DOI: https://doi.org/10.20372/afnr.v2i1.972
ISSN: 2520-7687 (Print) and 3005-7515 (Online)
Journal of Agriculture, Food and Natural Resources
J. Agric. Food Nat. Resour. Jan-Apr 2024, 2(1): 27-39
Journal Home page: https://journals.wgu.edu.et

Original Research

Variability and Extremes of MAM Season Rainfall in Ethiopia: Insights from the 2023 Anomalous Event

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Abstract

The variability of MAM (March to May) rainfall in Ethiopia is among the most important agrometeorological parameters for the success of agriculture and water management practices. This study therefore set out to analyze the anomalous increase of MAM season rainfall in 2023 using high-resolution Tropical Applications of Meteorology using Satellite data and ground-based observations (TAMSAT) rainfall estimate. A combination of multiple statistical methods was used to analyze and compare the 2023 MAM season rainfall with baseline mean across Ethiopia using the 40 years (1983-2022) dataset. Results showed that MAM rainfall in 2023 (412.81mm) was 79% above average for the baseline period, with extremely wet conditions in the March and April months. Similarly, the 2023 MAM season rainfall anomaly exceeded historical short rainy seasons by 80-130mm and was spatially concentrated in the southwestern and central parts of Ethiopia. Statistical analyses (t-test) also confirmed significant differences between the MAM season rainfall of 2023 and the 1983-2022 averages at p<0.001 for all months solely and at the seasonal scale. Comparisons with previous high rainfall years indicated that the 2023 MAM season was an extreme and anomalous event. The study highlights the importance of understanding seasonal rainfall variability and extremes in Ethiopia, as they have direct implications for food availability, water resource management, and climate change adaptation strategies. Further research using other datasets is needed to demonstrate the utility of high-resolution satellite rainfall estimates for monitoring anomalies and improving early warning systems in the country.

Article Information

Article History:
Received: 31-01- 2024
Revised: 08-04-2024
Accepted: 17-04-2024

Keywords:
Anomaly
Belg season
Climate indices
TAMSAT
Trend

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INTRODUCTION

Rainfall plays a vital role in overall socio-economic development and agricultural production systems. Particularly, in developing countries like Ethiopia where rainfed agricultural practices are dominant. This implies that rainfall is one of the most imperative hydroclimate elements for the livelihoods of people and agricultural production and productivity (Abegaz & Abera, 2020). Because, the temporal distribution and amount of rainfall during the growing season have a direct influence on crop yields (Berhane, 2018; Tesfa & Mekuriaw, 2014). On the other hand, lack of rainfall and fluctuations in rainfall patterns can lead to famine and drought, which further aggravate food insecurity and poverty in the country. Furthermore, rainfall variability affects directly the sustainability of water resources management, utilization, and availability (Abegaz & Abera, 2020; Cheung *et al*., 2008).

Ethiopia experiences distinct rainfall seasons throughout the year. According to the World Bank (WB, 2020) and the Ethiopian National

Meteorological Agency (NMA, 2023), there are three main seasons in Ethiopia each exhibiting unique temperature and rainfall characteristics: the main rainy season (*Kiremt*), the dry season (*Bega*), and the short rainy season (*Belg*). Seasonal rainfall in Ethiopia is driven mainly by the migration of the Inter-Tropical Convergence Zone (ITCZ) and there is strong inter-annual variability of rainfall across the country. The main rainy season, *Kiremt*, occurs from mid-June to mid-September and accounts for 50–80% of annual rainfall. Parts of central and northern Ethiopia experience an irregular, secondary wet season, *Belg*, which often has considerably less rainfall. Southern regions of Ethiopia experience two distinct wet seasons, *Belg*, from March to May, and the Bega occurring from October to December, which has drier and colder conditions (*WB*, 2020; Tabari et al., 2015; Legesse, 2016; Bedane et al., 2022).

The factors that contribute to the formation and variability of seasonal rainfall in Ethiopia include the movement of a weather phenomenon called the Inter Tropical Convergence Zone (ITCZ). This brings moisture and precipitation to the region. Another important factor is the interaction between two air masses, the high and thermal low over South Sudan. These interactions play a role in influencing rainfall seasonal patterns in Ethiopia (Palmer et al., 2023; Endris et al., 2019). Researchers have also conducted studies to understand these drivers of variability including looking at atmospheric processes like El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) as well as local factors such as changes in topography and land use (Endris et al., 2019; Palmer et al., 2023; Nicholson, 2017). Berhane et al. (2020) explored trends and variations in seasonal rainfall, in Southeast Ethiopia finding that ENSO and IOD were major drivers of this variability. Another study also revealed that the IOD and sea surface temperature (SST) anomalies are the main drivers of rainfall variability in the region (Degefu & Bewket, 2017; Ndomeni et al., 2018; Bedane et al., 2022).

The MAM season is the second rainfall season of Ethiopia next to the main rainy season which covers the months from June through September (JJAS season, locally *Kiremt*). It contributes a significant portion of the annual rainfall, typically ranging from 10% to 50% (Tadese et al., 2019; Gebremichael et al., 2019; Weldegerima et al., 2018). The MAM rainy season typically occurs from March to the end of May and is the main rainy season for southern and southeastern parts of the country. During this period, the ITCZ moves from south to north, bringing rain to southern Ethiopia (Worqlul et al., 2014; Alemayehu et al., 2020; Palmer et al., 2023). The MAM season is known for its variability in duration and intensity across different regions of the country and it is influenced by its location and the movement of weather systems (Gummadi et al., 2018).

The trend of the MAM rainy season in Ethiopia has shown contradicting results in both directions and magnitudes across basins. For instance, according to Bedane et al. (2022), there has been a decline in MAM rainfall throughout East Africa, including Ethiopia. Additionally, Ware et al. (2023) have observed a decrease in the Belg rainfall in southern Ethiopia. However, Tabari et al. (2015) discovered statistically insignificant trends within the Blue Nile basin. Similarly, Tadese et al. (2019) reported a decreasing trend in stations located within the Awash River Basin. These findings underscore the variation that exists regarding MAM rainfall patterns in Ethiopia with some areas experiencing declines while others witness increases. This highlights the localized nature of rainfall distribution, within the country.

The MAM rainy season plays a role in agriculture and the availability of water. However, its variable nature creates difficulties for farmers when it comes to timing their planting activities and managing irrigation water resources (Gebremichael et al., 2014). Several factors characterize the MAM or Belg season including the timing, duration, location, and intensity of rainfall (Seregina et al., 2021; Bayable et al., 2021). Therefore, it is crucial to monitor, predict, and understand the characteristics, variability, trends, and drivers of this season. Doing so is essential for planning ensuring food security managing water resources efficiently predicting droughts and issuing early warnings. ultimately, to contribute to the overall development of the country (Alemayehu et al., 2020; Gebrechorkos et al., 2019; Sigdel et al., 2022; Dixon et al., 2019; Seleshi & Camberlin, 2006).

The very common sources of rainfall datasets for various purposes are in-situ or ground-based observations, remotely sensed products (Satellite and weather radar), and numerical weather predictions (He et al., 2024; Nielsen et al., 2024). The in-situ measurements are more common and preferable than the other sources if meet the requirement intended purpose. Despite accuracy and reliability, the gauge-based rainfall datasets are scarce and unevenly distributed in many areas of the world particularly in African countries including Ethiopia (Ibrahim et al., 2024; Knudsen, 2023). Recently, technological advancements in the remote sensing sector developed a number of high-resolution Satellite rainfall estimate (SRE) products to supplement ground-based measurements by providing high-resolution rainfall data covering wider spatial areas where rain gauge stations are either not existed or sparse (Roversi et al., 2024; Ndemere et al., 2024; Cattani et al., 2018).

In light of this, rainfall characteristics of Ethiopia were analyzed using different data sources including satellite products (Knudsen, 2023; Cattani et al., 2018; Geleta & Deressa, 2021), observation data (Woldegerima et al., 2018; Wodage et al., 2016), reanalysis data (Tamene et al., 2021; Elzopy et al., 2020; Ware et al., 2023), climate change data (Mellander et al., 2013), and gridded data (Alhamshry et al., 2019) at regional (Cattani et al., 2018; Seregina et al., 2020), national (Elzopy et al., 2020; Knudsen, 2023), basin (Mellander et al., 2013; Tadese et al., 2019; Toni et al., 2022), subbasin (Woldegerima et al., 2018; Wodage et al., 2016;), segment of the country (Jacob et al., 2013) and administrative boundary (Teshome et al., 2021; Tolosa et al., 2023; Ware et al., 2023; Feke et al., 2019) levels for different time slices at daily, decadal, monthly, seasonally and annual scales.

This study was focused on MAM season rainfall across Ethiopia using TAMSAT satellite rainfall product to analyze the unusual increase of Belg season rainfall of the 2023 water year compared to 1983 to 2022. The anomalous increase in MAM rainfall observed in 2023 presents a motivation to investigate the characteristics and implications of this shift. By conducting a comprehensive analysis of historical data and comparing it with the recent anomaly, this research aims to shed light on the characteristics of the event and provide valuable insights for policymakers, researchers, and stakeholders involved in climate change adaptation and agricultural planning. Moreover, the study highlights the abnormal increase in MAM rainfall in Ethiopia in 2023, the study contributes to the growing body of evidence on the impacts of climate change on regional rainfall patterns.

This study was motivated by the unexpected event of an increase in MAM rainfall observed during 2023. Therefore, the main aim of this study was to analyze the 2023 MAM season rainfall, in Ethiopia. High-resolution TAMSAT satellite rainfall product was used to examine and compare the uncharacteristic rise events in MAM season rainfall during the 2023 water year in reference to the mean of 1983 to 2022. The study investigated the events' tempo spatial characteristics and its implications to provide valuable insights for stakeholders involved in water resources, climate change, and agricultural planning and contributed to a growing body of evidence on the effects of climate change on rainfall patterns.

MATERIALS AND METHODS

Description of Ethiopia

Ethiopia, a country situated in the Horn of Africa and lacking access, to the sea covers an area of 1.12 million square kilometers (Figure 1). It shares borders with Eritrea, Djibouti, Somalia, Kenya, Sudan and South Sudan. The tropical climate experienced in the country is influenced by factors like altitude, latitude, and topography resulting in fluctuations in temperature and rainfall patterns (Figure 2). There are two rainfall seasons; a shorter one called *Belg* which occurs from February/March to May and a longer one known as *Kiremt* from June to September. The dry season typically lasts from October to January. Annual rainfall varies from less than 200 mm in lowland areas to over 2,000 mm in highland regions (Figure 1b-d). Temperature averages span from around 10°C in the highlands to about 35°C in the lowlands (Figure 1a).

Ethiopia comprises landscapes that include high mountains, vast lowlands, and a range of climates along with agricultural ecosystems and water basins. It can be classified into three zones; highlands (accounting for 45% of the country) suitable for crop cultivation; midlands (covering 35%) ideal, for mixed farming and livestock production; and lowlands (occupying 20%) primarily used for pastoralism (*World Bank Open Data*, 2017; Yirgu et al., 2020; Fazzini et al., 2015; Seleshi & Camberlin, 2006; Mekonen & Berlie, 2020; Awulachew *et al.,* 2007).

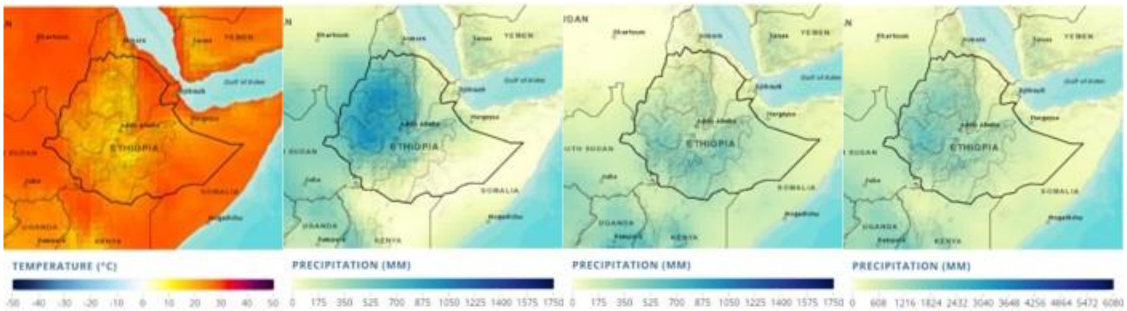
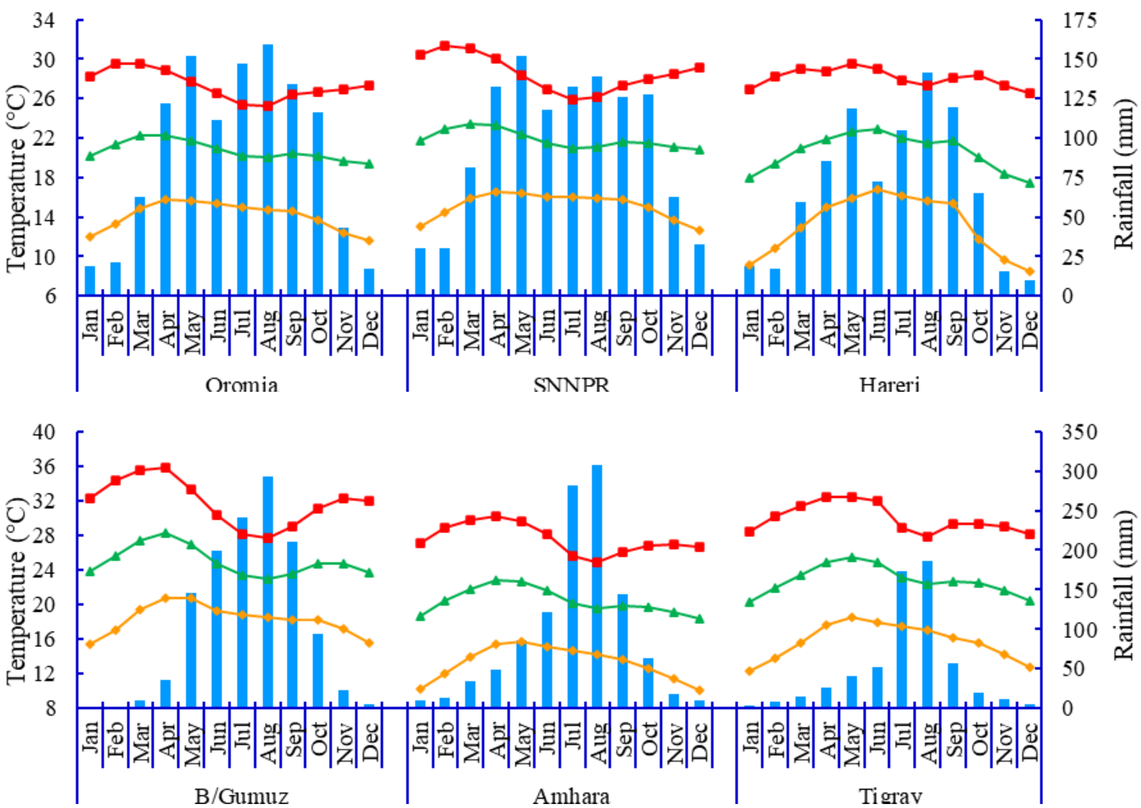


Figure 1: Spatial distribution of mean annual temperature (a), JJAS season rainfall (b), MAM season rainfall (c), and Annual rainfall (d) of Ethiopia (Adopted from *World Bank Climate Change Knowledge Portal*, 2020)



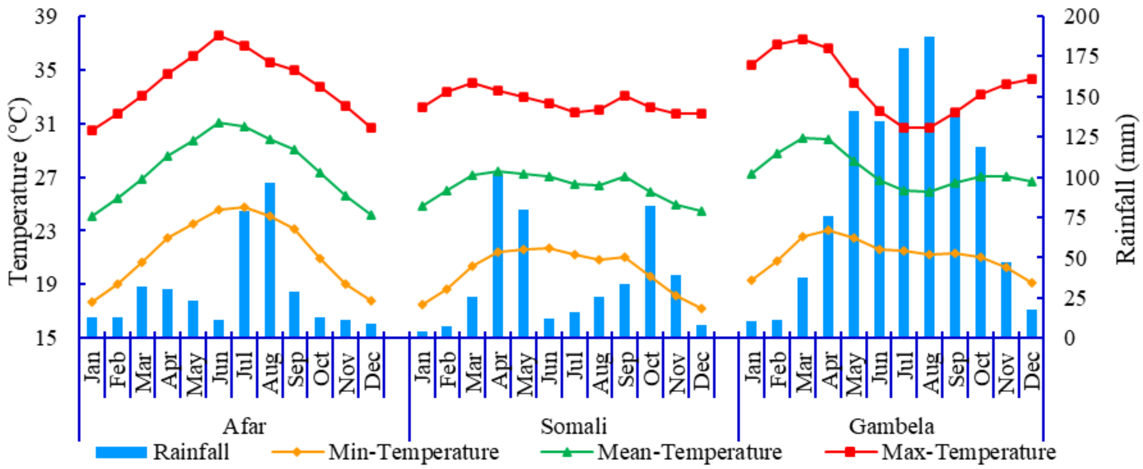


Figure 2: Monthly rainfall, maximum temperature, minimum temperature and mean temperature distribution of the nine regions of Ethiopia (Based on the data obtained from the *World Bank Climate Change Knowledge Portal*, 2020).

Rainfall Dataset

The TAMSAT satellite rainfall product, which combines satellite data and ground-based observations was utilized to examine the increase, in rainfall during the MAM season (belg season) in Ethiopia for the year 2023. The latest version of this product v3.1, officially replaced v3.0 on July 1st, 2020. It is accessible in both netCDF and CSV formats (Maidment et al., 2014; Maidment et al., 2017; Tarnavsky et al., 2014). Covering an area of the African continent with a spatial resolution of approximately 4km x 4km (0.0375° x 0.0375°) this dataset spans from latitude 38.025°N to 35.9625°S and from longitude 19.012°W to 51.975°E. With coverage from January 1st, 1983 until today the TAMSAT dataset offers a long-term perspective on rainfall patterns, within the region (Maidment et al., 2014; Maidment et al., 2020; Tarnavsky et al., 2014; Boult et al., 2020).

The TAMSAT dataset is available, in timeframes, such as daily, every five days (pentadal), every ten days (dekadal), monthly, and seasonal. The daily and pentadal data are generated on the 6th, 11th, 16th, 21st, and 26th of each month. The decadal data is generated on the 11th, and 21st. Monthly data is created on the day of each month while seasonal data is created quarterly on March 1st, June 1st September 1st and December 1st. This variety of temporal resolutions caters to research requirements. The TAMSAT dataset has a latency period of up to two days after each of five days. This means that the data is updated promptly after each period ends ensuring its timeliness, for research purposes and decision-making (Maidment et al., 2014; Maidment et al., 2017; Tarnavsky et al., 2014; Boult et al., 2020).

In this study TAMSAT was used for the following reasons; First, the TAMSAT satellite dataset provides a long-term record of rainfall estimates for the region, spanning over three decades (Maidment et al., 2017). Second, the TAMSAT satellite dataset uses a unique algorithm that combines satellite data with ground-based observations to produce high-quality rainfall estimates (Maidment et al., 2020). This algorithm has been extensively validated and has been shown to produce reliable rainfall estimates, particularly in data-sparse regions. Third, the TAMSAT satellite dataset provides rainfall estimates at a high spatial resolution (finer than 4 km x 4 km), which is particularly useful for analyzing rainfall patterns at the local level and for identifying areas that are prone to drought or flooding (Maidment et al., 2017). Fourth, the TAMSAT satellite dataset is freely available and accessible to researchers and decision-makers, making it an important resource for monitoring and assessing the impacts of climate variability and change on agriculture and food security in the region (Tarnavsky et al., 2014). Finally, the use of the TAMSAT satellite dataset in this study ensures that the results are based on a robust and reliable dataset, which enhances the credibility of the findings and supports evidence-based decision-making for agriculture and food security policy in the region (Maidment et al., 2017: Maidment et al., 2020).

Furthermore, the better performance of TAMSAT satellite rainfall products across Ethiopia has been indicated in several studies. For instance, in the Lake Tana basin, UBN sub-basin, TAMSAT outperforms CHIRPS products both in lowland and highland areas (Fenta et al., 2018). TAMSAT accurately captured the temporal pattern of ground observations in Ethiopia, although there was some slight overestimation during the rainy season at certain sites. The satellite-based product showed a better reflection of rainfall distributions at seasonal and annual scales compared to the ERA5 reanalysis product (Dubache et al., 2021). Gella, (2018) analyzed the performance of six high-resolution satellite derived rainfall estimates including CHIRPS, TAMSAT, TRMM3B42, PERSIANN-CDR, ARC, and CMORPH in the eastern part of Ethiopia. The results indicated that TAMSAT has relatively better capability in rainfall amount estimation.

Methods of Data Analysis and Presentations

Rainfall data were analyzed using various methods of computing tempo-spatial patterns of rainfall depth over a given geographic area or region or country or basin or planning units. In this study, the spatiotemporal characteristics of the 2023 short rainy season in Ethiopia were compared and evaluated thoroughly in reference to the mean of 1983 to 2022. Methods of rainfall analysis used in this study were briefly explained as follows;

a) ***Percentage of normal*:** The percentage of MAM season was calculated for each year (from 1983 to 2022) as a percentage of the baseline mean. Particularly, the percentage of 2023 MAM season rainfall was compared with those eight wettest years in which MAM season rainfall was increased by more than 50 mm

(21%) from baseline mean MAM season rainfall. This allowed easier and quicker comparisons across years in Ethiopia.

b) ***Rainfall totals:*** In this study, total rainfall accumulated over the MAM season was compared. It was graphically analyzed creating bar charts showing totals for each year. Statistical t-tests were also performed to analyze the statistically significant difference between months of MAM season. That means, the 2023 monthly rainfall for March, April, and May against the long-term monthly means years were compared using t-tests at the 95% confidence level.

c) ***Trend Analysis:*** The non-parametric Mann-Kendall and Sen's slope tests were applied to assess the presence of monotonic trends and their magnitude in MAM season rainfall from 1983 to 2023 in Ethiopia.

d) ***Variability Analysis:*** The coefficient of variation (CV), defined as the ratio of the standard deviation to the mean, was calculated for the March, April, May, and MAM seasonal rainfall in Ethiopia over the 1983-2023 period to quantify the interannual variability.

e) ***Rainfall anomalies**:* Using this method anomaly was calculated by subtracting mean rainfall for the baseline period (1981 – 2022 climatology) from rainfall in each year's MAM season rainfall. Anomaly was more recognized by creating anomaly spatial maps.

f) ***Spatial analysis***: Create rainfall distributions and anomaly maps to identify regions with the strongest signals. The spatial interpolation (IDW) and analysis were performed using ArcGIS software for Windows.

Finally, the analyzed data were presented using tables, charts, and maps.

RESULTS AND DISCUSSION

Depth of MAM Season Rainfall in Ethiopia

The monthly rainfall values for March, April, and May as well as the overall rainfall during the MAM season for Ethiopia from 1983 to 2023 were displayed in Figure 3. The figure indicates that there was a considerable variation in both the overall rainfall for the MAM season and the rainfall amounts for each month in the season. With a total of 412.81 mm, 2023 received the highest rainfall during the MAM season. Compared to the previous years (1981-2022), which gives a mean rainfall of 209.68 mm, this represents a substantial increase. Similarly, 1999 had the least amount of rainfall overall (173.42 mm) during the MAM season for the study period.

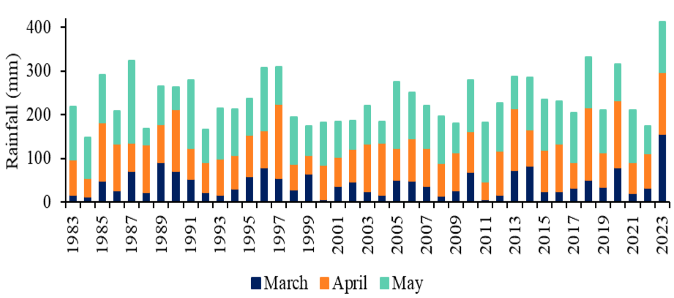


Figure 3: The monthly total rainfall values (in mm) for March, April, and May and the total rainfall for the MAM season for each year from 1983 to 2023 across Ethiopia

The mean monthly rainfall values for March, April, and May were 40.61mm (17.6%), 91.26mm (39.55%), and 98.89mm (42.85%), respectively. These values indicated that May was the wettest month of the three. April was the second wettest month, while March was the relatively less wet month. Further, the maximum monthly rainfall of 90.34mm, 169.84mm, and 188.47mm were obtained for March, April, and May, respectively (Figure 4). However, in 2023, the rainfall values for March, April, and May were 155.45mm (37.66%), 141.66mm (34.31%), and 115.7mm (28.03%), respectively. These values were much higher than the long-term averages for each month, indicating that 2023 was a very wet year. Particularly, in March Ethiopia received exceptionally increased rainfall, which was nearly four-fold than mean amount. The high rainfall in 2023 could have significant impacts on water resources, agriculture. and food supply in the country, as it could lead to waterlogging of crops, flooding, and erosion of the soil.

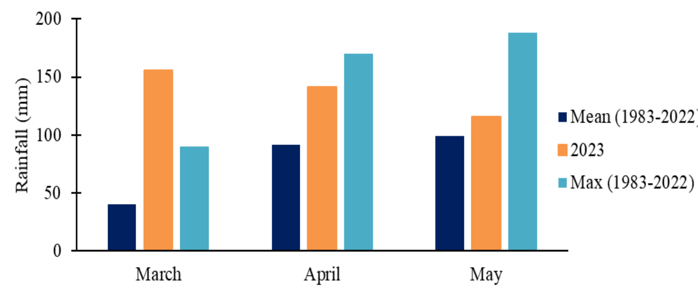


Figure 4: Comparison of monthly rainfall of 2023 MAM season with mean monthly rainfall (in mm) from 1983 to 2022 MAM in Ethiopia. It includes the maximum monthly rainfall values for the year from 1983 to 2022 to compare it with that of the 2023 MAM season months rainfall totals.

Contribution of MAM to Annual Rainfall in Ethiopia

The contribution of the MAM season rainfall to the total annual rainfall over Ethiopia varies substantially from year to year, ranging from 18.2% in 1984 to 50.7% in 2023 during the 1983-2023 analysis period. On average, the MAM season accounts for 28.9% of the total annual rainfall. However, in certain extreme anomaly years, the contribution was much higher - for instance, 50.7% in 2023 and 40.8% in 2018. In contrast, during drought years like 1984 and 2022, the MAM season contribution dropped to around 20% of the annual total (Figure 5). Overall, these results highlight the significant interannual variability in the contribution of the MAM rains to the annual water budget in Ethiopia. The finding that the MAM season contributes 28.9% on average matches well with Gebrechorkos et al. (2019), who found a similar value for the 1961-2015 period using station observations. The substantial fluctuation from year to year poses significant challenges for agricultural management and water resource planning in Ethiopia, particularly in areas that rely heavily on the MAM rains. This highlights the need for seasonal forecasting and preparedness for both extremes of rainfall variability during this critical growing and rainy season in the region.

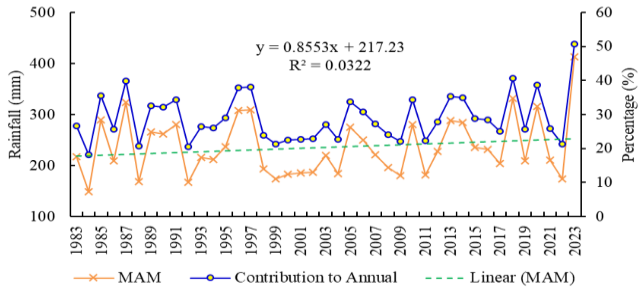


Figure 5: MAM season rainfall amounts and their contribution to annual rainfall total in Ethiopia from 1983 to 2023 (41 years). The linear trend line indicated with a dashed green line shows an increasing trend of MAM season rainfall at the country level.

Variability of MAM Season Rainfall in Ethiopia

For the period from 1983 to 2023, CV was calculated at seasonal, monthly, and daily time scales to examine the interannual variability of MAM season rainfall over Ethiopia. Accordingly, CV analysis for 92 days (March 1 – May 31) indicates that there was more daily variability earlier in the season (Figure 6b). With a coefficient of determination of 67% for March rainfall, there is a high degree of yearly variability in this data. The CV showed more moderate interannual variability in April and May, with values of 35% and 31%, respectively (Figure 6a). The CV for the entire MAM season was 24%, indicating lower variability than for the individual months. March's low average rainfall combined with its high CV of 67% show that March was the most variable month of the MAM season in Ethiopia.

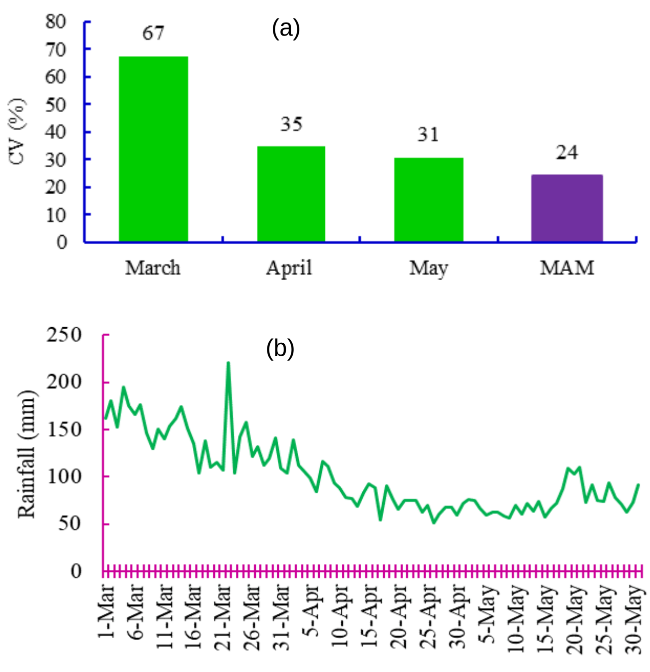
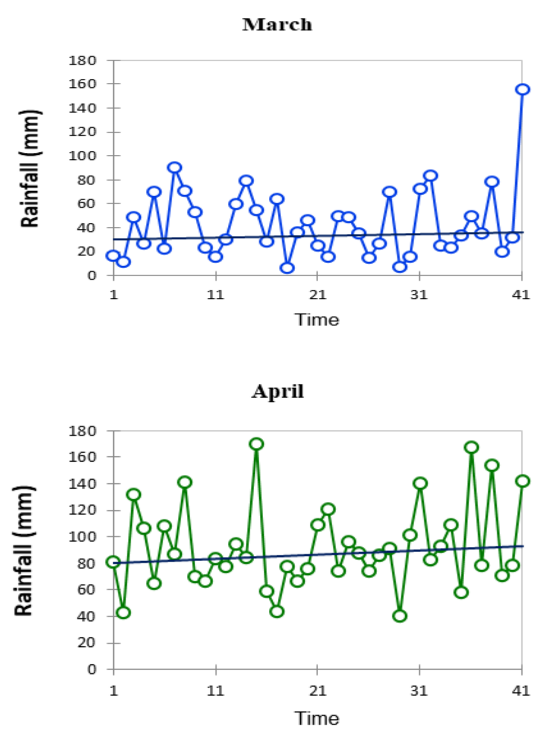


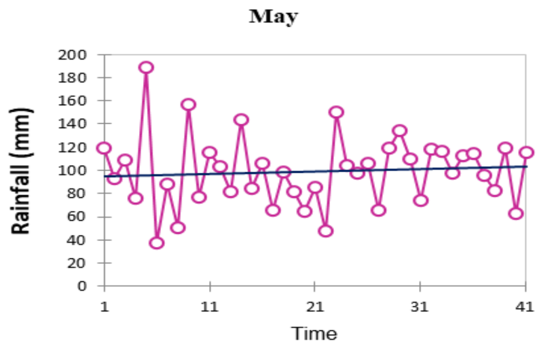
Figure 6: CV of rainfall MAM season rainfall from 1983 to 2023 at (a) seasonal and monthly and (b) daily scales over Ethiopia based on TAMSAT3.1 satellite rainfall product

However, a CV of 24% for the MAM season still implies significant interannual variability in seasonal rainfall, which can have major impacts on agriculture. These results are consistent with findings from Gebrechorkos et al. (2020) and Gummadi et al (2018), who reported high rainfall variability in March and moderate seasonal variability over Ethiopia based on station data analysis. The observed variability in rainfall in Ethiopia can be attributed to several factors, including climate change, El Niño and La Niña events, local weather patterns, and topography (Getahun et al., 2021; Getahun, 2015). Moreover, studies have shown that climate change has led to an increase in the frequency and intensity of extreme weather events, including droughts and floods, which can significantly impact agriculture and food availability dimension of food security (Suryabhagavan, 2017; Mekonen et al., 2020; Kilavi et al., 2018). Thus, the high interannual variability poses substantial challenges for rainfed agriculture in the region (Kassie et al., 2014).

The trend of MAM Rainfall in Ethiopia

The Mann-Kendall test revealed no statistically significant trends at the 95% confidence level for any of the monthly or seasonal rainfall series, with p-values ranging from 0.328 to 0.661. However, Sen's slope estimates indicate modest positive slopes for March (0.146 mm/year), April (0.325 mm/year), May (0.219 mm/year), and the MAM season (0.755 mm/year) over the analysis period (Figure 7).





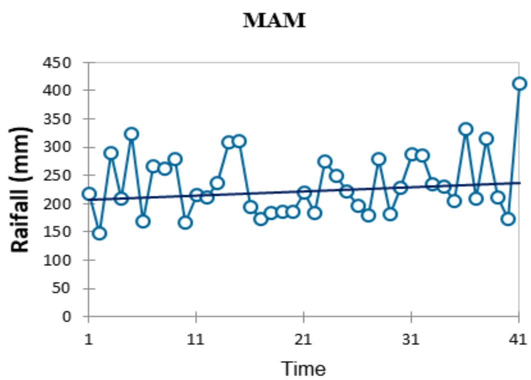


Figure 7: Trends of March, April, May, and MAM from 1983 to 2023 (41 years) in Ethiopia with Sens slope (in mm).

Several studies have been conducted on rainfall patterns in Ethiopia, and many of them have found similar results to the data provided in Figure 7. For example, a study by Gebrehiwot and van der Veen (2013) analyzed rainfall patterns in Ethiopia from 1976 to 2007 and found that there was significant variability in rainfall from year to year, with no clear trend or pattern. Similarly, a study by Bewket and Conway (2007) analyzed rainfall patterns in Ethiopia from 1983 to 2002 and found that the rainfall was highly variable, with some years having significantly lower or higher rainfall than others.

Another study by Bayissa et al. (2017) analyzed rainfall patterns in Ethiopia from 1983 to 2015 and found that there was a significant increase in rainfall in the country over the period, particularly in the northern and central regions. However, the study also found that the rainfall was highly variable from year to year, and there was no clear trend or pattern in the data. Besides, it is important to note that some studies have found regional differences in rainfall patterns in Ethiopia. For example, some studies found that there were significant differences in rainfall patterns between the highland and lowland regions of Ethiopia. The study found that the highland regions had more consistent rainfall patterns, while the lowland regions had more variable rainfall patterns (Enyew & Steeneveld, 2014; Degefu & Bewket, 2014; Mohammed et al., 2018). The lack of coherent significant trends highlights the complexity of Ethiopian rainfall variability.

Anomaly of MAM Rainfall Across Ethiopia

The anomaly analysis results indicate that the MAM season rainfall in Ethiopia was highly variable, with some years receiving significantly more or less rainfall than the long-term average (Figure 8). For instance, in 2018 and 1987 the anomaly was +101.1 mm and +93.3mm respectively, indicating higher rainfall than the long-term average. Conversely, in 1984 and 2011, the anomaly was -82.7 mm, and -49.04 mm respectively, showing lower rainfall than the long-term average of MAM seasons. It also noticed that the MAM rainfall has been highly variable in recent years. These findings of the analysis support the findings of other studies on rainfall anomalies across Ethiopia (Tamiru et al., 2015; Alemayehu et al., 2020).

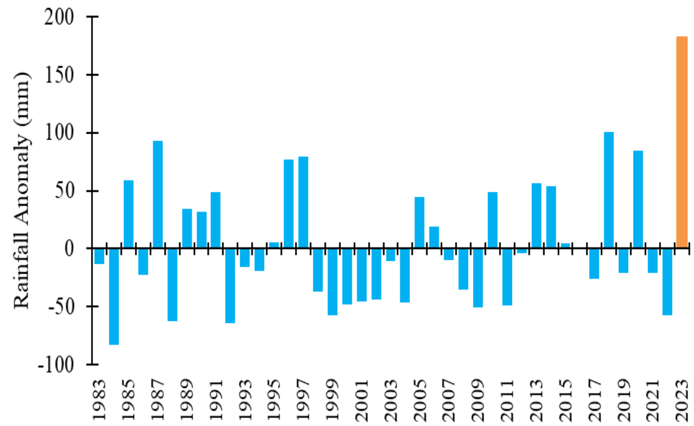


Figure 8: Anomaly histogram of mean MAM season total rainfall from long-year mean value (1983-2022) over 40 years (1983 - 2023) in Ethiopia. The 2023 MAM season anomaly indicated with odd (Orange) color.

Comparison of 2023 MAM to Long-Term Average

When comparing the rainfall data for the MAM season between 1983 to 2022 and 2023, it shows a significant difference. The total rainfall for the MAM season in 2023 was 412.8mm, which is much higher than the average of the previous years (1983-2022) which was 230.75mm. This represents a 79% increase in rainfall compared to the average for the previous years (Figure 9).

Looking at the monthly rainfall data, the result shows that the increase in rainfall in 2023 was mainly due to the very high rainfall in March and April. In March 2023, the mean rainfall was 155.45 mm, which is much higher than (nearly triple) the average of the previous years (1983-2022) which was 43.4 mm. This represents a 282% increase in rainfall compared to the average for the previous years. Similarly, in April 2023, the mean rainfall was 141.66 mm, which is much higher than the average of the previous years (1983-2022) which was 91.3mm. This represents a 55.2% increase in rainfall compared to the average for the previous years. In contrast, the rainfall for May 2023 was 115.70 mm, which was slightly higher than the average of the previous years (1983-2022) which was 98.8 mm. This represents a 17% increase in rainfall compared to the average for the previous years (Figure 9).

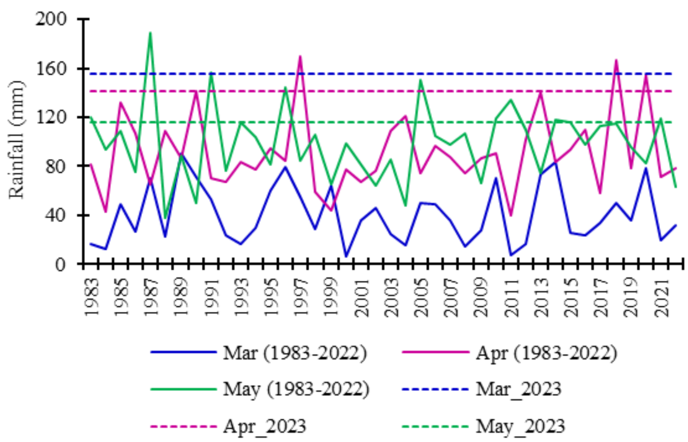


Figure 9: Comparison of 2023 MAM with 1983 to 2022 MAM rainfall (in mm) for the three months of the season (March, April, and May) across Ethiopia. The 2023 MAM season months are indicated using hidden lines with different colors indicating different months which are extended over the years from 1983 to 2022 for comparison purposes.

Independent two-sample t-tests were conducted to determine if the March, April, May, and MAM season rainfall in 2023 was significantly different from the long-term historical means over the 1983-2022 reference period. The t-test results indicated highly statistically significant differences ($p<0.001$) for the rainfall means in all months and the overall MAM season between the historical period and 2023. These results provide robust statistical evidence that the rainfall means in 2023, especially for March and April, was anomalously and significantly higher than the typical rainfall distribution seen in the prior four decades from 1983-2022.

The results of the t-tests have important implications for the agriculture and food availability dimension of food security in the region. The unusually high rainfall in 2023 could have both positive and negative impacts on crop production and water availability. On the positive side, the high rainfall could increase the water availability for crops and improve soil moisture, leading to higher crop yields. However, on the negative side, the high rainfall could also lead to flooding and waterlogging of crops, as well as erosion of the soil. The impacts of the high rainfall on crop production and water availability will depend on the specific characteristics of the crops and soils in the region, as well as the management practices used by farmers.

Comparison of 2023 MAM with Higher Rainfall Anomaly Years

Among 41 years (1983 – 2023) of MAM seasons under consideration in this study, in 17 years Ethiopia gained a higher rainfall amount than the mean value in MAM season rainfall (positive anomaly) across the country. Accordingly, the 2023 MAM season total rainfall (+178.89mm) was compared with 8 years (Figure 10) in those the increased MAM season rainfall was incurred by more than 50mm (>21%) over that of the long-year average (230.76mm). These include 2020 (+84.55mm), 2018 (+101.1mm), 2014 (+53.93mm), 2013 (+56.89mm), 1997 (+79.07mm), 1996 (+77.06mm), 1987(+93.25mm), and 1985 (+59.32mm).

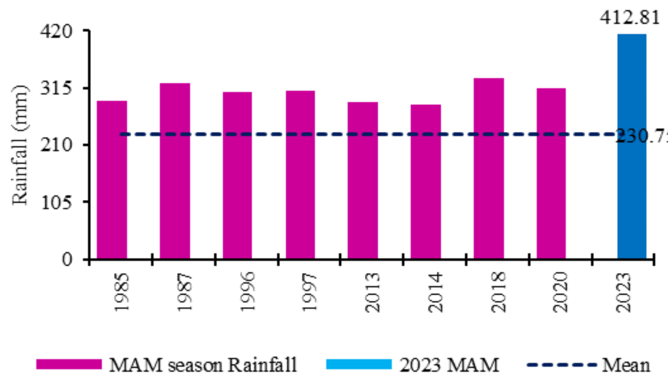


Figure 10: Comparison of MAM season total rainfall (in mm) of 2023 with the selected years having positive and higher anomaly values above the mean MAM season total rainfall across Ethiopia

The analysis of the data shows that the selected years with an anomaly greater than 50mm (1985, 1987, 1996, 1997, 2013, 2014, 2018, and 2020) had different levels of rainfall in the MAM season, ranging from 284.72 mm in 2014 to 331.86 mm in 2018. The percentage of MAM contribution to annual rainfall also varied significantly between the selected years, ranging from 28.50% in 1997 to 42.45% in 1987 (Table 1).

Table 1: Illustration of the increase in the 2023 MAM season rainfall total as compared with the selected historical years that experienced higher values of MAM season rainfall across Ethiopia

Year	Annual Rainfall	MAM season (xi)	JJAS season	Percentage of MAM	2023 MAM (412.8mm) - xi
1985	711.12	290.08	368.33	40.79	122.73(42.3%)
1987	763.26	324.01	339.79	42.45	88.80 (27.4%)
1996	905.8	307.82	524.55	33.98	104.99(34.1%)
1997	1087.18	309.83	440.17	28.50	102.98(33.2%)
2013	941.42	287.65	465.07	30.55	125.16(43.5%)
2014	877.47	284.72	423.61	32.45	128.09(45.0%)
2018	871.34	331.86	422.61	38.09	80.95 (24.4%)
2020	1034.46	315.31	581.29	30.48	97.50 (30.9%)

When comparing the selected high positive anomaly years to the MAM season rainfall in 2023, the results show that the MAM season rainfall in these years was significantly lower than the MAM season rainfall in 2023 (Table 1). The difference in MAM season rainfall between these years and 2023 ranged from 80.95 mm in 2018 to 128.09 mm in 2014. This suggests that the MAM season rainfall in these years was much lower than in 2023, which could have significant implications for agriculture and the supply side of food security in the country. Therefore, it is important for policymakers and farmers to be aware of the variability in rainfall patterns and to develop strategies to mitigate the impacts of droughts and floods on agricultural production and the supply wing of food security in the country.

Spatial Comparison of MAM rainfall in Ethiopia

MAM Rainfall Distribution

As illustrated in Figure 11, the distribution of MAM season rainfall in Ethiopia for 2023 and other years in which MAM season rainfall was increased by more than 50 mm (21%) from the baseline (1983 – 2022) mean. It indicated the significant spatial increase in 2023 MAM rainfall which was visible across the country. Most in all regions of the country, there was an increase in MAM season rainfall. Amazingly, some portions of the South and South-West of the country received triple the mean amount, which makes it an anomalous event. The maps also indicate that the direction of increase in MAM rainfall in the previous years also shows a similar pattern, even though their magnitude was less than the 2023 MAM rainfall.

The spatial distribution map also shows that the 2023 MAM season rainfall was highest in the majority of southwestern and central regions of Ethiopia, such as Gambela, Oromia, Sidama, Southern Ethiopian, South-West, and Southern Nations, Nationalities, and Peoples' Region (SNNPR). These regions received more than 450 mm of rainfall during the 2023 MAM season which was more than twice the country's long-year mean. The figure also shows that the MAM season rainfall was lowest in the northern and eastern regions of Ethiopia, such as Tigray, Afar, Somali, and parts of Amhara and Benishangul Gumuz. These regions received less than 230 mm of rainfall during the MAM season which was less than the long-year mean.

The spatial distribution of MAM season rainfall in Ethiopia is influenced by various factors, such as sea surface temperatures (SSTs) in the Indian Ocean and the Pacific Ocean, atmospheric circulation patterns over Africa and beyond, and local topography and land use (Knudsen, 2023; Alemu & Bawoke, 2020; Palmer et al., 2023). Some studies have found that the MAM season rainfall is positively correlated with SSTs in the western Indian Ocean and negatively correlated with SSTs in the eastern Pacific Ocean (Degefu et al., 2017). Other studies have found that the MAM season rainfall is associated with upper-level geopotential height anomalies over Madagascar and lower-level westerly wind anomalies over the Congo basin (Alemu & Bawoke, 2020; Knudsen, 2023). These factors can affect moisture transport and convergence over Ethiopia, leading to wetter or drier conditions during the MAM season.

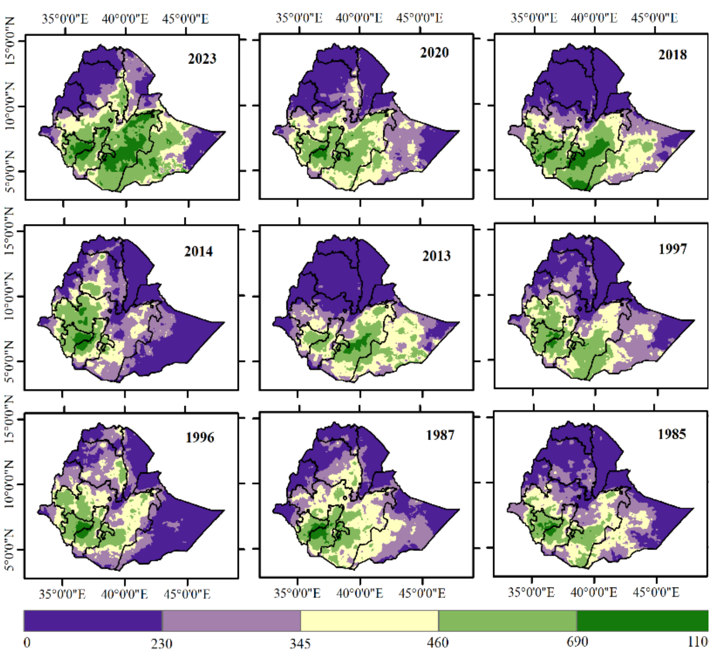


Figure 11: Comparison of the spatial distribution of MAM season total rainfall of 2023 with the selected years having positive and higher anomaly values above the mean MAM season total rainfall across Ethiopia.

The MAM season rainfall is also subject to interannual variability and long-term trends, which can have significant impacts on the food availability dimension of food security, water resources, hydropower generation, and disaster risk management in Ethiopia (Kebacho, 2022; Palmer et al., 2023). Some years' experience above-normal or below-normal rainfall during the MAM season, which can cause floods or droughts respectively. For example, in 2019, Ethiopia experienced below-normal rainfall during the MAM season, which resulted in crop failure, water shortage, livestock mortality, and increased food availability for millions of people. On the other hand, in 2020, Ethiopia experienced above-normal rainfall during the MAM season, which caused flooding, displacement, crop damage, and disease outbreaks for thousands of people (Agrilinks, 2022). Furthermore, some studies have detected a decreasing trend in MAM season rainfall over parts of Ethiopia since the late 20th century (Degefu et al., 2017), which could be related to global warming and human-induced land degradation.

MAM Anomaly Distribution

Figure 12 shows the MAM season rainfall spatial anomaly in Ethiopia, based on the difference between the baseline mean (1983 – 2022) rainfall and the selected eight years in which MAM season rainfall has a high positive anomaly. The result shows that the MAM season rainfall anomaly varies across Ethiopia, depending on the year and the region. Some regions experience wetter or drier conditions than usual during the MAM season, while others experience normal conditions. For example, in 2018 and 2013, most of Northern Ethiopia experienced negative anomalies, meaning below-normal rainfall during the MAM season. This was especially severe in the Tigray, Amhara, and Afar regions, where the anomaly was below -100 mm. This caused drought, crop failure, water scarcity, and food shortages for millions of people. However, for the same years, the Central, South-east, and Eastern parts of the country received higher rainfall amounts during the MAM season which resulted in a positive anomaly at the country level. For example, in 2018 the Southern parts of Ethiopia, particularly around the Kenya border, received the amount of twice the long-year mean (Figure 12).

On the other hand, in 1985, 1987, 1996, and 1997, most of Ethiopia experienced positive anomalies, meaning above-normal rainfall during the MAM season. This was especially pronounced in the western and central parts of the country, such as Gambela, Benishangul-Gumuz, Oromia, and SNNPR, where the anomaly was above 200 mm. Exceptionally, the 2023 MAM season rainfall anomaly map shows that the country experienced higher rainfall volume distributed in most of the regions. Particularly, the central, east, and south portions of the country received anomalous MAM season rainfall, even more than twice (460mm) of the mean (Figure 12). This finding is strengthening the report of the Ethiopian Meteorology Institute seasonal agrometeorological report (EMI, 2023).

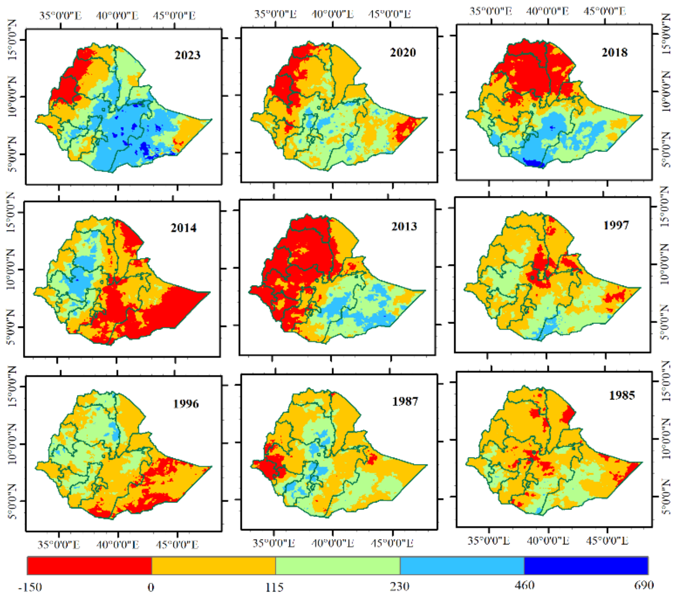


Figure 12: The spatial distribution of anomaly of mean MAM season total rainfall from long-year mean value from 1983 to 2022 in Ethiopia.

CONCLUSION

This study comprehensively analyzed the anomalous increase in rainfall during the March-April-May (MAM) season over Ethiopia in 2023 using high-resolution TAMSAT satellite rainfall estimates. The results provided robust evidence that the MAM seasonal rainfall total in 2023 (412.81 mm) was 79% higher than the 1983-2022 average, with extremely wet conditions in the March and April months. Statistical analyses also confirmed that the rainfall means for all months and the overall MAM season in 2023 were significantly different from the historical baseline period at a p-value of 0.001. Spatially, the anomaly was most pronounced in southwestern and central Ethiopia, with totals over 460 mm (>200% of average). Comparisons with previous high rainfall years showed the 2023 anomaly exceeded historical wet seasons by 80-130 mm.

The anomalous MAM rainfall could have both beneficial and detrimental impacts on agriculture, water resources, floods, and food production across different regions of Ethiopia. This study enhances understanding of heavy precipitation events and long-term variability patterns, which is critical for climate change adaptation and agriculture planning. While the specific oceanic-atmospheric drivers need further investigation, the results align with climate model projections of increased extreme rainfall under global warming. Further research using other datasets is needed to demonstrate the utility of high-resolution satellite rainfall estimates for monitoring anomalies and improving early warning systems in the country.

Limitations of the study

The study relied solely on the TAMSAT satellite rainfall product. While this dataset is valuable, it may have inherent uncertainties and biases compared to ground-based observations, especially in areas with sparse rain gauge networks. The study focuses on the national-level analysis of Ethiopia. However, rainfall patterns can vary significantly at local and regional scales, and the national-level analysis may not capture these finer-scale variations. Further, the study describes the anomalous rainfall event but does not delve into the potential drivers or causal factors behind this extreme event, such as the influence of large-scale climate patterns (e.g., El Niño–Southern Oscillation, Indian Ocean Dipole) or local factors (e.g., land use/land cover changes).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

None.

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