A 40-Year Remote Sensing Analysis of Spatiotemporal Temperature and Rainfall Patterns in Senegal

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Scope Statement

This study utilizes multiple satellite-based climate datasets - including CHIRPS precipitation, MODIS land surface temperature, and ERA5-Land air temperature reanalysis - to comprehensively analyze recent spatiotemporal trends and variability in rainfall, temperature, and vegetation across Senegal from 1981 to 2020. The research demonstrates the value of leveraging remote sensing data products to monitor climatic changes and extremes where ground-based observations are limited. The findings quantify significant increases in rainfall and warming across different agro-ecological regions in Senegal. The study assesses the implications of these climate trends for agriculture, water resources, flooding, and other impacts. The focus on historical climate data recovery and monitoring of environmental changes using satellite Earth observations aligns with the scope of Frontiers in Climate's Climate Monitoring section. The spatiotemporal analysis of multiple climate variables provides insights into climate dynamics, extremes, threats, and human influences through land use changes in Senegal. The research has multidisciplinary relevance, touching on climate science, environmental monitoring, agriculture, and sustainability. Therefore, this study's novel remote sensing-based climate trend analysis for an understudied region makes it well-suited to the Climate Monitoring specialty in Frontiers in Climate.

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

Credit Author Statement

Mamadou Adama Sarr: Writing – review & editing. Catherine Lilian Nakalembe: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. Diana Botchway Frimpong: Data curation, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. Hannah Kerner: Writing – review & editing.

Keywords

Senegal, climate variability, satellite remote sensing, Google Earth Engine, Timeseries analyses, dynamics

Abstract

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Climate change impacts manifest differently worldwide, with many African countries, including Senegal, being particularly vulnerable. The decline in ground observations and limited access to these observations continue to impede research efforts to understand, plan, and mitigate the current and future impacts of climate change. This occurs at a time of rapid growth in Earth observations (EO) data, methodologies, and computational capabilities, which could potentially augment studies in data-scarce regions. In this study, we utilized satellite remote sensing data leveraging historical EO data using Google Earth Engine to investigate spatio-temporal rainfall and temperature patterns in Senegal from 1981 to 2020. We combined CHIRPS precipitation data and ERA5-Land reanalysis datasets for remote sensing analysis and used the Mann-Kendall and Sen's Slope statistical tests for trend detection. Our results indicate that annual temperatures and precipitation increased by 0.73°C and 18 mm in Senegal from 1981 to 2020. All six of Senegal's agroecological zones showed statistically significant upward precipitation trends. However, the Casamance, Ferlo, Eastern Senegal, Groundnut Basin, and Senegal River Valley regions exhibited statistically significant upward trends in temperature. In the south, the approach to climate change would be centered on the effects of increased rainfall, such as flooding and soil erosion. Conversely, in the drier northern areas such as Podo and Saint Louis, the focus would be on addressing water scarcity and drought conditions. High temperatures in key crop-producing regions, such as Saraya, Goudiry, and Tambacounda in the Eastern Senegal area also threaten crop yields, especially maize, sorghum, millet, and peanuts. By acknowledging and addressing the unique impacts of climate change on various agroecological zones, policymakers and stakeholders can develop and implement customized adaptation strategies that are more successful in fostering resilience and ensuring sustainable agricultural production in the face of a changing climate.

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Studies involving human subjects

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Inclusion of identifiable human data

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Data availability statement

Generated Statement: The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: GEE Application to be shared.

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Abstract. Climate change impacts manifest differently worldwide, with many African countries, including Senegal, being particularly vulnerable. The decline in ground observations and limited access to these observations continue to impede research efforts to understand, plan, and mitigate the current and future impacts of climate change. This occurs at a time of rapid growth in Earth observations (EO) data, methodologies, and computational capabilities, which could potentially augment studies in data-scarce regions. In this study, we utilized satellite remote sensing data leveraging historical EO data using Google Earth Engine to investigate spatio-temporal rainfall and temperature patterns in Senegal from 1981 to 2020. We combined CHIRPS precipitation data and ERA5-Land reanalysis datasets for remote sensing analysis and used the Mann-Kendall and Sen's Slope statistical tests for trend detection. Our results indicate that annual temperatures and precipitation increased by 0.73°C and 18 mm in Senegal from 1981 to 2020. All six of Senegal's agroecological zones showed statistically significant upward precipitation trends. However, the Casamance, Ferlo, Eastern Senegal, Groundnut Basin, and Senegal River Valley regions exhibited statistically significant upward trends in temperature. In the south, the approach to climate change would be centered on the effects of increased rainfall, such as flooding and soil erosion. Conversely, in the drier northern areas such as Podo and Saint Louis, the focus would be on addressing water scarcity and drought conditions. High temperatures in key crop-producing regions, such as Saraya, Goudiry, and Tambacounda in the Eastern Senegal area also threaten crop yields, especially maize, sorghum, millet, and peanuts. By acknowledging and addressing the unique impacts of climate change on various agroecological zones, policymakers and stakeholders can develop and implement customized adaptation strategies that are more successful in fostering resilience and ensuring sustainable agricultural production in the face of a changing climate.

Keywords: Senegal, Climate variability, Satellite Remote Sensing, Google Earth Engine

1. Introduction

The impacts of climate change manifest uniquely across the world's regions, and Africa remains one of the hotspots of its crippling effects [1, 2]. Climate change impacts ecosystems, people, infrastructure, and agriculture. Extensive empirical research has shown that many African countries, including Senegal, face substantial exposure, have limited adaptive capacity, and exhibit low resilience to climate change and its impacts [3, 4, 2]. This is a significant environmental injustice because Africa has contributed the least to global greenhouse gas emissions of all populated continents [5, 6].

In Senegal, poverty and food insecurity compound climate impacts, and research has shows that the impacts on agriculture are mixed. Araya et al. [7] predicted significant declines of 16 to 20% in peanut yields in Senegal for the period 1981-2005 due to rising temperatures. In contrast, Konte et al. [8] found that rising temperatures could positively impact rice and maize yields in Senegal while potentially harming the growth of other crops, such as sorghum. Ultimately, the impacts of climate change vary across countries within and across agroecological zones, and understanding how to mitigate these impacts will require more localized research.

Access to reliable station-based climate data in Africa remains a significant challenge owing to the uneven distribution of weather stations and poor data quality, resulting in substantial data gaps [9, 10, 11, 12]. Despite these limitations, research on climate trends in countries such as Senegal has primarily relied on data from in situ meteorological stations [13, 9]. However, approaches that depend solely on in-situ station data face challenges in remote and sparsely gauged areas, in addition to the well-documented difficulty in accessing hydrological and meteorological data [9, 14, 15, 16].

The accuracy of data collected from meteorological stations is often questionable because of unusual data values, errors in handwritten records, data unavailability, and significant data gaps [17, 10]. Undetected data quality issues can profoundly affect climatological analyses, leading to biased results and substantial uncertainties [18]. Consequently, it is crucial to explore alternative approaches to study climate trends in regions with limited station data to fill informational gaps and provide a more comprehensive understanding of the climate in these areas.

Advances in geospatial technology and easier access to high-performance computing resources such as Google Earth Engine (GEE), which stores multi-petabyte curated satellite datasets and facilitates the processing of large datasets, make it possible to implement complex data-intensive analyses of remote sensing data quickly and effectively [19]. Satellite data cover vast, remote areas that are difficult to access or lack dense networks of climate stations [20]. The increasing availability of satellite data has enabled the development and application of machine learning models to analyze climate data with greater precision and detail [21]. This has the potential to help the world understand the dynamics and effects of climate change at different scales and solve urgent environmental problems, such as food insecurity [22]. GEE houses easily obtainable high spatial and temporal resolution agriculture, precipitation, and atmospheric observation data. Some of these include the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS), Tropical Rainfall Measuring Mission (TRMM 3B42), and ECMWF atmospheric reanalysis 5 (ERA5) [19]. Satellite-based rainfall and temperature retrieval algorithms are becoming increasingly popular for climate research owing to their scalability and complementary data to station-based hydro-meteorological data. CHIRPS data, for example, has a strong correlation and relatively lower bias compared to using only station data for monitoring precipitation or drought [23, 24]. However, satellite-derived estimates still have limitations, particularly in high elevation regions and poorer estimates on a daily timescale in Africa due to insufficient data required for downscaling [25, 26, 27]. Other satellite-based products, including the Moderate Resolution Imaging Spectroradiometer (MODIS) and ERA5, have also been evaluated. These studies showed highly consistent results between ERA5 and MODIS in evaluating global and regional land warming trends over the past decades, with strong correlations to observed meteorological station data [28]. The Collection 6 MODIS Land Surface Temperature (LST) product has been validated in various studies, particularly over bare soil surfaces [29, 30, 29].

This study aims to assess the unique spatio-temporal trends in precipitation and temperature in Senegal from 1981 to 2020, leveraging satellite-retrieved datasets accessible in GEE. We analyzed annual and seasonal temperature and precipitation across Senegal and estimated them in all six agroecological zones of Senegal. The methods presented in this study offer a robust and reproducible approach for regions in which ground-based observations are scarce.

1.1. Study Area

Senegal is a West African country located between 12.5°C and 16.7°C N latitudes and 11.3° and 17.5°W longitude (Figure 1). Its population was 16,876,720 in 2020, representing a 15% increase from 2015 [31]. Senegal has a tropical climate with a distinct dry season from November to June and a rainy season from July to October. Average annual temperatures have increased from 28.6°C in 2000 to 29.56°C in 2020, with a hot semi-arid climate inland and coastal tropical conditions [32].

Senegal is divided into six major agro-ecological zones based on climate, soil, and vegetation characteristics: the Niayes, Senegal River Valley, Peanut Basin, Casamance, Eastern Senegal, and Sylvo-Pastoral Zone [33, 34]. The Niayes zone along the coast has cooler temperatures and unique humid micro-climates conducive to horticulture. The Senegal River Valley in the north has hot, dry conditions but supports irrigated agriculture. The Peanut Basin in the central regions has relatively abundant rainfall for rainfed agriculture. Casamance and Eastern Senegal receive high rainfall with frequent risks of flooding. The Sylvo-Pastoral Zone has a hot, semi-arid climate suitable for agro-pastoralism.

Agriculture is Senegal's main economic sector, employing 22% of the workforce and contributing 15.7% to GDP in 2022, despite a decline since the 1990s [32, 35]. With

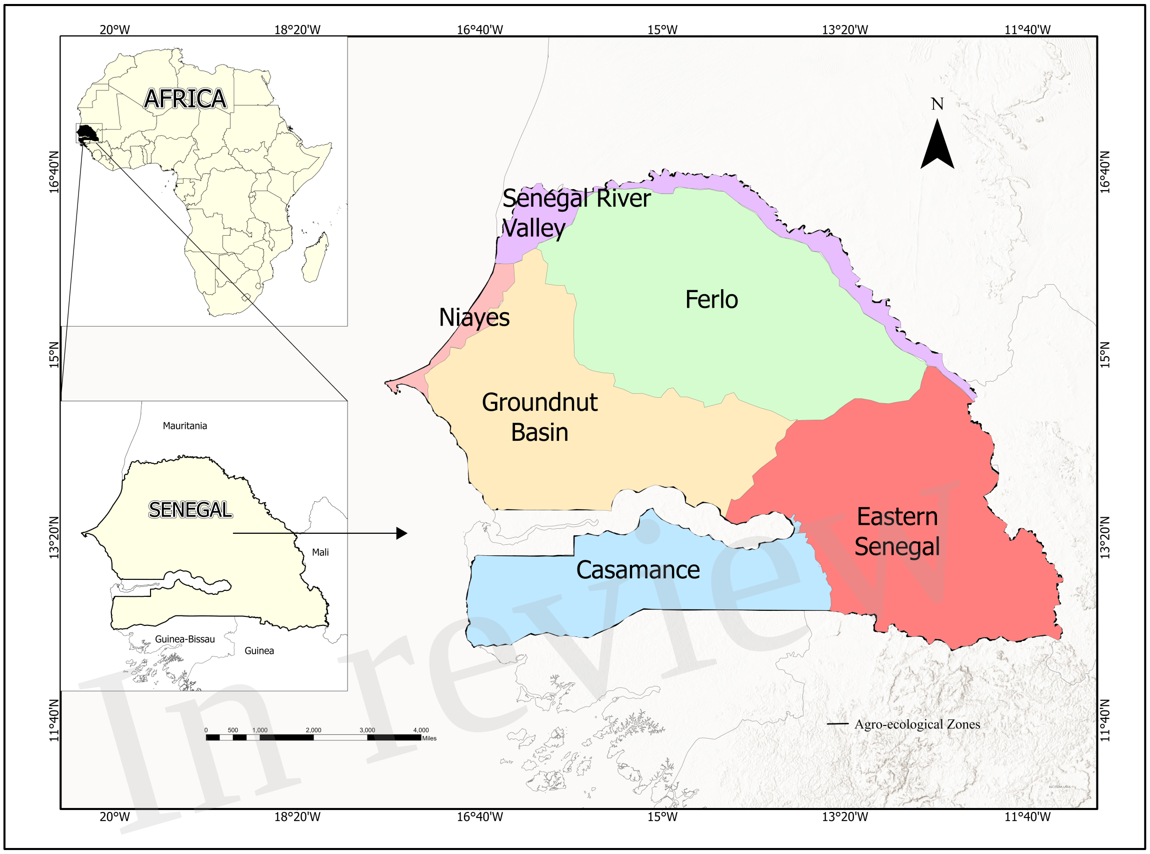


Figure 1. Map of Senegal Showing the Major Agro-Ecological Zones/Ecoregions defined in [33]

over 95% of arable land being dependent on rainfall, agriculture is highly vulnerable to climate change impacts on crop yields [36, 37]. Limited resources and reliance on smallholder farming constrain Senegal's adaptive capacity, whereas poverty and food insecurity exacerbate the effects of climate change [38, 39]. Although peanut farming has dominated, crop diversification has increased since the 1980s [40]. Climate-smart strategies are crucial for enhancing resilience and ensuring future food security amidst climate change. To address these challenges, the government should prioritize development strategies through the continuous assessment and monitoring of changes in agro-ecological zones.

2. Methodology

2.1. Datasets

Table 1 summarizes the datasets used in this study. These include the gridded rainfall data from CHIRPS and air temperature data from ERA5-Land reanalysis.

Table 1. Summary of the datasets used in the study

Dataset	Resolution	Dataset Provider	Duration
CHIRPS	0.05°	USGS and CHC CHIRPS Data	1981-2020
ERA5-Land Reanalysis	0.1°	ECMWF / Copernicus Climate Change Service	1981-2020

2.1.1. CHIRPS Rainfall Data: CHIRPS incorporates satellite imagery and station data to produce a 0.05° resolution gridded rainfall product for trend analysis and drought monitoring [41]. We accessed CHIRPS data via GEE monthly from 1981 to 2020 (ee.ImageCollection("UCSB-CHG/CHIRPS/PENTAD") [41]. Previous studies validated CHIRPS against station observations and other satellite precipitation datasets and showed high accuracy in West Africa [42, 43, 44]. The availability of a 40-year CHIRPS time series enabled this study's precipitation trend analysis in Senegal.

2.1.2. ERA5-Land Air Temperature: The ERA5-Land dataset from the European Center for Medium-Range Weather Forecasts provides consistent global atmospheric reanalysis data from 1950-present at $\sim$ 11 km resolution, dynamically downscaled from the native 9 km product [45]. Although coarse, ERA5-Land has been effectively downscaled using statistical and machine learning techniques in Africa and provides reliable temperature data for long-term trend analysis [46, 47, 48, 45]. ERA5-Land data are readily available as an asset from GEE from 1950 to three months from real-time. (ee.ImageCollection("ECMWF/ERA5_LAND/HOURLY").

3. Approach

We analyzed precipitation and temperature patterns in Senegal from 1981 to 2020 using CHIRPS rainfall and ERA5-Land temperature data. Seasonal and monthly averages were calculated, and zonal statistics were derived for each agroecological zone [33]. Figure 2 summarizes the workflow.

Data were extracted and processed in GEE. Monthly and seasonal statistics were calculated efficiently using ee.Reducer functions allowed for the derivation of temporal patterns. Zonal statistics were computed with ee.Image.reduceRegions() to analyze spatial variability across different regions. GEE's powerful processing capabilities facilitated a robust and streamlined workflow for data extraction, quality checking, and statistical analysis.

3.1. Trend Analysis

We quantified trends in each pixel using the non-parametric Mann-Kendall test for trend significance and Sen's slope estimator for magnitude [49, 50]. These methods are robust for assessing monotonic trends in climate time series without requiring assumptions regarding data distribution. They are increasingly used for precipitation

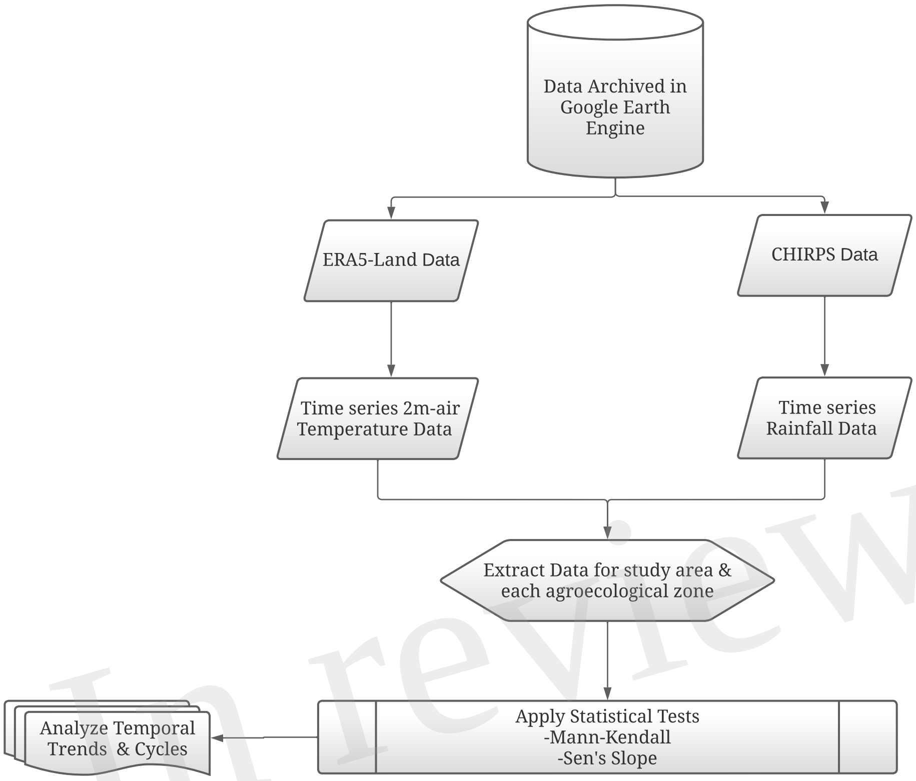


Figure 2. Methodological flowchart outlining the key steps in analyzing temperature and precipitation trends across Senegal from 1981–2020 using CHIRPS, MODIS, and ERA5-Land datasets in GEE and R.

and temperature change analysis, including recent implementations in Google Earth Engine [51, 52].

The Mann-Kendall test was applied to each pixel time series to determine the presence of significant increasing or decreasing trends. In GEE, this was implemented using the ee.Reducer.mannKendall() function, which calculates the Mann-Kendall test statistic (S) and p-value based on the rank correlation between the time series values and their temporal order. Pixels with an absolute S value greater than 1.96 (corresponding to a p-value < 0.05) were considered to have a significant trend at the 95% confidence level.

We used Sen's slope, which calculates the median slope between all pairwise points in a time series, to estimate the magnitude of significant trends. In GEE, this was implemented using the ee.Reducer.sensSlope() function. For each pixel, the median slope was calculated if the Mann-Kendall test indicated a significant trend (p ¡ 0.05).

To summarize trends at the agroecological zone level, we first calculated the spatial averages of the annual precipitation and temperature time series within each zone using the ee.Image.reduceRegions() function with the agroecological zone boundaries [33] as input features. Each zone's resulting annual time series were then exported to R, where the Mann-Kendall and Sen's slope tests were applied using the 'trend' package to assess long-term regional trends.

This approach leverages the computational power of GEE to efficiently apply trend tests to each pixel across the entire study area, while also allowing for more detailed regional summaries. The 40-year CHIRPS and ERA5-Land datasets enabled a statistically robust assessment of recent climate changes at both the pixel and agroecological zone scales. The key equation is simplified as follows:

Calculate the Mann-Kendall test statistic S using Equation 1[50]:

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

where

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

For $n > 10$, compute the variance of S:

$$\mathrm{VAR}(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)}{18} \tag{3}$$

where n is the number of observations, g the number of tied groups, and t_p is the number of observations tied to a particular value.

Compute the Mann-Kendall test statistic Z_{MK}:

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\mathrm{VAR}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\mathrm{VAR}(S)}}, & \text{if } S < 0 \end{cases} \tag{4}$$

To test for a monotonic trend at a significance level α, compare Z_{MK} to the critical values of the standard normal distribution: For an upward trend, reject H_0 if $Z_{MK} \geq Z_{1-\alpha}$ For a downward trend, reject H_0 if $Z_{MK} \leq -Z_{1-\alpha}$ For a two-tailed test, reject H_0 if $|Z_{MK}| \geq Z_{1-\alpha/2}$

The MK test determined whether the precipitation or temperature time series of each pixel showed a significant trend at the 95% confidence level. Pixels with $MKstatistic \geq 1.96$ were considered to have a significant trend.

Additionally, we quantified the magnitude of the trend using non-parametric Sen's slope method [49]. Sen's slope estimates the magnitude of the change per unit time. It calculates the median of all pairwise slopes between sequential data points and quantifies the trend slope. Equation 5 estimates the slope from the time series data [49]:

$$dijk = \frac{xij - xik}{j - k} \tag{5}$$

where xij and xik are the data values and j and k are the time series.

We implemented Sen's slope in GEE to estimate the monotonically increasing/decreasing tendency over time and in R for each agro-ecological zone. Temperature and precipitation data were extracted for each zone, and statistical tests were applied to detect trends over time.

However, it is important to recognize the limitations of this approach. Although the satellite-based datasets used here have been extensively validated and shown to perform well, there is still potential for bias and uncertainty, particularly in areas with complex topography or limited in-situ data for calibration [25, 26]. The 0.05° and 0.1° spatial resolutions of CHIRPS and ERA5-Land, respectively, may also smooth out fine-scale variability. Integrating the available station observations could help refine the trends identified here.

Additionally, while non-parametric trend tests are robust to non-normality and missing values, they assume the observations are independent. A positive serial correlation can increase the likelihood of detecting significant trends in which none exists [53].

4. Results

4.1. Precipitation Distribution and Variation from 1981-2020

Figure 3 shows the spatial distribution of the mean annual and seasonal precipitation across Senegal, from 1981 to 2020. There was considerable variation in the spatial distribution of precipitation across the different seasons. In the rainy season, the maximum rainfall did not exceed 55mm average rainfall between 1981-2000. However, the average rainfall patterns in the southeast and southwest regions showed distinct shifts between 1981–2000 and 2001–2020, exceeding 65mm in certain regions. Conversely, during the dry season, the entire country experiences exceedingly arid conditions, with the average precipitation across the region for the past four decades falling below 5mm. This stark seasonal contrast underscores the significant variations in precipitation throughout the year.

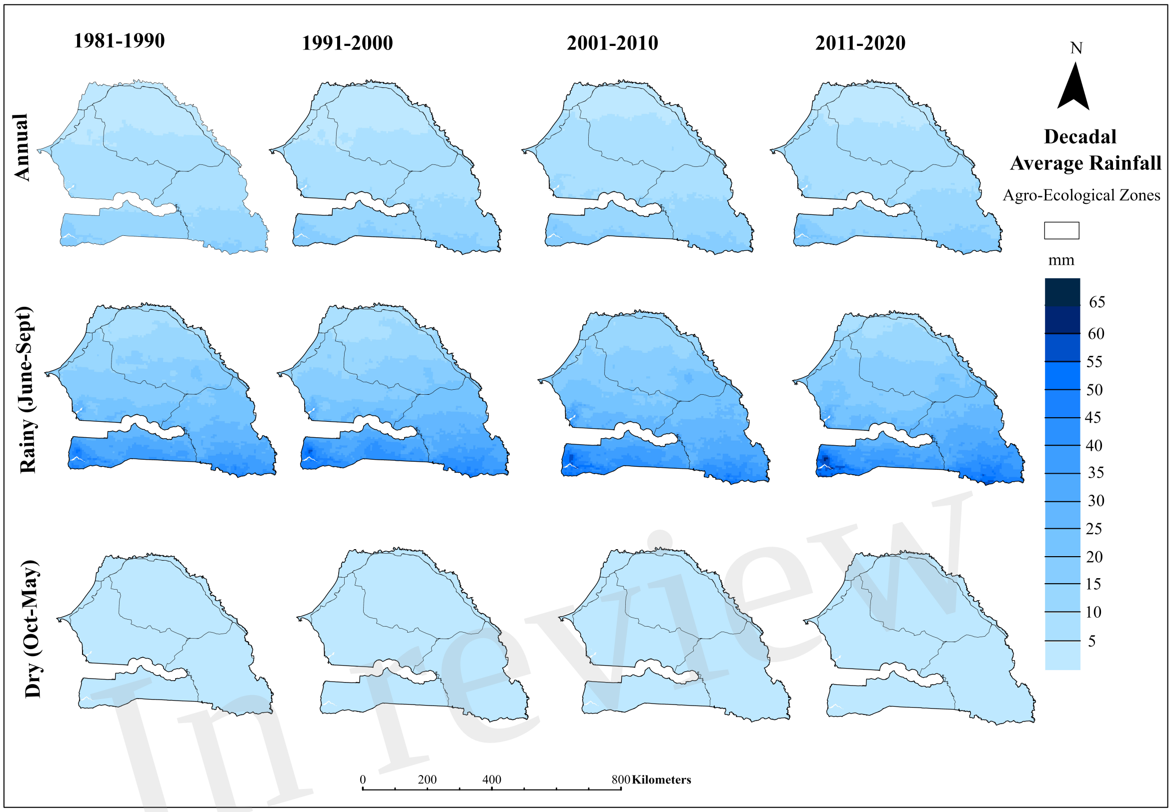


Figure 3. Decadal Mean Annual and Seasonal Rainfall for Senegal, 1981-2020

Figure 3 shows the annual rainfall variations from 1981 to 2020 with alternating periods of dry and wet years within the recorded timeline. This pattern indicates variability in precipitation, with specific years (1983, 1990, 1991, 2011, 2014, and 2019) exhibiting notably drier conditions with lower yearly averages and others displaying increased rainfall or wetter conditions (1999, 2010, and 2020) with higher yearly averages in Senegal. Such variability in annual precipitation suggests fluctuations in the region's climate, with alternating periods of drought and increased moisture levels, potentially impacting agricultural practices, water resource management, and ecological systems. This may be linked to recurrent El Niño events, which significantly affect climatic variability in the Sahel region [54]. Overall, there was a statistically significant increase ($R2 = 0.26$, $p \leq 0.05$) of approximately 18mm in average annual rainfall from 1981 to 2020 (Figure 4).

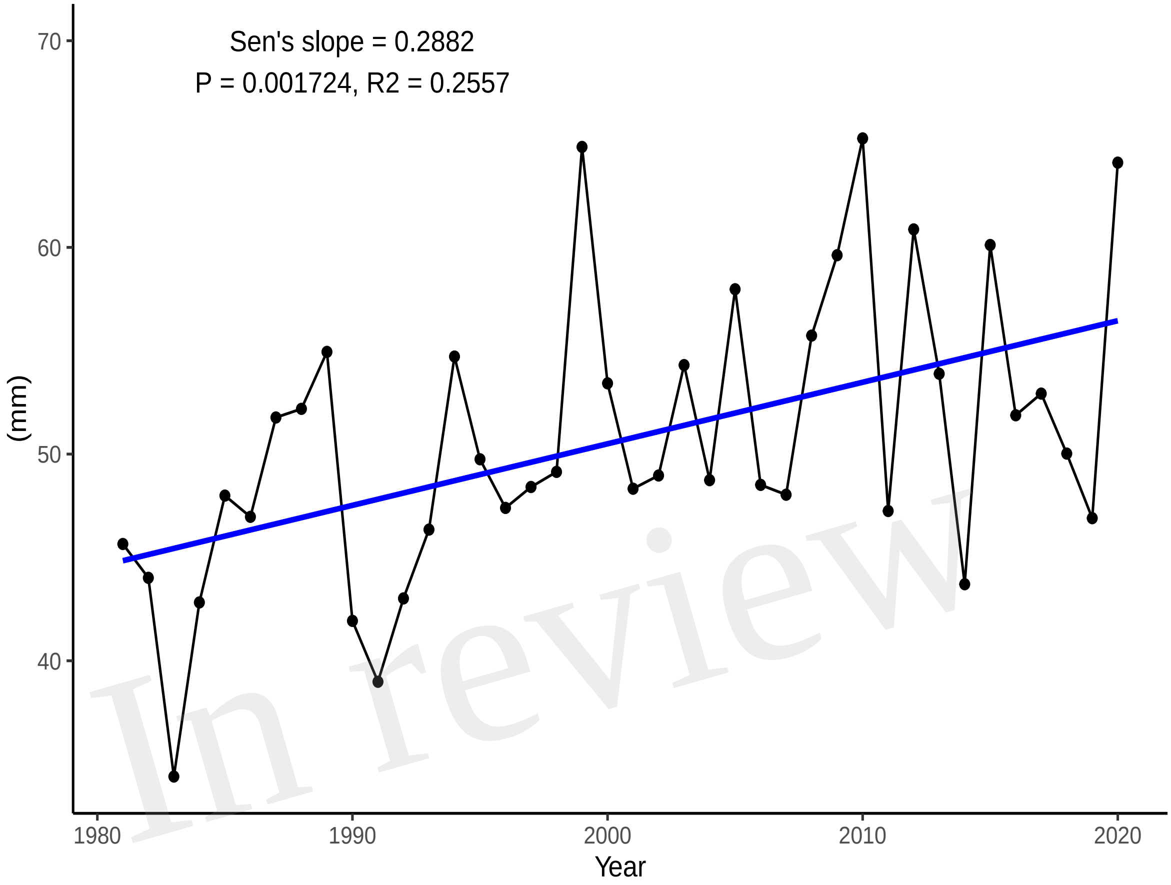


Figure 4. Average Precipitation Trend in Senegal from 1981 - 2020

4.2. Temperature Distribution and Variation from 1981-2020

Figure 5 illustrates the mean temperatures for both the rainy season (June-September) and dry season (October-May) for the periods 1981-2000 and 2001-2020, respectively. Notably, regions closer to water bodies and located in the southern areas, such as Saint Louis, Louga, Keberner, Ziguinchor, and Tivaoune, consistently exhibited lower temperatures ranging from 22°C- 27°C in all seasons. Compared to inland areas, these locations experience a distinct cooling effect owing to proximity to the Atlantic Ocean. The overall analysis revealed a statistically significant increase of 0.73°C ($R2 = 0.24$, $p \leq 0.05$) in the mean temperature from 1981 to 2020 (Figure 6).

Despite the significant increase in temperature across the region over the past four decades, the most recent decade (2011-2020) exhibited a 0.69% decrease compared with the previous decade (2001-2010), as shown in Figure B1 in the supplementary material.

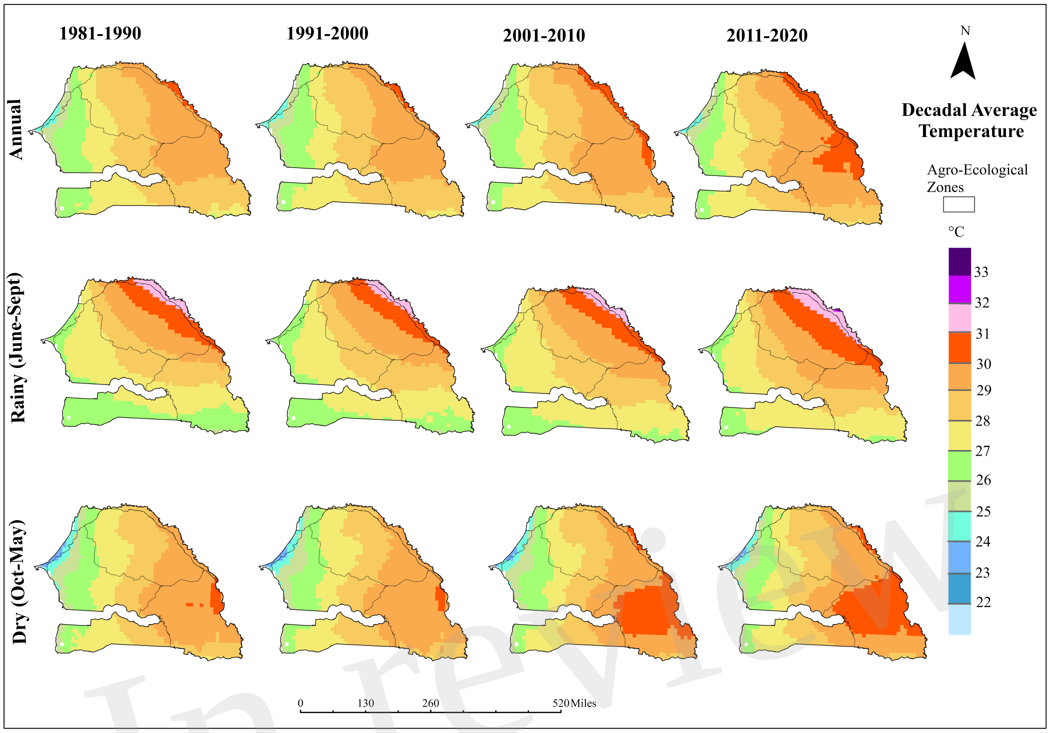


Figure 5. Decadal Mean and Seasonal Temperatures for Senegal, 1981-2020

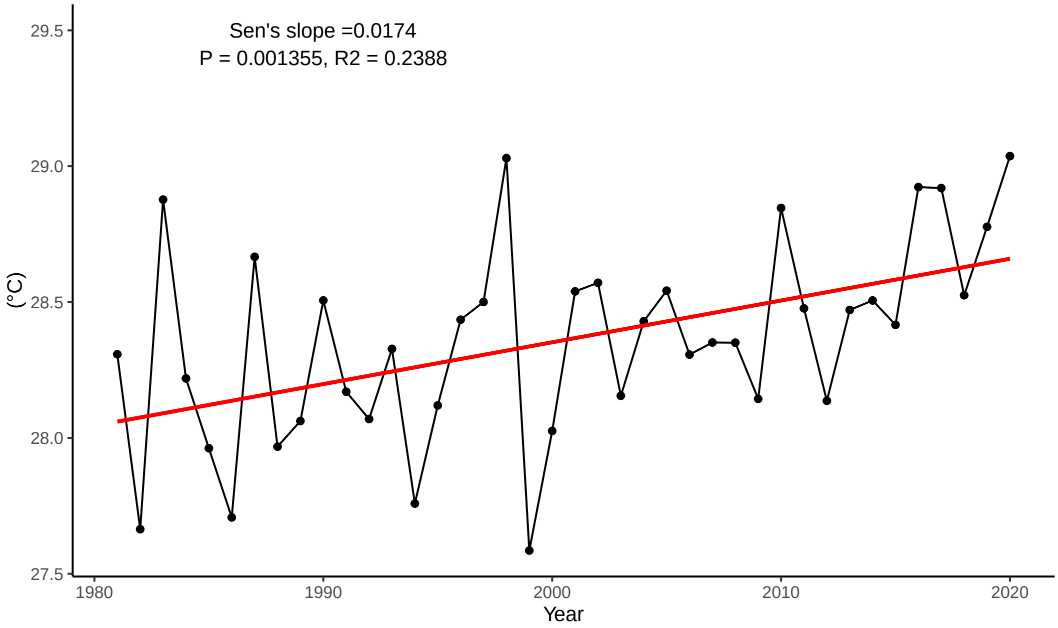
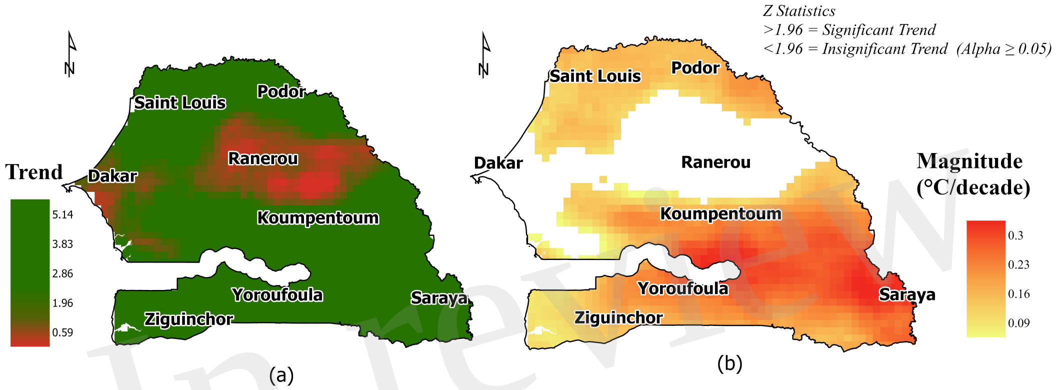


Figure 6. Average Temperature Trend in Senegal from 1981 - 2020

4.3. Spatial Distribution of Temperature Trends

Figure 7 shows the spatial distribution of the temperature trends (a) and the magnitude of the statistically significant trends (b) across Senegal over the past 40 years

(1981–2020). The results revealed widespread warming, with the largest temperature increase concentrated in the inland regions. Areas around Saraya, Goudiry, and Tambacounda have experienced a pronounced warming of 0.2-0.3°C per decade. The hardest-hit areas align with the agriculturally vital Eastern Senegal agroecological zone, a major producer of corn, cotton, millet, peanuts, and sorghum. Considerable warming in this region suggests that crop yields could face mounting heat stress in the coming decades, portending the risk to Senegalese food security.



(a)

(b)

Figure 7. Spatial distribution of (a) temperature trend from 1981 to 2020 using the Mann-Kendall's correlation reducer, and (b) the magnitude of trend in areas with statistically significant trend using the Senslope reducer.

4.4. Spatial Distribution of Precipitation Trends

Figure 8 shows the spatial distribution of the annual precipitation trends from 1981 to 2020 using the Mann-Kendall's correlation reducer and the magnitude of the trend in areas with statistically significant trends. Over the past four decades, most areas in the north, known to be the dry regions of the country, have shown an increasing precipitation tendency, but at a lower magnitude of about 1.42mm per decade. However, the southeast, western parts and coastal Senegal had relatively higher rainfall magnitudes of 6.33 and 17.77 mm per decade, respectively. This includes Bignonia, Goudomp, Ziguanchor, Oussouye, Saraya, Foundiougne, Fatick, and Keberner, which are also known as the wet regions of Senegal (Figure 8b).

4.5. Trends in Precipitation across Agro-Ecological Zones

To further analyze climate variability across Senegal's agroecological zones, we used the Mann-Kendall and Sen's slope statistical tests to identify significant precipitation and temperature trends from 1981 to 2020. Our analysis revealed widespread increases in precipitation, even in the typically driest Senegal River Valley and Ferlo regions (Figure 9). Specifically, the Senegal River Valley has experienced a significant positive precipitation trend over the past four decades ($R2 = 0.14$, $p = 0.04$). Ferlo showed a similar trend ($R2 = 0.18$, $p = 0.01$), both at $P \leq 0.05$.

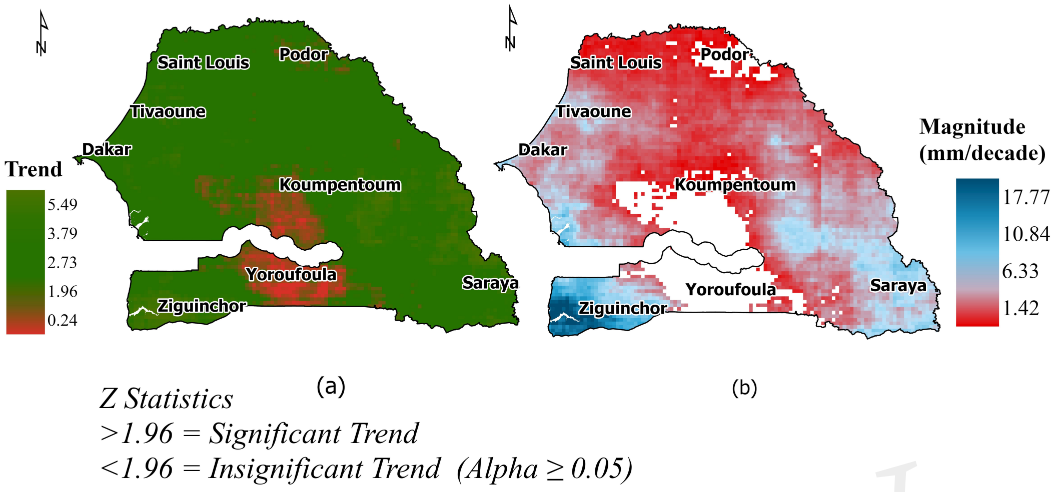


Figure 8. Spatial distribution of (a) yearly precipitation trend from 1981 to 2020 using the Mann-Kendall's correlation reducer, and (b) the magnitude of trend in areas with significant trend using the Senslope reducer.

Table 2. Precipitation trend statistics by agro-ecological zone all significant at $\alpha = 0.05$.

AEZ	P-value	Sen Slope	Z score	Tau	Var(s)
Casamance	0.01	0.35	2.5	0.27	7366.67
Eastern Senegal	0.00	0.39	3.6	0.40	7366.67
Ferlo	0.01	0.18	2.5	0.28	7366.67
Groundnut Basin	0.01	0.25	2.5	0.27	7366.67
Niayes	0	0.34	2.9	0.32	7366.67
Senegal River Valley	0.04	0.15	2.0	0.22	7366.67

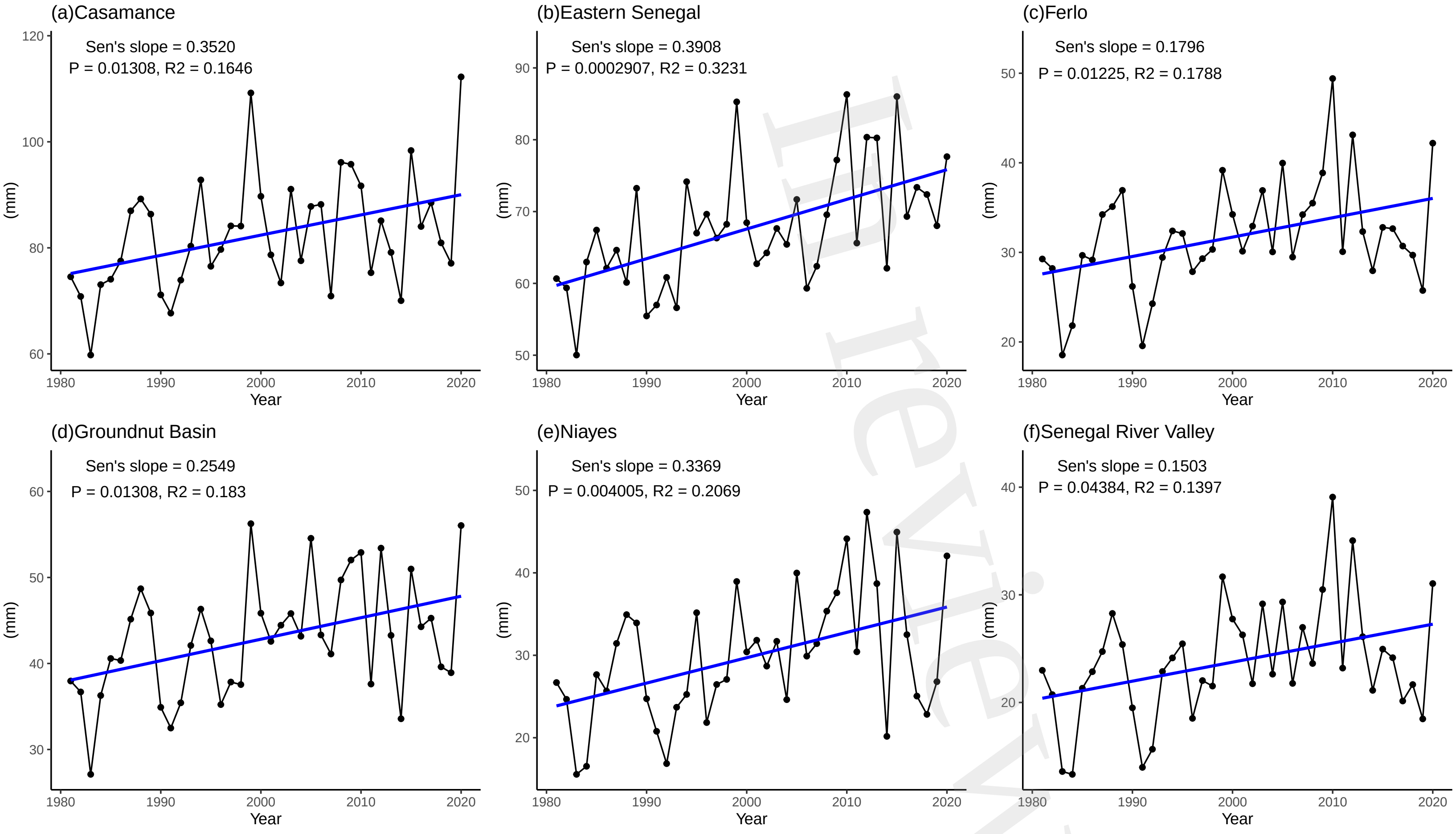


Figure 9. Trends in Precipitation using the Mann-Kendall test for the periods 1981 - 2020

4.6. Trends in Temperature across Agro-Ecological Zones

Our analysis revealed significant warming trends across most of Senegal's agroecological zones from 1981 to 2020, highlighting the spatially heterogeneous nature of climate change impacts. As shown in Figure 10 and Table 3, the Casamance, Eastern Senegal, Ferlo, Groundnut Basin, and Senegal River Valley zones experienced statistically significant temperature increases over the past four decades. The most pronounced warming occurred in the Casamance and Eastern Senegal regions, with Sen's slope values indicating an average increase of 0.16 °C and 0.19 °C per decade ($p < 0.05$) respectively (Table 3). The Ferlo, Groundnut Basin, and Senegal River Valley saw slightly lower but significant warming rates, with average temperatures rising between 0.13°C, 0.12°C, and 0.08°C per decade.

In contrast, the Niayes zone along the coast exhibited moderate and statistically insignificant warming ($R = 0.24$, $P = 0.14$). This result suggests that the cooling may buffer the Niayes from the more rapid temperature increases seen inland.

The divergent temperature trends identified across Senegal's agroecological zones have important implications for planning climate adaptation. The pronounced warming in the southern and eastern regions threatens the productivity of staple crops such as maize, millet, and sorghum, vital for food security [7, 8]. In the Ferlo and Senegal River Valley, increasing temperatures may exacerbate existing drought and desertification risks, with consequences for pastoralist communities [38]. The gradual warming in the Niayes offers some respite but warrants monitoring and preparedness.

Table 3. Temperature trend statistics by agro-ecological zone. Bold indicates significance at $\alpha = 0.05$.

AEZ	P-value	Sen Slope	Z score	Tau	Var(s)
Casamance	0	**0.02**	4.3	0.47	7366.67
Eastern Senegal	0	**0.02**	4.0	0.44	7366.67
Ferlo	0.02	**0.02**	2.4	0.26	7366.67
Groundnut Basin	0.01	**0.01**	2.6	0.29	7366.67
Niayes	0.11	0.01	1.6	0.18	7366.67
Senegal River Valley	0	**0.02**	2.9	0.32	7366.67

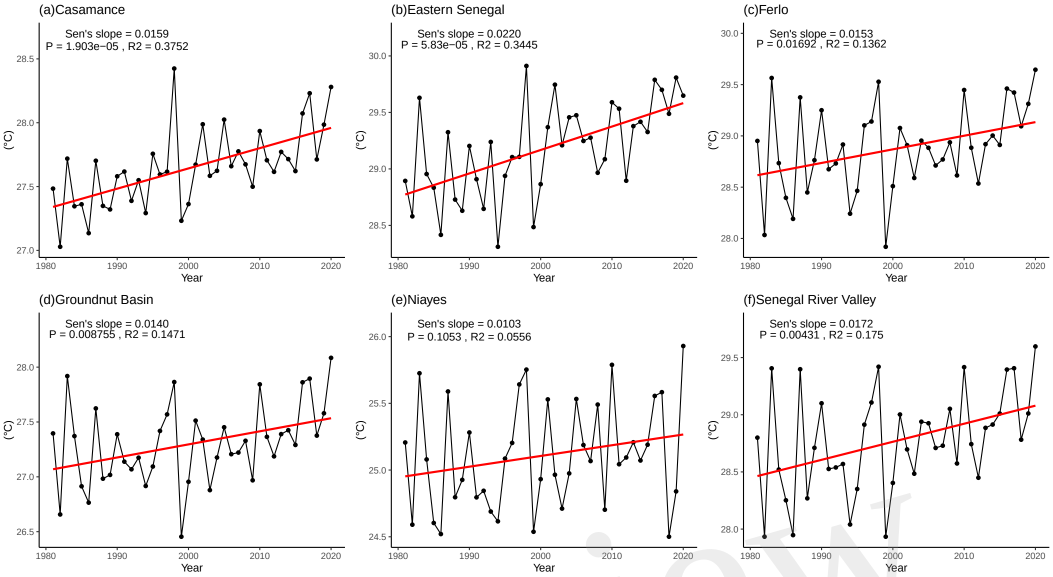


Figure 10. Trends in Temperature using the Mann-Kendall Test for the period 1981-2020

5. Discussion

This study analyzed precipitation and temperature patterns across Senegal from 1981 to 2020, revealing insights into the country's climate variability. Examining mean rainy and dry season temperatures showed interesting geographic contrasts, notably cooler temperatures near water bodies than inland areas. Locations along the coast and near rivers (Saint Louis, Louga, and Ziguinchor) consistently experienced 22-27°C across seasons, while inland sites experienced higher temperatures. This localized cooling effect suggests that the presence of water bodies moderates temperature extremes.

Monitoring such spatial temperature differences and cooling influences is essential for understanding climate change. If inland warming outpaces coastal areas, it could compound existing climate risks, such as droughts or heat stress for inland farmers and pastoralists. Sustained inland warming could also pressure internal migration toward cooler coastal cities. Further analysis of the temperature-moderating effects of Senegal's lakes, rivers, and oceans is therefore important.

Additionally, our study provides valuable insights into localized climatic variations across the six agroecological zones of Senegal. These findings reveal that Senegal's climate exposure is far from uniform. The southern Casamance and Eastern Senegal zones receive more intense rainfall than the central and northern areas. Over the past four decades, the Groundnut Basin, Ferlo, Senegal River Valley, and Niayes zones saw generally increasing but lower magnitude precipitation trends between 6.33mm and 1.4mm per decade, with insignificant changes in areas like Medina and Kolda. This variability aligns with previously noted inconsistent rainfall patterns [55].

The rise in temperature was significant across most zones except the coastal Niayes region, likely due to the moderating effects of the Atlantic Ocean. Cooling ocean breezes offer seasonal heat relief. These climatic nuances underscore the need for adaptation strategies tailored to each region's distinct climate risks rather than one-size-fits-all national policies. For instance, rainfall variability may be a priority concern in drier central/northern areas, whereas combined rainfall and warming changes pose a compound risk in the crop-critical south. Tracking subnational climate divergence can provide localized adaptation.

5.1. Impacts of Rising Temperatures

The persistent rise in temperature, particularly in relatively hot areas such as Saraya, Goudiry, and Tambacounda, threatens crop yields. These areas are the major producing regions of corn (75,000–150,000 metric tons), sorghum (25,000–65,000 metric tons), millet (18,000–95,000 metric tons), and peanuts (100,000–200,000 metric tons) [56].

Climate studies reviewed by Tall et al. [57] and Ahmed et al. [55] project Senegal's temperature will rise by a median of 0.90°C (0.70-1.50°C) by 2035, 2.10°C (1.60-3.30°C) by 2065, and 4.00°C (2.6-5.90°C) by 2100. In 2020, temperatures in Casamance, Senegal River Valley, and Ferlo already exceeded 29.5°C. Our study adds spatial nuance, showing that Eastern Senegal and the Senegal River Valley regions will exceed 30.0°C by 2030. Prasad et al. [58] found that exposing peanuts to temperatures $\geq$ 33°C during the floral development stage significantly lowers fruit set due to pollen sterility, affecting the overall peanut yield in the long run. Unless targeted adaptation efforts are promptly implemented, this could significantly affect crop yields in the future.

Therefore, implementing targeted interventions tailored to Senegal's diverse climatic zones is imperative. Heterogeneous climate trends underscore the critical importance of localized climate analysis in adaptive planning. Flexible, climate-smart management strategies that can adapt to variable conditions are essential for the sustainable development of Senegal's agriculture and its overall resilience to climate change.

5.2. Implications of Variable Rainfall and Future Projections

Based on the Sen's slope values and assuming a linear continuation of observed trends, rainfall projections for 2035 in Senegal's agroecological zones show a slight increase compared to estimated 2020 values, with the highest increases in Casamance (0.35 mm/year) and Eastern Senegal (0.39 mm/year), and the lowest in the Senegal River Valley (0.15 mm/year). While these projections assume a linear continuation of observed trends and do not account for potential non-linear changes, tipping points, or detailed emission scenarios and climate forcings, the unpredictability and variability of rainfall in Senegal pose multifaceted challenges for the country's rainfed agriculture, economy, food security, farmer livelihoods, and livestock. While increased rainfall benefits crop growth, it also increases the risks of flooding, erosion, and malaria outbreaks owing to favorable transmission conditions. Devastating flood events in 1999, 2005, 2009, and 2012 underscores the urgent need for effective flood mitigation measures. Proactive malaria prevention strategies are essential [59, 60, 61]. Furthermore, variable rainfall patterns disrupt pastoralist migratory routes, contributing to livestock losses. Comprehensive strategies are required to address these multifaceted challenges effectively [62].

Investing in sustainable water management strategies is imperative to enhance resilience across all regions. These should include developing water storage and irrigation infrastructure, adopting climate-smart practices such as cultivating drought-tolerant crops and implementing agroforestry. Additionally, strengthening the institutional capacity for integrated water resource management and promoting cross-sectoral collaboration will be key to effectively addressing the challenges posed by variable rainfall patterns and climate change.

6. Conclusions

This study analyzed the meteorological trends in Senegal from 1981 to 2020 using remote sensing data and GEE. The results show that Senegal experienced a statistically significant increase in annual temperatures, with an overall rise of 0.73°C, and a rainfall increase of 18mm over the past four decades. However, the magnitude of warming and precipitation patterns varied across the country's agroecological zones, with the southern regions experiencing significantly more intense rainfall than the central and northern areas. These findings highlight the importance of conducting localized climate trend analyses to understand better the specific impacts and risks different regions face in Senegal.

The study demonstrates the value of leveraging satellite data and cloud computing to uncover regional climate trends where ground-based observations are limited. Future work could apply this methodology to conduct crop-specific climate trend analyses across Senegal's agricultural areas, informing climate impact assessments to guide adaptation policies and investments that improve food security. An integrated approach coupling satellite monitoring, ground truthing, participatory planning, and localized impact studies is essential to devise climate adaptation strategies that strengthen the resilience of Senegal's agricultural and pastoral communities across localized geographies. Capacity building for decentralized adaptation planning, supportive policies, and financing is paramount.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The maps and other datasets used in this study can be visualized and compared in a Google Earth Engine app at:

- Climate Trend's App
- Data

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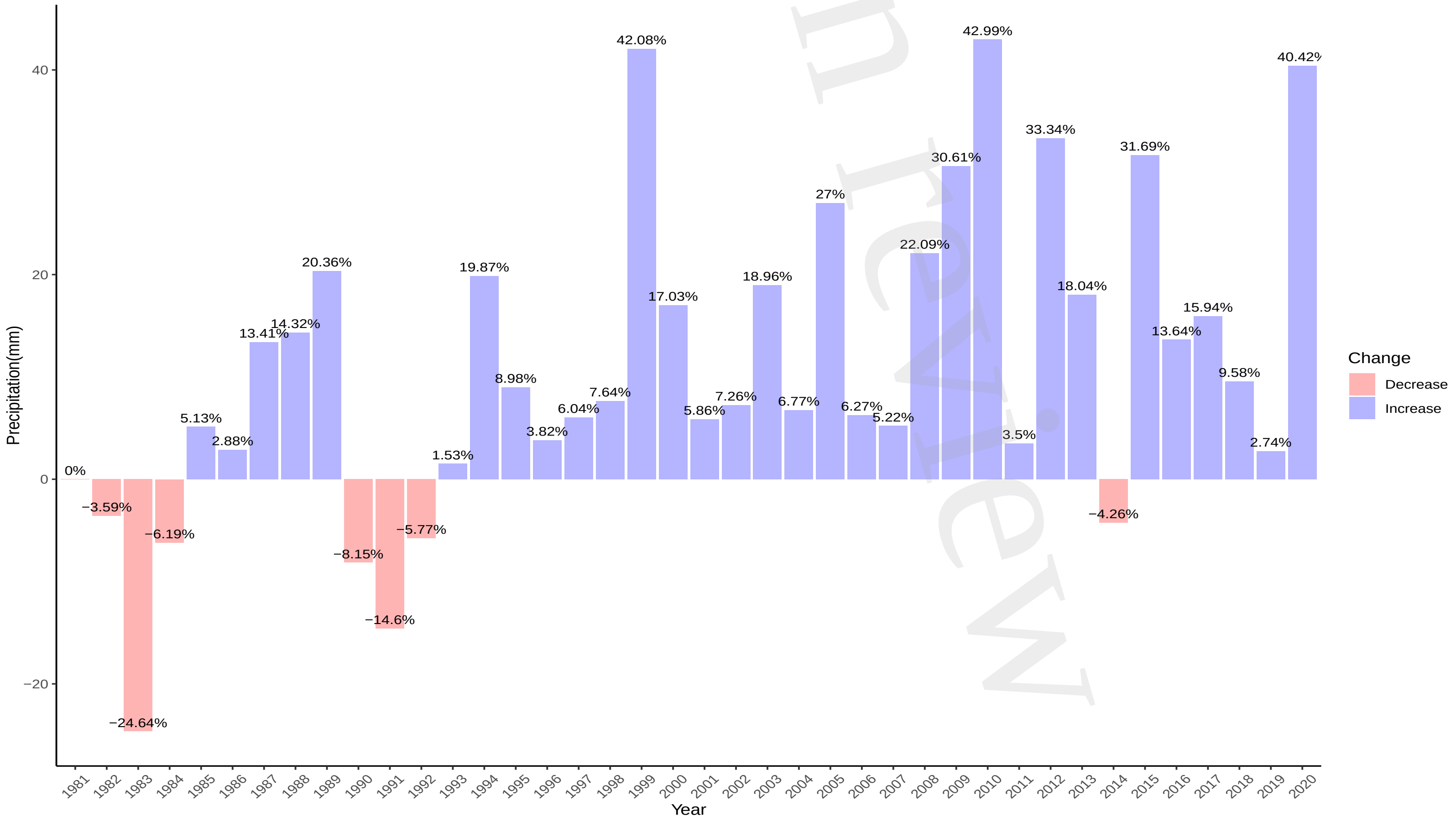
Appendix A. Supplementary Materials - Precipitation

Percentage change from Year 1981 -Supplementary Data 1

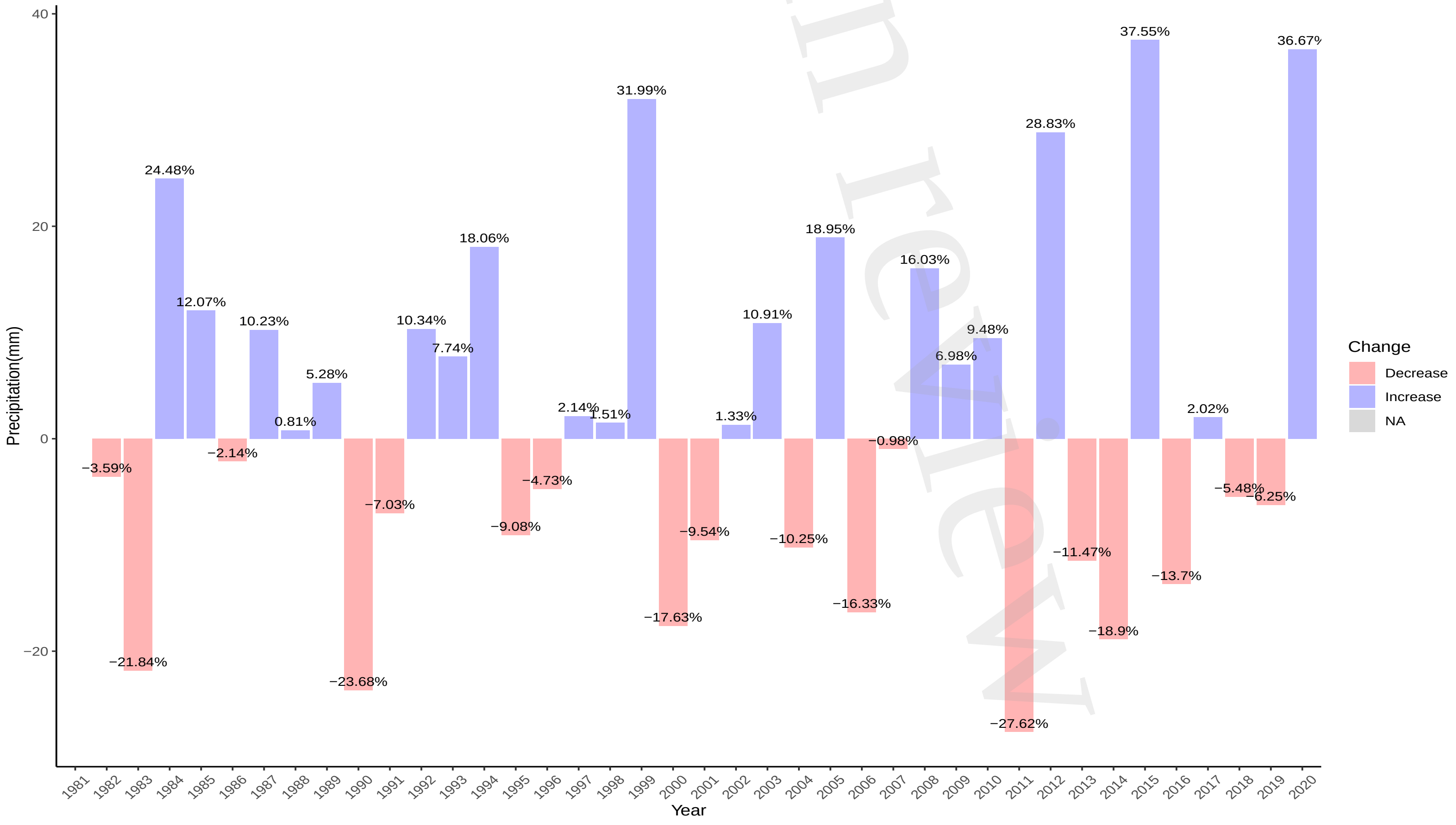
Figure A1. Percentage Change in Average Precipitation from 1981



Appendix A.1. Annual Percentage Change in Precipitation

Supplementary Data 2

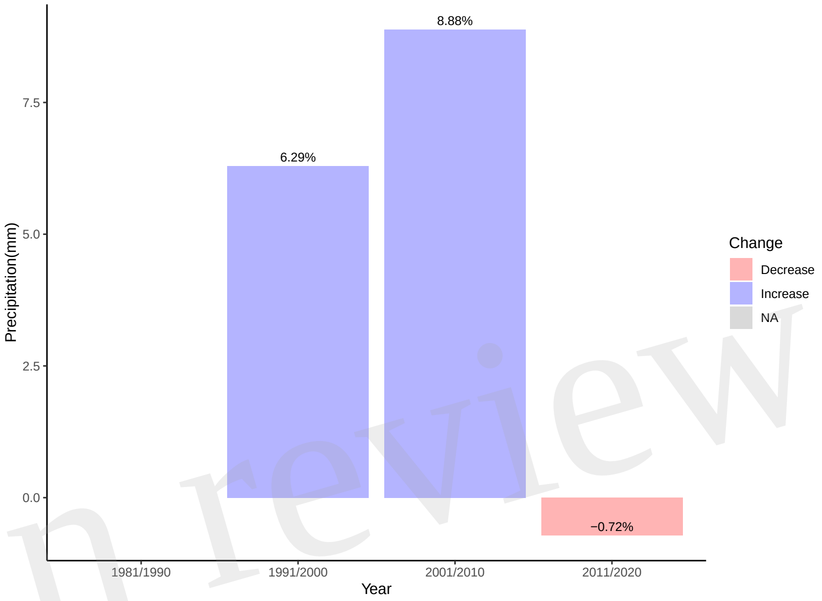
Figure A2. Average Precipitation with yearly % change



Appendix A.2. Decadal Percentage Change in Precipitation

Supplementary Data 3

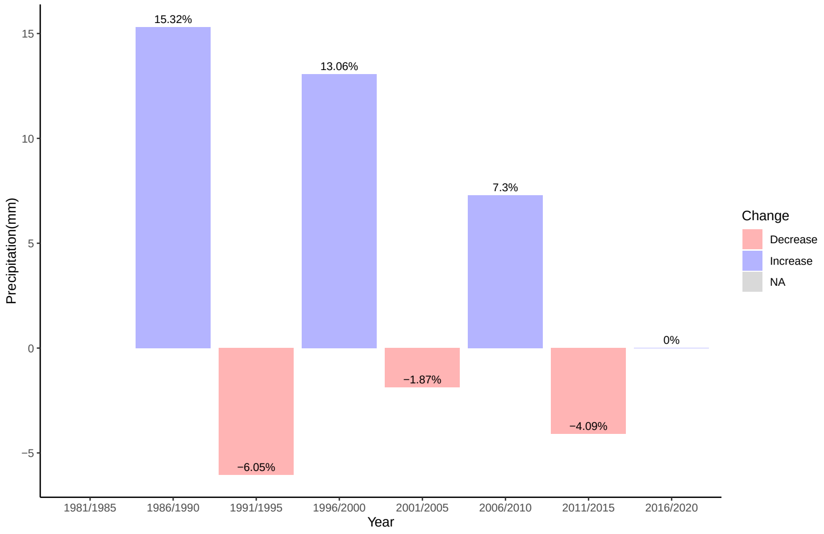
Figure A3. Decadal Percentage Change of Average Precipitation from 1981



Appendix A.3. Quinquennial Percentage Change in Precipitation

Supplementary Data 4

Figure A4. Quinquennial Percentage Change of Average Precipitation from 1981

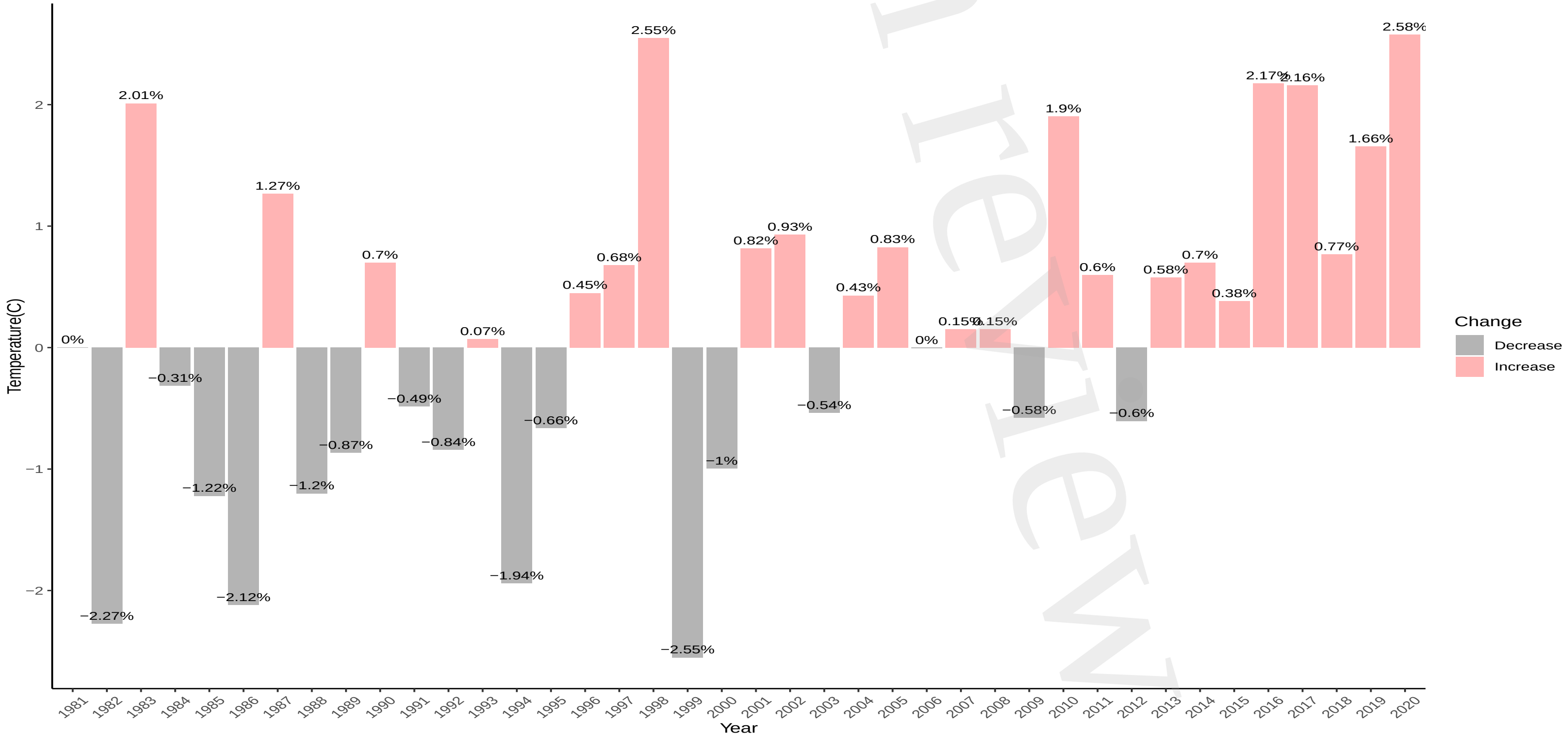


Appendix B. Supplementary Materials - Temperature

Appendix B.1. Percentage Temperature change from 1981

Supplementary Data 5

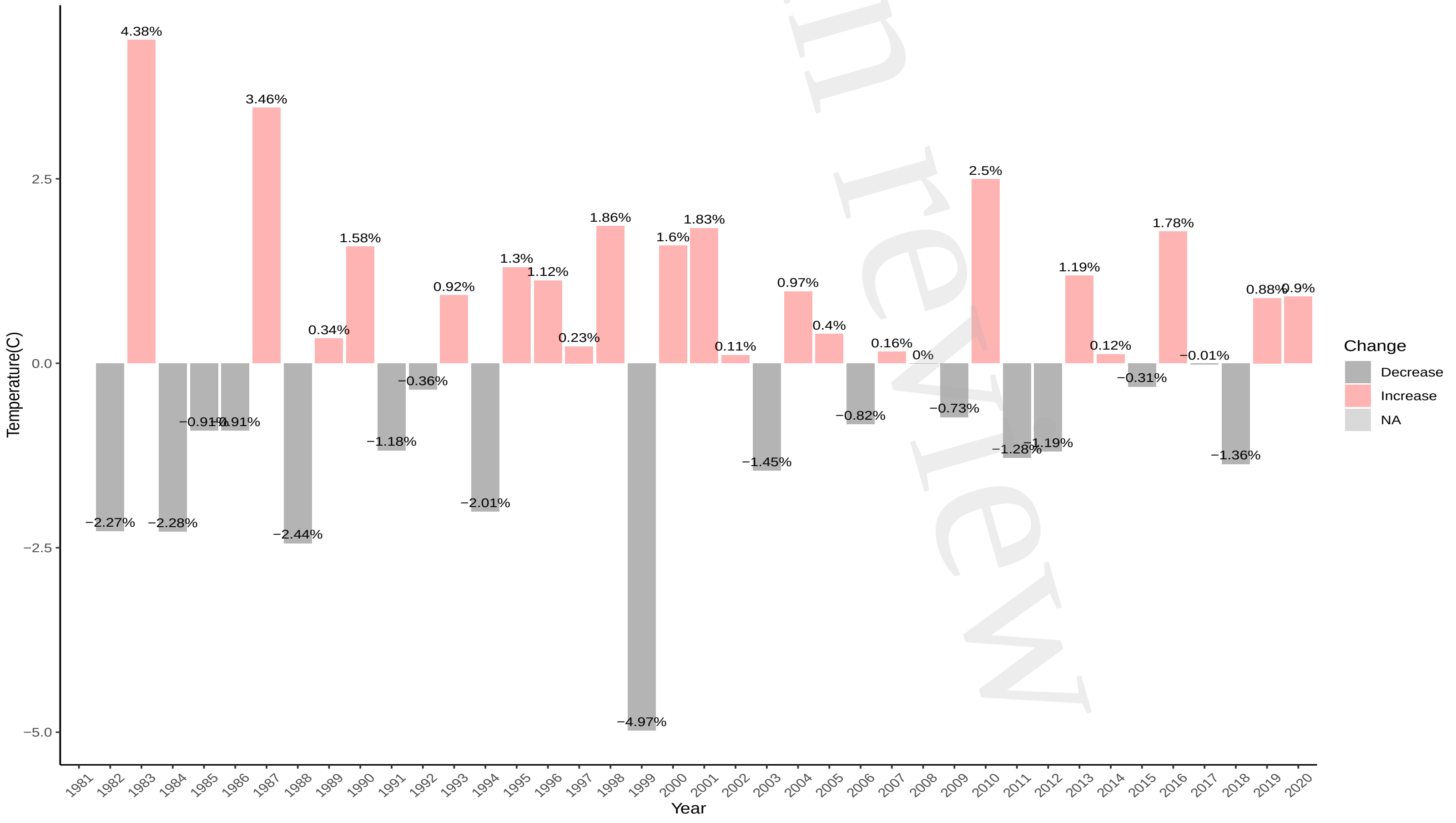
Figure B1. Average Temperature with % change from year 1981



Appendix B.2. Yearly Percentage Change in Temperature

Supplementary Data 6

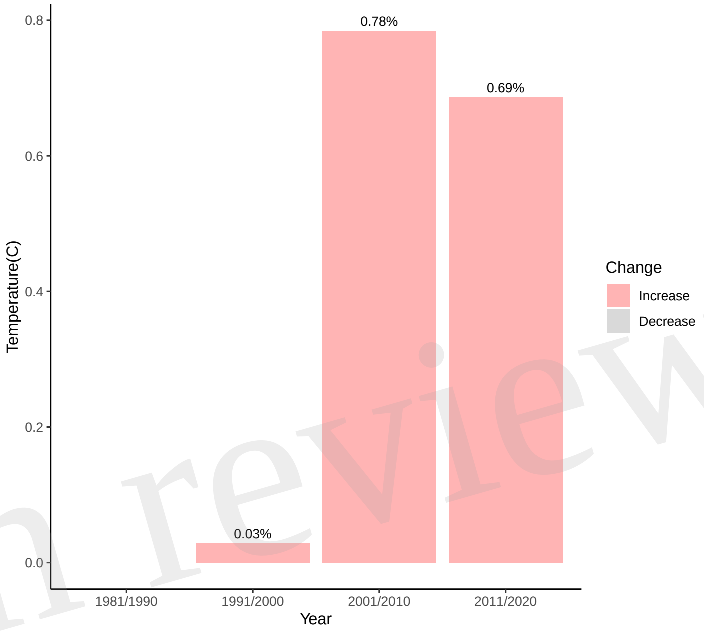
Figure B2. Average Temperature with yearly % change



Appendix B.3. Decadal Percentage Change in Temperature

Supplementary Data 7

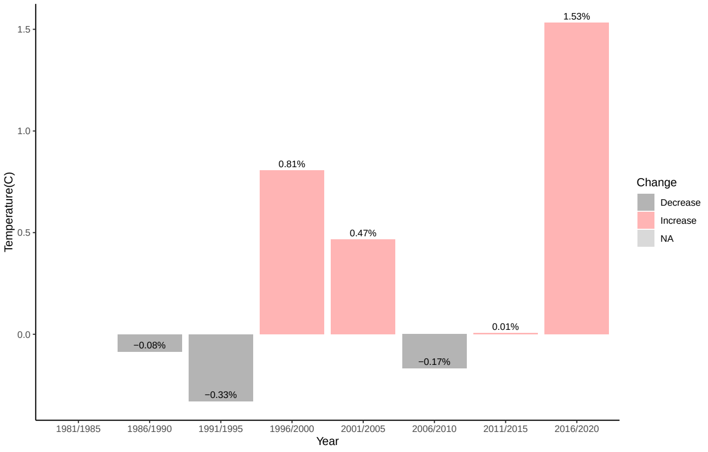
Figure B3. Decadal Percentage Change of Average Temperature from 1981



Appendix B.4. Quinquennial Percentage Change in Temperature

Supplementary Data 8

Figure B4. Quinquennial Percentage Change of Average Temperature from 1981



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