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Spatial–Temporal Analysis of Impacts of Climate Variability on Maize Yield in Kenya

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Abstract: This study examined the spatial temporal impacts of climate variability on maize yield in Kenya. The maize yield data were obtained from the Kenya Maize Yield Database while climatic variable data were obtained from the Climatic Research Unit gridded Time Series (CRU TS) with a spatial resolution of 0.5° × 0.5°. The non-parametric Mann–Kendall and Sen's slope tests showed no trend in the data for maximum temperature, minimum temperature and precipitation. The spatial maps patterns highlight the rampancy of wetter areas in the Lake Victoria basin and Highlands East of Rift Valley compared to other regions. Additionally, there is a decreasing trend in the spatial distribution of precipitation in wetter areas and an increasing trend in maximum temperature in dry areas, albeit not statistically significant. Spearman's rank correlation test showed a strong positive correlation between maize yield and the climatic parameters for the Lake Victoria basin, Highlands East of Rift Valley, Coastal Strip and North Western Regions. The findings suggest that climate variability has a significant impact on maize yield for four out of six climatological zones. We recommend adoption of policies and frameworks that will augment adaptive capacity and build resilience to climatic changes.

Keywords: climate variability; maize yield; Kenya

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1. Introduction

The objective of Sustainable Development Goal 2 is to eradicate hunger, guarantee food security, and improve nutrition by advocating for sustainable agriculture techniques [1,2]. This is because agriculture is essential for our diets and nutrition, economic growth, environmental sustainability, equity, and inclusion, and can contribute to the improvement of healthcare systems by promoting good health for all [3]. Climate change exacerbates food security risks for vulnerable countries and communities, with its effects being multidimensional and impacting various sectors and regions worldwide due to its transdisciplinary nature [4]. A Food and Agricultural Organization report highlights that climate change exacerbates food security risks for the most vulnerable nations and populations [5]. In the 21st century, global agriculture has experienced significant impacts from climate change, including increased average temperatures, stressed water resources, more frequent and intense heat waves, altered precipitation patterns, and desertification [6–9].

In 2015, an estimated 800 million people experienced chronic malnutrition, and 161 million children under the age of five were stunted, while 500 million individuals suffered from obesity, and 2 billion people lacked essential micronutrients for a healthy life [1]. These statistics emphasize ongoing challenges in achieving food security globally. It is estimated that about 3.5 billion people live in areas that are most likely to be affected by the impacts of climate change, and the connection between human and ecosystem vulnerability is interdependent. Regions, as well as individuals with limited development opportunities, are particularly exposed to climate-related hazards [10]. The rising impact of climate change has caused a surge in extreme weather conditions, leading to millions of individuals facing immediate food shortages and a lack of access to water. This jeopardizes the advancements made in addressing hunger and malnutrition [5,11,12].

The impact of climate change is most dire in regions like Africa, Asia, Central and South America, least developed countries (LDCs), small islands, and the Arctic, as well as worldwide, for low-income households, indigenous peoples, and small-scale food producers. Data unequivocally show that between 2010 and 2020, human fatalities and climate-induced extreme events were 15 times higher in extremely susceptible areas as opposed to locations with extremely minimal vulnerability [13–16]. Moreover, climate change, encompassing the rising occurrence and severity of extreme events, has adversely affected food and water security, posing challenges to the attainment of the Sustainable Development Goals [7].

Approximately 75% of Kenya's population engages in agriculture, primarily rainfed, but only 20% of the land is arable, resulting in unprecedented alterations to the ecosystem and environmental process in the country [17,18]. Nearly 56% of the Kenyan population experiences food insecurity at some point during the year. Among these, about 2 million people rely on relief food due to persistent food insecurity. During droughts, this number increases to 5 million, affecting both rural (53%) and urban (49%) populations. The current shortage of food restricts the availability of safe and healthy food in adequate amounts, which hurts both physical health and economic stability [19]. Kenya heavily depends on agriculture, particularly imports of maize, wheat, and rice. This emphasizes the need for enhancing agricultural productivity through the implementation of enduring and adaptable methods to guarantee both food sustainability and economic development [20]. Based on a report by the International Institute of Tropical Agriculture [21], maize has become a highly important cereal crop in sub-Saharan Africa, acting as a staple food for almost half of the region's population. Maize is a versatile crop that can thrive in various agroecological zones, with a high yield potential of 8.6 tons in developed countries and 1.3 tons in developing countries. Every part of the crop, including the grain, leaves, stalk, tassel, and cob, holds economic value and can be utilized in the production of a wide range of food and non-food products. In Kenya, maize is an essential staple food, cultivated by approximately 90% of farms. It plays a critical role in the food security of both urban and rural populations, and low yields can lead to severe food shortages and famine. The impact of climate variability on precipitation, soil moisture, and production poses a constant threat to food security in Kenya, particularly because a significant portion of the population relies solely on rainfed agriculture for their livelihoods [22]. Maize yield variability is greatly influenced by changes in air temperature and precipitation, followed by radiation [23,24]. Additionally, conventional agricultural practices leading to land fragmentation have significantly impacted arable land, resulting in decreased fertility and increased degradation.

Similar to many other countries in sub-Saharan Africa, Kenya has experienced variations in both seasonal and annual temperature and rainfall over the last five decades; this is thought to be connected to the changes in the climate [4]. Given that Kenya depends solely on rainfed agriculture, extreme events caused by climate variability are anticipated to disrupt the typical functioning of the rainfall seasons and patterns, rendering the country vulnerable to climate-induced food insecurity. This situation is compounded by the fact that about 75% of the Kenyan population engages in agriculture, but only about 20% of the total land area is suitable for farming [17,18]. The rapid urbanization and population growth in Kenya have led to significant changes in land use, impacting soil and water quality and reducing crop yields in the already shrinking croplands. Human-induced disasters, like the severe drought in Northeastern Kenya, and changes in land use and cover further strain the limited land resources, contributing to food insecurity. It is essential to assess how climate variability affects maize yield to understand the issue and suggest strategies to improve resilience and food security in the country.

Most of the studies previously conducted on climate variability and crop yield in Kenya concentrated on particular areas within the country. For instance, Ref. [3] worked on climate stressors and household food security in Murang'a County and Ref. [25] worked on climate variability and maize yield in the southeastern parts of Kenya, that is, Machakos, Mwingi, and Makueni. Other similar studies have been performed in Nyeri [17], as well as in Busia, Siaya, and Migori counties. Another study has also been performed by [4] on the climate change response in a rainfed production system in Western Kenya. On the regional level, Ref. [26] conducted a study on the distribution of trends in rainfall in Eastern Africa, while Ref. [27] conducted a review on the effects of climate change on key crops. The studies mentioned above examined smaller geographic areas within the country, but there has been no comprehensive study on the relationship between climate variability and maize yield in the entire country. Another Scholar Ref. [22] conducted a nationwide study, but their focus was on the impact of climate variability and change on revenue from maize and tea. Given the limited research on this topic, the connections between climate variability and maize yield across the entire country have not been extensively explored. Most studies have concentrated on specific regions. Therefore, this study aims to analyze the spatial and temporal effects of climate variability on maize yield in Kenya from 2012 to 2020.

2. Materials and Methods

2.1. Study Area

Kenya covers an area of about 582,650 square kilometers and lies between latitudes 5° N and 5° S and longitudes 34° and 42° [28]. Its diverse geography, characterized by intricate landforms, influences the varying climate patterns observed throughout the country. Kenya experiences bimodal rainfall and temperature patterns influenced by the Inter-Tropical Convergence Zone (ITCZ). The intensity and seasonality of rainfall vary due to altitude disparities [29]. The country has two main rainy seasons: the "long rains" from March to May and the "short rains" from October to December. The long rainy season is essential for agricultural production, which is a major contributor to the country's economy. The highlands, known for their cool climate and fertile soil, support a wide range of crops such as tea, coffee, flowers, vegetables, pyrethrum, wheat, and maize. These areas, situated at elevations of 1500 to 3000 m above sea level, are also conducive to livestock production [20].

Kenya is classified as a lower-middle-income country and has the largest economy in East Africa. Its population was approximately 52.6 million in 2019, with an annual population growth rate of 2.3%. Around 27% of the population resides in urban areas, with projections indicating an increase to 33% and 46% by 2030 and 2050, respectively. The Gross Domestic Product (GDP) was USD 95.5 billion in 2018, with an annual growth rate of 5.4% in 2019 [20]. The study area (Figure 1) was divided into six rainfall climatological zones as previously delineated by the Kenya Meteorological Department [30].

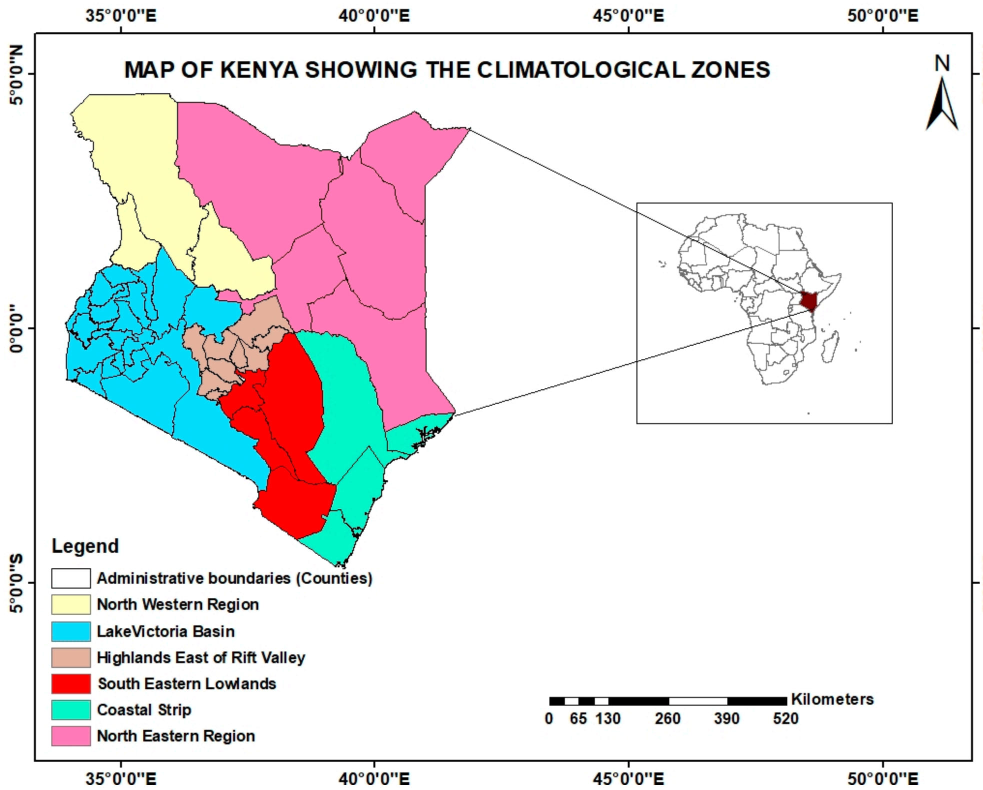


Figure 1. Map of Kenya showing the climatological zones.

2.2. Data Sources

Maize yield data for the 2012–2020 period was retrieved from the Kenya Maize Yield Database, https://nipfn.knbs.or.ke/download/maize-production-by-county-2012-2020/. (Accessed on 15 January 2024) On the other hand, gridded monthly precipitation, maximum temperature, and minimum temperature data were obtained from the CRU TS version 4.07 website, https://crudata.uea.ac.uk/cru/data/hrg/. (Accessed on 18 January 2024). CRU TS (Climatic Research Unit gridded Time Series) is a widely used climate dataset with a 0.5° latitude by 0.5° longitude grid covering all land domains worldwide except Antarctica. This dataset, chosen for its long period and finer resolution, is derived from the interpolation of monthly climate anomalies from extensive networks of weather station observation [31].

2.3. Analysis

The non-parametric Mann–Kendall (MK) test [32] was employed to evaluate the trend in the climatic data, i.e., rainfall and temperature. The MK test was used because it is robust and allows for the effective treatment of outliers [33,34]. Apart from the robustness of the MK test, its non-parametric nature also means that it does not depend on regularly distributed data [35]. The variation of Kendall's Tau is between −1 and 1; this means that when the trend increases, it is positive, and when the trend decreases, it is negative.

MK test was used to test whether or not to reject to reject the null hypothesis, where:

H_0. *No monotonic trend in the series.*

H_a. *A monotonic trend is present in the series.*

The MK test was used to analyze the sign of the difference between data measurements in the later period and those measured earlier in the study. Each value measured in the later period compared to the earlier measurements, resulting in $\frac{n(n-1)}{2}$ possible data pairs, where n was the total number of observations. Missing values were allowed and the data did not need to follow any particular distribution. To calculate the MK test, differences between values measured in the later and earlier periods were computed, $(y_j - y_i)$, where $j > \beth$. The differences were assigned an integer value of 0, 1, or −1 corresponding to either no differences, or positive, or negative differences, respectively. The test statistic, S, was then computed as sum of the integers:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\ (y_j - y_i) \tag{1}$$

where $sign\ (y_j - y_i)$ represents either 0, 1, or −1 as indicated above.

An upward trend was indicated when S was a large positive number, and no trend was indicated if the absolute value of S was small. The test statistic, τ, was computed as $\tau = \frac{s}{n(1-1)/2}$, and this had a range of −1 to +1, which is similar to the regression analysis correlation coefficient. The null hypothesis of no monotonic trend in the series was rejected when S and τ were statistically different from zero, and if a significant trend was found, the rate of change was calculated using Sen's slope estimator [34].

Sen's slope estimator was obtained by computing the median of the slopes for all pairs of data measurements that were used to compute S as follows:

$$\beta_1 = median\left(\frac{y_j - y_i}{x_j - x_i}\right) \text{ for all } i < j \text{ } and \text{ } i = 1, 2, \ldots, n-1 \text{ } and \text{ } j = 2, 3, \ldots, n \tag{2}$$

Hence, Sen's slope estimates the overall slope of the time series. The trend is statistically significant when the p-value is less than 0.05.

Time series analysis was adopted to determine the trend in mean annual and seasonal rainfall and annual maximum, as well as minimum temperature, for the period 2012–2020. ArcGIS 10.8 was used to analyze the trends in the climatic variables as well as to generate spatial maps for the study period while Microsoft Excel 2021 was used to develop curves and graphs in a bid to visualize the results obtained. In establishing the degree of the monotonic relationship between maize yield and the climatic parameters, which in this case are minimum temperature, maximum temperature, and precipitation, Spearman's Rank Correlation test was employed, whereby maize yield was considered the dependent variable and the climate parameters was considered the independent variables.

The formula for Spearman's correlation that was used was as follows:

$$\rho = 1 - \frac{6\Sigma_i^2}{n(n^2 - 1)} \tag{3}$$

where $_i$ was the differences in paired ranks, that is, $_i = R_{x_i} - R_{y_i}$ and n was the total number of observations, which is 9 observations for each climatic region. The value of ρ lies between −1 and 1 and direct associations were indicated by positive values, whereas inverse associations were indicated by negative values. Microsoft Excel performed the statistical analysis and the results were considered significant at a 0.05 probability level. According to the IPCC, [14], during 2010–2019, annual average greenhouse gas emissions were higher compared to any previous decade. Thus, this period of study was chosen to assess if this higher-than-normal rate of GHG emission may have impacted agricultural productivity in Kenya. Maize was chosen because it is the staple food of the country and thus an index for measuring food security.

3. Results

3.1. Precipitation

Mann–Kendall test results showed that the p-value = 1.00, meaning the series has no trend (Table A1). For the mean annual precipitation, (Figure 2) Lake Victoria basin had the highest rainfall followed by North Western Region. The lowest annual rainfall patterns were recorded by the Highlands East of Rift Valley and the North Eastern Region.

Generally, there is a decreasing trend in the annual rainfall for all the regions; nonetheless, it is not statistically significant. The MAM seasonal rainfall patterns (Figure 3a) show an overall decreasing trend with Lake Victoria basin still recording the highest rainfall. In the OND seasonal rainfall results (Figure 3b), Lake Victoria basin still records the highest rainfall, while North Eastern Region records the lowest for most parts of the study period. The North Western Region recorded the highest rainfall of about 800 mm in 2018 and then drastically dropped to less than 300 mm by the year 2020. Generally, the OND short rain season shows greater rainfall variability in comparison to the long rain season of MAM. The spatial precipitation (Figure 4) patterns highlight the ubiquity of wetter areas in the Lake Victoria basin and Highlands East of Rift Valley compared to the North Eastern and North Western Regions. Additionally, there is a decreasing trend is observed in the spatial distribution of precipitation in wetter areas.

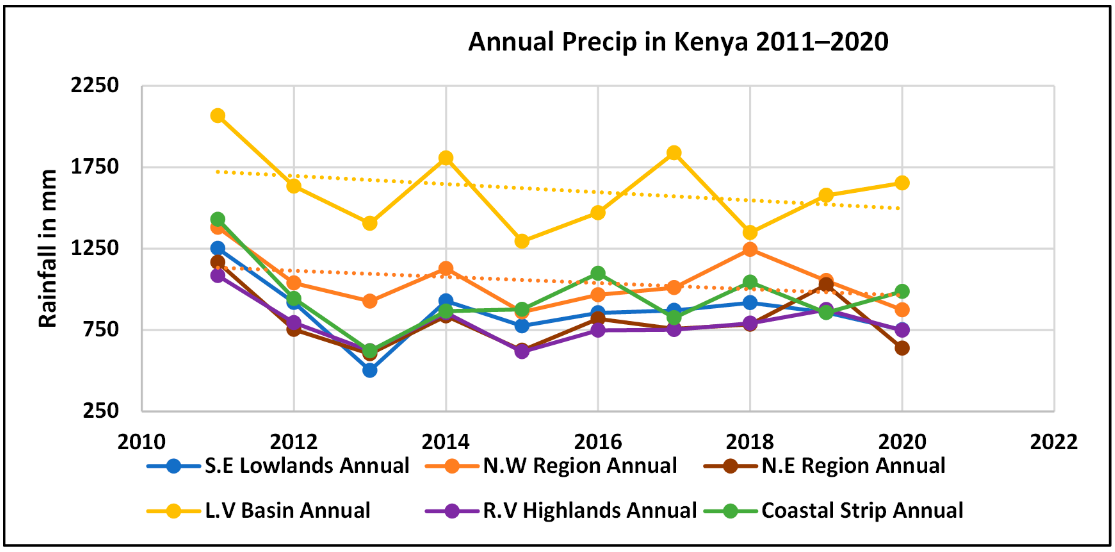
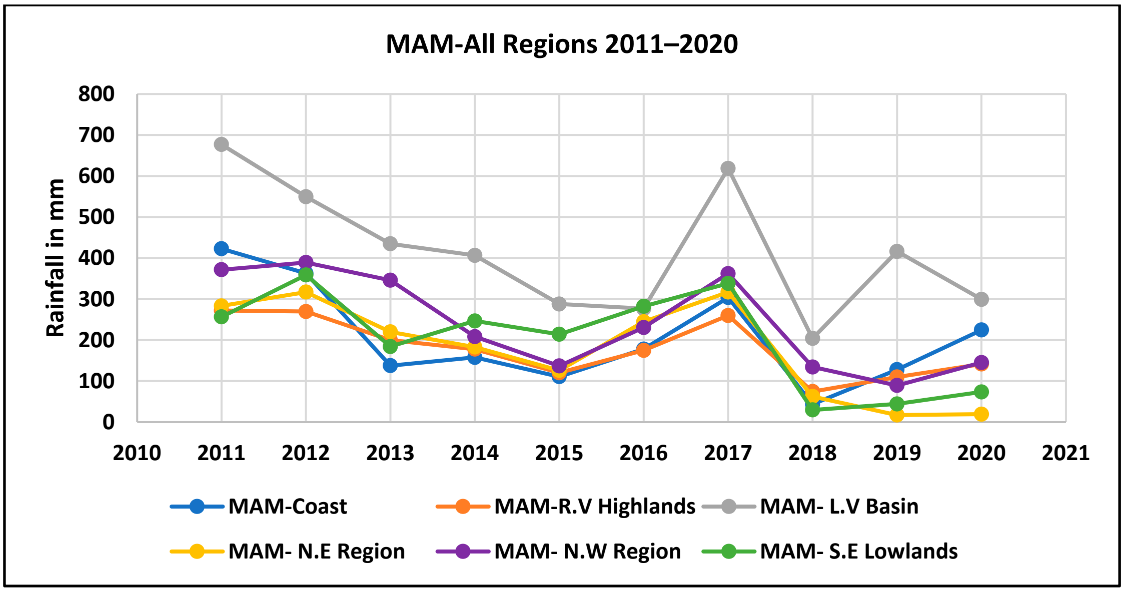
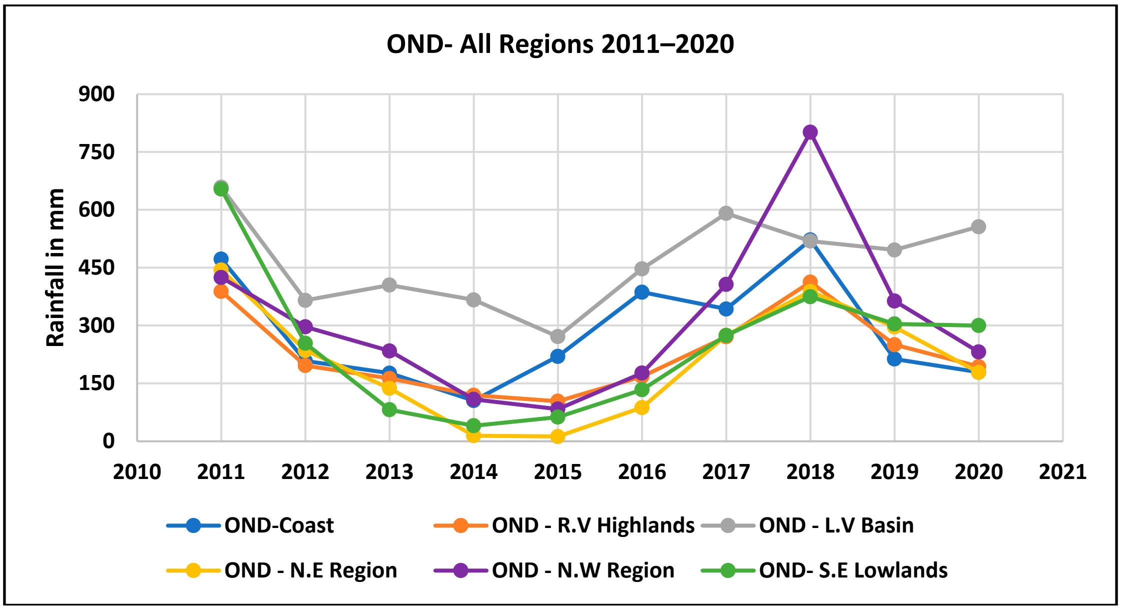


Figure 2. Annual distribution of precipitation, 2011–2020.



(**a**)

Figure 3. *Cont.*



(**b**)

Figure 3. Seasonal rainfall 2011–2020 for (**a**) MAM and (**b**) OND.

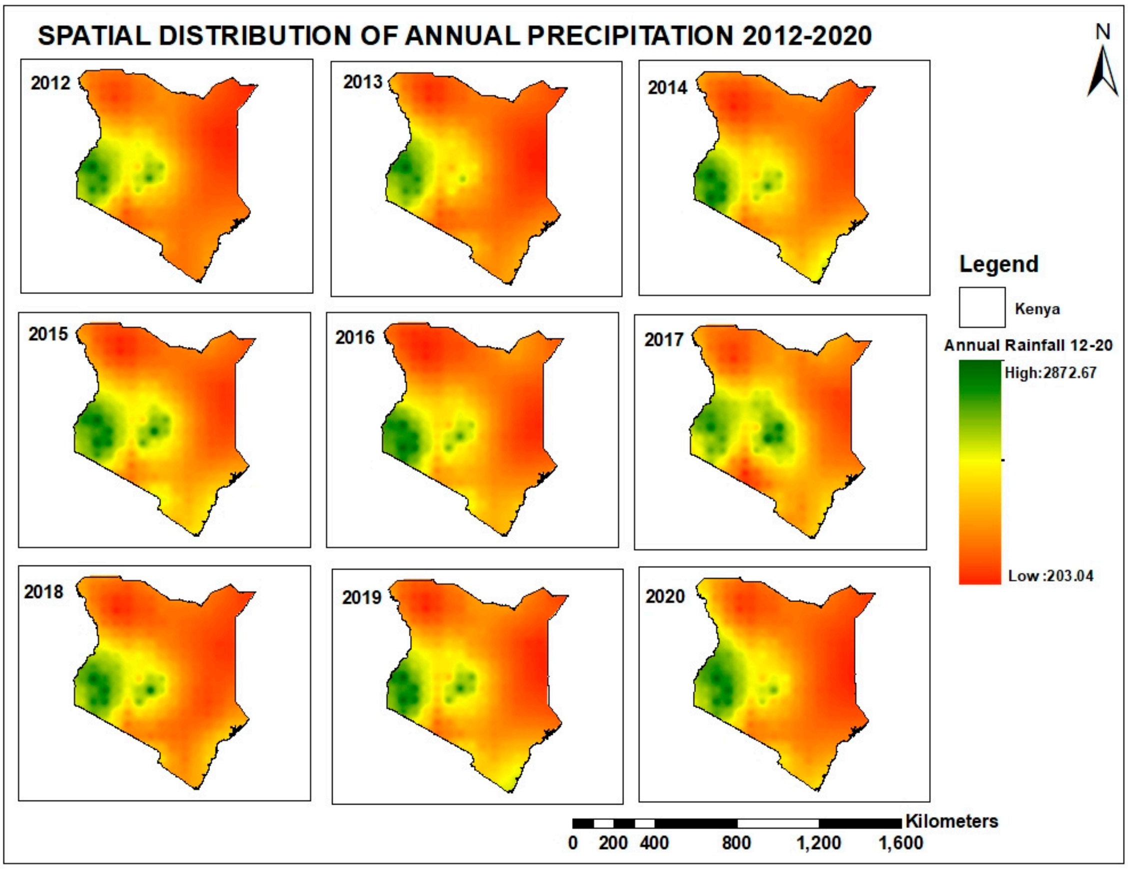


Figure 4. Spatial distribution of precipitation in mm 2011–2020.

3.2. Maximum Temperature

The Mann–Kendall test results for average maximum temperature showed a *p*-value of 0.592, which means no trend in the series (Table A2). Generally, an increasing trend is observed in the annual maximum temperature across all regions but it is not statistically significant (Figure 5). The North Eastern Region records the highest mean maximum temperature ranging from 32.79 to 33.58 °C throughout the study period, followed by the Highlands East of Rift Valley ranging from 30.88 to 31.55 °C. South Eastern Lowlands and Lake Victoria basin show lowest mean maximum temperature ranging from 29.34 to 29.93 °C and 29.15 to 29.91 °C, respectively. The MAM seasonal T-max in Figure 6a shows a slight general increase from 2011 to 2014, after which the trend decreases for other regions except the North Eastern region, which remains fairly constant. The North Eastern Region also records the highest T-max ranging from 31.27 °C to 34.86 °C, while the Lake Victoria basin and South Eastern Lowlands record the lowest. On the other hand, the OND seasonal T-max, as shown in Figure 6b, shows a slightly increasing trend, with the North Eastern Region recording the highest T-max, ranging from 31.75 °C to 34.98 °C, and the South Eastern Lowlands recording the lowest. The spatial distribution of the maximum temperature (Figure 7) shows that the Lake Victoria basin and Highlands East of Rift Valley experience lower maximum temperatures throughout the study period compared to the northern, eastern and the coastal parts.

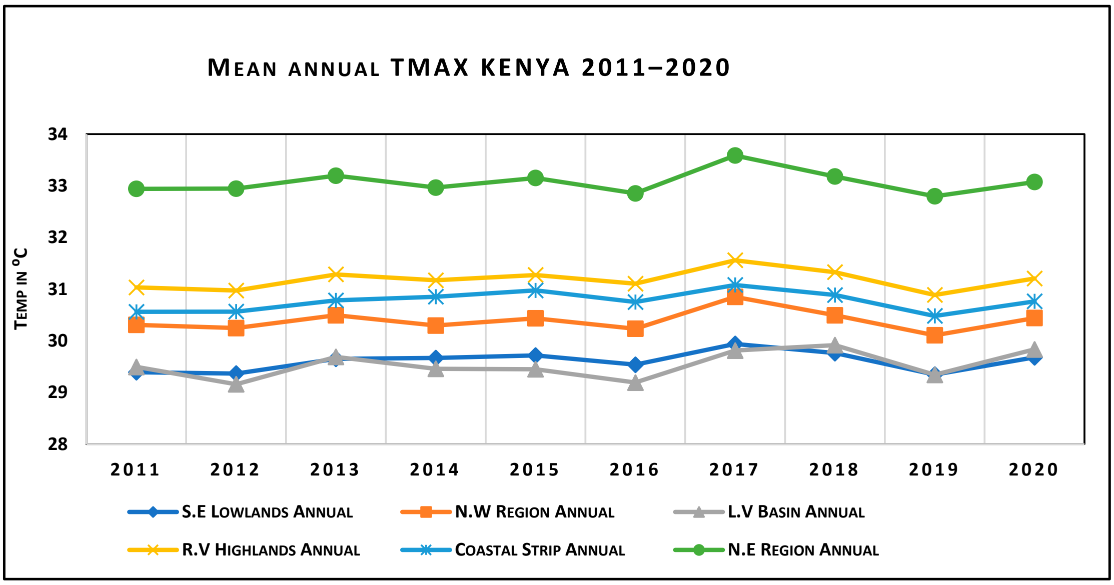
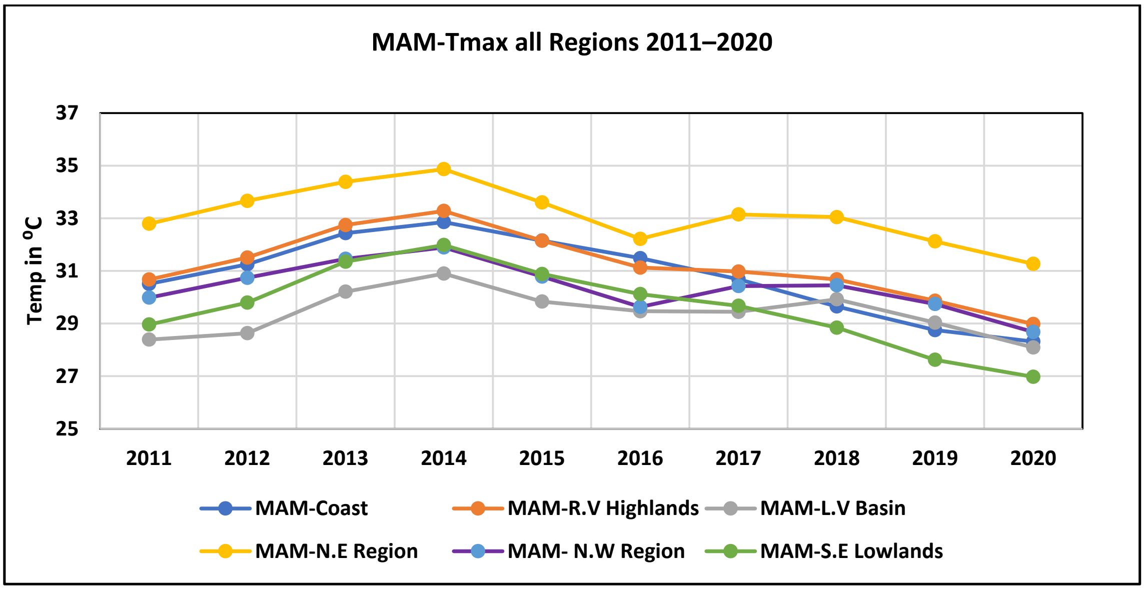
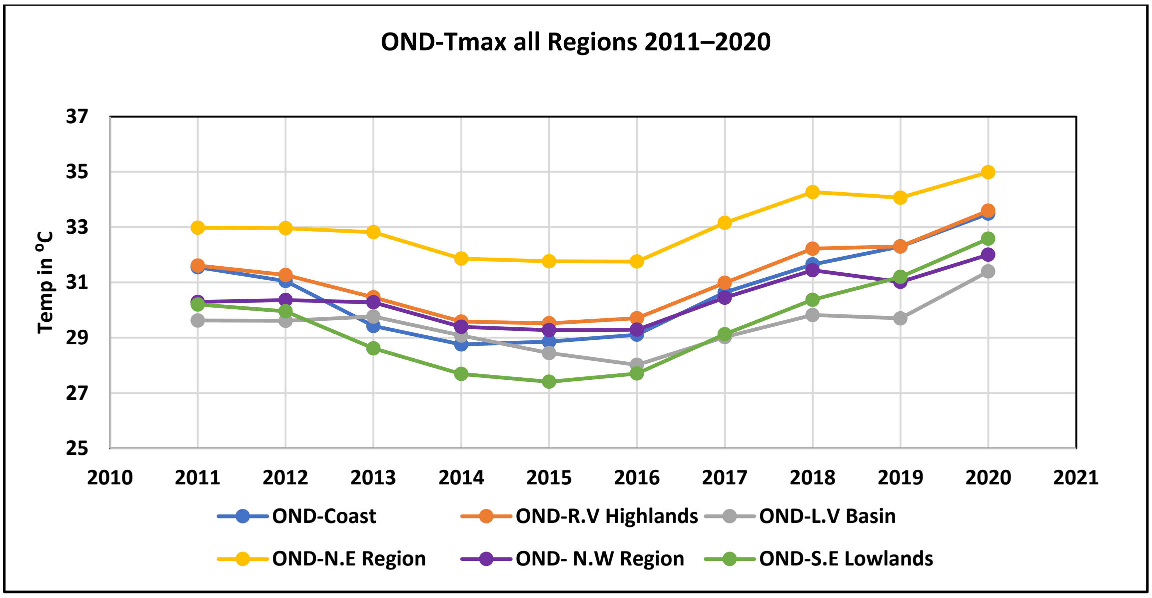


Figure 5. Mean annual Tmax 2011–2020.



(**a**)

Figure 6. *Cont.*



(**b**)

Figure 6. Seasonal Tmax 2011–2020 for (**a**) MAM and (**b**) OND.

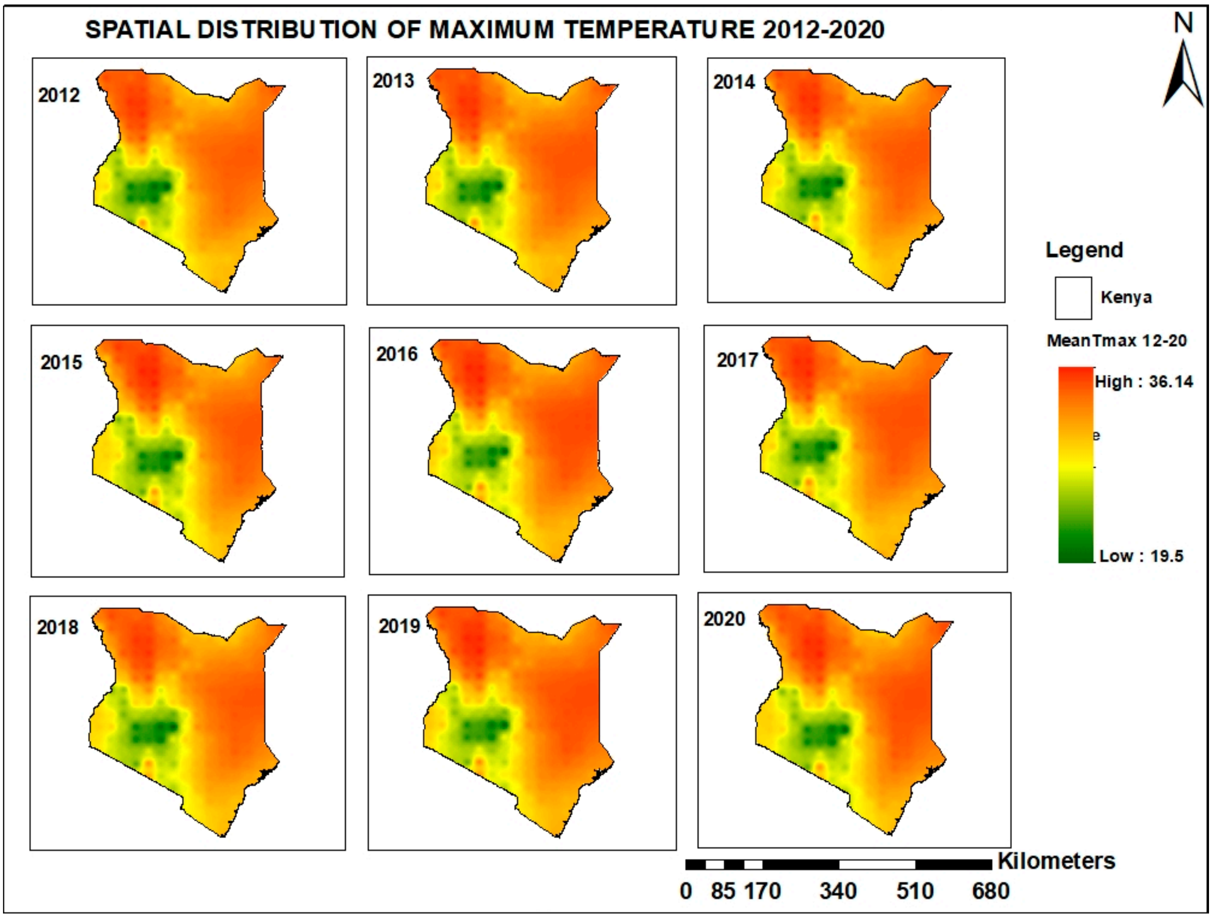
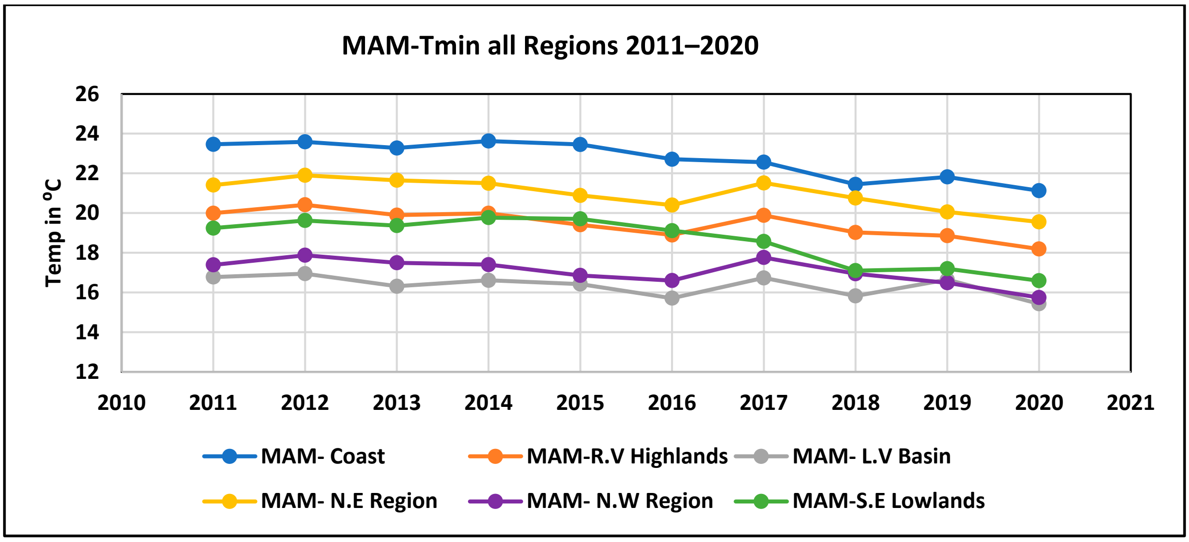


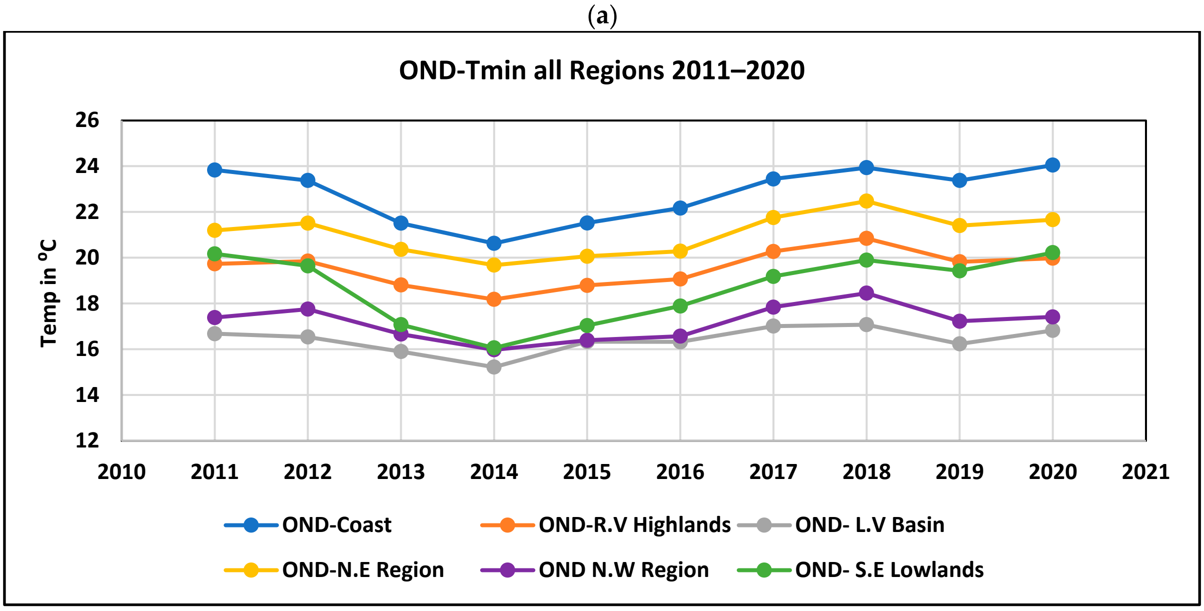
Figure 7. Spatial distribution of Tmax in degrees Celsius 2011–2020.

3.3. Minimum Temperature

The Mann–Kendall test results for average minimum temperature showed a *p*-value of 0.592, which means no trend in the series (Table A3). As shown in Figure 8a, the MAM seasonal Tmin shows a decreasing trend, with the coastal region recording the highest mean Tmin ranging from 22.28 °C to 23.27 °C, followed by the North Eastern Region, 20.70 °C to 21.48 °C, while the North Western Region and the Lake Victoria basin recorded the lowest mean seasonal Tmin. For the OND seasonal Tmin, the trend is fairly constant in Figure 8b, with the coastal region again recording the highest Tmin, followed by the North Eastern Region. The North Western Region and Lake Victoria basin once again records the lowest mean seasonal Tmin. The spatial maps of minimum temperature, as shown in Figure 9, depict a fairly constant distribution throughout the study period with the Eastern and Northern Region experiencing higher temperatures, while the central and western side experiences low temperatures. Annual Tmin in Figure 10 shows no significant trend over time. The Coastal Strip records the highest annual mean Tmin ranging from 22.28 to 23.27 °C, followed by the North Eastern Region, 20.69 to 21.48 °C. North Western Region and Lake Victoria basin record the lowest annual Tmin, ranging from 16.81 to 17.59 °C and 16.02 to 16.80 °C, respectively.



(a)



(b)

Figure 8. Seasonal Tmin (**a**) MAM and (**b**) OND.

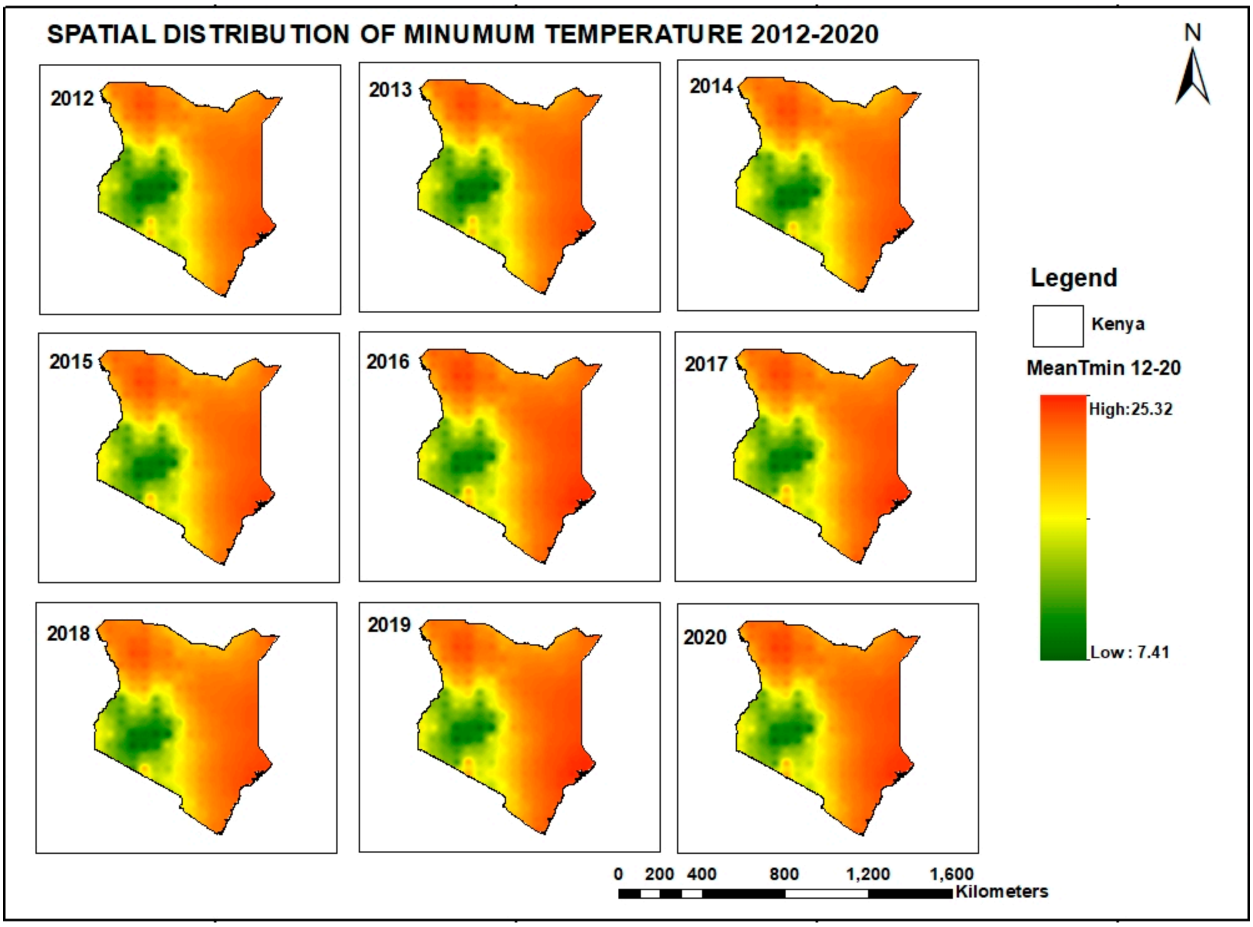


Figure 9. Spatial distribution of Tmin in °C 2011–2020.

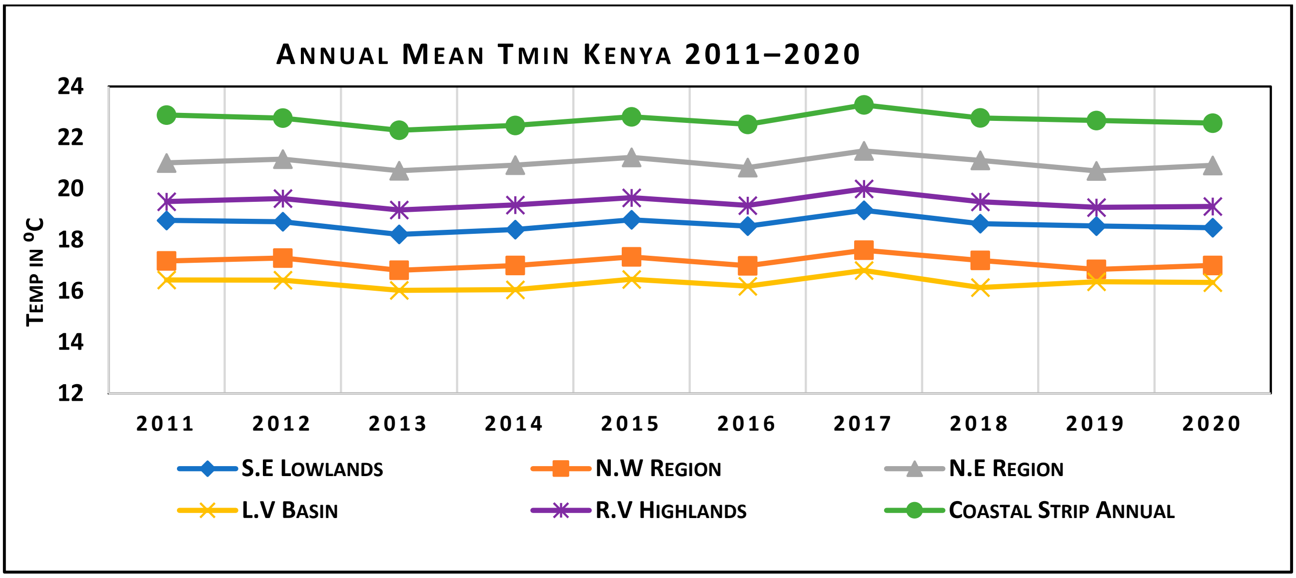


Figure 10. Annual distribution of Tmin 2011–2020.

Average precipitation ranges from 282.34 mm to 2031.23 mm, as shown in Figure 11. The Lake Victoria basin in the western part of Kenya experiences more precipitation throughout the year than other climatological zones and is thus considered wetter. Additionally, the mean annual rainfall over Kenya from 2011 to 2020 was found to be about 1010 mm. The mean maximum temperature for the 2011–2020 period, as in Figure 11, ranges from 21.71 °C to 35.58 °C with an overall mean of 28.65 °C, while the mean minimum temperature ranges from 8.69 °C to 24.74 °C with an overall mean of 16.72 °C.

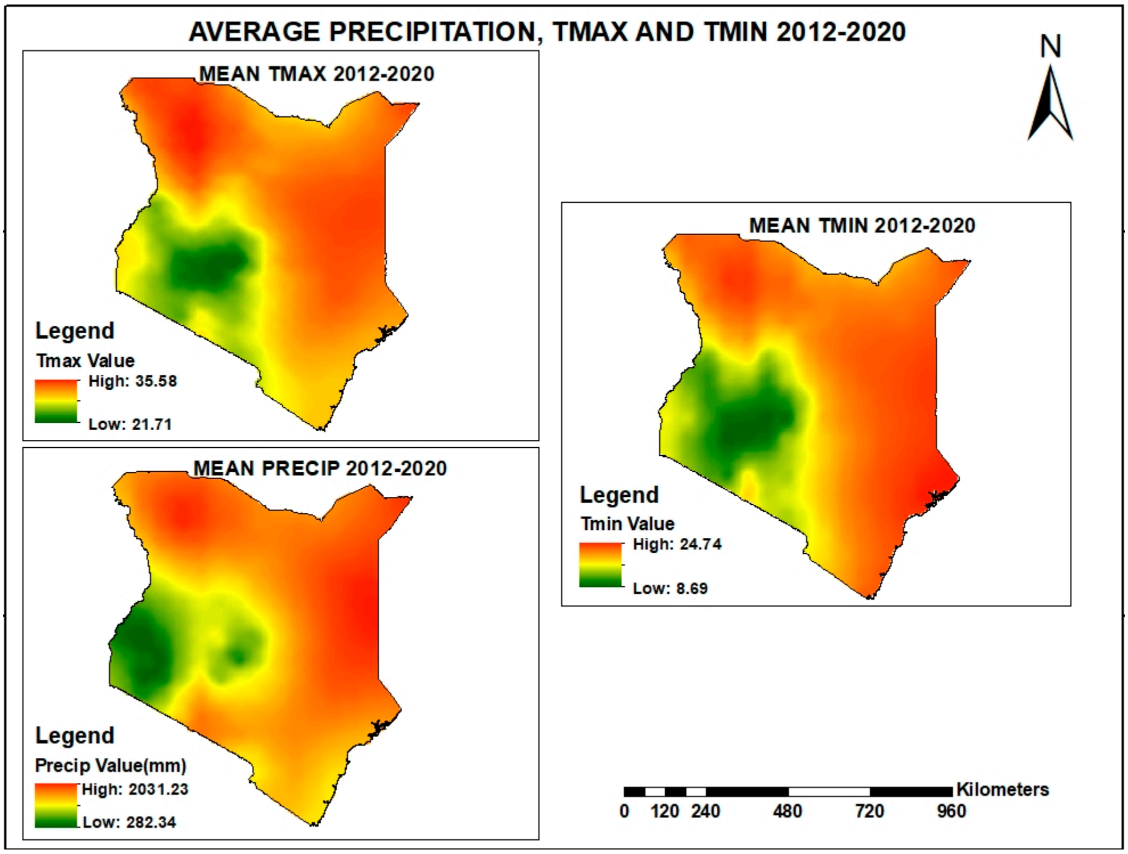


Figure 11. Average precipitation (mm), Tmax (°C), and Tmin in (°C).

3.4. *Effects of Rainfall and Temperature Variability on Maize Yield*

Generally, the display in the spatial distribution of annual maize yield (Figure 12) shows that the central and western parts of the country produce more maize compared to the Northern Region. The Lake Victoria basin records the highest yield throughout the 9 years (ranging from 40.12 to 46.40 MT/ha, followed by the Highlands East of Rift Valley (7.93–12.27 MT/ha). The North Eastern Region and South Eastern lowlands receive low amounts of rainfall, thereby recording low maize yield, ranging from 1.83 to 4.73 MT/ha and 1.52 to 2.61 MT/ha, respectively.

These results (Table 1) show that variability in climatic parameters, which is rainfall, maximum temperature, and minimum temperature, has an impact on maize yield for four climatological zones. According to the results there is a strong positive correlation between maize yield and the climatic parameters for Lake Victoria basin, Highlands East of Rift Valley, Coastal Strip, and North Western Region. In all the four cases, except T-max for the Coastal Strip, the R^2 is 0.5 and above, while the p value is <0.05, indicating that there is a significant relationship between maize yield, rainfall, T-min and T-max. In the North Eastern Region and the South Eastern Lowlands, however, there was no significant correlation between maize yield and the climatic parameters. The p value was > 0.05 for both cases.

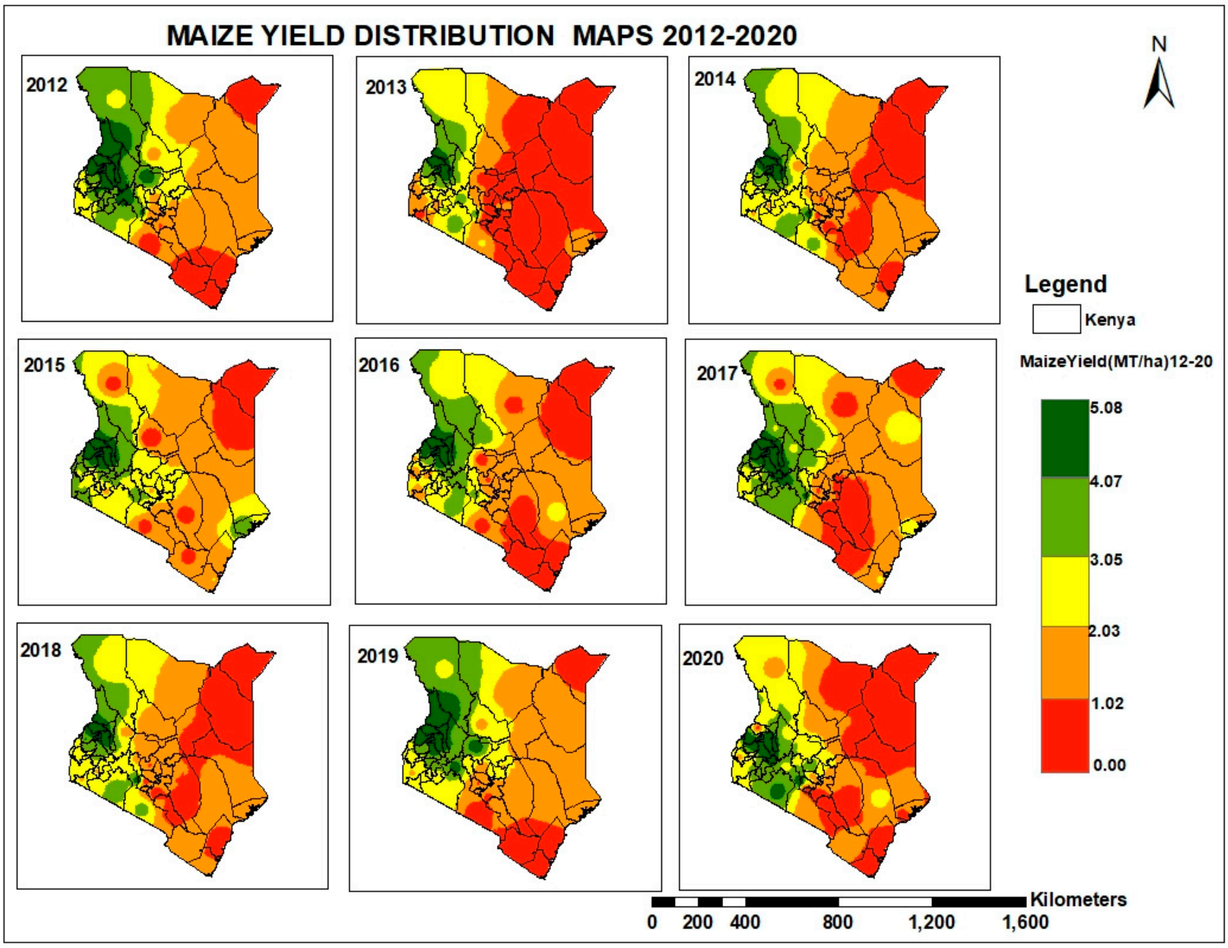


Figure 12. Spatial distribution of maize yield 2011–2020.

Table 1. Spearman's rank test correlation results. The symbols of *, ** and *** indicate *p*-values less than 0.05, 0.01, and 0.001 respectively.

Zone's Yield (*y*)	Factor (*x*)	r	R^2	T Student	*p* Value
LVB_y	Rainfall	0.83	0.694	3.99	0.0053 **
	Tmax	0.93	0.871	6.874	0.0002 ***
	Tmin	0.85	0.730	4.35	0.0034 **
RVH_y	Rainfall	0.85	0.723	4.27	0.0037 **
	Tmax	0.73	0.538	2.85	0.0246 *
	Tmin	0.74	0.551	2.93	0.0219 *
CS_y	Rainfall	0.92	0.853	6.38	0.0004 ***
	Tmax	0.63	0.401	2.17	0.0671 *
	Tmin	0.71	0.500	2.65	0.0331 *
NWR_y	Rainfall	0.82	0.667	3.74	0.0072 **
	Tmax	0.72	0.514	2.72	0.0298 *
	Tmin	0.75	0.563	3.00	0.0199 *
NER_y	Rainfall	0.33	0.111	0.94	0.3807
	Tmax	0.07	0.004	0.18	0.8647
	Tmin	0.05	0.003	0.13	0.8984
SEL_y	Rainfall	0.50	0.250	1.53	0.1705
	Tmax	0.18	0.034	0.49	0.6368
	Tmin	0.55	0.303	1.74	0.1250

4. Discussion

4.1. Precipitation

A study conducted by [36] outlined no trend in the precipitation in the Turkana region for the study period of 1950 to 2012. Generally, there is a decreasing trend in annual rainfall in all the regions; nonetheless, it is not statistically significant. Additionally, a study by [37] also reported the same results while working on the precipitation variability and change in the Somali Peninsula between 1979 and 2012. Our results, however, contradict the results of a study conducted in Nigeria between 1980 and 2015, where the overall annual rainfall trend was increasing, but not statistically significant [38]. This disparity in the results can be attributed to the differences in the study period and geographical locations. The MAM seasonal precipitation patterns (Figure 3a) show an overall decreasing trend, with Lake Victoria basin still recording the highest rainfall. This is in agreement with past studies [38–44]. A study conducted by [45] on the rainfall variability in Kenya also established a reducing trend in MAM seasonal rainfall between 2010 and 2014. The decline in precipitation for the MAM can be linked to climate variability and has negative impacts on maize yield, given that it is the long rainy season. Generally, the OND short rain season (Figure 3b) shows greater precipitation variability in comparison to the MAM long rain season. This greater variability could be attributed to the influence of the El Nino Southern Oscillation Index (ENSO) and Indian Ocean Dipole (IOD), which result in greater annual fluctuations. Both systems are known to influence the OND rainfall more than MAM rainfall [37,44–47]. A study conducted by [36] between 1950 and 2012 also confirmed our results by indicating a decreasing trend for the MAM seasonal precipitation and an increasing trend for the OND seasonal rainfall. In another study, Ref. [48] discovered a notable downward trend in precipitation during the MAM season in Central-Eastern Ethiopia and Kenya. Furthermore, a remarkable upward trend in precipitation during the OND season was recorded in many parts of the region.

4.2. Maximum Temperature

A study conducted by [36] on the Tmax and Tmin temperature trends in Turkana County 1979–2012 confirms our results that the slight positive and negative trends observed were not statistically significant. Generally, an increasing trend is observed in the annual maximum temperature across all regions but it is not statistically significant (Figure 5). This confirms the results of a study conducted in Kitui County, which is part of the South Eastern Region, from 1981 to 2011 [49]. Although temperature variations exist throughout Kenya, there is a noticeable warming trend, especially since the 1960s, with inland regions experiencing greater increases in both the minimum and maximum temperatures [20]. Another study was performed in Nigeria between 1980 and 2015, which indicated that the trend statistics of the annual maximum temperature was increasing generally for all stations, but was nevertheless not statistically significant [38]. The North Eastern Region records the highest mean maximum temperature ranging from 32.79 to 33.58 °C throughout the study period, followed by the Highlands East of Rift Valley, 30.88 to 31.55 °C. South Eastern Lowlands and Lake Victoria basin show the lowest mean maximum temperature, ranging from 29.34 to 29.93 °C and 29.15 to 29.91 °C, respectively. According to a report by the WBG, [20] there is a significant variation in temperatures across Kenya. Highlands experience much lower temperatures compared to the lowland and coastal regions. Based on a study performed in the East African region, a noticeable rise in the seasonal maximum temperature of up to +3 °C was recorded in many areas, distinctly during the MAM season. In the cause of the OND season, just a few regions in the area, for example, Eastern Kenya, and Southern and Southwestern Tanzania, showed a non-significant increase in T-max from 1979 to 2010 [48]. Another study performed on trends in surface air temperature over Kenya for the 1971–2010 period indicated that there was generally an upward trend for Tmin and Tmax [50].

4.3. Minimum Temperature

A study conducted by B. O. Ayugi and Tan [28] on Kenya from 1971 to 2010 confirmed that the highlands located in the central and western parts of Kenya exhibit low temperatures compared to the ASALS of Eastern and Northern Kenya. He also noted a similar variation in the spatial distribution. A study performed on the East African region between 1981 and 2016 depicted a remarkable upward trend in Tmin in MAM (up to +2 °C), particularly in Kenya and Tanzania. Statistically significant increasing trends in Tmin were also observed in the southern part of Ethiopia of up to +1.2 °C during the MAM. For the OND, however, the observed increasing trend was not statistically significant [51]. Another study conducted in the same region between 1986 and 2020 reported a positive trend in most of the meteorological stations both for the seasonal as well as annual timescales [52].

Concerning the average precipitation, maximum temperature, and minimum temperature (Figure 11), our results confirmed the outcomes of a study conducted by [26] in East Africa, where he established that the mean precipitation is between 300 and 1200 mm, significantly higher over the highlands and considerably lower over the lowlands. Additionally, Ref. [51] also reported that the long-term average maximum precipitation was up to 2000 mm in the western parts of Kenya and Ethiopia and some parts of Tanzania. In their study, Ref. [53] outlined that between 1981 and 2012, the maximum temperature of Kieni Constituency, located in Nyeri County, had been increasing as a result of climatic changes being exhibited in the area. This confirms a report by the IPCC, which states that most countries would experience an increased average temperature due to climate change [7]. In the East African region, Ref. [48] reported that the area with a lower precipitation record exhibited higher T-max (up to 35 °C) and T-min (up to 25 °C) records, especially in the eastern segment of the zone from 1979 to 2010. The observed T-min was low (<5 °C) in Southwestern Tanzania and Central Ethiopia and high (up to 25 °C) in the Eastern Region of Ethiopia and Kenya. In general, the Eastern Region of the study area displayed lower precipitation and higher temperature (T-max and T-min) records during 1981–2016 and 1979–2010, respectively [48]. This is consistent with the spatial distribution of the average Tmax, Tmin, and precipitation, as they show the eastern part of the country to be experiencing higher temperatures compared to the western and central parts.

4.4. Effects of Rainfall and Temperature Variability on Maize Yield

The spatial distribution of the annual maize yield (Figure 12) shows that the central and western parts of the country produce more maize compared to the northern part. This is in agreement with a report by the World Bank Group [20], which states that the population of the country is predominantly concentrated in the coastal, western, and central, zones, which make up below 20% of the country's total area, but are home to almost 90% of the population. These regions are also known for their productive agricultural land, which is primarily dependent on rainfall [20].

According to the results, there is a strong positive correlation between maize yield and the climatic parameters for the Lake Victoria basin, Highlands East of Rift Valley, Coastal Strip, and North Western Region. In all four cases, except T-max for the Coastal Strip, the R^2 is 0.5 and above, while the p value is <0.05, indicating that there is a significant relationship between maize yield, rainfall, T-min, and T-max. In the North Eastern Region and the South Eastern Lowlands, however, there was no significant correlation between maize yield and the climatic parameters. The p-value was > 0.05 for both cases. This result validates a study conducted by [54], where the correlation between climate parameters and maize yield was higher in the stations largely known for growing maize, while the strength of the relationship decreased in the arid and semi-arid lands. The high correlation values implied that the station largely contributes to the national harvest and its precipitation variability impacted the yield nationally. Another study [55], on the seasonal rainfall variability effect on smallholder farmers in Nyeri County, established that at 1% level of significance, there was a strong positive correlation between the precipitation and maize yield. According to [54], the minimum temperature anomalies exhibited significant detrimental impacts at the Kisii and Kakamega stations, which happen to be crucial maize-growing regions in Kenya's highlands. Both stations, situated in the highlands of the country, suggest that the rise in the minimum temperature has surpassed acceptable thresholds and is now inflicting negative consequences on maize production. These two stations fall under the Lake Victoria basin, which recorded the highest maize yield according to our study. This study therefore validates our findings that, in the Lake Victoria basin, there is a significant correlation between maize yield and the minimum temperature at $p = 0.0034$. In a study on six districts in Zambia, which represents the three agroecological zones of the country, Ref. [56] showed that only one district, Nyimba, showed a significant variation in the yield of maize that can be attributed to the climatic variables of precipitation and temperature. On the other hand, Ref. [57], obtained results that slightly differ with our findings. In a study exploring the effects of climatic changes on maize yield in China, his results showed that, from 1979 to 2016, temperature negatively affected maize yield, while precipitation had a positive but overall negligible impact. In the North Eastern Region and the South Eastern Lowlands, however, there was no significant correlation between maize yield and the climatic parameters. The p value was > 0.05 for both cases. A study conducted by [25] on the effects of climate variability on maize yield in the ASALS of lower Eastern Kenya confirms our result that, in the South Eastern Lowlands, there is no correlation between maize yield and climatic variables. A study conducted by [58] in Ghana found that the climatic parameters of soil moisture, maximum temperature, minimum temperature, and precipitation collectively accounted for 75% of variations in maize yield under conditions that were wetter than normal.

5. Conclusions

To summarize, the spatial maps highlight the prevalence of wetter areas in the Lake Victoria basin and Highlands East of Rift Valley compared to the North Eastern and North Western Regions. Lake Victoria basin had the highest mean annual precipitation, followed by the North Western Region. The lowest annual rainfall patterns were recorded by the Highlands East of Rift Valley and the North Eastern Region. Generally, the OND short rain season shows greater rainfall variability in comparison to the MAM long rain season. The variability could be attributed to the influence of the El Nino Southern Oscillation Index (ENSO) and Indian Ocean Dipole (IOD), which result in a higher inter-annual variability. The spatial distribution of the annual maize yield shows that the central and western parts of the country produce more maize compared to the northern and eastern parts. This is because the population of the country is predominantly concentrated in these regions, which make up below 20% of the country's total area, but are home to about 90% of the population. These regions are also known for their productive agricultural land, which is primarily dependent on rainfall. The results of Spearman's rank correlation test show that there is a strong positive correlation between maize yield and the climatic parameters for the Lake Victoria basin, Highlands East of Rift Valley, Coastal Strip, and North Western Region. In all the four cases, except T-max for the Coastal Strip, the R^2 is 0.5 and above, while the p value is <0.05, indicating that there is a significant relationship between maize yield and the climatic parameters in these regions. The findings suggest that climate variability in the study area has a significant impact on the yield of maize for four out of six climatological zones, as evidenced by the decline in precipitation trends for the March–April–May season, which is the long rainy season. The climatic parameters did not exhibit statistically significant trends because of the short study period. To enhance the capacity of communities to cope with climate-related extremes and build resilience, it is crucial to develop policies and frameworks that clearly articulate the overall response priorities. Through the development and implementation of these policies and frameworks, governments can ensure that climate change considerations are integrated into development planning, budgeting, and implementation throughout all sectors. These policies should aim to promote a low-carbon development pathway while enhancing the adaptive capacity and ensuring greater resilience to climate change.

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Appendix A

Table A1. Mann–Kendall test results for precipitation.

Mann–Kendall Test for Precipitation			
Series/Test	**Kendall's Tau**	***p*-Value**	**Sen's Slope**
Year	1.000	<0.0001	1.000
January	−0.111	0.721	−2.637
February	−0.244	0.371	−3.072
March	−0.200	0.474	−5.230
April	−0.244	0.371	−2.792
May	−0.156	0.592	−1.547
June	0.111	0.721	3.911
July	0.289	0.283	3.456
August	0.022	1.000	0.599
September	−0.022	1.000	−0.349
October	−0.067	0.858	−1.407
November	−0.067	0.858	−3.848
December	0.111	0.721	1.021
Average	−0.022	1.000	−0.311

Table A2. Mann–Kendall test results for T-max.

Mann–Kendall and Sen's Slope Test Results for Tmax			
Series/Test	**Kendall's Tau**	***p*-Value**	**Sen's Slope**
Year	1.000	<0.0001	1.000
January	−0.556	0.032	−0.289
February	−0.422	0.107	−0.224
March	−0.644	0.012	−0.410
April	−0.378	0.152	−0.465
May	−0.022	1.000	−0.101

Table A2. *Cont.*

Mann–Kendall and Sen's Slope Test Results for Tmax			
Series/Test	**Kendall's Tau**	***p*-Value**	**Sen's Slope**
June	0.244	0.371	0.174
July	0.378	0.152	0.196
August	0.200	0.474	0.176
September	0.289	0.283	0.107
October	0.467	0.074	0.324
November	0.244	0.371	0.279
December	0.022	1.000	0.038
Average	0.156	0.592	0.019

Table A3. Mann–Kendall test results for Tmin.

Mann–Kendall and Sen's Slope Test Results for Tmin			
Series/Test	**Kendall's Tau**	***p*-Value**	**Sen's Slope**
Year	1.000	<0.0001	1.000
January	−0.244	0.371	−0.066
February	−0.156	0.592	−0.040
March	−0.556	0.032	−0.291
April	−0.422	0.107	−0.167
May	−0.467	0.074	−0.147
June	0.156	0.592	0.075
July	0.378	0.152	0.081
August	0.244	0.371	0.132
September	0.244	0.371	0.120
October	0.022	1.000	0.047
November	0.333	0.210	0.187
December	0.289	0.283	0.163
Average	−0.156	0.592	−0.008

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