulation across historical and projection (period near-, mid- and end-term) on SSP2-4.5 and SSP5-8.5 emission scenarios increment on seasonal and annual.*

Scenario	Period	Bega_Î”	Belg_Î”	Kiremt_Î”	Annual_Î”
SSP2-4.5	Near-term	0.5	0.9	0.9	0.7
SSP2-4.5	Mid-term	1.3	1.9	1.7	1.6
SSP2-4.5	End-term	1.8	2.3	2.4	2.1
SSP5-8.5	Near-term	0.6	1.0	1.0	0.8
SSP5-8.5	Mid-term	1.6	2.2	2.2	1.9
SSP5-8.5	End-term	3.3	3.9	3.8	3.6

NB. Î” means an increasing maximum temperature during the periods of near-, mid- and end-term.

4.3.2. Historical and Projected Minimum Temperature

Historical minimum temperatures of Begarange from 8 ℃ to 9.5 ℃, with an average of about 8.75 ℃. CMIP6 projections under SSP2-4.5 and SSP5-8.5 indicate a steady increase. In the near term, both scenarios project slight warming, with SSP2-4.5 initially higher (~18.75 ℃). By the mid-term, temperatures rise linearly and converge, while in the end term, SSP5-8.5 exceeds SSP2-4.5. Projected values reach ~10 ℃ (SSP2-4.5) and ~15.9 ℃ (SSP5-8.5) by 2100 (Figure 7a).

Historical minimum temperatures of Belgrange from 10 ℃ to 11.8 ℃, averaging 10.9 ℃. Projections show increases under both scenarios, with SSP2-4.5 initially warmer (~11 ℃). Mid-term warming is linear with overlapping values, while end-term projections diverge, with SSP5-8.5 higher. By 2100, minimum temperatures reach ~14.2 ℃ (SSP2-4.5) and ~18 ℃ (SSP5-8.5) (Figure 7b).

Historical minimum temperatures of Kiremt range from 11 ℃ to 12 ℃, averaging 11.5 ℃. Projections suggest gradual increases across all periods. Near-term values are slightly higher under SSP2-4.5 (~12 ℃). Mid-term projections overlap, but by the end term, SSP5-8.5 is higher. Projected values reach ~14.5 ℃ (SSP2-4.5) and ~17.5 ℃ (SSP5-8.5) by 2100 (Figure 7c).

Historical annual minimum temperatures range from 9 ℃ to 11 ℃, averaging 10 ℃. Both scenarios indicate progressive warming, with SSP2-4.5 initially higher (~10.5 ℃). Mid-term projections overlap, while end-term values diverge, with SSP5-8.5 exceeding SSP2-4.5. By 2100, annual minimum temperatures reach ~13.5 ℃ (SSP2-4.5) and ~17.5 ℃ (SSP5-8.5) (Figure 7d).

Generalized findings on minimum temperature, analysis of historical (1981–2014) and projected (2015–2100) minimum temperatures reveals a consistent warming trend across all seasons and annually. Historical values ranged from ~8 ℃ to ~9.5 ℃ in Bega, ~10 ℃ to ~11.8 ℃ in Belg, with annual averages of ~10 ℃. Projections under both SSP2-4.5 and SSP5-8.5 show that gradual increment, with slight near-term warming, linear mid-term trends, and stronger end-term rises. By 2100, minimum temperatures are projected to reach ~10.5–13.5 ℃ under SSP2-4.5 and ~11–17.5 ℃ under SSP5-8.5, with higher magnitudes under the high-emission scenario. Overall, results indicate progressive and sustained warming across all seasons, with SSP5-8.5 amplifying the long-term temperature rise.

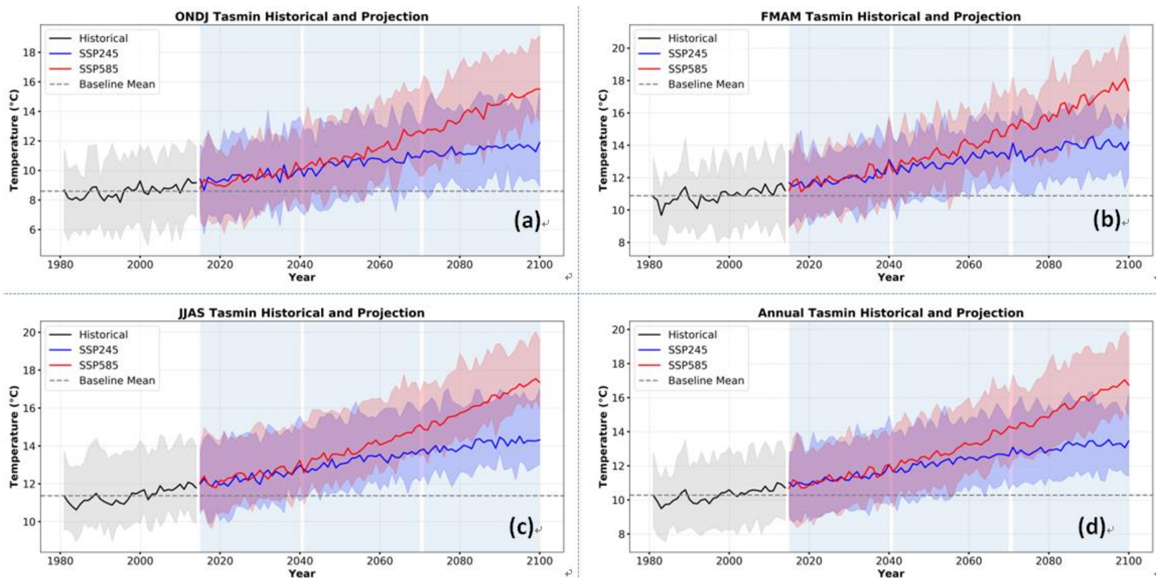


Figure 7. Temporal minimum temperature analysis of Bega [historical-black line (1981-2014) and projection (SSP2-4.5-blue line and SSP4-8.5-red line) trends], Belg [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends], Kiremt [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends] seasons and annual [historical (1981-2014) and projection (SSP2-4.5 and SSP4-8.5) trends (2015-2100)] with baseline mean over Tiyo Woreda.

4.3.3. Historical and Projected Rainfall Frequency

Historical rainfall simulations (1981–2014) indicate increases in Bega (48.5% over 16 years) and decrease (51.5% over 17 years), increases in Belg (48.5% over 16 years) and decrease (51.5% over 17 years), and increases in Kiremt (48.5% over 16 years) and decrease (51.5% over 17 years). Under CMIP6 projections for 2015–2100, SSP2-4.5 shows increases in Bega (51.8% over 44 years) and decrease (48.2% over 41 years), increases in Belg (49.4% over 42 years) and decrease (50.6% over 43 years), and increases in Kiremt (54.1% over 46 years) and decrease (45.9% over 39 years). Similarly, SSP5-8.5 projects increases in Bega (50.6% over 43 years) and decrease (49.4% over 42 years), increases in

Belg (51.8% over 44 years) and decrease (48.2% over 41 years), and increases in Kiremt (43.5% over 37 years) and decrease (56.5% over 48 years). Overall, historical simulations suggest decreasing trends in Bega and Belg, but an increase in Kiremt. In contrast, future projections under both SSP2-4.5 and SSP5-8.5 indicate enhanced rainfall in Belg and Kiremt, with Bega showing mixed responses.

For the near term (2015–2040), SSP2-4.5 projects increases in Bega (48.0% over 12 years), increases in Belg (44.0% over 11 years), and increases in Kiremt (56% over 14 years). Mid-term (2041–2070) projections show increases in Bega (55.2% over 16 years), increases in Belg (48.3% over 14 years), and increases in Kiremt (51.7% over 15 years). End-term (2071–2100) projections show increases in Bega (55.2% over 16 years), increases in Belg (55.2% over 16 years), and increase in Kiremt (55.2% over 16 years). On average, SSP2-4.5 indicates near-term increases in Bega and Kiremt but a decline in Belg; mid-term decreases in Bega but increases in Belg and Kiremt; and end-term decreases in Kiremt but increases in Bega and Belg (Table 2).

Under SSP5-8.5, near-term increases are projected in Bega (56.0% over 14 years), increases in Belg (48.0% over 12 years), and increases in Kiremt (32.0% over 8 years). Mid-term increases are projected in Bega (51.7% over 15 years), increases in Belg (51.7% over 15 years), and increases in Kiremt (51.7% over 15 years). End-term projections indicate increases in Bega (48.3% over 14 years), increases in Belg (51.7% over 17 years), and increases in Kiremt (48.3% over 14 years).

In summary, historical records show mixed rainfall trends, but CMIP6 models project overall increases in seasonal rainfall, with Belg and Kiremt showing stronger and more consistent increases, particularly under SSP5-8.5. Historical simulations show mixed rainfall trends, with decreases in Bega and Belg but increases in Kiremt. CMIP6 projections under SSP2-4.5 and SSP5-8.5 indicate overall increases in seasonal rainfall, with Belg and Kiremt exhibiting stronger and more consistent gains, particularly under the high-emission scenario.

Table 2. *CMIP6 models average rainfall simulation of historical and projection on SSP2-4.5 and SSP5-8.5 emission scenarios across seasonal and annual enhancing and reducing rainfall.*

Historical	**Historical Bega**	**Historical Belg**	**Historical Kiremt**	**Historical Annual**
Years increase Rainfall (1981-2014)	16(48.5%)	16(48.5%)	16(48.5%)	15(45.5%)
Years decrease Rainfall (1981-2014)	17(51.5%)	17(51.5%)	17(51.5%)	18(54.5%)

SSP2-4.5	**Projection SSP2-4.5 Bega**	**Projection SSP2-4.5 Belg**	**Projection SSP2-4.5 Kiremt**	**Projection SSP2-4.5 Annual**
Years increase Rainfall (2015-2100)	42(51.8%)	42(49.4%)	46(54.1%)	43(50.6%)
Years decrease Rainfall (2015-2100)	41(48.2%)	43(50.6%)	39(45.9%)	42(49.4%)

SSP5-8.5	**Projection SSP5-8.5 Bega**	**Projection SSP5-8.5 Belg**	**Projection SSP5-8.5 Kiremt**	**Projection SSP5-8.5 Annual**
Years increase Rainfall (2015-2100)	43(50.6%)	44(51.8%)	37(43.5%)	42(49.4%)
Years decrease Rainfall (2015-2100)	42(49.4%)	41(48.2%)	48(56.5%)	43(50.6%)

Seasonal	**SSP2-4.5 Bega**	**SSP2-4.5 Belg**	**SSP2-4.5 Kiremt**	**SSP5-8.5 Bega**	**SSP5-8.5 Belg**	**SSP5-8.5 Kiremt**
Near term-years increase	12(48%)	11(44%)	14(56%)	14(56%)	12(48%)	8(32%)
Near term-years decrease	13(52%)	14(56%)	11(44%)	11(44%)	13(52%)	17(68%)
Mid-term-years increase	16(55.2%)	14(48.3%)	15(51.7%)	15(51.7%)	15(51.7%)	15(51.7%)
Mid-term-years decrease	13(44.8%)	15(51.7%)	14(48.3%)	14(48.3%)	14(48.3%)	14(48.3%)
End term-years increase	16(55.2%)	16(55.2%)	16(55.2%)	14(48.3%)	15(51.7%)	14(48.3%)

Seasonal	SSP2-4.5 Bega	SSP2-4.5 Belg	SSP2-4.5 Kiremt	SSP5-8.5 Bega	SSP5-8.5 Belg	SSP5-8.5 Kiremt
End term-years decrease	13(44.8%)	13(44.8%)	13(44.8%)	15(51.7%)	14(48.3%)	15(51.7%)

Annual	SSP2-4.5	SSP5-8.5
Near term-years increase	14(56.0%)	12(48.0%)
Near term-years decrease	11(44.0%)	13(52.0%)
Mid-term-years increase	14(48.3%)	15(51.7%)
Mid-term-years decrease	15(51.7%)	14(48.3%)
End term-years increase	15(51.7%)	14(48.3%)
End term-years decrease	14(48.3%)	15(51.7%)

Table 3*. CMIP6 models average maximum temperature simulation of historical and projection on SSP2-4.5 and SSP5-8.5 emission scenarios across seasonal and annual enhancing and reducing temperature.*

Scenario	Type	Bega	Belg	Kiremt	Annual
Historical 1981-2014	Years increase Tmax	14 (41.2%)	18 (52.9%)	16 (47.1%)	16 (47.1%)
	Years decrease Tmax	20 (58.8%)	16 (47.1%)	18 (52.9%)	18 (52.9%)
SSP2-4.5 (2015-2100)	Years increase Tmax	85 (98.8%)	78 (90.7%)	84 (97.7%)	86 (100.0%)
	Years decrease Tmax	1 (1.2%)	8 (9.3%)	2 (2.3%)	0 (0.0%)
SSP5-8.5 (2015-2100)	Years increase Tmax	84 (97.7%)	83 (96.5%)	84 (97.7%)	86 (100.0%)
	Years decrease Tmax	2 (2.3%)	3 (3.5%)	2 (2.3%)	0 (0.0%)
SSP2-4.5 Near-term	Years increase Tmax	25 (96.2%)	19 (73.1%)	24 (92.3%)	26 (100.0%)
	Years decrease Tmax	1 (3.8%)	7 (26.9%)	2 (7.7%)	0 (0.0%)
SSP2-4.5 Mid-term	Years increase Tmax	30 (100.0%)	29 (96.7%)	30 (100.0%)	30 (100.0%)
	Years decrease Tmax	0 (0.0%)	1 (3.3%)	0 (0.0%)	0 (0.0%)
SSP2-4.5 End-term	Years increase Tmax	30 (100.0%)	30 (100.0%)	30 (100.0%)	30 (100.0%)
	Years decrease Tmax	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
SSP5-8.5 Near-term	Years increase Tmax	24 (92.3%)	23 (88.5%)	24 (92.3%)	26 (100.0%)
	Years decrease Tmax	2 (7.7%)	3 (11.5%)	2 (7.7%)	0 (0.0%)
SSP5-8.5 Mid-term	Years increase Tmax	30 (100.0%)	30 (100.0%)	30 (100.0%)	30 (100.0%)
	Years decrease Tmax	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
SSP5-8.5 End-term	Years increase Tmax	30 (100.0%)	30 (100.0%)	30 (100.0%)	30 (100.0%)
	Years decrease Tmax	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)

5. Conclusion and Discussion

We conclude that depend on the results, CMIP6 models of historical and projection trends indicated with simulations and future high-emission scenarios across rainfall, maximum and minimum temperature slightly increased over seasonal and annual.

5.1. Rainfall Trends

Historical analysis (1981–2014) indicates a mixed pattern in seasonal rainfall across Arsi Zone Tiyo Woreda. Bega and Belg seasons experienced decreases in rainfall, while the Kiremt season showed an increase. These findings align with broader regional trends observed in TiyoWoreda, where rainfall variability and extremes have intensified due to climate change.

Future projections under CMIP6 scenarios (SSP2-4.5 and SSP5-8.5) suggest an overall increase in seasonal rainfall by the end of the 21st century. Notably, Belg and Kiremt seasons are expected to experience more significant increases compared to Bega. This pattern is consistent with projections for other parts of Ethiopia, where climate models indicate enhanced rainfall during the main rainy seasons under higher emission scenarios.

5.2. Temperature Trends

Both historical and projected data reveal a consistent warming trend in minimum temperatures across all seasons. Historical data (1981–2014) show increases in minimum temperatures, with projections under SSP2-4.5 and SSP5-8.5 scenarios indicating further warming by the end of the century. This aligns with findings from other studies in Ethiopia-TiyoWoreda, where CMIP6 models project significant increases in both maximum and minimum temperatures under various emission scenarios.

5.3. Implications for Agriculture and Livelihoods

The observed and projected climatic changes have profound implications for agriculture and livelihoods in Arsi ZoneTiyoWoreda. The mixed rainfall trends, with decreases in Bega and Belg seasons and increases in Kiremt, could affect crop production patterns, particularly for crops dependent on the Belg rains. The consistent warming trend may exacerbate evapotranspiration rates, potentially leading to water stress during critical growing periods.

Adaptation strategies are essential to mitigate these impacts. These may include adjusting planting schedules, selecting drought-resistant crop varieties, and improving water management practices. Additionally, enhancing climate resilience through community-based approaches and integrating climate information into agricultural planning will be crucial for sustaining livelihoods in the face of changing climatic conditions.

Abbreviations

CHIRPS	Climate Hazards Group Infra-Red Precipitation with Stations
CMIP6	Coupled Model Intercomparison Project Phase 6
ECMWF	European Centre for Medium-Range Weather Forecasts
ESMs	Earth System Models
FMAM	February, March April, May
GCMs	Global Circulation Models
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
JJAS	June, July, August, September
MME	Multi-Model Ensemble
MMM	Multi-Model Mean
°C	Degree Centigrade
ONDJ	October, November, December, January
S3S	Copernicus Climate Change Service
SSPs	Shared Socioeconomic Pathways

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Data Availability Statement

The data is available as request.

Conflicts of Interest

The authors declare no conflicts of interest.

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