Spatiotemporal analysis of rainfall and temperature variability and trends for a mixed crop-livestock production system: its implications for developing adaptation strategies

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Abstract

Purpose – The purpose of this study is to analyze the seasonal spatiotemporal climate variability in the Borena zone of Ethiopia and its effects on agriculture and livestock production. By examining these climate variables in relation to global sea surface temperatures (SST) and atmospheric pressure systems, the study seeks to understand the underlying mechanisms driving local climate variability. Furthermore, it assesses how these climate variations impact crop yields, particularly wheat and livestock production, providing valuable insights for developing effective adaptation strategies and policies to enhance food security and economic stability in the region.

Design/methodology/approach – The design and methodology of this study involve a multifaceted approach to analyzing seasonal spatiotemporal climate variability in the Borena zone of Ethiopia. The research uses advanced statistical techniques, including rotated empirical orthogonal function (EOF) and rotated principal component analysis (RPCA), to identify and quantify significant patterns in seasonal rainfall, temperature and drought indices over the period from 1981 to 2022. These methods are used to reveal the spatiotemporal variations and trends in climate variables. To understand the causal mechanisms behind these variations, the study correlates seasonal rainfall data with global SST and examines atmospheric pressure systems and wind vectors. In addition, the impact of climate variability on agricultural and livestock production is assessed by linking observed climate patterns with changes in crop yields, particularly wheat and

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livestock productivity. This comprehensive approach integrates statistical analysis with environmental and agricultural data to provide a detailed understanding of climate dynamics and their practical implications.

Findings – The findings of this study reveal significant seasonal spatiotemporal climate variability in the Borena zone of Ethiopia, characterized by notable patterns and trends in rainfall, temperature and drought indices from 1981 to 2022. The analysis identified that over 84% of the annual rainfall occurs during the March to May (MAM) and September to November (SON) seasons, with MAM contributing approximately 53% and SON over 31%, highlighting these as the primary rainfall periods. Significant spatiotemporal variations were observed, with northwestern (35.4%), southern (34.9%) and northeastern (19.3%) are dominant variability parts of the zone during MAM season, similarly southeastern (48.7%), and northcentral (37.8%) are dominant variability parts of the zone during SON season. Trends indicating that certain subregions experience more pronounced changes in climate variables in both seasons. Correlation with global SST and an examination of atmospheric pressure systems elucidated the mechanisms driving these variations, with significant correlation with the southern and central part of Indian Ocean. This study also found that fluctuations in climate variables significantly impact crop production, particularly wheat and livestock productivity in the region, underscoring the need for adaptive strategies to mitigate adverse effects on agriculture and food security.

Research limitations/implications – The implications of this study highlight the need for robust adaptation strategies to mitigate the effects of climate variability. Detailed research on seasonal climate patterns and the specific behaviors of livestock and crops is essential. Gaining a thorough understanding of these dynamics is critical for developing resilient adaptation strategies tailored to the unique ecological and economic context of the Borana zone. Future research should focus on seasonal climate variations and their implications to guide sustainable development and livelihood adjustments in the region.

Originality/value – This study offers significant originality and value by providing a detailed analysis of seasonal spatiotemporal climate variability in the Borena zone of Ethiopia, using advanced statistical techniques such as rotated EOF and RPCA. By integrating these methods with global SST data and atmospheric pressure systems, the research delivers a nuanced understanding of how global climatic factors influence local weather patterns. The study's novel approach not only identifies key trends and patterns in climate variables over an extensive historical period but also links these findings to practical outcomes in crop and livestock production. This connection is crucial for developing targeted adaptation strategies and policies, thereby offering actionable insights for enhancing agricultural practices and food security in the region. The originality of this work lies in its comprehensive analysis and practical relevance, making it a valuable contribution to both climate science and regional agricultural planning.

Keywords Drought, Rainfall, Temperature, Pastoral, Agropastoral, Climate variability, REOF, Crop-livestock production

Paper type Research paper

1. Introduction

The agriculture sector is critical to the global economy, and weather and climate are major factors influencing the productivity and profitability of agropastoral systems. Weather-related hazards pose considerable obstacles to agropastoral livelihoods (Food and Agriculture Organization of the United Nations, 2019, 2021; IPCC, 2019; 2022; Paparrizos *et al.*, 2023). Borna zone is one of Ethiopia's most vulnerable agropastoral areas to climate change and variability that threaten people's lives and livelihoods. Like other regions climate change and variability have created a bottleneck for livestock production, affecting agropastoralists and pastoralists in the zone, as the availability and spatial distribution of pasture and water are affected by rainfall (Napier and Solomon, 2011; Ayal *et al.*, 2015; Martin *et al.*, 2016; Radeny *et al.*, 2019; Guye *et al.*, 2022). Climate variability and extremes are manifested in increasing temperatures and erratic rainfall distribution (Nicholson, 2017). Over the past decades, the Zone has experienced discernible shifts in rainfall and temperature patterns, posing challenges to the agricultural sector and the pastoral communities (Zeleke *et al.*, 2017; Azemir *et al.*, 2021; Filho *et al.*, 2021). In the zone, the interplay between climate variability and agropastoral productivity holds profound implications for the well-being of its inhabitants (Azemir *et al.*, 2021; Filho *et al.*, 2020; 2021). Climate variability and extremes aggravate rangeland degradation (IPCC, 2019) allowing scarcity of water and pasture to create conducive conditions for the outbreak of diseases (Filho *et al.*, 2021). Undoubtedly, these conditions adversely affect the livestock sector and livelihood of agropastoralists and pastoralists (Ayal *et al.*, 2015; Martin *et al.*, 2016; Radeny *et al.*, 2019; Guye *et al.*, 2022).

Climate variability and change have a substantial impact on crop production in Ethiopia's Borena zone. The region experiences increasingly erratic rainfall patterns and rising temperatures, leading to prolonged droughts and unpredictable growing seasons. These conditions pose serious challenges to agriculture, impacting crop yields and food security for local communities (Ayal *et al.*, 2015). Farmers in Borena struggle with adapting traditional agricultural practices to these new climatic realities, highlighting the urgent need for adaptive strategies and sustainable agricultural policies to mitigate the adverse effects of climate change on crop production in the region.

Thus, climate variability and extreme events are a real danger to the livestock sector which could undermine its contribution to the national economy and household food security (IFPRI and UNDP, 2019). In pastoral areas like Borana, the impact of climate variability on the livelihood of pastoralists worsens because of limited technology, lack of precise and timely climate and seasonal weather forecast information, limited access to finance, health services and facilities, lack of appropriate policy and population pressure (Martin *et al.*, 2016; Radeny *et al.*, 2019; Azemir *et al.*, 2021; Ayal *et al.*, 2021; Filho *et al.*, 2021). Very recently, Food and Agriculture Organization of the United Nations (2021) reported that over 68,000 animals died; over 1 million animals were in bad condition and 443,000 people in Borana suffered a catastrophic scarcity of drinkable water because of the impact of recurrent droughts in 2020–2021. Thus, understanding climate change and variability at a local scale could help suggest local adaptation responses to manage climate-associated risks (Ayal *et al.*, 2018; Balehegn *et al.*, 2019; Ali *et al.*, 2021).

Climate variability is not a new phenomenon in Borana (Ayal *et al.*, 2015, 2018). The traditional pastoral production strategies in the area are well adapted to the changing environments, incorporating social structures and resource management systems that respond to different climates (Mitiku and Expert, 2022). However, there are indicators that general climate variability and change are becoming more extreme and overwhelm pastoral production strategies (Ayal *et al.*, 2015, 2018, 2021; Radeny *et al.*, 2019; Azemir *et al.*, 2021; Filho *et al.*, 2021). The five consecutive failed seasons recently experienced are indicative of increasingly extreme events and devastating impacts that are beyond pastoralists' capacity to adapt. Therefore, proactive climate change response provision of understandable weather information is at the heart of pastoralism sustainability and pastoralists' food security (Cowan *et al.*, 2020). Long-term fluctuations in precipitation and temperature, as well as their causes and effects on pastoral and agropastoral production, are understudied components of climate risk that affect Borana pastoralists' current and future vulnerability. This gap in previous research has hampered a common understanding of the problem and the relevance of research findings in shaping climate change policies and community adaptation measures. As a result, understanding the dynamic nature of climate variables, its causes and impacts on agropastoral product causes is a critical starting point for developing effective adaptation and mitigation strategies and increasing local community resilience to climate change.

Therefore, this paper endeavors to provide a comprehensive analysis of the spatiotemporal characteristics and underlying causes of rainfall and temperature variability in the Borana zone. By scrutinizing climate data over specific seasons, such as spring and autumn, we aim to elucidate the intricate dynamics shaping the local climate regime. Moreover, we delve into understanding the association between observed seasonal climate variability and associated global sea surface temperatures (SST), as well as examining the influence of known sea surface oscillations to unravel the broader climatic influences affecting the region. These are then related to the observed impacts on the mixed crop-livestock production system, including variability of crop yield and other critical agropastoral commodities such as milk and butter, analyzing the association with rainfall variability. By explaining these linkages, we hope to gain significant insights into the vulnerability of pastoral and agropastoral systems to changing climate conditions. Our analysis is to deliver actionable insights and information that will help them adapt.

2. Materials and methods

2.1 Study area description

Borana is an administrative zone in Ethiopia’s Oromia Region (Figure 1). Borana zone spans approximately 45,434.97 km^2, and it is in the southern part of the country stretching approximately between 3°36’ and 6°38’ North latitude and 3°43’ and 39°30’ East longitude. The zone is located 570 km south of Addis Ababa and is bordered by Kenya in the South, West Guji zone in the North, Somali region and Guji zone in the East and South Region in the West. The zone is predominantly characterized by lowlands (~83%, Figure 1), which play a significant role in shaping its climate into arid and semiarid areas, with pockets of subhumid parts which in turn determine their agropastoral practices (Figure 1). Rangelands are dominated by tropical savannah vegetation with varying proportions of open grasslands and perennial woody vegetation (Coppock, 1994). The main economic activity in the zone is pastoralism and agropastoralism (CSA, 2021).

2.2 Data and data sources

The study used long-term gridded Climate Hazards Group Infrareds Precipitation with Station [CHIRPS, Index of/products/CHIRPS-2.0/global_daily/netcdf/p05 (ucsb.edu)] in University of California Santa Barbara (Dinku *et al.*, 2014; Funk *et al.*, 2015) and Climate Research Unit [CRU-TS4.08, CRU TS v4.08 Data Variables (uea.ac.uk)] in University of East Anglia (Mitchell *et al.*, 2005). The Hadley Centre Global Sea Ice and SST are used to understand the global scale variables and their impact on the local climate modulation (Rayner *et al.*, 2003). The temporal scope of the data spans from 1981 to 2022, allowing for a robust analysis of climate variability over time. Moreover, agricultural product data were obtained from the Ethiopian Center of Statistics Agency (CSA), which provides comprehensive seasonal records of crop yields and livestock productivity in the Borana zone.

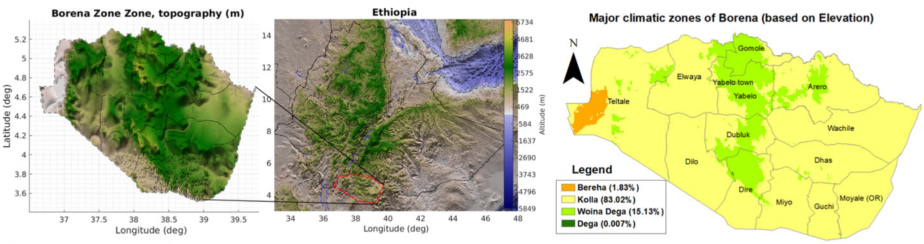

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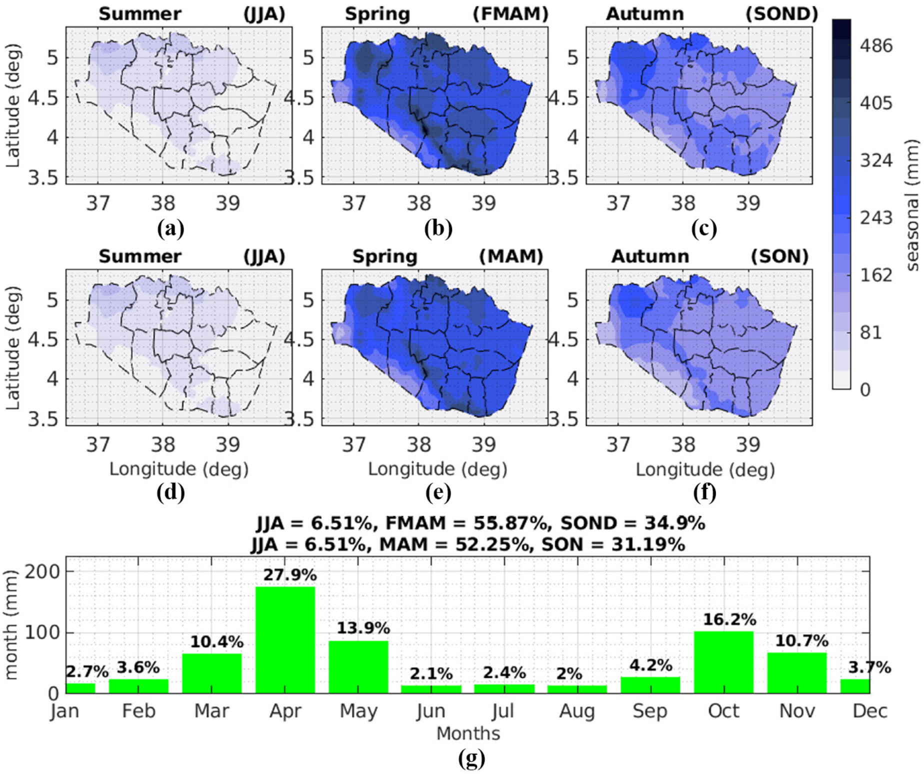
Figure 1. Topography Borena zone and Ethiopia

2.3 Data analysis

This study is focused on the March to May (MAM) and September to November (SON) seasons, which are important periods for agropastoral activities in the Borana zone (Figure 2). Analyzing climate data specifically during these seasons, rainfall, temperature and drought indices variability that are most relevant to agropastoral productivity were examined. Thus, various statistical techniques, including rotated empirical orthogonal function (REOF) analysis (Rencher, 1998; Von Storch and Zwiers, 1999; Camberlin and Philippon, 2002; Navarra and Simoncini, 2010), trend analysis (Zeleke and Damtie, 2017; Zeleke *et al.*,2017), correlation analysis (Rencher, 1998; Zeleke *et al.*, 2017) and time series analysis to discern patterns and trends in climate data were used. These analyses provide insights into the magnitude and direction of multi-scale climate variability over time and space. The REOF was used to detect the spatiotemporal variability of precipitation, temperature and drought indices across the Borena zone. This approach enabled to identification of localized patterns and hotspots of climate variability within the study area (Zeleke *et al.*, 2013; Zeleke *et al.*, 2017). The Pearson correlation method was used to investigate the relationship between SST and precipitation,



Notes: The Borena zone is a bimodal rainfall cycle, MAM domination with followed SON season rainfall pattern

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Figure 2. Seasonal rainfall climatological patterns of Borena zone and seasonal cycle averaged from 1981 to 2022 (42 years, since 1981)

and we investigated the influence of known sea surface oscillations, such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean dipole (IOD), on local climate patterns. Seasonal drought indices such as Standardized Precipitation Index (SPI) and the Standardized Precipitation-Evapotranspiration Index (SPEI), are calculated over the zone and their methodologies are described by McKee *et al.* (1993) and Vicente-Serrano *et al.* (2010), respectively. These indices enable the identification, characterization and analysis of drought events by considering parameters such as intensity, duration, severity and spatial extent. The SPI and SPEI, have been designed to evaluate deviations in precipitation and temperature from historically established norms over a defined period, in our case 1981–2022. The SPI and SPEI classify values from −0.49 to 0.49 as normal. Positive values are categorized as slightly humid (0.5–0.99), moderately humid (1–1.49), very humid (1.5–1.99) and extremely humid (≥2), while negative values represent corresponding degrees of drought severity. Furthermore, a detailed analysis of crop production data, including wheat, grain and cereal-type crops harvested across different rainy seasons was conducted (Ethiopian CSA). Similarly, the temporal trends of key livestock products such as milk, and butter and their correlation with rainfall patterns were studied.

3. Results and discussion

3.1 Spatiotemporal variability of climate

In this section, we examine the regional patterns of seasonal climatology of precipitation and its seasonal cycle (interannual) variability from 1981 to 2022 (Figure 2). The rainfall pattern is akin to equatorial East African countries such as Kenya. 52.3% of the annual rainfall occurring during MAM (MAM/spring/"*Ganna*") season (Figure 2), with a warm dry period during December to February (DJF/*winter*/"*Bonna*"), cool dry during June to August (JJA/summer/"*Adoolessa*") (Figure 3) and about 32% of the total rainfall occurring during SON (autumn/"*Haggaya*") season. April stands out as the rainiest month, receiving a significant portion of the annual precipitation (28% of the yearly rainfall (Figure 2).

The areal mean rainfall is characterized by a bimodal rainy season featuring short rains during SON, and the main rainy season from MAM (Figure 2). The pattern shown during both seasons (Figure 2) demonstrates the decreasing gradient from northcentral to west tip and to southeast regions of the zone. The observed precipitation (Figure 2) in the zone during both the main (spring) and small (autumn) seasons are mostly confined to mountainous regions of Borena, while lowland regions in all directions of these mountainous regions are predominantly drier. The pattern is reasonable because of the mountainous lifting of the low-level moisture from the neighboring ocean basins during both seasons (Zeleke and Damtie, 2017; Zeleke *et al.*,2017; Munday *et al.*, 2022; 2023). As one moves from northern and southwestern mountainous regions toward southeastern and other lowland areas, the climatological pattern of spring rainfall decreases and becomes drier over the low-land regions (Figure 2).

The CRU (mean 2-m) temperature distribution (Figure 3) shows approximately a zonal pattern with the lowest values (∼21°C) typically found in the northcentral complex terrain regions of Borena in July. During March, the 2-m mean warmest temperature (∼25°C) was reported at the zone's border regions, moving from the northcentral complex terrain region (Figure 3). However, the coefficient variation rate (Table 1) of seasonal rainfall and temperature climatology has resulted in greater variability affecting pasture availability (NAPA, 2007). Noteworthy temperature variation observations include cooler nights (∼16°C) in December warmer nights (∼18°C) during the spring season and daytime temperatures exceeding 32°C from February to May. The southwestern part is hotter throughout the year compared to the

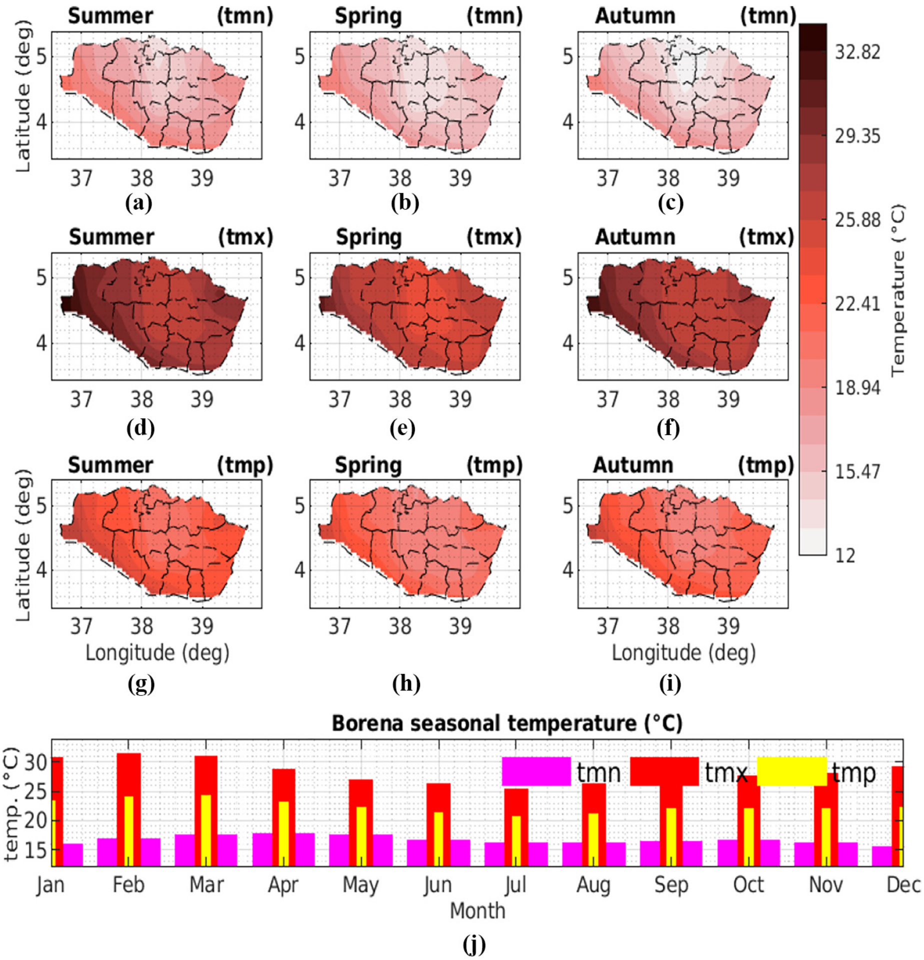

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Figure 3. Seasonal minimum, maximum and mean temperature patterns and seasonal cycle of temperature

Table 1. The statistical characteristics of seasonal and areal mean time series rainfall data

Season	Sen slope	*p*-value	Mank-H	Coff-var (CV)	IQR	Range	Skewness	Kurtosis
MAM	−0.7192	0.2034	0	0.2656	111.9	375.8	0.3172	3.126
SON	−0.5675	0.0057	1	0.4289	82.22	346.7	1.708	5.505

Note: The station mean data displayed similar features as the areal mean gridded data
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north-central part of the zone. Daytime temperatures are cooler (~26°C) during JJA, with the maximum diurnal temperature range observed in December and January (Figure 3).

In spring season, Borana's precipitation exhibits the largest variance in northwestern areas, which explains 35.4%; the second most variance happened region is south and southeastern regions, which demonstrate 34.9%; and northeastern regions explained 19.3% of the overall variance of the zone (Figure 4). The corresponding temporal components or rotated principal component of these dominating variability subregions of the zone show nearly identical anomalies, with minor magnitude differences [Figure 4(d)]. Similarly, the prominent three variability patterns seen throughout autumn are the southeastern, northcentral and western portions of the zone, explaining 48.7%, 37.8% and 8%, respectively

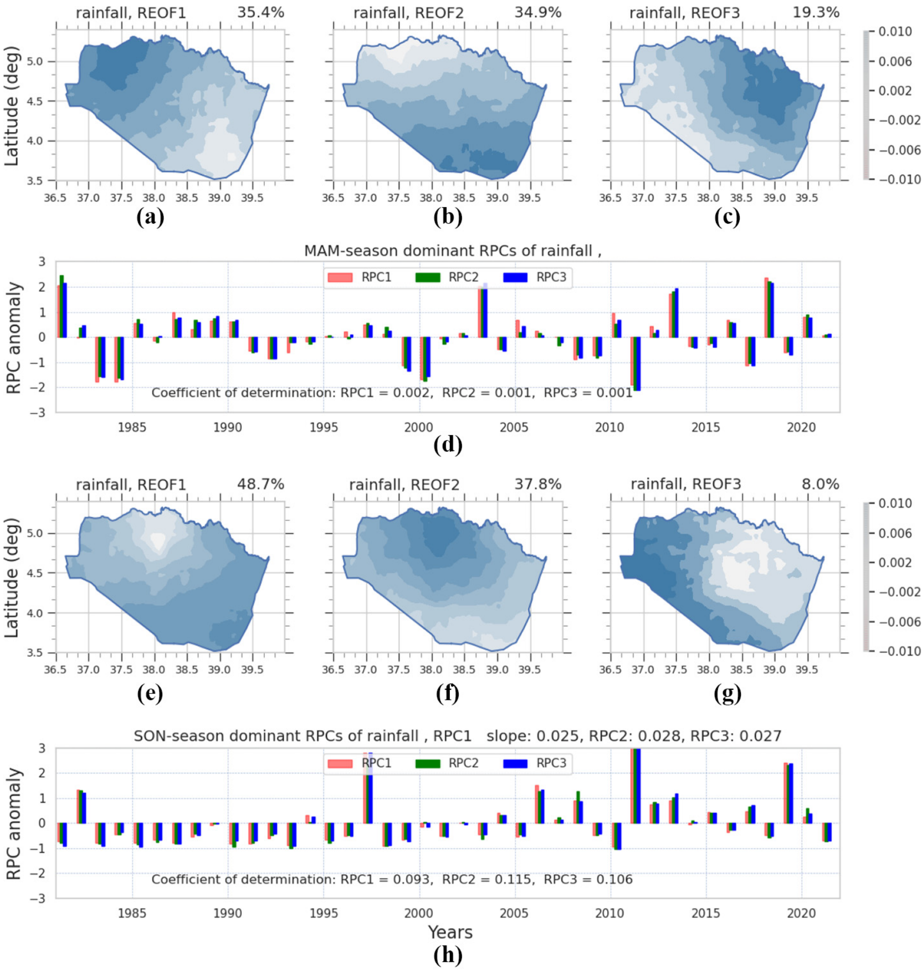

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Figure 4. Dominant seasonal rainfall variability regions of Borena zone

[Figure 4(e)–(g)]. During the spring seasons, the wettest years were 1981, 2003, 2013 and 2018 whereas 1983, 1984, 1999, 2000, 2011 and 2017 were observed to be the driest years of the Borena zone [Figure 4(d)]. 1982, 1997, 2006, 2011 and 2019 were wet years and relatively 1985, 1990, 1993, 1998 and 2010 were the drier years for the Borena zone during the autumn season [Figure 4(h)].

During the study period (1981–2022), ten dry and eight wet circumstances were noted during the spring season. In addition, more than 13 drier years and 8 wet years were recorded during the autumn season. We noticed that in both seasons, 1983, 1984, 1992, 1993, 1999 and 2009 were drier, whereas 1997 and 2013 were the wettest years. The coefficient of variation of the zone's areal mean rainfall anomaly in the spring and autumn is 0.27 and 0.43, respectively (more statistical characteristics are presented in Table 1). Camberlin (2006) reported similar findings, indicating that the highest rainfall variability occurs during the small rainy season in this part of Ethiopia (Zeleke *et al.*, 2017).

Figure 5 presents a comprehensive analysis of drought indices applied to the Borana zone using the SPI and the SPEI. These indices are essential tools for quantifying and understanding drought risk and occurrence by integrating precipitation and temperature data. They provide critical insights into drought trends, offering a nuanced perspective on the vulnerability of the Borana area to climatic fluctuations. The spatiotemporal analysis conducted across seasons, including summer (JJA), reveals intricate patterns of drought intensity and distribution. For instance, during the MAM, JJA and SON seasons of 1983 and 1984, drought events significantly impacted agropastoral sectors, exacerbating vulnerabilities when consecutive seasons experienced rainfall deficits. This effect is magnified over successive years (Figure 5). Notably, negative anomalies observed during the JJA season often influence subsequent SON seasons (e.g. 1990, 1993, 2010), underscoring the persistent effects of drought conditions. Conversely, positive anomalies in JJA can reduce drought severity in the following SON season (e.g. 1982, 2019), illustrating the complex interplay of seasonal variability and drought dynamics. Figure 5(a)–(c) and (e)–(g), depict discernible trend patterns across all seasons. Particularly striking is the concentration of drought-prone areas in the southern and eastern parts of the zone during the MAM season, directly impacting subsequent seasons. These regions consistently exhibit higher frequencies of drought occurrences during JJA and SON seasons, highlighting localized vulnerabilities exacerbated by climatic factors.

Figure 5 illustrates significant drought occurrences during critical periods such as the summer of 2009, the autumn of 2010 and the summer and spring of 2011. In addition, moderate to severely dry conditions were observed in 1983, 1984, the autumn of 1987 and 1998, the spring of 2000 and 2009 and the summers of 2002, 2004 and 2015. In the Borana zone, SPEI analysis highlights a pronounced negative variance predominantly across the southeastern region throughout all seasons, with summer exhibiting the most extensive coverage (see Figure 5). This geographical distribution underscores the susceptibility of these areas to prolonged dry spells, which can lead to significant socioeconomic impacts, including asset loss and severe food insecurity. The compounded effects of consecutive poor rainfall seasons are evident, particularly during severe drought events in years such as 1983/1984, 1988/1989, 1999/2000, 2007/2008, 2011, 2014, 2015/2016 and 2017.

Research indicates that communities severely affected by intense droughts may face a recovery period lasting 7–13 years (Ayal *et al.*, 2015, 2018, 2021; Zeleke *et al.*, 2017). Consequently, households in the Borana zone continue to grapple with the enduring impacts of successive El Niño-induced droughts from previous years. The situation has been further exacerbated by the desert locust invasion since 2019, which thrived under favorable breeding conditions exacerbated by drought. The cumulative effects of these environmental stresses have profound implications for the lives and livelihoods of millions of people in Borana,

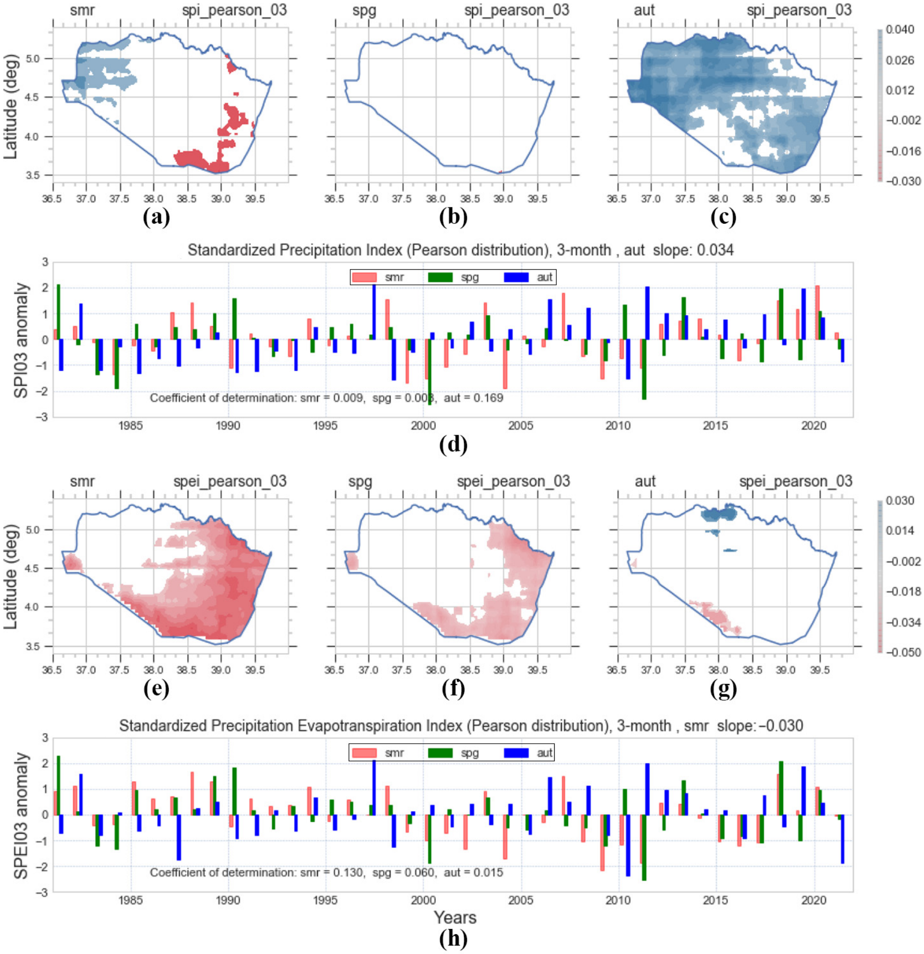

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Figure 5. Significant (p-value ≤0.05) seasonal trends of drought indices in Borena zone

posing ongoing challenges in terms of food security, economic stability and community resilience. Addressing these challenges requires not only immediate humanitarian responses but also sustainable strategies for drought resilience and adaptation to mitigate future impacts (Ayal *et al.*, 2015, 2018, 2021).

Figure 6 reveals notable trends in minimum and maximum temperatures across the Borana zone, highlighting distinct seasonal variations. Nighttime temperatures exhibit a pronounced increase, particularly in the southeastern areas during the summer, spring and autumn seasons, tapering toward the northwest. Analysis shows that during the period from 1980 to 2000, nighttime temperatures frequently registered as negative anomalies across all seasons, shifting to predominantly positive anomalies after 2000. Exceptions to this trend include occasional lower nighttime temperatures observed primarily during the spring

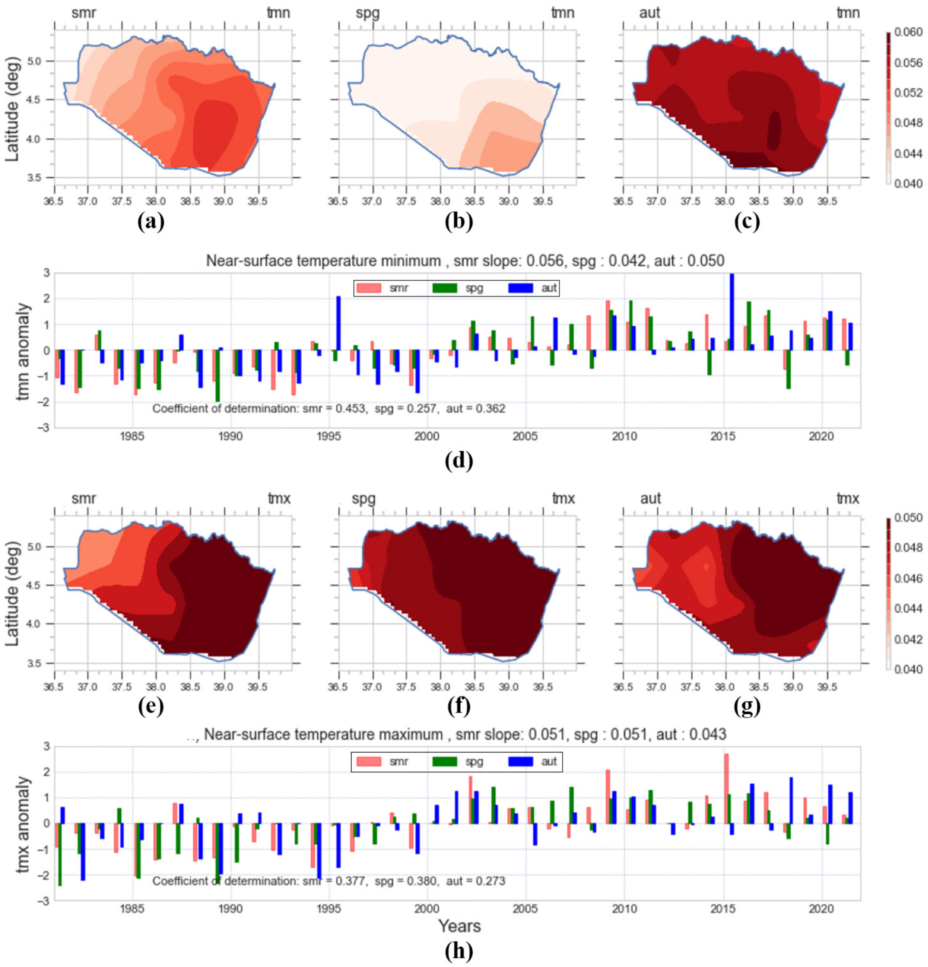

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Figure 6. Seasonal minimum and maximum temperature significant (p-value ≤0.05) trend patterns

season. Conversely, daytime temperatures in Borana have shown a consistent increase in mean values over the past two decades, as depicted in Figure 6. The temperature anomaly analysis indicates a shift from predominantly negative anomalies to predominantly positive ones since around 2000, with infrequent occurrences of below-average daytime temperatures noted mainly during the autumn and spring seasons. These trends underscore a significant warming trend in both nighttime and daytime temperatures across all seasons in Borana, with implications for local climate patterns and agricultural practices. The observed changes suggest a need for adaptive measures to mitigate potential impacts on water resources, agriculture and community livelihoods in response to ongoing climate variability and warming trends.

3.2 *The potential causes of the observed variability of climate*

In the spring (MAM) and autumn (SON) seasons, the observed variability in rainfall shows notable connections with specific oceanic patterns, distinct from typical ENSO variability (Figure 7). During these seasons, the rainfall patterns exhibit stronger associations with SST gradients in the Indian Ocean rather than with ENSO. In the western Pacific Ocean (coast of Peru), there is a significant negative correlation between precipitation and SST during the MAM season, while a weaker positive correlation is observed during SON (Figure 7). Conversely, the western equatorial Indian Ocean displays a positive correlation with rainfall during SON, with a less pronounced relationship during MAM (Figure 7). Notably, there is a robust positive correlation between precipitation and SST across the entire equatorial Indian Ocean during SON, whereas the correlation is weaker during MAM.

Cooler SSTs around Madagascar enhance moisture-carrying winds, leading to increased rainfall over the Borana region during MAM (Figure 7). Unlike the MAM season, increased SSTs in the equatorial Indian Ocean (east of Somalia) redirect moisture-carrying winds toward the region (low pressure), correlating with wetter conditions in Borana (Munday *et al.*, 2022; 2023). These correlations, whether positive or negative, are spatially extensive

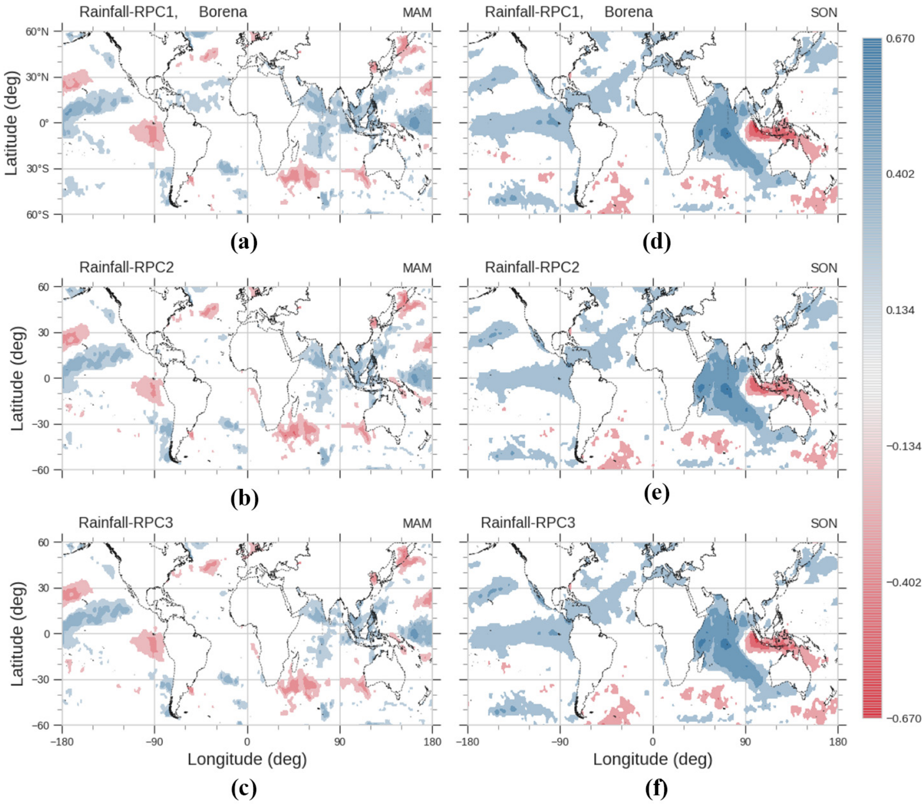

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Figure 7. Seasonal global sea surface temperature (SST) significant correlation (p-value ≤0.05) with the corresponding Borena zone dominant seasonal rainfall variability

and more pronounced during SON and MAM seasons. These findings underscore the complex interactions between regional rainfall patterns and oceanic oscillations, highlighting the influence of SST gradients in shaping seasonal precipitation variability in the Borana zone. Understanding these dynamics is crucial for improving climate prediction models and enhancing resilience strategies against climate variability and change.

Furthermore, we conducted a thorough analysis to assess the potential association between known seasonal oceanic oscillations and corresponding areal mean standardized anomalies of MAM and SON rainfall time series, revealing significant correlations (at a 95% significance level) (Figure 8). Specifically, the standardized precipitation anomaly in spring (MAM) shows significant correlations (p-value ≤ 0.05) with SST anomalies in the Niño 4 region and the Dipole Mode Index (DMI) of the Indian Ocean (Saji *et al.*, 1999; Saji and Yamagata, 2003; Munday *et al.*, 2022; 2023).

Similarly, SON season standardized precipitation anomaly is significantly (p-value ≤0.05) correlated with the corresponding DMI, global mean SST, Niño 1.2, Niño 3.4 and Niño 3 SST with values of correlation ~0.7, 0.3, 0.35, 0.32 and 0.35, respectively (Table 2).

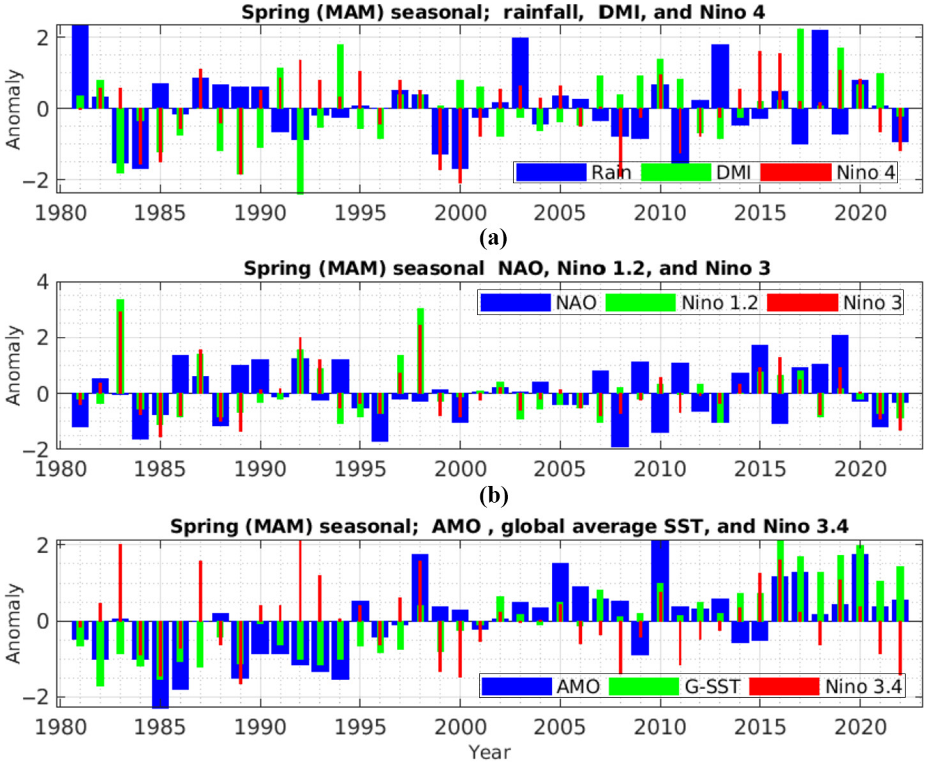

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Figure 8. The standardized anomaly of rainfall and different oscillations of SST during the spring season

Table 2. The correlations of different oceanic autumn (SON) season oscillations with the corresponding Borena zone average rainfall

	Rain	AMO	DMI	Global	NAO	Niño 1.2	Niño 3.4	Niño 3	Niño 4
Rain	1	0.1385	0.6977	0.2944	0.1698	0.3477	0.3166	0.3522	0.238
AMO	0.1385	1	0.1051	0.8654	−0.1838	−0.1679	−0.1234	−0.121	−0.0474
DMI	0.6977	0.1051	1	0.3002	−0.0275	0.5492	0.6177	0.6049	0.5758
Global	0.2944	0.8654	0.3002	1	−0.116	−0.1626	−0.0797	−0.0929	0.01258
NAO	0.1698	−0.1838	−0.0275	−0.116	1	0.06924	0.05948	0.08058	0.02701
Niño 1.2	0.3477	−0.1679	0.5492	−0.1626	0.06924	1	0.8089	0.914	0.6121
Niño 3.4	0.3166	−0.1234	0.6177	−0.0797	0.05948	0.8089	1	0.9715	0.9389
Niño 3	0.3522	−0.121	0.6049	−0.0929	0.08058	0.914	0.9715	1	0.8457
Niño 4	0.238	−0.0474	0.5758	0.01258	0.02701	0.6121	0.9389	0.8457	1

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Figure 9 demonstrates the Borena zone's climate is significantly influenced by the IOD, a climate phenomenon characterized by the spatial difference in SST between the western and eastern parts of the Indian Ocean (Saji *et al.*, 1999; Saji and Yamagata, 2003; Funk *et al.*, 2008; Munday *et al.*, 2022; 2023). Positive phases of the IOD, marked by warmer waters in the western Indian Ocean and cooler waters in the east, can lead to above-average rainfall in the Borena zone, while negative phases may result in drier conditions (Behera and Yamagata, 2010).

ENSO, particularly the Niño 4 region, located in the Central Pacific Ocean, influences climate variability in the Borena zone particularly during SON and MAM seasons. El Niño events, characterized by warmer-than-average SSTs in the central and eastern Pacific, tend to correlate with wet conditions in the region, while La Niña events, marked by cooler SSTs, may lead to decreased rainfall, which is unlike with northern regions of Ethiopia during the summer season (Zeleke and Damtie, 2017; Zeleke *et al.*,2017).

Changes in the Walker Circulation, a large-scale atmospheric circulation pattern in the tropical Pacific, can influence weather patterns in the Borena zone (Zeleke *et al.*, 2017; Munday *et al.*, 2022; 2023). During La Niña events, the horizontal shifting of Walker circulation can disrupt normal rainfall patterns, leading to drought conditions during MAM season. Conversely, El Niño events may overlay the Walker circulation over the region, enhancing moisture transport to the region and promoting above-average rainfall during MAM season. The Borena zone's climate is also influenced by Indian Ocean circulation patterns, particularly monsoon circulation. Variations in the strength and timing of the Indian Ocean monsoon can have an impact on rainfall patterns, particularly toward the end of the spring season, potentially causing a late cession of rainfall (Webster *et al.*, 1999; Zeleke and Damtie, 2017; Munday *et al.*, 2022; 2023).

These observed variability of climate in the Borena zone can be attributed to a combination of factors, including ocean surface temperatures (SSTs), atmospheric circulation patterns and local geographical features. For instance, the Indian Ocean is highly linked with this region in all seasons. In addition, the Niño 4 region also significantly correlated during the spring and autumn seasons. All these demonstrate the climate of Borena is influenced by the variation of different SST surfaces. The topography of the Borena zone, characterized by mountain ranges and valleys, can influence local climate patterns through orographic effects (Smith, 1993). Mountainous areas may experience better rainfall due to orographic lifting, while rain shadow effects may lead to drier conditions in leeward regions.

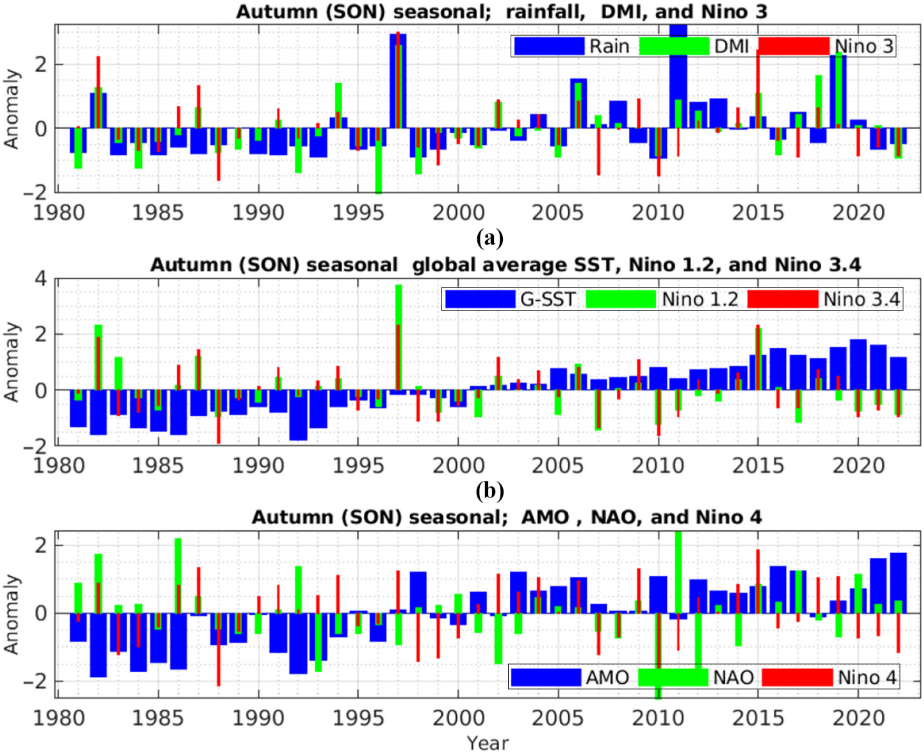

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Figure 9. The standardized anomaly of rainfall and different oscillations of SST during the autumn season

Proximity to the Indian Ocean, can modulate local climate variability through land–sea temperature contrasts and moisture transport (Neelin, 2007). The interplay between upwelling and downwelling in East African coastal areas is influenced by various factors, including the seasonal monsoon winds, coastal geography and large-scale oceanic circulation patterns (Camberlin and Philippon, 2002). For instance, during the southwest monsoon season (June–September), upwelling tends to be stronger along the East African coast due to the prevailing winds that drive offshore Ekman transport (Walker, 1924; Funk *et al.*, 2008; Segele *et al.*, 2009; Diro *et al.*, 2011). Conversely, during the northeast monsoon season (December–March), downwelling may become more prevalent as winds shift and weaken, allowing surface waters to sink and accumulate along the coast. These upwelling and downwelling processes may contribute to the dynamic of climate and ecological conditions along the East African coastal communities.

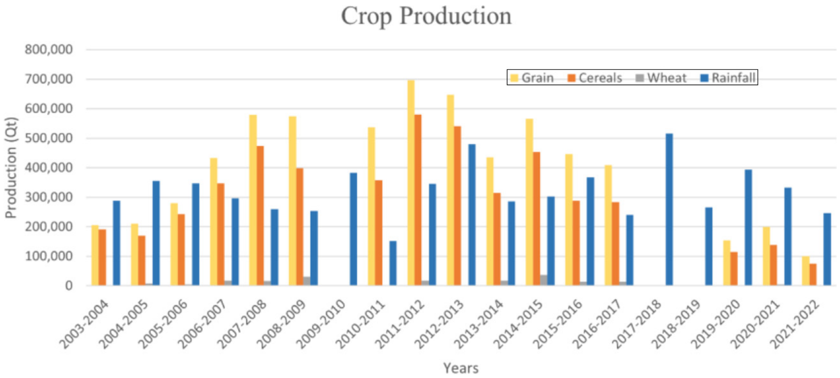
Climate variability in the Borena zone results from the complex interaction of oceanic, atmospheric and terrestrial factors, influenced by both regional and global drivers. Large-scale climate modes affecting pressure systems and atmospheric dynamics are key contributors to this variability in southern Ethiopia (Shanko and Camberlin, 1998; Giannini *et al.*, 2003; Segele and Lamb, 2005; Segele *et al.*, 2009; Diro *et al.*, 2011; Zeleke *et al.*, 2017). Additional studies have also emphasized the role of oceanic basins on south Ethiopian rainfall patterns (Kassahun, 1987; Camberlin and Philippon, 2002; Williams and Funk, 2011; Williams *et al.*, 2012; Funk *et al.*, 2014; Funk and Hoell, 2015; Vigaud *et al.*, 2016). Understanding these factors is crucial for predicting climate trends and crafting adaptation strategies to mitigate impacts on local communities and ecosystems.

3.3 *The impact of climate variability on pastoral and agropastoral production*

3.3.1 The impact of climate variability on crop production. Our analysis has highlighted significant spatiotemporal variability in climatic conditions within the Borena zone, particularly evident in rainfall patterns, which profoundly impact crop production, as illustrated in Figure 10. The irregular distribution of precipitation has increasingly led to prolonged dry spells and erratic rainfall patterns, significantly affecting wheat production in the region (Figure 10). Over the period from 1981 to 2022, the temporal variability of annual rainfall across the zone has been marked by unpredictability, a phenomenon well-documented to disrupt agricultural activities, particularly rainfed crop production (Figure 10). Studies by Bekele *et al.* (2019) and Teshome and Zhang (2019) corroborate that such annual rainfall variability adversely affects crop productivity in Ethiopia. Given that crop production in the Borena zone relies predominantly on rainfed agriculture, the risks associated with rainfall variabilities such as delayed onsets, premature cessations and dry spells throughout the growing season pose significant challenges (Bahiru *et al.*, 2020; Mugalavai *et al.*, 2008).

Figure 10 demonstrates a statistically significant correlation (p-value ≤ 0.05) between seasonal rainfall and crop production, emphasizing how rainfall variability affects the critical stages of crop growth, thereby constraining overall production and productivity. For instance, correlations such as Grain production with rainfall = 0.345, Cereal's production with rainfall = 0.416 and wheat production with rainfall = 0.23 underscore the variability's impact on agricultural outputs during different cropping seasons and constrain the production and productivity of crops, ultimately affecting food security of farmers.

The unpredictability of these weather patterns exacerbates challenges for farmers, particularly smallholders who constitute the majority of the agricultural workforce in the



Notes: Rainfall value is multiplied by 500 correlation grain production with rainfall = 0.345, Cereal's production with rainfall 0.416, wheat production with rainfall = 0.23) sensitivity (CSA)
Source: Created by authors

Figure 10. Crop production with annual total rainfall

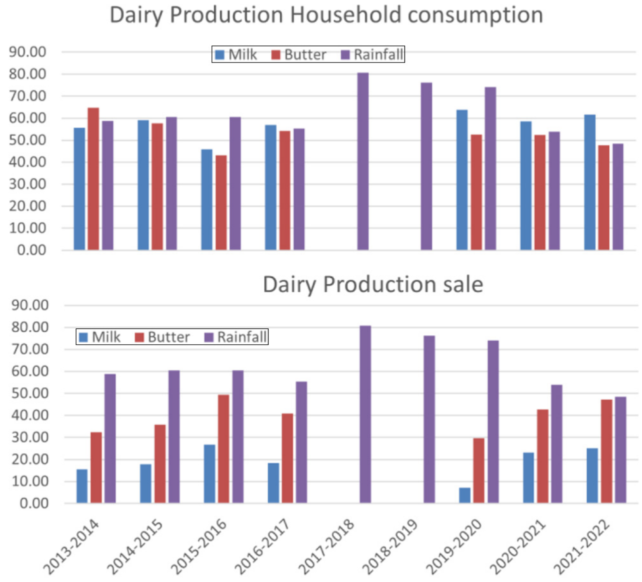
Borena zone. This vulnerability is well-documented in studies by Azemir *et al.* (2021), Gebeyehu *et al.* (2021) and Ayal *et al.* (2021), indicating that limited access to resources such as irrigation infrastructure, improved seed varieties and weather forecasting tools further impedes adaptive capacity.

Consequently, fluctuations in crop yields directly threaten food security and livelihoods in the region, exacerbating poverty and food insecurity among rural communities (Figure 10). It became evident that addressing these challenges posed by climate variability necessitates a comprehensive approach integrating both adaptation and mitigation strategies (Azemir *et al.*, 2021; Gebeyehu *et al.*, 2021; Ayal *et al.*, 2021).

Investing in climate-resilient agricultural practices such as conservation agriculture and agroforestry holds promise in enhancing soil moisture retention and reducing the risk of crop failure (Azemir *et al.*, 2021; Ayal *et al.*, 2021). Similarly, promoting the adoption of drought-resistant crop varieties and improving water management techniques are crucial steps toward mitigating the adverse effects of erratic rainfall patterns.

3.3.2 The impact of climate variability on livestock production. Climate variability profoundly influences pastoral production in the Borena zone, significantly affecting the productivity of livestock. Prolonged droughts can lead to dwindling forage resources and water scarcity, resulting in malnutrition, reduced reproduction rates and increased mortality among livestock. Conversely, excessive rainfall may trigger waterborne diseases and flooding, further jeopardizing the well-being of livestock populations.

Livestock-derived products such as milk and butter play a crucial role in the pastoral economy of the Borena zone. Variations in climate directly affect the availability and quality of these products, impacting both household consumption and market sales (Figure 11).



Source: Created by authors

Figure 11. Livestock production with rainfall (rainfall value is multiplied by 0.1, to comprising purpose) (CSA)

During drought periods, milk production tends to decrease, affecting nutrition and income generation for pastoral households. Fluctuations in forage availability similarly influence the quality and quantity of dairy products, thereby affecting their market value and economic viability (Figure 11).

Pastoral communities in the Borena zoneBorena zone are highly vulnerable to climate variability due to their heavy reliance on livestock for sustenance and income. Limited access to alternative livelihood options exacerbates their vulnerability, making them disproportionately affected by climate-related shocks. Socioeconomic factors such as land tenure insecurity and inadequate access to veterinary services further compound these challenges.

To build resilience among pastoral communities facing climate variability, a multifaceted approach is essential, integrating traditional knowledge with innovative solutions (Conway and Schipper, 2011). Investments in climate-resilient livestock breeds, sustainable rangeland management practices and improved access to water and veterinary services are critical interventions. In addition, diversifying livelihoods through activities like beekeeping and small-scale agriculture can enhance adaptive capacity and reduce dependency on livestock alone.

From our analysis, and literature review, the study recognizes that community-based initiatives guided by local knowledge and participatory approaches are crucial for enhancing resilience to climate variability among pastoral communities. Strengthening community-based natural resource management institutions and promoting collaborative decision-making processes empower pastoralists to adapt effectively to changing environmental conditions (Conway and Schipper, 2011; Seid *et al.*, 2016). Policymakers should prioritize supportive policies and investments in infrastructure to foster sustainable pastoralism and ensure resilient livelihoods in the Borena zone.

3.4 The implications of the study

The study on the seasonal spatiotemporal climate variability in the Borena zone of Ethiopia reveals important insights into the region’s climate dynamics and their broader impacts. By applying REOF and its time component, rotated principal component analysis, we uncovered significant variations in seasonal rainfall, temperature and drought indices across the zone from 1981 to 2022. These methods allowed us to discern notable spatiotemporal patterns and trends in these climate variables, with particular emphasis on how they fluctuate over time and across different subregions (Figure 4). The observed trends indicate that climate variability is not uniformly distributed but varies significantly, which has implications for both short-term weather patterns and long-term climate projections (Figures 5 and 6).

Moreover, our correlation analysis between seasonal rainfall and global SST, alongside the examination of pressure systems and wind vectors (not shown here), has elucidated some of the mechanisms driving these climate variations. These findings suggest that global climatic factors play a crucial role in influencing local weather patterns in Borena zone (Figures 7–9). The impact of these climatic variations extends beyond mere weather changes; they significantly affect agricultural productivity and livestock production (Figures 10 and 11). Our study found that fluctuations in climate variables, particularly those related to rainfall and temperature, directly influence crop yields, notably wheat and also have repercussions for livestock (Figures 10 and 11). This underscores the importance of incorporating these climatic factors into agricultural planning and management to mitigate the adverse effects on food and livestock production in the region.

3.5 Limitations of the study

Despite the valuable insights gained from this study on the seasonal spatiotemporal climate variability in the Borena zone, several limitations should be acknowledged. First, the analysis relied on historical climate data spanning from 1981 to 2022, which, while extensive, may not fully capture very recent or emerging climate trends. The inherent limitations of historical data on agricultural products, such as gaps in the data set or inconsistencies in measurement techniques over time, could affect the accuracy and completeness of the findings. In addition, the focus on quantitative climate variables and their correlations with global SSTs and atmospheric conditions may not account for the full range of contemporary factors influencing climate variability, including recent anthropogenic impacts, socioeconomic, political and localized environmental changes. Furthermore, the impact assessment on crop and livestock production, while indicative, is constrained by the availability and accuracy of agricultural data. Variability in farming practices, local adaptation measures and socioeconomic factors could influence the observed impacts, suggesting the need for a more nuanced approach that incorporates qualitative data and local knowledge to complement the quantitative findings.

4. Conclusion

The Borena zone in Ethiopia exhibits notable spatiotemporal climate variability, characterized by bimodal rainfall patterns with distinct seasonal contributions. From 1981 to 2022, the spring (MAM) rainy season accounted for more than half of the annual rainfall, with April being the wettest month, while the autumn (SON) season contributed significantly as well. Variability in rainfall distribution across the zone, particularly notable in its southwest versus north-central areas, correlates with distinct temperature gradients throughout the year, with notable variations during different seasons.

The analysis identified three dominant variability patterns for both the spring and autumn seasons, explaining a significant portion of variance across various geographic regions within the zone. These patterns highlight localized impacts, such as increased drought occurrences in the southeastern region during the spring season, contrasting with more stable conditions in autumn. The study underscores the utility of indices like SPI and SPEI in assessing drought severity and informing adaptive strategies to mitigate socioeconomic impacts.

Furthermore, the observed climate variability in the Borena Zone shows a strong correlation with the Indian Ocean Oscillation, influencing rainfall characteristics. While ENSO has minimal impact on seasonal rainfall variability, Atlantic and Indian Ocean SST gradients play a significant role, highlighting the interconnectedness of regional climate dynamics.

Climate change and variability pose substantial threats to agricultural productivity in the Borena zone, particularly affecting crop production and livestock health. Prolonged droughts linked to shifting ocean oscillations have led to severe agricultural losses, including total crop failures and significant livestock mortality. These challenges necessitate urgent attention and targeted interventions to enhance resilience and ensure food security for vulnerable communities.

Addressing these challenges necessitates a multifaceted approach. First, enhancing meteorological monitoring networks and developing tailored early warning systems is crucial for improving preparedness against climate-related risks. Second, promoting climate-resilient agricultural practices, such as conservation agriculture, drought-resistant crops and advanced water management techniques, can mitigate the adverse effects of unpredictable rainfall patterns on crop yields. Third, safeguarding livestock-based livelihoods requires adopting climate-resilient livestock breeds, implementing sustainable rangeland management practices and improving veterinary services. Furthermore, empowering local communities through participatory methods and integrating traditional wisdom with modern technologies can strengthen adaptive capacity and foster sustainable development. In addition, policymakers must prioritize supportive policies and infrastructure investments to facilitate sustainable agricultural practices. By focusing on these strategies, stakeholders can collaboratively fortify the agricultural sector in the Borena zone, effectively reducing vulnerabilities to climate variability and ensuring enduring food security for future generations.

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