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COMBINED IMPACT OF INDIAN OCEAN DIPOLE AND EL NIÑO SOUTHERN OSCILLATION FEATURES ON DROUGHT OVER SOUTHEAST ETHIOPIA.

MSc THESIS

BY

ASALFEW NIGUSSIE CHERU

JUNE, 2024

ADDIS ABABA, ETHIOPIA

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A THESIS SUBMITTED TO UNIT OF ATMOSPHERIC AND OCEANIC SCIENCE, INSTITUTE OF GEOPHYSICS SPACE SCIENCE AND ASTRONOMY, ADDIS ABABA UNIVERSITY

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This is to certify that the thesis entitled "Combined Impact of India Ocean Dipole and El Niño Southern Oscillation Feature on Drought over Southeast Ethiopia" has been developed by Asalfew Nigussie Cheru (ID No GSR/5282/15), under our supervision. Therefore, we recommend that the student's thesis can be presented for review and open oral presentation.

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DEPARTMENT OF ATMOSPHERIC AND OCEANIC SCIENCE

EXAMINERS' THESIS APPROVAL SHEET

As members of the Board of Examiners for the MSc Thesis Open Defense Examination, we certify that we have read and evaluated the thesis prepared by Asalfew Nigussie. Having examined the candidate, we recommend that the thesis be accepted as fulfilling the requirements for the degree of Master of Science in Earth System Physics (Atmospheric and Meteorology Science). We the examiner board approve that this thesis has passed through the defense and review process

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ACRONYMS

AGHRYMET	Agro-meteorological and Hydro-meteorological
CHRIPS	Climate Hazards Group Infrared Precipitation with Station data
CDT	Climate Data Tool
DMI	Dipole Mode Index
ENSO	El Niño Southern Oscillation
EMI	Ethiopian Meteorology Institute
NOAA	National Oceanic and Atmospheric Administration
ENSO	El Niño Southern Oscillation
ERSSTv5	Extended Reconstructed Sea Surface Temperature version 5
FMAM	February, March, April and May
GDP	Gross Domestic Product:
HoA	Horn of Africa
ICPAC	IGAD Climate Prediction and Applications Center
IGAD	Intergovernmental Authority on Development
IOD	India Ocean Dipole
JJAS	June, July, August and September
nIOD	Negative India Ocean Dipole
NOAA-CPC	National Oceanographic and Atmospheric Administration Climate Prediction Center
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
PDSI	Palmer Drought Severity Index
pIOD	positive India Ocean Dipole
RDI	Reconnaissance Drought Index
SADC	Southern African Development Community
SDI	Stream flow Drought Index
SOI	Southern Oscillation Index
SPEI	Standardized Precipitation Evapotranspiration Index
SPI	Standardize precipitation Index

SPI-3	Standardize precipitation Index for three month
SST	Sea Surface Temperature
SWSI	Surface Water Supply Index
VHI	Vegetation Health Index
WFP	World Food Program

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DEDICATION

This MSc thesis work is dedicated to our honest Father **Nigussie Cheru Pedane**. He was a true and honest Father. He gave all his time and everything he had to his family.

Thank you, Father everything you did for us

We do not forget you. You are always with us.

We know that your root is long and wide

Declaration

I certify that this thesis is my work to the best of my knowledge, and it has not been submitted or published elsewhere for examination, award of degree, or publication. Where other people's work or my work has been used, this has properly been acknowledged and referenced by the requirements of Addis Ababa University.

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Unit of Atmospheric and Oceanic Science

This MSc thesis is submitted for examination with our approval as research supervisors:

ABSTRACT

Several studies have revealed that ENSO and IOD teleconnections significantly impact drought Thus, understanding these impacts is critical for expressing effective adaptation and mitigation strategies. Specifically, the combined effects of El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) SSTs on drought events throughout the primary rainy season (February–May) over southeast Ethiopia are the focus of this thesis. For the analysis, we used historical climate data for the period spanning 1992–2022, ENSO, and IOD data. The data used to examine the relationship among the different indices with drought using the statistical analysis method. Therefore, the Thornthwaite method used to calculate SPI-3, and Pearson correlation was applied to identify the association between different phases of ENSO/IOD and drought. The characteristic analysis depicts that the study area had a long duration, frequent intensity, and moderate to extreme drought severity from 1992 to 2022. Accordingly, the results show that the combined occurrence of ENSO and IOD (El Niño/pIOD) enhanced the rainfall, thus reducing the occurrence of drought events. In contrast, the independent occurrence of pure El Niño, pure La Niña, and pure positive IOD, where their corresponding indices phases were neutral, were associated with drought events. These findings' implications highlight how crucial it is to include climate teleconnections like pure La Niña and pure El Niño; pure positive IOD association with drought, which is important to drought monitoring and seasonal climate outlook preparation for Southeast Ethiopia.

Keywords: ENSO; IOD; SPI; rainfall; drought; Southeast Ethiopia

1. INTRODUCTION

1.1 Background

The drought phenomenon is a water imbalance brought on by variable weather patterns and inadequate precipitation (Dabar et al., 2023). Drought affects economic activity around the world (Spinoni et al.,2014), and the droughts that occurred in the past and present have severely impacted the production of crops, forages, and water resources, severely hurting the GDP and family consumption (Ghazaryan et al., 2020; Kogan et al., 1994). Many droughts prone areas of sub-Saharan Africa have experienced severe droughts in current periods and centuries, which have resulted in catastrophic humanitarian disasters brought on by El Niño Southern Oscillation (ENSO) (Seyoum et al., 2017).

A prolonged drought and famine have severely damaged Ethiopia's food supply as a result of large losses to crops and livestock, especially in the southeast of the country, where most people are pastoralists (Funk et al., 2023). Ethiopia has a very varied climate, with equatorial rainforests and highly variable rainfall among its features. Numerous effects, such as frequent droughts, famines, and a drop in agricultural productivity, have resulted from these variations (Eshete, Sterck, and Bongers 2011).

The three seasons in Ethiopia are Belg (February–May), Bega (October–January), and Kiremt (June–September). The Belg season contributes differently to the nation's rainfall totals, which differ from location to location.

Drought and flooding have been major causes of crop losses and livestock, which in turn have been associated with increases in poverty, destitution, and complex vulnerabilities in southeastern Ethiopia. As a result, people occupying the study area experience an endless range of social and economic issues because of the prolonged drought during the ensuing rainy seasons (Jury, 2016). In addition to these intensely frequent droughts, people are frequently questioned about their access to food, drinking water, and forage for their livestock's water (Abraham n.d; Figures, 2023).

The Oromia and Somalia regional states have frequently faced frequent droughts. For instance in 2022, 3.4 million people in Oromia (the Guji and West Guji zones) and 3.5 million people in Somalia (the Afder, Daawa, Liban, and portions of the Shabelle zone) were impacted by the drought, which is primarily affecting the eastern and southeast regions of Ethiopia. Almost 163,000 people were affected by the drought between October 2021 and June 2022, and approximately 372,000 people were displaced in the Borena zone between March and September 2022. Likewise, because of the drought, over 175,000 people in the Somali region were forced to relocate between October 2021 and June 2022 (Anon n.d.2022).

Several reasons may contribute to the drought, but the primary cause is the inconsistency and lack of precipitation. In the Pacific, El Niño-Southern Oscillation (ENSO) and the India Ocean Dipole (IOD) in the Indian Ocean are the causes of this lack and variability of rainfall (Singh et al., 2022). It has been discovered that El Nino events in Ethiopia, especially in the southeast during the Belg season, positively affect the variability of rainfall (Gobie & Miheretu, 2021). El Nino, however, has a negative overall effect on the nation's economy and agriculture, resulting in food shortages, droughts, and a drop in agricultural GDP (Worku & Sahile, 2018).

According to the above explanation, there is a persistent and frequent drought in southeast Ethiopia; however, there are research gaps because the influence of ENSO and IOD on this drought hasn't been thoroughly documented (Gitima and Mersha 2020). This research aims to fill existing gaps, contributing valuable insights to the scientific understanding of drought, to forecast the weather and climate and grasp of how IOD and ENSO features affect the drought in southeast Ethiopia.

1.2 Statement of the problem

Previous studies have examined the general characteristics of drought and explored the influence of ENSO on rainfall variability. In addition to this it assessed the impact of drought on the socioeconomic activities. Therefore the aforementioned studies did not focus on the cause of drought it's relation with the climate indices independently and combined. But the impact of the combined feature of IOD and ENSO on drought has been studied on a continental and sub-continental scale; instead, it has not been studied in specific areas like southeast Ethiopia (Yin et al., 2022). This relation has been remains largely unexplored (Bekele-Biratu et al., 2018; Legese et al., 2018; Abara et al., 2020).

Southeast Ethiopia has a diverse and different climate condition from the rest part of the country, Therefore despite the existing research on drought in the region, there is a notable gap in understanding the combined impact of the Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) on drought, specifically in southeast Ethiopia. Consequently this work focused on the study of the independent and combined impact of IOD and ENSO feature on drought over in southeast Ethiopia.

This study aims to fill this crucial gap by investigating the combined impact of IOD and ENSO features on drought severity in southeast Ethiopia. In addition to this, this work identified which features of IOD and ENSO have a greater effect on the strength of the drought in southeast Ethiopia. The results of this study will address this research gap and will support researchers and local communities, particularly in creating focused mitigation and adaptation plans for drought affected areas of southeast Ethiopia.

1.3 Objectives

1.3.1 Main objective

The main objective of this study is to examine the statistical relationship between ENSO and IOD with drought, focusing on identifying dominant indices influencing drought severity. Additionally, the study aims to evaluate the characteristics of drought.

1.3.2 Specific objectives

- To examine the statistical relationship between the occurrence of drought in southeast Ethiopia and the influences of ENSO and IOD.
- To evaluate the characteristics of drought in terms of duration, frequency and severity over southeast Ethiopia.
- To verify the dominant indices and their significant effect on the strength of the drought in southeast Ethiopia.

1.4 Research questions

- What is the association between the indices (IOD and ENSO) with the frequent occurrence of drought in southeast Ethiopia?
- What are drought characteristics regarding duration, severity, and frequency in southeast Ethiopia?
- Which indices (IOD or ENSO) have a greater effect on the severity of the drought in southeast Ethiopia?

1.5 Significance of the study

The results of this study will address the research gap. It will support researchers and local communities, particularly in creating focused mitigation and adaptation plans for drought-affected areas of southeast Ethiopia.

The study's conclusions will be a great source of information for the southeast portions of Ethiopia regarding the predictability, readiness, and adaptation of drought risk. It will also be used as an important input to climate outlook preparation. The researchers will determine the effect of IOD and ENSO on drought in the study area. They will identify the variability and periodicity of the dry spells, further contributing to climate prediction over the study area.

The Ethiopian Meteorology Institute will continue providing a seasonal outlook three times per year on a national level; therefore, the result of this study will add important knowledge on seasonal climate forecast preparation regarding the study area. Accurate and reliable predictions of drought will support the pastoralists by providing information to decide to sell their cattle before they starve and go to death. This is necessary because, during the dry (drought) season, there will be a shortage of forage and water availability.

Drought over the study area caused poor pasture quality and scarce water resources, and the health condition of the livestock also affected, resulting in a decrease in their productivity and leading to economic loss. This thesis result will contribute to the health sector to minimize the risk caused by drought. During the extended drought season, there will be an outbreak of water-borne disease due to the limited water supply. Therefore, this study will contribute by providing relevant information to the preparation of a good forecast and proper early warning information in southeast Ethiopia. Furthermore, this study will support the administrative sectors in thinking about sustainable practices to be implemented in the pastoral community and build long-term resilience. With this knowledge, food will be supplied, and other economic sectors will be ready for the effects of the drought (Wolde-Georgis, 1997).

1.6 Delimitation and Scope of the Study

This study is delimited to examine the combined effects of the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) on drought events during the primary rainy season (February–May) over the southeast region of Ethiopia. The analysis is bounded by the following delimitations: The study is focused on the southeast region of Ethiopia, excluding other regions of the country. On the temporal scope, the historical climate data utilized in the analysis spans the period from 1992 to 2022. Regarding the climate indices the study specifically investigates the influence of ENSO (El Niño and La Niña) and IOD (positive IOD) indices on drought in the study region. The drought characterization using the Standardized Precipitation Index (SPI-3) was calculated with the Thornthwaite method. On the analytical approach, the study employs statistical analysis methods, particularly Pearson correlation, to identify the association between ENSO/IOD phases and drought occurrence.

Overview of delimiting the geographical scope, temporal period, climate indices, drought characterization, and analytical approach, this study provides a focused examination of the combined impacts of ENSO and IOD on drought in southeast Ethiopia during the primary rainy season. The findings from this delimited scope can inform drought monitoring and seasonal climate outlook preparation for the study region

2. REVIEW OF RELATED LITRATURE

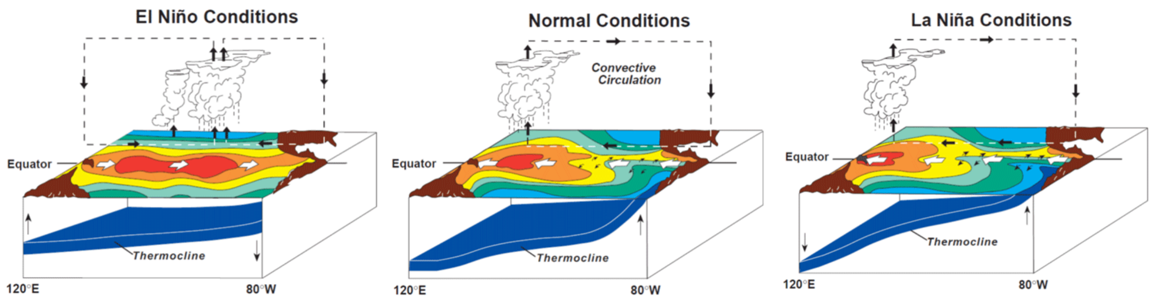
The effects of the various ENSO and IOD phases on the drought were covered in this section. This is important to understand the general and complex impact of the indices on the study area. This section also covers the impact of the existed drought in southeast Ethiopia. The information discussed in this section gathered from other similar study findings

2.1 The El Niño-Southern Oscillation

The different climate indices make the climate of the Earth variable, among these indices, the primary one is El Niño–Southern Oscillation (ENSO) (Tsidu, M., 2016). It developed in the Pacific Ocean around the tropics resulting from coupled interaction between the atmosphere of the earth and the Ocean ENSO varies between the warmer phase El Niño, and the colder phase, La Niña. This varies occurrence of ENSO happens when the equatorial Pacific is warm during El Niño and cool during La Niña (Santoso et al., 2017).

The largest inter-annual climate signal is the first climate phenomenon to be demonstrated to primarily rely on coupled interactions of the dynamics of the ocean and atmosphere. Therefore, it has served as a model for laying the theoretical and computational groundwork for ocean-atmosphere interaction in the tropics more broadly (Neelin et al., 1998). The eastern tropical Pacific's thermocline became deeper at this time, whereas the western tropical Pacific's became shallower due to the weakening of the trade winds, also known as the easterlies. As warm seas surge eastward along the equator, sea levels in the eastern and western tropical Pacific increase and decrease, respectively, by up to 25 cm. The cold tongue becomes weaker or vanishes because of decreased or stopped equatorial upwelling.

There are three phases of ENSO: La Niña, Neutral, and El Niño (Figure 1). El Niño, which lasts for 12–18 months, is a warming of the tropical Pacific that happens every three to seven years on average. El Niño causes the trade winds to weaken along the equator as atmospheric pressure changes in the eastern and western Pacific (Trenberth 2019).



Source: NOAA/PMEL/TAO Project Office

Figure 1 El Niño-Southern Oscillation (ENSO). This figure depicts a model of the tropical Pacific under El Niño, normal, and La Niña circumstances, including surface temperatures, winds, regions of rising air, and the thermocline (blue surface).

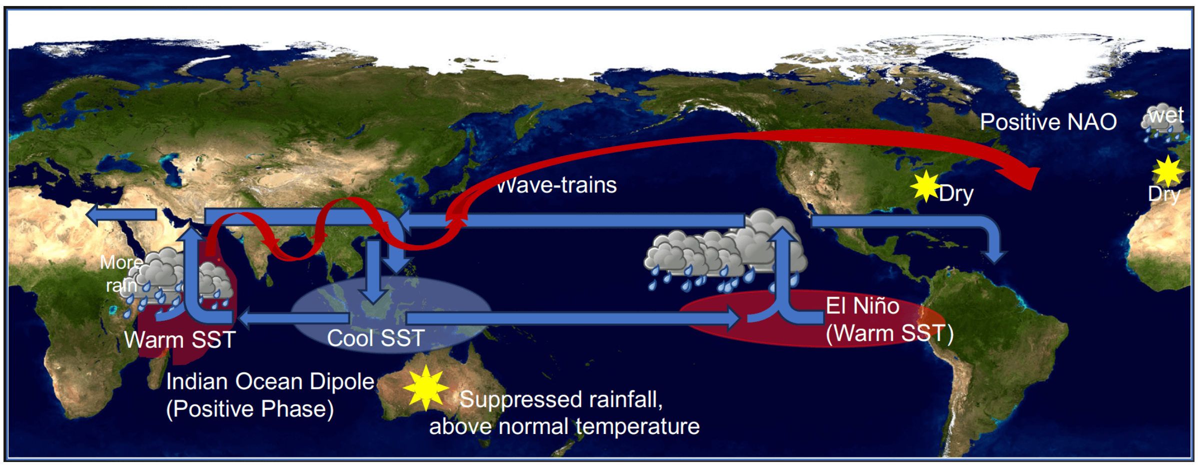
2.1.2 The impact of ENSO on drought

Two distinct phases of ENSO indices are now influencing the frequency and intensity of droughts (Serrano et al., 2017). Conversely, Gushchina et al.(2020), discovered that the seasonal fluctuation and geographic distribution of moisture anomaly conditions within the humid and sub-humid tropics are related to distinct El Niño and La Niña events. This information is relevant to the African tropics. After examining drought patterns, Zeleke et al. (2017),) studied ENSO occurrences in the year 2000 to 2016 and confirmed that each the two opposite phases of ENSO over Ethiopia displays a unique signal of droughts connected to rainfall and vegetation. El Niño and La Niña have both influenced the drought at distinct phases of its development according to Yin et al. (2022), El Niño occurs throughout the emerging and mature periods of drought, whereas La Niña mostly affects the mature and decaying phases of drought, with the former reaching its highest severity. Similarly, El Niño and La Niña respond to seasonal droughts differently, as demonstrated by research conducted by (Fan et al., 2023).

2.2 The India Ocean Dipole

A climatic phenomenon in the Indian Ocean is known as the Indian Ocean dipole (IOD). The western Indian Ocean experiences warmer sea surface temperatures (SSTs) during the positive phase of the IOD, whereas the eastern Indian Ocean has cooler SSTs (Figure 2). The Indian

Ocean Dipole (IOD) is a naturally occurring mode that links the ocean and atmosphere and is crucial for driving seasonal and inter-annual climatic fluctuations (Yamagata et al., 2004). For these intrinsic air-sea-coupled climatic phenomena in the tropical Indian Ocean, the term "Indian Ocean Dipole" (IOD) was developed due to the dipolar structure of both oceanic and atmospheric anomalies toward the equator (Ashok et al., 2004). IOD has two phases Positive and negative phases comprise it pressure gradient between the east and west is created when there is a positive IOD (pIOD), which causes SST to warm in the west and cool in the east. Eastward SST warming and westward SST cooling creates a west-east pressure gradient when the negative IOD (nIOD) happens.(Zhang et al., 2018)



Source https://gmao.gsfc.nasa.gov/research/science_snapshots/slides/2023/IOD.pdf

Figure 2 The different phase of Indian Ocean dipole (IOD)

The development of increasing sea surface temperatures over the Indian Ocean, particularly during the Northern Hemisphere spring, reduces moisture transport towards the Greater Horn of Africa by increasing convection over the ocean and producing surface wind anomalies (Degefu et al., 2021). Therefore, Ethiopia's Belg season, a major rainy season during MAM (March, April, and May), is influenced by the Indian Ocean Dipole (IOD) and its impact on drought.

2.2.2 The impact of IOD on drought

The impact of the Indian Ocean Dipole (IOD) varies in its effects across different seasons within a country. During FMAM, a negative phase of IOD may contribute to drier and warmer conditions. The warmer sea surface temperatures in the western Indian Ocean can lead to suppressed rainfall and delayed or insufficient Belg season rains in Ethiopia. During this season, the reduced rainfall in southeast Ethiopia affects the water supply, livestock life, and agriculture activities.

While February-May (FMAM) period is the main rainy season in southeast Ethiopia, it is the secondary rainy season in the central and northeastern parts of the country. During this season, there is a week-long correlation with every SST index. On the other hand, Pohl and Camberlin, (2006) report showed that one of the main causes of the Madden-Julian Oscillation's variations is the region's MAM rainfall variability. In southeast Ethiopia, the Indian Ocean Dipole (IOD) has a profound influence on the regional climate. During a positive IOD phase, when the western Indian Ocean warms relative to the east, southeast Ethiopia typically experiences drier than normal conditions and an increased risk of drought. This disruption to the normal rainfall patterns can have severe consequences for the region, where the local population heavily depends on rain-fed agriculture and access to water resources for their livelihoods (Yamagata et al., 2004).

2.3 The combined impact of ENSO and IOD on drought

Various combinations of IOD and ENSO conditions might have various effects on droughts across the world. The observed variability in rainfall and the large-scale climate variables, especially the Nino 3.4 and IOD indices, are linked to the occurrence of droughts in this region. Drought episodes are consequently becoming a significant problem in the area, hurting the environment and economy overall (Funk, Andreas H. Fink, et al., 2023) (Gebrechorkos, Hülsmann, and Bernhofer, 2020). An annual time series and ENSO in the summer and winter, as well as IOD in the winter, showed a statistically significant negative association with drought variability. (Bile et al., 2022), However, Behera et al. (2006), stated that the predictability study of the IOD events is a real challenge, and its progress will also contribute to the ENSO forecast.

The Sea surface air temperature anomaly is a common indicator of both phenomena, and it has an impact on precipitation (Ashok et al., 2004). The observed variability in rainfall and the large-scale climate, especially the Nino 3.4 and IOD indices, are linked to the occurrence of droughts in this region. Drought is the main problem in the area, hurting the community overall (Hrudya,Varikoden, and Vishnu, 2021).

Different research results show that IOD and ENSO influence short-term drought (SPI-3) in a better way than other long or medium term drought indices (Science, n.d.). On the other hand, Yin et al. (2022) and Funk et al. (2023) report that the co-occurrence of ENSO and IOD influences the drought patterns in the study area. The two phases of ENSO, affected the Indian monsoon, but since the 1980s, the negative relationship has been weakening. Most of the scientific community agreed that this relationship was weakening due to global warming. The positive and negative IOD events will reduce the impact of ENSO when two events co-occur (Hrudya et al., 2021).

2.4 The impact of drought in the southeast Ethiopia

Ethiopia's reliance on a rain-fed agricultural system makes it very sensitive to climatic unpredictability and change. Drought reduced 26% of the number of cattle herd sizes in Dire and Yabelo District, Borana Zone, southern Ethiopia, in the 2010–2011 year (Demem, 2023). According to historical data, drought has impacted almost every industry in Ethiopia, including agriculture (loss of crops and livestock), water resources (increased evaporation and decreased freshwater availability leading to water stress), industry (inadequate water supply), and hydropower (reduced electricity production). The impact on ecosystems is significant, despite improper assessment and documentation (loss of wetlands and lakes, loss of forest and soil cover, increased soil erosion and land degradation, etc.). Significantly important are the social and economic effects, which include an increase in diseases that affect humans and livestock, migration and conflicts related to water, and a decrease in the national gross domestic product (GDP) (Mera, 2018). Drought is the main challenge of the study area; therefore, the prolonged drought faced in the area from year to year affects human life as well as livestock

The people in the study area have a predominantly pastoral lifestyle, supplemented by some agro-pastoralist activities. Traditional livestock rearing and pastoral livelihood systems are severely impacted by the declining trend in March-May rainfall, which is the main rainfall season over the southern and eastern portions of the study area. This is because there is a severe shortage of water and pasture availability (Few & Tebboth, 2018).

3 MATERIAL AND METHOD

3.1 Description of the Study Area

Southeast Ethiopia is located between 06°33′ N and 06°75′ N and 039°95′ E and 040°29′ E (Figure 3). It covers some Zones from the Somalia and Oromia regions states. The key focus areas mentioned span across two regional states in Ethiopia - the Somali regional state and the Oromia region. In the Somali regional state, the areas of focus include Afder, Daawa, Erer, Liben, Nogob, and Shabelle. In the Oromia region, the focus areas are Bale, Borena, East Bale, Guji, and West Guji. It is characterized by its arid and semi-arid climate. It has a diverse landscape, ranging from flat plains to hills and valleys. Based on Debela et al. (2019), the study area is categorized into four different rainy and dry spells, which include the long dry spell from December to February, the long rainy period from March to May, the short dry spell from June to August, and the short rainy period from September to November.

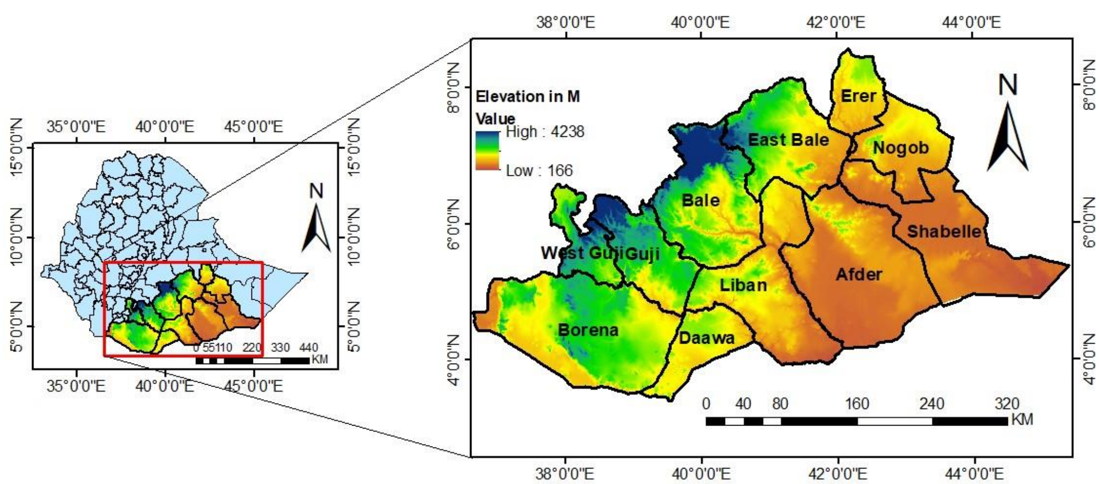


Figure 3 Map of the study area

The main rainy season in the study area occurs from February to May. This extended rainy period is the primary source of precipitation for the region. In contrast, the months from June to September, known as the Kiremt season, receive relatively less rainfall. As a result, this period is relatively dry compared to the main rainy season experienced across the country. Due to the disparity in rainfall patterns, with a prolonged dry season during the Kiremt months, the study area is considered a very vulnerable region within the country. The lack of consistent, well-distributed rainfall makes this area prone to challenges related to water scarcity and potentially increased food insecurity (Mera, 2018). The populations living in the study area are composed of different ethnic groups, and most of them are pastoralists and agro-pastoralists. Based on the WFP drought response report, it was stated that five consecutive rainy seasons (Belg) have caused such severe water shortages that pastures and livelihoods have been devastated across the south and southeast of Ethiopia (WFP, 2022).

3.2 Data collection

To analyze the combined impact of ENSO and IOD on drought in southeast Ethiopia during the Belg season, a multi-step data collection process was involved. We use the climate data; SST data relate to IOD (positive and negative) and ENSO (El Niño and La Niña) phases. We collect the ground base data to validate the satellite data and analysis the long year mean.

3.2.1 Climate data

The meteorological data used in this study is the Climate Hazard Group Infra-Red Precipitation with Stations (CHIRPS) (Funk et al., 2015) rainfall data from 1992–2022. We had also collected monthly rainfall data from the Ethiopian Meteorological Institute (EMI). The study area has a scarcity of observational meteorological stations; this is the reason why we focus on CHIRPS data. We chose CHIRPS because it is validated by comparing the satellite products with the rain gauge data every month and resulting a correlation value of 0.93 (Dinku et al., 2018). The study area (Shukla et al., 2021) has been an interesting area for doing different researches related to drought. In this study, we focus on the southeast part of Ethiopia because the area has recently been a hot spot for frequent droughts.

3.2.2 ENSO and IOD Data

The El Niño-Southern Oscillation (ENSO) satellite data was collected from the National Oceanographic and Atmospheric Climate Prediction Center, (NOAA-CPC) the website is https://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.sh tml. The other satellite data was Indian Ocean Dipole (IOD) collected from the International Desks Climate PredictionCenter:https://www.cpc.ncep.noaa.gov/products/international/ocean_monitoring/indian/IODMI/DMI season.html. As indicated by Endris et al. (2019), The SST anomaly data is located between the south-eastern and western equatorial Indian Oceans (90°–110°E and 10°–0°S) and 50°–70°E and 10°–10°N, respectively. Similarly, Manatsa et al. (2012), used the IOD data to analyze its impacts and associations with East African rainfall. On the other hand, Sazib et al. (2020), used the ENSO to identify ENSO on agriculture in Africa. The figure below shows the application diagram of all the data.

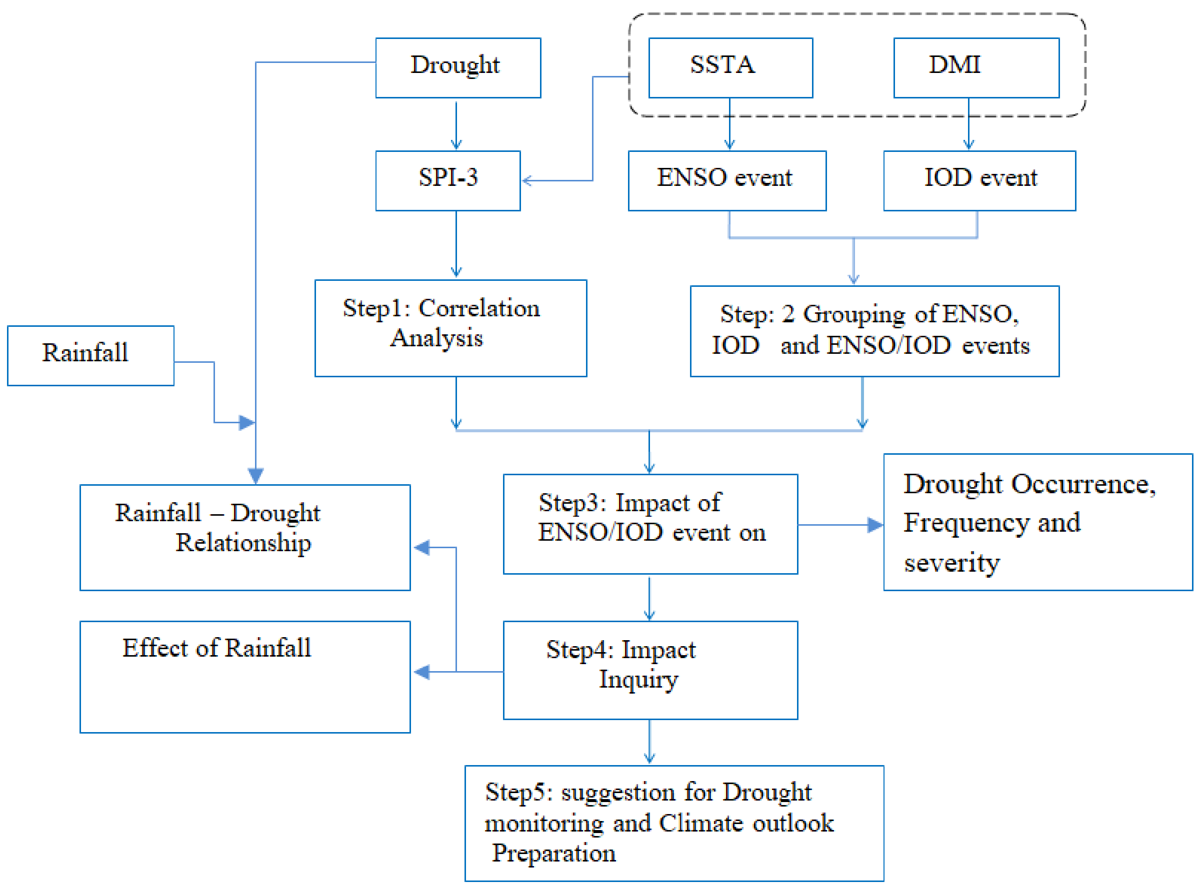


Figure 4a the data Diagram

We grouped the ENSO and IOD based on their phase (Table 1). The ENSO phase being pure El Niño or pure La Niña means that the IOD phase is neutral; similarly, pure positive IOD and pure negative IOD simultaneously, the ENSO phase is neutral.

Table 1 the grouping of the indices in 1992-2024.

Pure EI Niño	Pure La Niña	Pure (pIOD)	Pure (nIOD)	EI Niño (pIOD)	La Niña (nIOD)
2002,2004,2009,2014,2015	1995,1999,2000, 2007,2008,2011, 2020	2019	1996	1994,1997, 2006,2018	1998,2005,2010,2016,2021, 2022

3.2.2.1 Classification of ENSO and IOD Years

For an ENSO event to be classified as warm and cold in the Niño 3.4 zone, its three-month running averages of sea surface temperature (SST) anomalies must surpass ± 0.5 ^{0}C for a minimum of five months in the region (120^{0}W–170^{0}W)◦, 5^{0}N–5^{0}S). IOD events were identified using monthly DMI values that represented the SST anomaly (exceed ±0.4 ^{0}C) difference between the western and southeastern equatorial Indian Oceans (50^0–70^{0}E, 10^{0}S–10^{0}N) and the southeastern equatorial Indian Ocean (90^0–110^{0}E, 10^{0}S–0^{0}N) (Figure 4), which is similar to a prior study (Jia et al., 2023). IOD events are defined as occurring if the monthly DMI value surpasses 0.75 of the standard deviation in this investigation (Ashok et al., 2004; Li and Zhao 2019). The classification of ENSO and IOD was based on the above definitions.

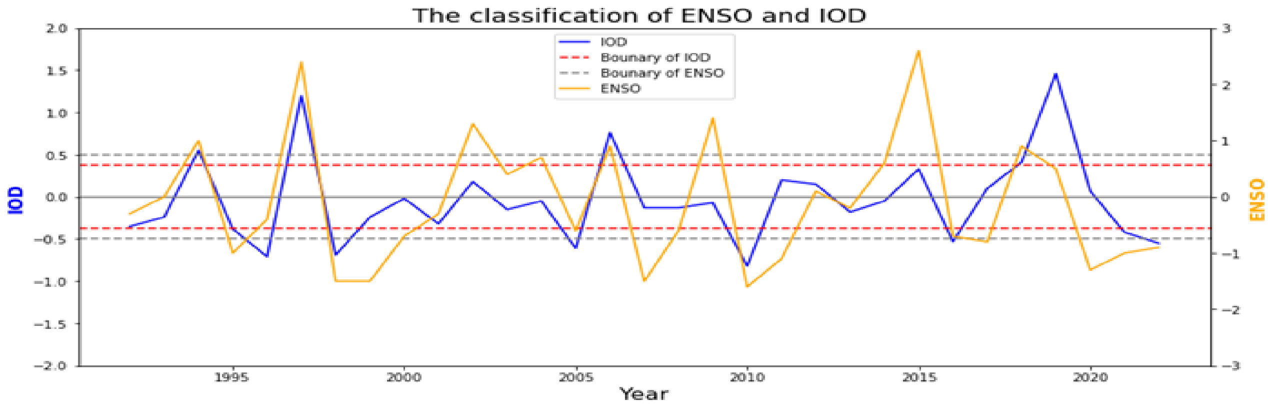


Figure 4 classification of ENSO and IOD

3.2.3 Drought Indices

Drought indices are numerical instruments that evaluate and track drought conditions according to a range of hydrological and meteorological factors. Various indices concentrate on distinct facets of drought, and the selection of an index is contingent upon the features of the area, the data at hand, and the objectives of the research. The following are a few popular drought indices: Palmer Drought Severity Index (PDSI), Standardized Precipitation Evapotranspiration Index (SPEI), Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI), Surface Water Supply Index (SWSI), and Soil Moisture Index (Zargar et al., 2011). In this study, SPI is used to measure the drought characteristics. Based on Belay et al. (2021) deductions, the World Meteorological Organization advised using the Standardized Precipitation Index (SPI) among the drought indicators to describe meteorological droughts.

3.3 Data quality control

On the data cleaning part, we will identify and handle missing data using K-Nearest Neighbors (KNN) imputation, which is a method for filling missing values based on the values of their nearest neighbors in the feature space. The formula for KNN imputation can be explained as follows:

$$\mathbf{X_{missin}} = \frac{1}{K} \sum_{i=1}^{K} \mathbf{X_i} \quad (1)$$

X_i represents the observed values of x. We used the Climate Data Tool (CDT) to check satellite climate data, access data availability, homogeneity, and validation of the climate data. The spatial alignment processed by using GIS tools to assess and confirm the spatial coverage of the datasets, ensuring they cover the entire southeast part of Ethiopia. It is also used to address any spatial misalignments or inconsistencies. This data quality control is important to validate the satellite data (Appendix Fifure 2).

3.4 Method of Data analysis

In the study, we used statistical analysis to identify periods of El Niño, La Niña, positive IOD, and negative IOD events. To find the relationship among the indices, we correlated ENSO and IOD events with drought occurrences in Southeast Ethiopia by using the Pearson correlation. In addition to this, we explored the temporal relationship between the onset of ENSO/IOD events and subsequent drought events. The spread of the drought during ENSO and IOD event was displayed using a spatial map analysis.

3.4.1 Seasonal Coefficient of Variation

The coefficient of variation is a statistical measure (Zhao et al., 2018); this study conveys the monthly, seasonal, and inter-seasonal variation of the rainfall. Based on this definition, we analyzed the monthly, seasonal, inter-seasonal, and annual variations of rainfall.

$$\mathbf{CV} = \left(\frac{\mathbf{SD}}{\bar{\mathbf{X}}}\right) * \mathbf{100} \qquad \bar{X} = \frac{\sum_1^N x_i}{N} \qquad \textbf{and} \quad \mathbf{SD} = \frac{\sqrt{\sum_1^N (X_i - X)^2}}{N-1} \quad (2)$$

Where, CV is the coefficient of variation, and $\bar{X}$ is the average of rainfall. Xi is the monthly, seasonal, or annual; SD is the standard deviation; Based on (Hare, 2003), the following thresholds represent the level of the variations: extremely high (CV > 70%), very high (CV > 40%), high (CV ≥ 30%), moderate (20% ≤ CV < 30%), less (CV < 20%).

3.4.2 The contribution of the seasonal rainfall

The contribution of the seasonal rainfall amount to the annual rainfall amount is varying depending on the seasonal rain bearing mechanism. Therefore, here we assessed the contribution of each season to the annual rainfall amount. Therefore, the contribution of the seasonal rainfall to the annual rainfall can be analyzed using the question below (Tolosa et al., 2023). We calculate each season's (Kiremt, Belg, and Bega) rainfall contribution to the annual rainfall amount. It investigated which season of the study area had the highest amount of rainfall contribution

$$\text{Contribution} = \frac{\overline{X}}{Annual\ RF} \quad \textbf{(3)}$$

Where $\overline{X}$ is the monthly or seasonal long-year average, Annual RF the annual long-year average of rainfall.

3.4.3 Correlation Coefficient

A correlation is a statistical measure that quantifies the degree of association between two variables. The Pearson correlation coefficient is a statistical measure used to quantify the direction and strength of a linear relationship between two continuous variables. It is commonly represented by the symbol "r" and has a range between -1 and 1, where perfect negative linear correlation is represented by a value of -1, no linear correlation is shown by a value of 0, and perfect positive correlation by a value of +1. The following formula can be used to get the Pearson correlation coefficient between two variables, X and Y:

$$\boldsymbol{r} = \frac{\sum(\boldsymbol{X_i}-\mathbf{X})\sum(\boldsymbol{Y_i}-\mathbf{Y})}{\sqrt{\sum(\boldsymbol{X_i}-\mathbf{X})^2\sum(\boldsymbol{Y_i}-\mathbf{Y})^2}} \quad (\,\mathbf{4})$$

The integration of the data sets of ENSO, IOD, and drought for analyses is using the statistical methods called correlation analysis. It enables us to validate the integration process to ensure data coherence and consistency. Positive values might suggest that as the ENSO or IOD index increases, drought conditions worsen, while negative values might suggest the opposite.

Ahmed et al. (2017), used Pearson's correlation coefficient to quantify the relationship between rainfall and the positive and negative values of ENSO and IOD. In this study, Pearson Correlation Coefficient (PCC) was used to analyze the relationship between different phases of ENSO or IOD and the drought (SPI-3), Additionally, the correlations between the combined ENSO/IOD events during 1992–2022 were also examined in order to take into account the various phases of ENSO and IOD events.

3.4.4 **The Standardized Precipitation Index**

When American scientists McKee, Doesken, and Kleist observed that diverse elements impacting groundwater, reservoir storage, soil moisture, snowpack, and stream flow are influenced differently by the absence of rainfall, they established the Standardized Precipitation Index (SPI) in 1993 (Svoboda, et.al 2012).

According to Tall et al. (2023), Standardized Precipitation Index (SPI) is the preferred used for meteorological drought monitoring, rather than the Palmer Drought Severity Index (PDSI) or the Standardized Precipitation. Evapotranspiration Index (SPEI). Some potential reasons the SPI may be preferred in this context could include The SPI's focus on precipitation anomalies, which may be more directly relevant to the meteorological drought conditions being examined. In addition to this the SPI in capturing short-term to long-term drought timescales compared to other indices.

Droughts in agriculture and hydrology are denoted by PDSI and SPEI, respectively. Different authors use the SPI to study the drought pattern using different time scales (1, 3, 6, 9, and 12 months) (Moreira, Martins, Svoboda et al., 2012) and also Iwata et al. (2012) use the SPI to monitor and measure drought. In this study, we use the SPI to calculate the drought because it is simple to compute, meaningful, and statistically significant. To identify the duration and severity of the drought, Angelidis et al.(2012), use SPI. In this study, we used the

Thornthwaite method to calculate the SPI. It was used by (Ogunrinde et al., 2020 ; Pramudya et al., 2019).

$$\boldsymbol{SPI} = \left(\frac{X_i - \bar{X}}{\sigma}\right) \qquad \textbf{(5)}$$

Table 2. SPI drought index-based classification of drought type

Drought severity index	**SPI value**
Extremely wet	SPI≥2.0
Severely wet	1.5≤SPI≤2.
Moderately wet	1.0≤ SPI ≤1.5
Near Normal	Moderate wet
Moderate drought	-1.5≤SPI≤ -1.5
Severely drought	-2.0 ≤SPI≤-1.5
Extreme drought	SPI≤ -2

In this case, σ is the data standard deviation, Xi is the data point, $\bar{X}$ is the mean, and SPI is the standard precipitation index.

Table 2, shows the SPI method's output values match drought categories, with negative scores indicating drought and insufficient precipitation and positive scores indicating drought and adequate precipitation. The intensity of the drought shifts from nonexistent to severe, with potential flash floods while the Frequency values indicate drought conditions at a station (Ibrahim et al., 2017). The Climate Data Tool (CDT), an open-source, R-based program with a user-friendly graphical user interface, was created by the IRI to satisfy the temporal analysis of SPI. CDT is being used by over 20 countries primarily in Africa, but also in some countries in Asia and South America (Dinku et al., 2022).

When evaluating the impact of a drought and identifying its different characteristics, including its duration, intensity, and severity, the primary variable is the drought index. The parameters of the drought are determined in (Table 2), by using the meteorological drought indicator (SPI) calculated for three months. Events classified as droughts or non-droughts occur when the SPI values are negative or positive. Negative SPI values are regarded as a drought event since drought is defined as a state in which SPI values drop below zero. Determining a threshold value is necessary to calculate the length of the drought and the severity of the drought. The drought duration is the amount of time the SPI value is consistently negative, starting with SPI value -1 and ending when its value starts to trend positively. The intensity of the drought determines the overall SPI readings over the course of the drought (Thomas B. McKee., 1993).

3.5 Data analysis Tools

To perform this research, we used different tools for data analysis, data quality control, and other activities. We used Arc GIS to clip the study area shape file from Ethiopia and also to show the distribution of meteorological stations. Geo CLIM software was used to combine the data and the SPI. We used the Climate Data Tool (CDT) to validate the data and Python was used to analyze the spatial data.

4. RESULT AND DISCUSSION

This section describes the findings of the study. We first analyzed and discussed the rainfall climatology of the study area including the monthly, seasonal, and annual rainfall climatology. Secondly, we discussed the characteristics of drought in the study area. Thirdly we discussed the temporal analysis and spatial distribution of drought. Finally, we discussed and compared the results of this study with other similar studies' findings.

4.1 The rainfall Climatology of the study area

The main economy of the southeast portions of Ethiopia, like southern and southeast Oromia and Somalia, is significantly dependent on livestock breeding (Birhan, 2013). Southeastern Ethiopia is characterized by significant rainfall during the Belg and Bega seasons, with Belg being the primary rainy season. Conversely, in other parts of the country, such as the North east, East, Central, and Southern regions, Belg represents the secondary rainy season. The study area exhibits diverse topography, including both lowlands and mountains. The annual rainfall amount ranges from 150 to 800 mm, with notable variations between sub regions and the eastern lowlands, including Shabelle, Afder, and Nogob their rain fall vary from 150 to 300 mm per year.

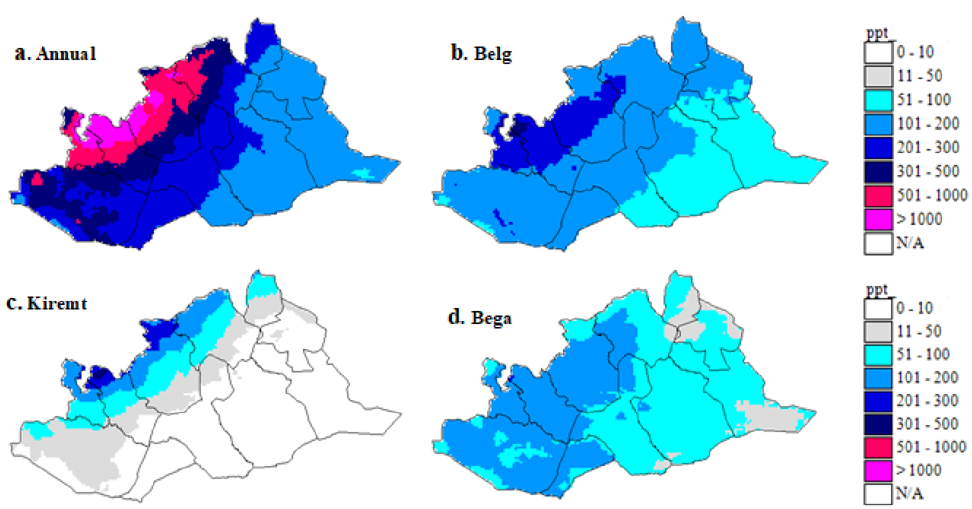


Figure 5 Spatial seasonal mean rainfall distribution (a) annual mean rainfall (b) Belg mean rainfall (c) Bega mean rainfall and (d) Kiremt mean rainfall.

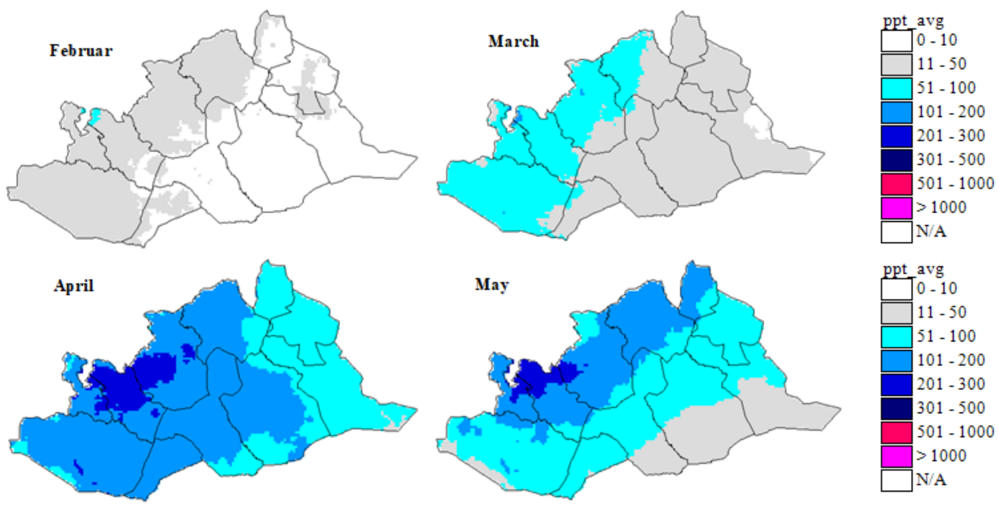
Based on the monthly mean rainfall distribution during Belg season (Figure 6a), April received the highest rainfall, and May is the second rainy month of Belg season. On the contrary, March and February received a smaller amount of rainfall. The rainfall starts in February, increases in amount and distribution in April, and extends to the middle of May. The study area experiences varying amounts of rainfall during Belg season, which is the main rainy season. The amount of rainfall during the Belg season varies between 106 and 162 mm in the eastern lowlands, between 163 and 273 mm in the central part of the study area, and reaches the highest levels of 274 to 329 mm in the highland regions like Bale, East Bale, and Guji (Figure 5b).

Rainfall increases toward the high land regions; the average annual total rainfall range from 145 to 850 mm. The highest annual rainfall amounts, which vary from 600 to 850 mm, are usually found in zones like Guji, East Bale, and Bale. Bega and Belg are the two main rainy seasons in the study area. Since highland regions receive the greatest amounts of rainfall, the importance of rainfall is generally greatest there. These patterns of rainfall have a significant impact on the study area's climate, with the main rain-bearing systems having a major influence on the region's environmental characteristics and agricultural potential.

The rain-bearing mechanisms that contribute to Southeast Ethiopia's rainfall are primarily impacted by local geographic features in addition to regional and global patterns of atmospheric circulation (Palmer et al., 2023). There are some major variables that affect rainfall are the Walker Circulation. The dry conditions over east Africa from March to May have a strong link with the Walker Circulation. Therefore, La Niña-related MAM droughts can be anticipated because of the Walker Circulation Enhancements (Fink, et al. 2023). Inter-Tropical Convergence Zone (ITCZ) and Indian Ocean Dipole (IOD) enhance moisture transport from the Indian Ocean (Funk, Fink, Harrison, Segele, Endris, Galu, Korecha, & Nicholson, 2023).

The complex interaction of climatic factors influencing the occurrence of drought in Southeast Ethiopia is highlighted by (Liou and Mulualem., 2019). Therefore, rainfall patterns are significantly influenced by the highlands and lowlands that make up Southeast Ethiopia's topography. Rainfall on windward slopes, like in the Bale Mountains, can be increased by orographic lift, which is the process of forcing moist air to rise over elevated terrain while producing rain shadows on the leeward side (Camberlin, 2023).

a.



b.

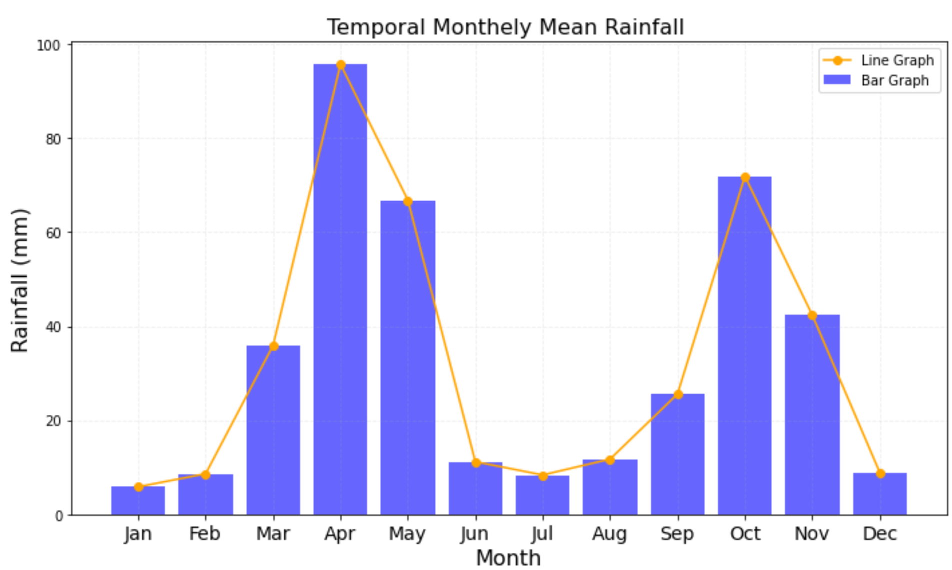


Figure 6 (a) Spatial Monthly Mean rainfall (mm); (b) temporal monthly mean rainfall.

Figure 6b the study area exhibits a bi-modal rainfall pattern, with two distinct rainy seasons. The primary rainy season occurs from February to May, which is the main rainy period for the region. During this time, the area receives the majority of its annual precipitation. The second rainy season is from September to November. The study area received the highest rainfall in April and October. Therefore, the study area has two wet and two dry periods. The annual time series of the rainfall and the Mann-Kendall trend line was described in (Appendix Figure 2)

4.1.1 The Seasonal Rainfall Contribution

The annual rainfall in this region is distributed across several distinct seasons. The Belg season contributes the highest percentage, making up 51% of the total yearly rainfall. This makes the Belg season the main rainy period, which is essential for maintaining ecosystems, boosting agricultural and livestock productivity, and supporting the economy throughout the year. The Bega season accounts for 34% of the annual rainfall, and this rainfall is very important for agriculture and replenishing water resources. The Kiremt season contributes 14% of the total rainfall, and while it is important, it is a relatively shorter period compared to the other seasons. Understanding the unique contributions of these different rainfall seasons is crucial for effectively managing the region's water resources and agricultural activities.

4.1.2 Rainfall variability

The coefficient of variation (CV) of rainfall was used to analyze the amount of rainfall and identify its trends. Figure 7(b) reveals that the annual rainfall variation observed over study districts like Afder, Shanelle, Nogob, and the southern part of Erer is highly variable as compared with the highlands. Based on the study of the recorded rainfall data, every month had a large coefficient of variation (CV range), indicating a very high variable. The monthly variability of the rainfall is described in (Appendix Figure 5).

However, in contrast to the other seasons, the rainfall coefficient of variation was less variable during the primary rainy season (Belg). During Bega season the area experienced high variability in rainfall; it was extremely high (Figure 7c). Meanwhile during the dry season (Kiremt) the area experienced moderate to high extreme variability (Figure 7d). The annual rain fall variability ranges from moderate to very high (Figure 7a).

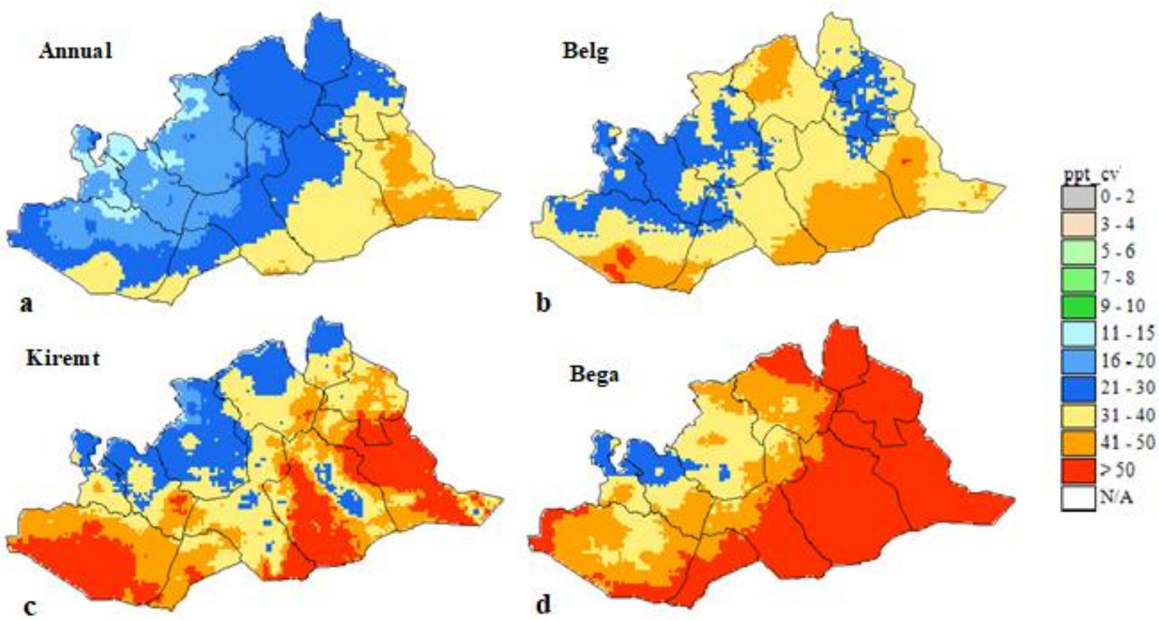


Figure 7 Seasonal and annual rainfall variability

4.2 Characteristic of the drought

Drought is a complex natural phenomenon mainly caused by climate variability. It is essential to understand the characteristics of drought in order to perform adaptation and formulate a good resilient strategy in the drought-prone area. Considering this and examining the features of drought, our study was characterized by the drought's duration, severity, and frequency in the primary study region during the rainy season. In this section, we describe the characteristics of drought in the study area in terms of its duration, frequency, and severity.

4.2.1 Drought duration and event

Figure 8 depicts that the drought event occurred over a 3 month time scale. The results of SPI-3 show that 45 to 54 drought events occurred from 1992 to 2022. Based on this analysis, Bale zones experience the longest drought events, followed by Borena zones.

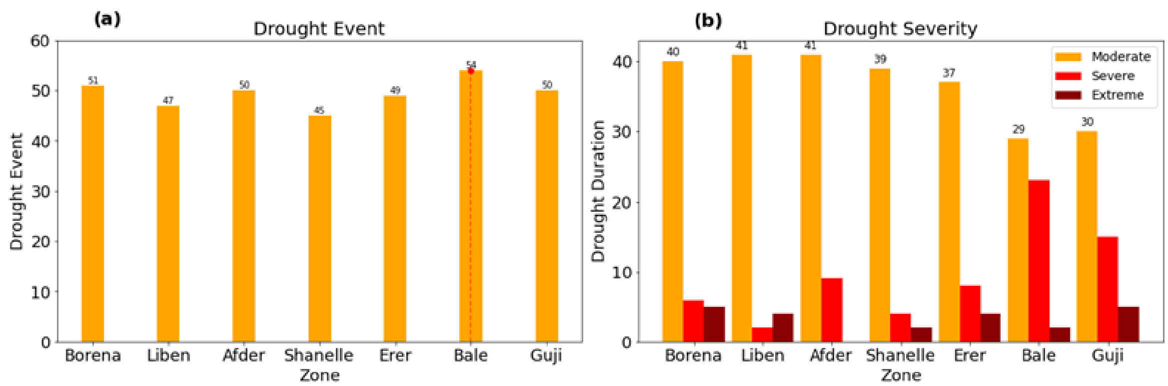


Figure 8 The temporal analysis of drought characteristics 1992 to 2022 (a) show the drought event for 30 years (b) the drought severity in terms of Moderate, severe and extreme high droughts.

The result of the SPI-3 shows the duration of the drought in each zone; therefore, the maximum duration of each zone is shown in (Table 5) and ranges between 4 and 2 months in seasonal level. There is one zone in Afder, Borena and Bale experienced four-month drought duration, which is the longest record in the year between 1992 and 2022. Based on (Table 3 and Table **4**) , Nogob zones experience moderate drought with an annual rainfall of 256.30 mm. Liben and Borena have received annual rainfall of 222.02 and 398.30 mm, respectively. Borena Zone experienced mild drought, whereas Liben experienced moderate drought. Shebelle and Afder are found in the Somali Regional State, they have 247.6 and 523 mm of annual rainfall respectively. They were experiencing a moderate drought. Bale, East Bale, and Guji are found in the highland of southeast Ethiopia. They had a high amount of annual rainfall (667.34, 491.99, and 635.08 mm, respectively). However, they are highlands and exhibit mild drought. Dawa has 350.09 mm of annual rainfall, and the drought was mild and moderate.

Table 3 Occurrence and frequency of drought (1992-2022)

Name Of District	Annual Mean Rainfall	Meteorological Drought Severity Index: probability of drought severity class				Drought Severity index	Drought Severity class
		No Drought	Mild Drought	Moderate Drought	Sever Drought		
Nogob	256.30	0.33	0.33	0.33	0	2.00	
Borena	398.30	0.36	0.46	0.13	0.03	3. 03	
Liben	222.02	0.23	0.3	0.37	0.1	2.33	
Ere	339.07	0.43	0.33	0.2	0.03	1.83	
Shebelle	247.60	0.33	0.36	0.3	0.13	2.1	
Afder	523.08	0.53	0.36	0.07	0.03	2.3	
Guji	635.08	0.5	0.4	0.1	0.03	2.13	
Bale	667.34	0.43	0.47	0.1	0	2.06	
Dawa	350.09	0.43	0.43	0.1	0.1	1.8	
East Bale	491.99	0.33	0.47	0.2	0	1.67	

Table 4 Meteorological Drought Severity Index (1992-2022)

Name of District	Occurrence and frequency of Drought: No Drought		Mild Drought		Moderate Drought		Severe Drought	
	Occurrence	Frequency	Occurrence	Frequency	Occurrence	Frequency	Occurrence	Frequency
Nogob	10.00	0.33	10.00	0.33	10.00	0.33	0.00	0.00
Borena	11.00	0.37	14.00	0.47	4.00	0.13	1.00	0.03
Liben	7.00	0.23	9.00	0.30	11.00	0.37	3.00	0.10
Ere	13.00	0.43	10.00	0.33	6.00	0.20	1.00	0.03
Shebelle	10.00	0.33	11.00	0.37	9.00	0.30	1.00	0.03
Afder	16.00	0.53	11.00	0.37	2.00	0.07	1.00	0.03
Guji	15	0.5	12	0.4	3	0.1	0.00	0.00
Bale	13.00	0.43	14.00	0.47	3.00	0.10	0.00	0.00
Dawa	13.00	0.43	13.00	0.43	3.00	0.10	1.00	0.03
East Bale	10.00	0.33	14.00	0.47	6.00	0.20	0.00	0.00

4.2.2 Drought frequency

On the other hand, the maximum frequency occurred in three zones, namely Guji Borena, Liben, and, which was -2.7 in 2000 and 2011 years, respectively. The second highest frequency occurred in Bale and Erer Zones; the value was -2.3 in the same year of 2011. Rainfall patterns exhibit both temporal and spatial variability, as shown by the analysis of the SPI values for the various stations in Southeast Ethiopia. While some stations may see fluctuating SPI values, indicating greater variability in rainfall, others may show consistent positive SPI values over multiple years, indicating a trend toward wetter conditions.

In (Figure 9a), the Afder zone is dominated by moderate and severe droughts, and the frequency was high between 1990 and 2010. Moreover, Bale is found in the highland area; however, it has experienced drought at different times (Figure 9). The zones had frequent, moderate, and severe droughts on different time scales. On the contrary, the Borena zone is found in the low-land category of the study area. The zone experiences moderate to severe drought at various times.

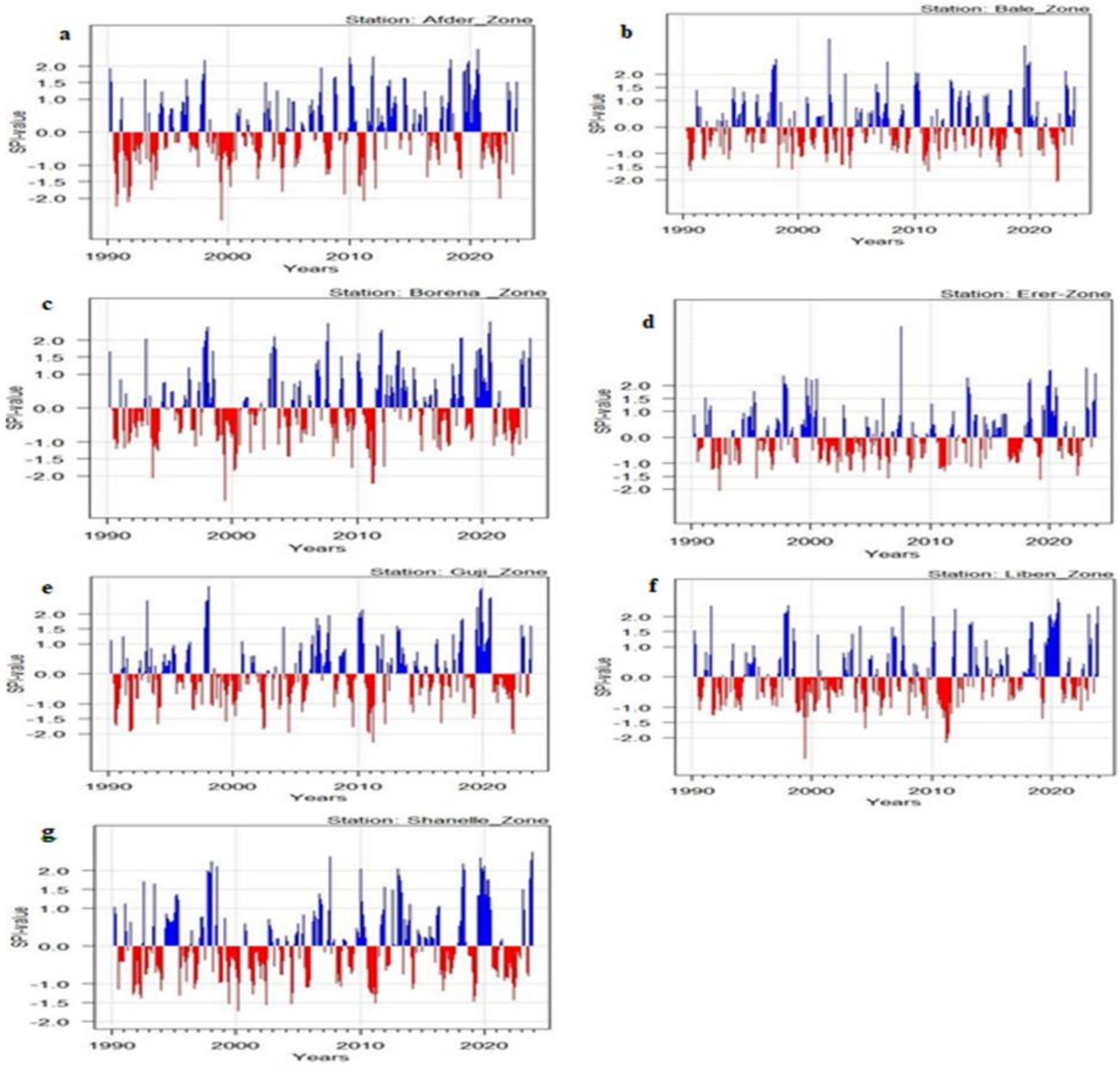


Figure 9 Drought frequency the blue color shows the wet years and the red color shows the dry years

The frequency of moderate droughts is higher than severe and extreme droughts. When comparing the drought frequency of Borena zone with rest zones, it is stronger (Figure 9c).. In the Erer Zone, drought frequency was moderate during the 2000-2010 periods, as shown in (Figure 9d). In contrast, the neighboring Guji Zone experienced a high frequency of drought, as indicated in (Figure 9e) Similarly, the Liber Zone also saw a high drought frequency, with moderate drought being the dominant condition, except for some instances of extreme drought, as depicted in (Figure 9f). Shanelle Zone, as illustrated in (Figure 9g), stands out as another area that received a high frequency of drought occurrences. These varied drought patterns across the different zones highlight the complex and localized nature of precipitation variability in the region, requiring tailored drought monitoring and management strategies for each affected area.

4.2.3 Meteorological Drought Severity

Based on (Figure 10), the maximum drought severity found in the Borena zone, which is -6.17 similarly Liben and Afder zones received a severe drought. While compare the severity and duration of drought Borena zone received a severe drought than the rest Zones. On the other hand, the Liben Zone experienced less severe drought as compared to its duration (Table 5).

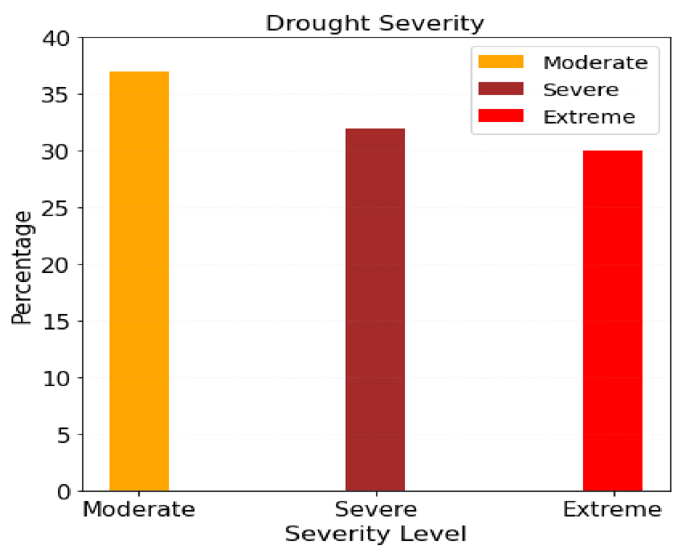


Figure 10 Drought Severity

Figure 10, compare the severity of the total drought occurred in study period, it indicates 37.5% were moderate drought. This drought caused all Zones to face slight deficits in rainfall that influenced agricultural activities and water resources. Approximately 32.5% were in severe drought conditions. This indicates the region faced more pronounced deficits in rainfall and water resources, leading to notable impacts on livestock, water availability, and possibly other sectors. Similarly, about 31% of droughts were extreme drought conditions. This suggests that during this drought period, there was acute water scarcity and significant deficits in rainfall, posing substantial challenges to livestock, water resources, food security, and overall socio-economic wellbeing in the study area. In general (Table 5), summarizes the overall result of the duration, severity, and frequency of each zone over a time scale of 3 months. This summary shows that the characteristics of the drought in one zone were different from those in other.

Table 5 Summary of drought characteristics

Zone	Time scale	Year	Duration	Year	severity	Year	Intensity
Afder	SPI-3	2011	4	2011	-5.49	2000	-1.72
Bale	SPI-3	2011	4	2011	-6.5	2011	-2.30
Borena	SPI-3	2011	4	2011	-6.17	2000	-2.36
Erer	SPI-3	2011	3	2011	-4.67	2022	-2.09
Liben	SPI-3	2000	3	2000	-5.99	2000	-2.20
Guji	SPI-3	2000	3	2000	-3.38	2011	-2.09
Shanelle	SPI-3	2011	2	2011	-2.43	1993	-2.06

4.3 Temporal Analysis

The temporal analysis of ENSO, IOD, and SPI was conducted for each zone to understand the relationship between ENSO, IOD, and SPI at the zonal level (Figure 11). The overall response of ENSO and IOD conditions varies significantly across all zones. This variation highlights how complex regional climate dynamics are, with local factors like land use, topography while atmospheric circulation patterns able to modify the effects of large-scale climate phenomena. (Shiferaw et al., 2023).

4.3.1 Association between ENSO/IOD and drought

Belg seasonal rainfall was significantly governed and influenced by both ENSO and IOD throughout the study periods. Figure 11, shows the relationship between ENSO, IOD, and SPI in the selected 6 zones during the Belg season. Shanelle and Afder have similar SPI trends, and Borena and Guji also have similar SPI trends. All zones have responded differently, with similar ENSO and IOD. Previous studies show MAM seasonal rains in East Africa forcing by ENSO and the IOD (Funk, Andreas H. Fink, et al., 2023; Yin et al., 2022). The seven Zone IOD, ENSO and SPI-3 was put relation was described in (Appendix Figure 3).

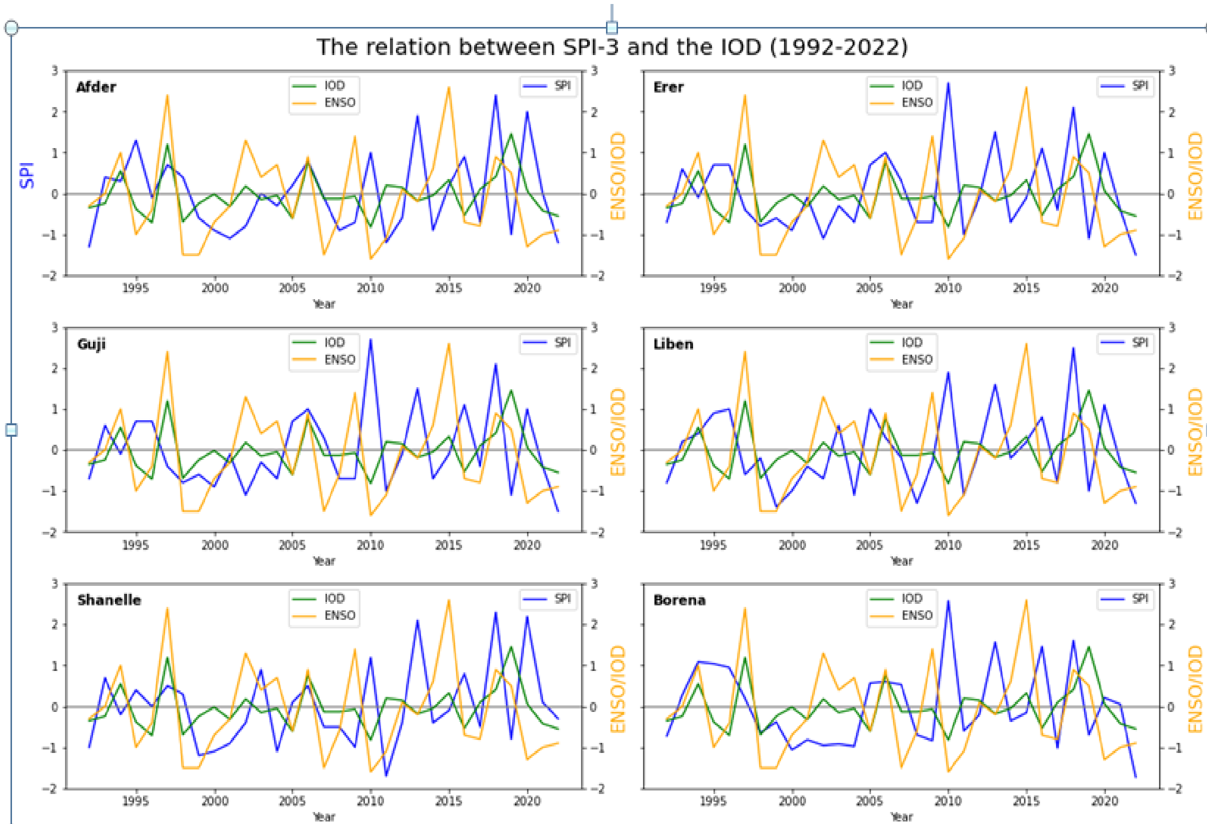


Figure 11 the relation between the IOD and ENSO (1992 to 2022) with SPI-3, during Belg Season.

4.3.1.1 The Association between ENSO and drought

Figure 12, demonstrated that the relationships between ENSO events and drought anomalies varied depending on the stage at which they occurred. We identified five pure El-Nino years from 1992 to 2022 (30 years). Using these pure El-Nino years, we compare them with the SPI value in the same year range. From the analysis result all Zones, except the Shabelle Zone which was a normal condition in 2015, experienced a normal to moderate drought. The highlands of the study area (Bale, Guji, and Liben) had a moderate drought. The lowlands experienced nearly normal conditions. From this result, we observed that El-Nino affects the high land area more than the low land. During the indicated El Nino years, the study had an impact by facing a moderate drought.

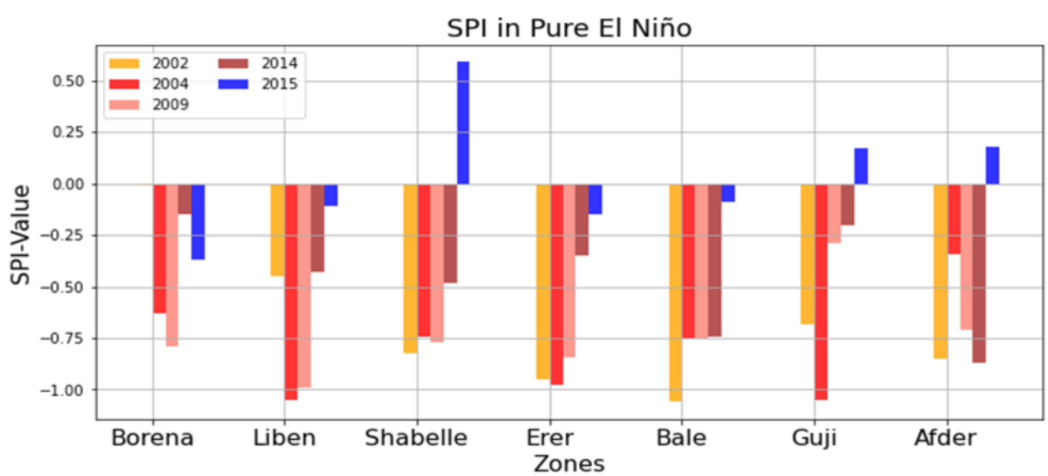


Figure 12 The association of pure El-Nino years with the SPI.

The result shows decrease of rainfall over the study area during pure El-Nino years (while the IOD was neutral), aligned with finding from previous studies it confirms that the drought was more frequent during El Niño years (Yin et al. 2022). The observed decrease in rainfall over the study area during the El-Nino years can be identified by the increase of the sea surface temperature over the equatorial Pacific. During El-Nino years, the season faced less rainfall, which led to the drought. The drought would last for three consecutive seasons. This confirms that the El-Nino year's control the climate variability of the study area.

La-Nina, the other ENSO phase, eight years was identified as pure La-Nina years. According to (Figure 13), most of the zones had moderate to severe drought in the identified La-Nina years, except 1995 and 2020 years. During 2011 moderate to severe drought was observed in the study area, which was the driest season (Dabar et al., 2022). Similarly, Abara et al.(2020) confirmed that the drought during 2011 was worst. In this drought years Borena and Liben zones experienced the worst drought. The only zone affected by a severe drought during the 2000 La Nina years was the Borena zone.

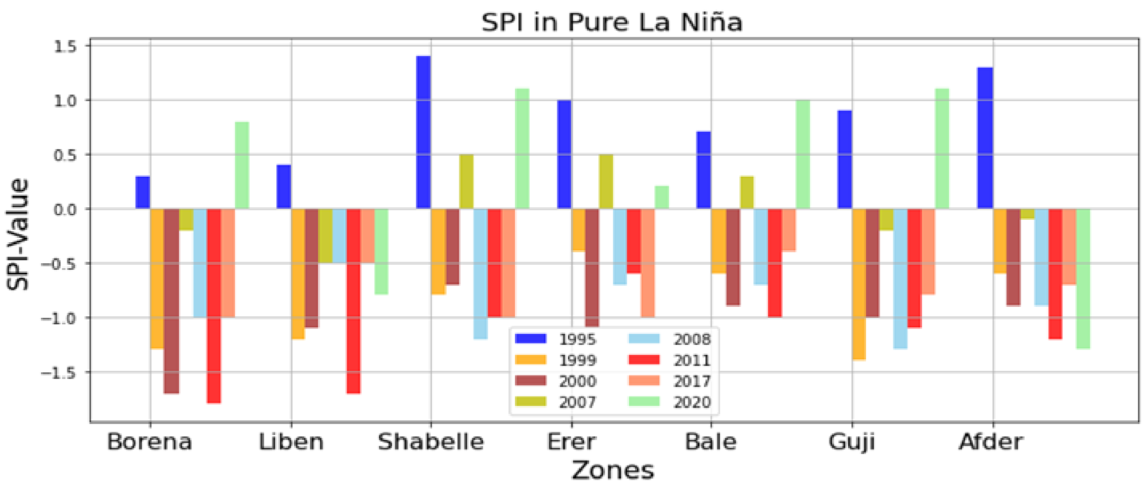


Figure 13 The pure La-Nina year's relation with the SPI in the same year.

4.3.1.2 The Association between IOD and drought

The association between pure negative or pure positive IOD and drought in southeast Ethiopia is shown in (Figure 14). Based on (Figure 14b,) the pure positive IOD year (2019) indicate drought condition in all zones; similarly, during the pure negative IOD years (Figure 14a), drought was weak in some area and the rest Zones wear normal condition therefore 1996 year was normal year. Meanwhile the positive and the negative India Ocean Dipole IOD described in line graph (Appendix Figure 1).

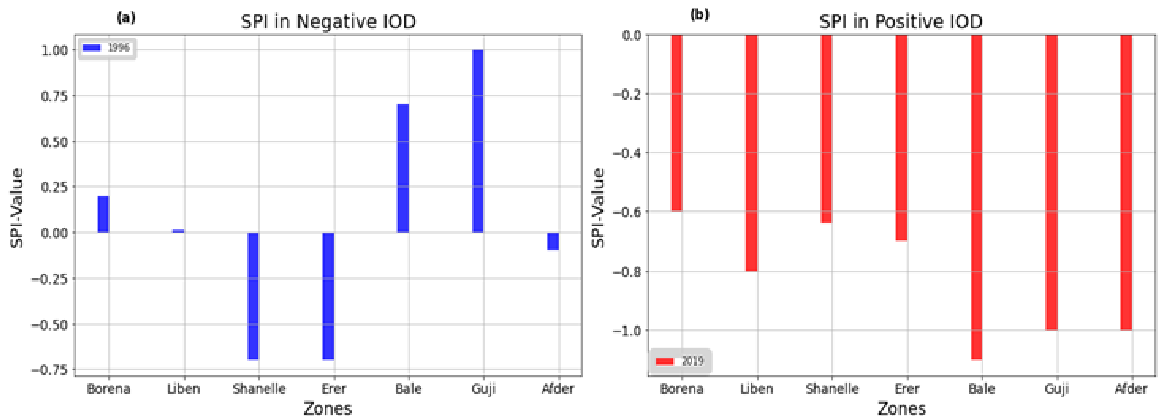


Figure 14. (a) The association of Negative IOD with SPI-3 and (b) The association of positive IOD with SPI-3

4.3.2 The association between the combined IOD and ENSO with drought

El Niño and pIOD are the most common combinations (Yin et al., 2022). The identified four combined years (1994, 1997, 2006, and 2018) of El Niño and pIOD experienced wet condition (Figure 15a). During 1997, only Bale and Guji Zones experience decreased rainfall, and then drought occurred. Overall, all Zones got wet during the Belg season, especially the lowland area. 2018 was the wettest year for all zones in the study area; therefore, the combination of pIOD and El Niño does not bring drought; rather, it makes the area wetter. From the selected four combined years, three of them were wet, especially in 2006 and 2018, when they were very wet, whereas in 1994, except for the high land Zones, the rest Zones were wet.

The other combined phase La-Nina and the negative IOD in the same Belg season (Figure 15b). From the selected six combined years, only 2022 was a drought year, in the rest of the five years drought did not occurred. During the 1998 combined year, Erer, Bale, and Guji's rainfall amounts decreased and were inclined toward drought, but the remaining combined drought was not experienced drought.

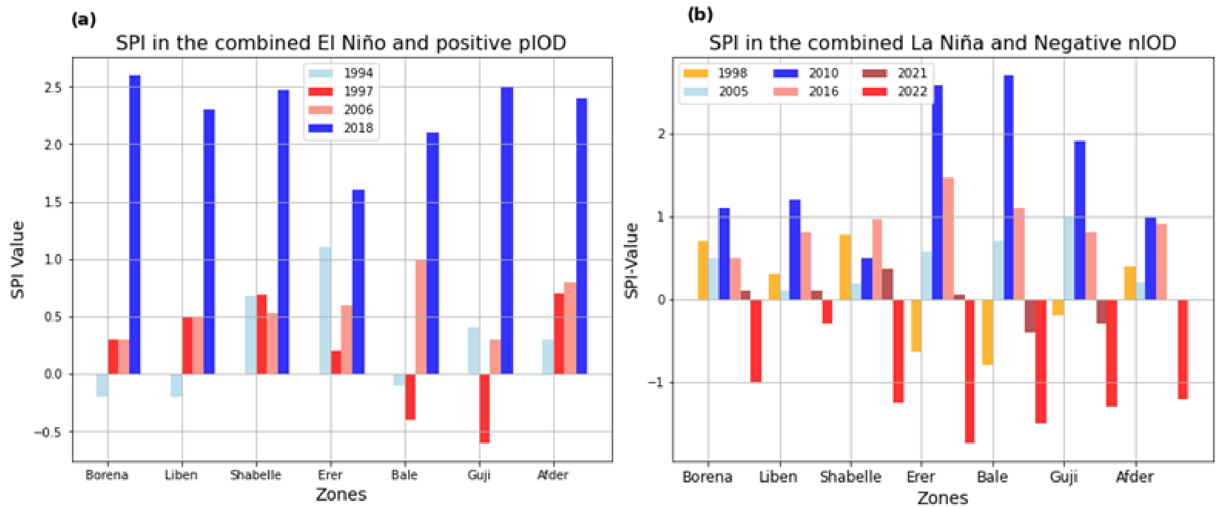


Figure 15. (a) The combined El Niño and India Ocean Dipole (IOD) on SPI-3, (b) the combined La-Nina and the negative IOD on SPI-3)

4.4 Spatial Analysis

This section presents the results obtained from the spatial analysis of IOD or ENSO with drought. The result of the connection between El Niño, and La-Nina, positive and negative IOD discussed. The combined phase's connection between Indian Ocean Dipole (IOD) and El Niño Southern Oscillation (ENSO) with drought also discussed.

4.4.1 The spatial association between ENSO and drought

In the selected El Nino years (Figure 16b), the spatial distribution showed moderate to severe drought in 2002, 2004, and 2009 years in different zones. During 2002, the northern tip of Afder, Liben, and the southern part of Bale experienced severe drought; on the other hand, most parts of Guji and Liben experienced moderate drought. Similarly, in 2004, the central part of the Bale, Liben, and the northern tip of Erer and Nagob experienced severe drought. The rest zones, including East Bale, Shanelle, and a few parts of Borena, experienced moderate drought conditions. In 2009, Borena, Daawa, and a few parts of Guji and Shanelle experienced a moderate drought. During 2015, there was no significant drought in all zones. On the other hand, during the known strong El Nino years (2015), the study area experienced wet condition especially the lowlands area as shown in (Figure 16b), except for the anthropogenic effects. During 2014 Shabelle zone experience severe drought as compare to Liben and Afder zones, East Bale also exhibited weak drought. Whereas the rest part of other Zones did not exhibit drought. The result of the spatial association of the 1999 La Nina year in northern Borena was that Guji experienced a moderate to severe drought. In 2000, severe droughts were seen in Borena, East Bale, and Erer, and the northern part of the Liben had a moderate drought. But in the other zones, there was no significant drought observed. During 2007, a weak to moderate drought was observed over Afder and Shanelle. Meanwhile, in 2008, some zones experienced a weak drought.

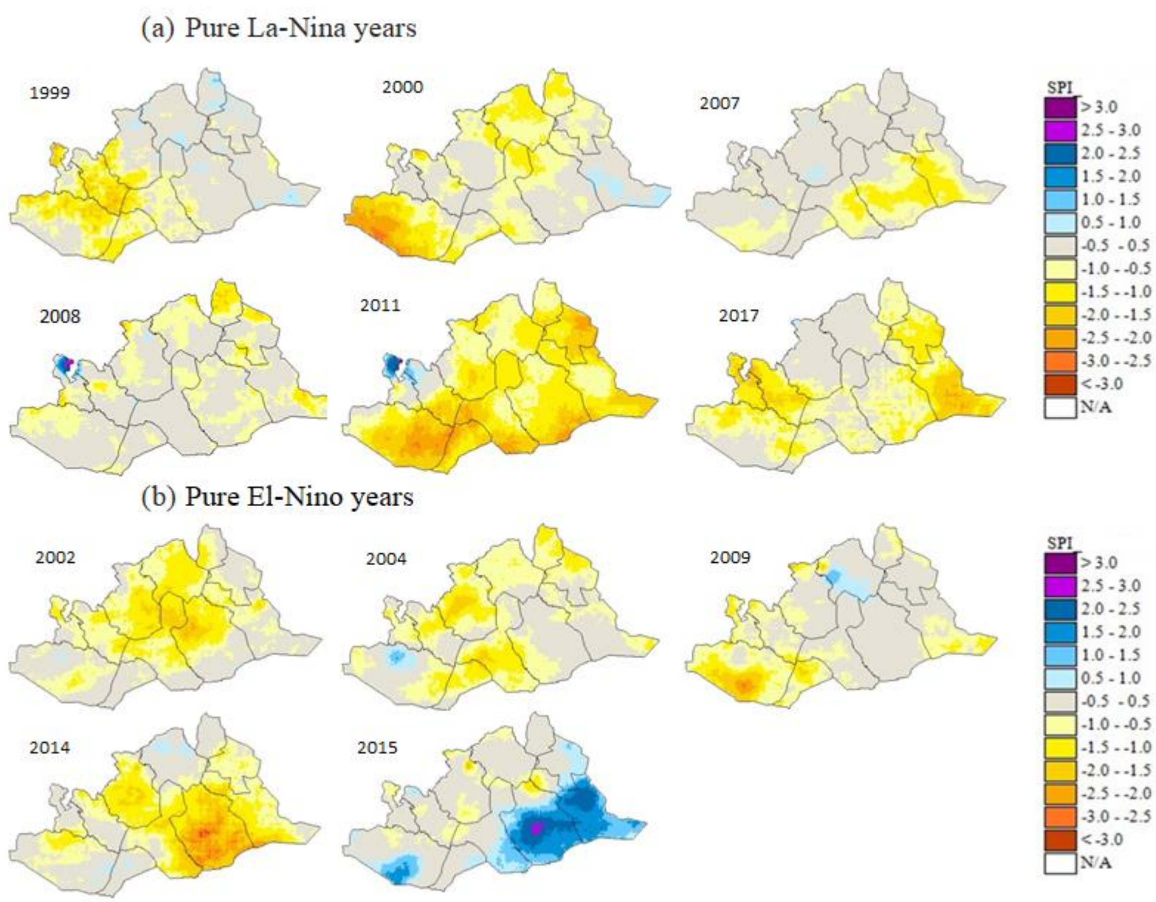


Figure 16 The association of ENSO and IOD on drought (a) the association of Pure La-Nina and SPI distribution (b) the association of Pure El Niño years and SPI distributions.

The rest of La Nina years 2011 and 2017 experienced moderate to extremely high droughts; especially during 2011, all zones were impacted by high extreme droughts (Figure 16a.). In 2011 La Nina was a dry year; all zones experienced severe to extreme drought. Therefore, Borena, the northern parts of Nagob, and the northern tip of Liben and Afder experienced an extremely high drought. The impact of the La Nina drought, especially in 2011, is well explained by (Lyon & Dewitt, 2012). In 2007 most part of the country experienced wetter condition but, some part of southeast Ethiopia were hit by drought (Kourouma et al., 2022).

4.4.2 The Association between IOD and drought

To identify association of the IOD on drought we select 2019 for pure positive IOD and 1996 for pure negative IOD years in (Figure 17) The pure pIOD year, there were severe to extreme drought conditions in the central part of Guji, Bale, and Liben. On the other hand, Borena, Afder, and Shanelle zones moderate to severe drought conditions were experienced. In 1996 except for the south tip of Borena and Liben, all Zones did not experience drought.

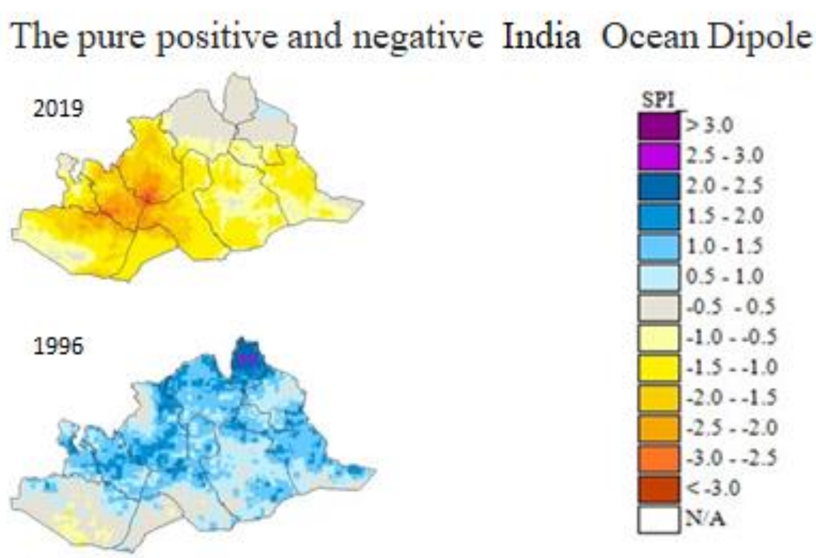


Figure 17 The spatial map of the pure positive IOD (2019) and pure negative IOD (1996)

4.4.3 The association of combined IOD and ENSO with drought

The spatial analysis shows the same result with the temporal analysis. El Niño and pIOD combined years experienced wet conditions based on the four combined years (Figure 18a). From the selected El Niño and pIOD combined years except 1997 which experienced drought in highland zones but, the rest all Zones were wet as discussed in section 4.3.2.

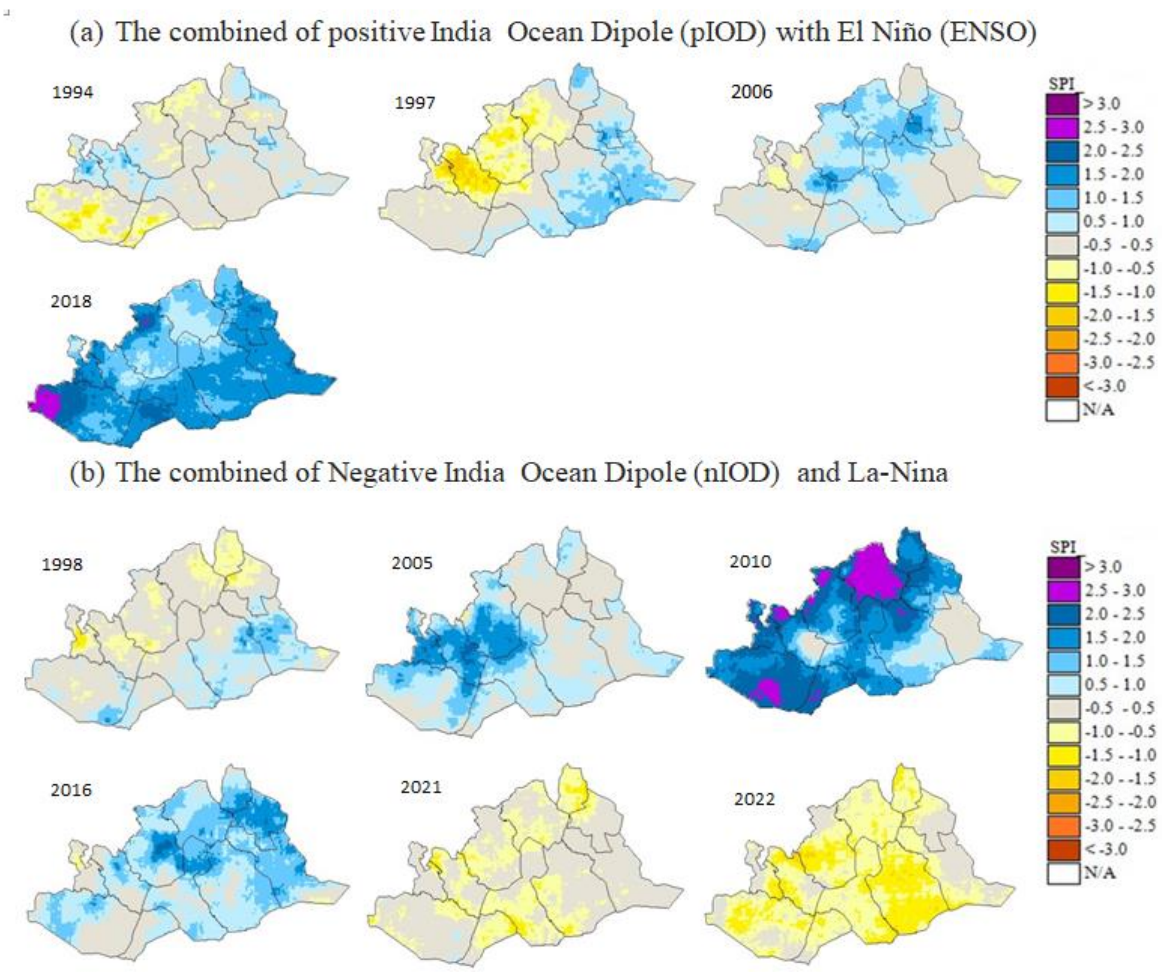


Figure 18 The spatial distribution map of the SPI (a) The combined positive India Ocean Dipole (IOD) with El Niño (b) The combined negative India Ocean Dipole (nIOD) and La-Nina.

The other combination is La-Nina and the negative IOD. In this combination, we have six combined years (Figure 18b). From the analysis, we found a different result from the El Niño and pIOD combination. Therefore, during 1998 except in some parts of Bale, Nogob, and Erer, there was moderate drought, but the rest Zones did not experience drought. In the combined years 2021 and 2022 a significant drought was observed.

In the combined consecutive years of 2021 and 2022, the significant drought started in 2021 and increased in its strength in 2022, and all zones experienced moderate to severe drought. The rest of the combined years 2005, 2010, and 2016 were not drought years; rather, they were wet years; especially 2010 was extremely wet year. Overall, this combination was not a drought year. Of the combined years, 66.7% were not significant drought years.

4.5 Identifying the dominance indices and their impacts

To identify the dominant climate indices that cause a drought events, we correlate the different phases of ENSO and IOD with the drought (SPI-3). Here we put the average correlation value of the indices, which represent the whole zone in the study area. Therefore, the average correlation between El Niño and drought was positively 0.52. Meanwhile, the average correlation value of La Niña was positive 0.27. On the other hand, Positive and negative IOD independently correlated with drought their average correlation values were 0.78 and 0.47, respectively. The combined phase of ENSO and IOD (El Niño/pIOD and La Niña/nIOD) correlation values were negatively 0.45 and 0.23 respectively. Therefore, El Niño and pIOD combined events were stronger than La Niña and nIOD combined events.

Based on these correlation values, El Niño, La Niña, and pIOD are the dominant phases of ENSO and IOD phases that relate to drought conditions in southeast Ethiopia, respectively. However, the two combined phases of ENSO and IOD (El Niño and positive IOD, La Niña and negative IOD) were related to the wetter conditions in southern Ethiopia.

The drought responds differently to the different ENSO and IOD events. During the combined El Niño/pIOD years, the study area experienced wet conditions; for instance, in 2018 and 2006, all the zones were wet, but in 1997, most of the lowlands were wet, the bale and Guji was dry. When La Niña events are combined with negative IOD, there is a tendency for wetter conditions. For instance, 2005, 2010, and 2016 were wetter combined La Niña and nIOD years, especially 2010, the wettest year, resulting more floods in the study area (Tesfay, 2018). On the other hand, 1997 and 2015 were the strong El Niño years in the country, but the drought during these years was weak, especially in 2015 when the lowland area of the study area got wet. In the study area, pure El Niño was associated with drought in some Zones and pure La Niña was also associated with drought. In section 4.4.1 discussed, 2011 was the drought year during La Niña years and impacted the study area (Iritani, 2018).

Based on section 4.4.1 discussed, all existed Pure El Niño years above 75% were drought year. Based on section 4.4.3 (Figure 18a), the simultaneous occurrence of positive IOD and El Nino (El Niño /pIOD) brought more rain, and the drought impact decreased. The combined phase of negative IOD and La Niña weakly correlated as compared to the combined El Niño/positive IOD.

4.6 Discussion

The results section of the thesis showed the characteristics of the drought, identifying the dominance indices and the combined impact of ENSO and IOD on the drought over southeast Ethiopia. To identify the characteristics of drought and assess the combined impact of ENSO and IOD on drought, we selected CHIRPS rainfall data. The validation of the CHIRPS monthly rainfall data in Ethiopia had a good correlation value (Dinku et al., 2018).

The characteristics of drought in southeast Ethiopia are described in terms of duration, severity, and frequency. Our results agree with Abara, Komariah, and Budiastuti's (2020), study on drought frequency, severity, and duration in Southeastern Ethiopia. They found the duration and intensity of the drought were closely similar to our result, especially over the lowlands. Comprehending the consequences of the drought is crucial to devising efficacious strategies for adaptation and mitigation against the increasing likelihood of drought in this vulnerable region.

The temporal and spatial analysis results were similar for the pure El Niño and pure La Niña years, while the IOD phase was neutral. The spatial distribution of drought in the neutral years was described in (Appendix Figure 4). Yin et al. (2022) confirm that the drought was high during La Niña years, which was Similar to our findings in the other studies (Funk, Andreas H. Fink, et al., 2023) Stronger heating and heat convergence, over warm tropical waters near Indonesia are observed during and after La Niña events. Due to this causal chain, dangerous consecutive droughts in East Africa are made possible by increased warm pool atmospheric heating and moisture convergence and also Wain wright et al. (2019) described the Pacific SST gradients, especially following recent La Niña, which appears related to the shorter East Africa rainy season. Belay et al. (2021) also confirm that during the Belg season, the rainfall decreases. Similarly, the study by (Viste et al., 2013), agrees with our result and discusses that the 2011 drought was high, especially in south Ethiopia.

The observed decrease in rainfall over the study area during the pure El Nino years can be identified by the increase in sea surface temperature over the equatorial Pacific Ocean. During strong, pure El Niño, Belg season faced drought. The drought would last for three consecutive seasons. This confirms that the El Niño years control the climate variability of the study area. During the pure positive IOD, all the zones experienced drought; this happened when ENSO was neutral. The 2019 positive IOD year is the best example of a pure positive IOD year. During this year, all zones of the study area experienced drought, similarly, Food et al. (2024), confirmed that 2019 was a dry year. Some studies have supported our result, for example, Behera et al. (2005), and Black et al.(2003), found a result that was consistent with the drought condition: a relationship between a decrease in rainfall and a positive IOD. Similarly, Williams and Funk's , (2011) findings also verified our findings.

The combined occurrence of pIOD and El Niño (pIOD and El Niño) increases the wet condition. From the combined years, 2018 was the wettest year for all zones in the study period; therefore, the combination of pIOD and El Niño did not bring drought; rather, it triggered wetter conditions in the study area. During 1994, except for the high land Zones, the rest Zones were wet. Our result was supported by Black, (2005), who revealed that the occurrence of strong El Niño causes the rebirth of the positive IOD event, and then they occurred simultaneously, bringing and subsequently high rainfall in coastal, equatorial East Africa. Cai, Sullivan, and Cowan (2011), also found similar results, indicating the combined occurrence of El Niño and positive IOD tends to increase the rainfall. Therefore, these findings highlighted the interaction between the climate features and those indices, providing a perfect evaluation of the flood risk due to the highly wet situation in the regions.

Many things make this study different even though similar studies have been carried out at both the continental and global levels; this research on the subject is unique within this particular field which studied in the local level. Second, for ENSO and IOD, we used a distinct grouping. This study is also different from others, not only by investigating the combined impact of ENSO and IOD on drought during the Belg season but also by identifying which indices are dominant in increasing the duration, frequency, and severity of drought in the study area.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This thesis aimed to evaluate the combined impact of El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) features on drought patterns and variability in southeast Ethiopia. To realize this different datasets were collected and analyzed. The results showed that drought dominated southeast Ethiopia during the pure El Niño and La Niña years.

The results conclude that the study area experienced a long duration of drought, extreme severity, and high frequency, especially over the lowland part of the study area. The severity of the drought ranged from moderate to extreme during the study periods, for instance, 2011 and 2019 were the most severe droughts in the study area. The different phases of ENSO and IOD have a strong effect on the drought events in the study area. During El Niño and La Niña, there was drought with different magnitudes, especially in the lowlands of the study area. Further, the results showed that the combined effect of positive IOD and El Niño (pIOD and El Niño) during the Belg season is associated with wetter conditions.

The other combination was the negative IOD and La Niña (nIOD/La Niña), which were associated partially with wetter conditions except in 2021 and 2022, which experienced drought. This is because the IOD phase during this combined phase of (nIOD/La Niña), especially during 2021 and 2022, was nearly neutral. Pure El Niño, La Niña, and positive IOD (pIOD) (in some zones) are the dominant phases of ENSO and IOD. They were highly related to drought conditions in southeast Ethiopia, respectively.

5.2 Recommendation

Monitoring the combined phases of the El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) is crucial since the teleconnections between the ENSO and IOD significantly contribute to the variability of the drought.

The result of this study contributes more to the preparation of the seasonal climate outlook in Belg seasons. The result contributes more to agriculture activities and livestock production; therefore, it is important to add knowledge of the combined effects of ENSO and IOD because agriculture and livestock production are highly susceptible to rainfall variability.

In the study area, there are not sufficient rainfall stations; however, EMI has very good blended (ground and satellite observation) high-resolution data, it is recommended that EMI establish new rainfall stations in the study area.

The study region has few rainfall monitoring stations, but the researchers were nonetheless able to make use of the excellent combined ground and satellite observation data from the EMI Because there isn't enough in-situ rainfall stations in the area, this EMI dataset makes up for it with high-resolution precipitation data. It is advised that the EMI set up more rainfall monitoring stations in the Southeast Ethiopia in the future. This would contribute to increasing the density of precipitation data collected on the ground, which would further improve the accuracy and granularity of the climate data that is now available for this area.

Further research is very important to understand the impact and relationship of ENSO and IOD on water management to combat drought conditions in terms of rainwater harvesting and to promote drought-resistant forage production. Meanwhile, the occurrence of the drought is also influenced by other factors, such as regional weather patterns and local climate variability. Therefore, further research and analysis may be needed to better understand the complex interactions between ENSO/IOD and drought in southeast Ethiopia, including the meteorological systems on a regional and global level.

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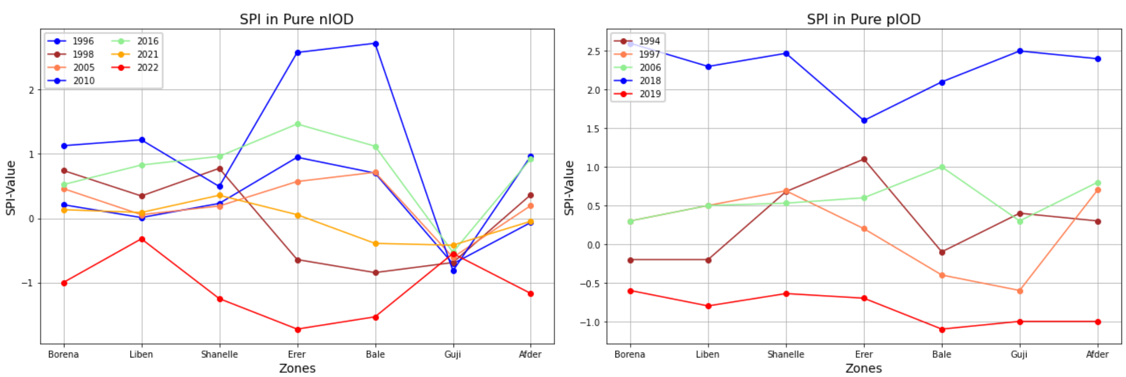
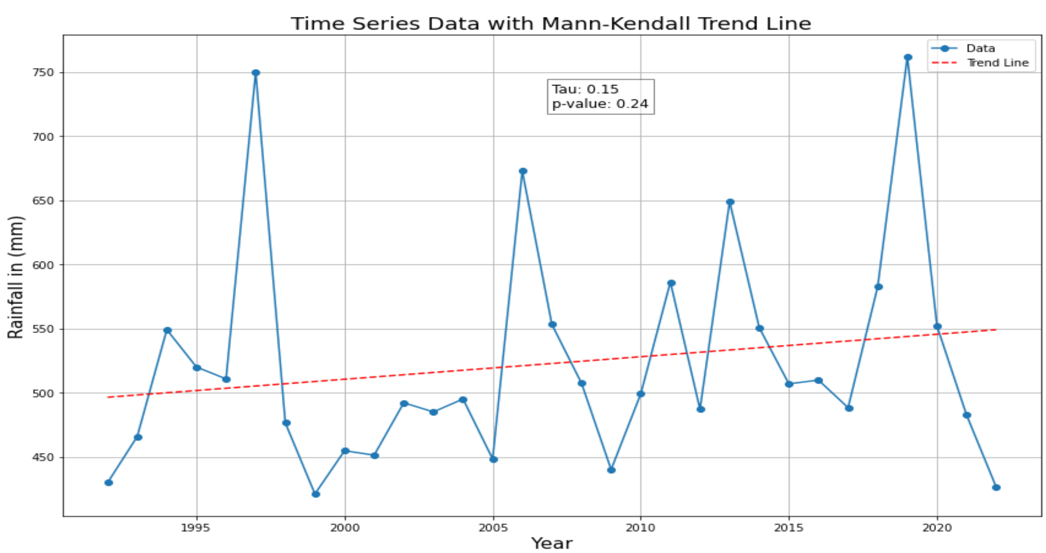
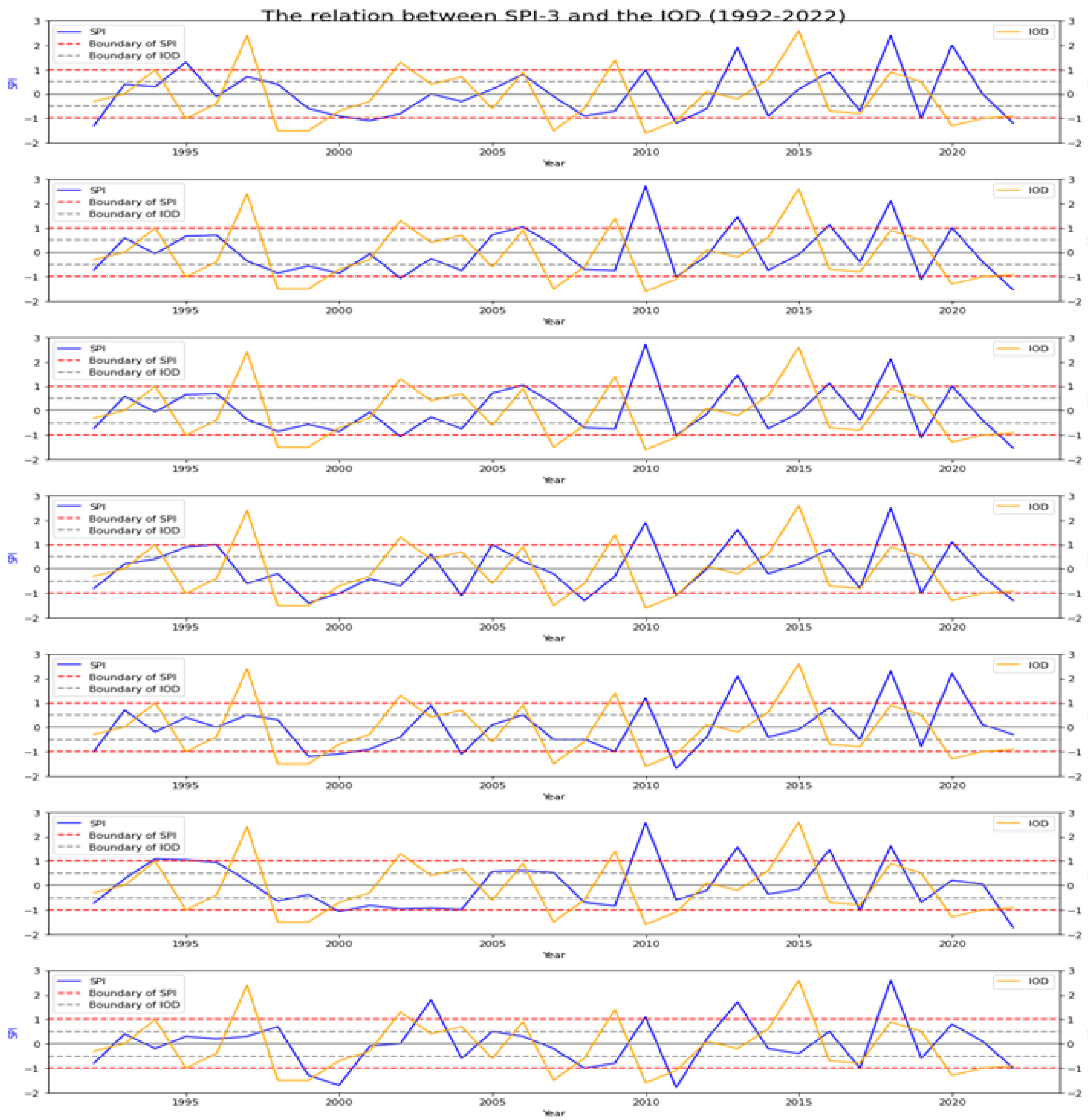
6. APPENDIX



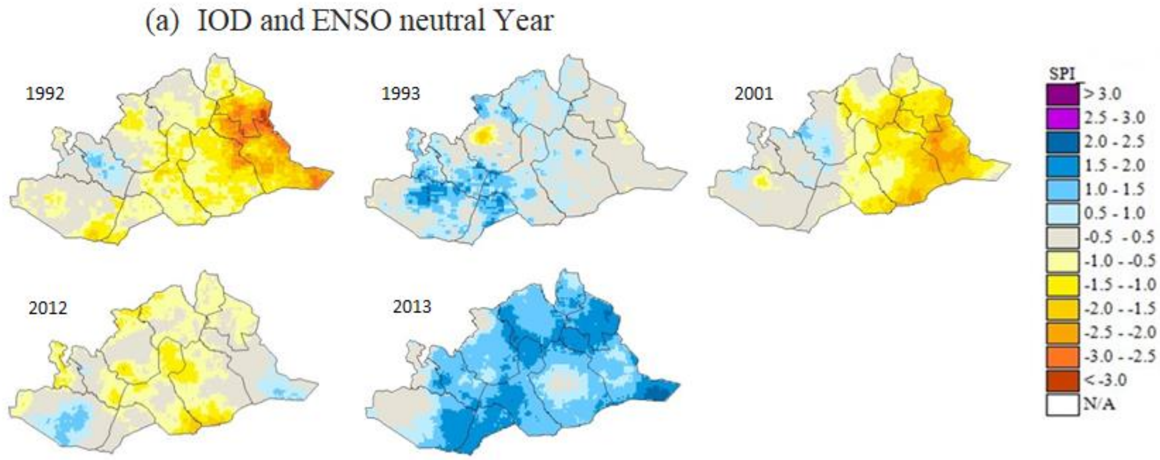
Appendix Figure 1 pure positive and negative IOD and SPI



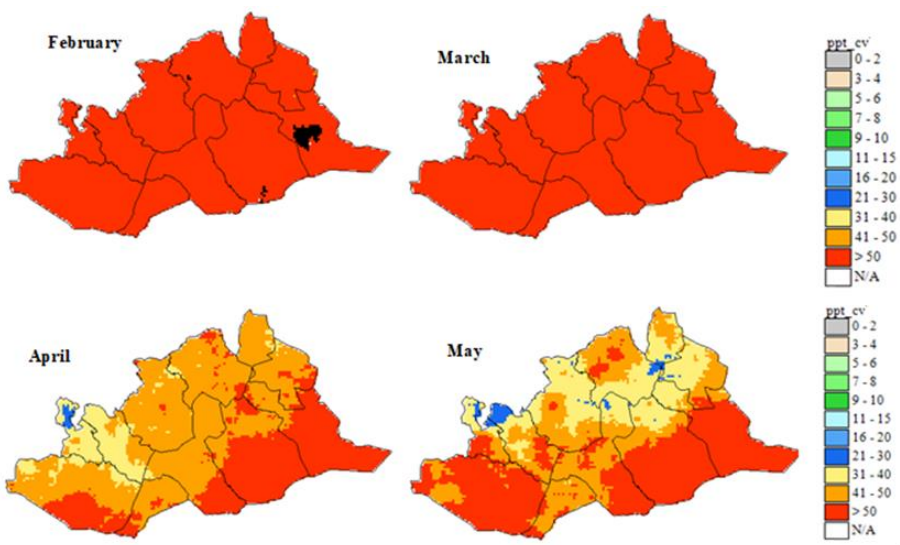
Appendix Figure 2 Mann-Kendall trends Line



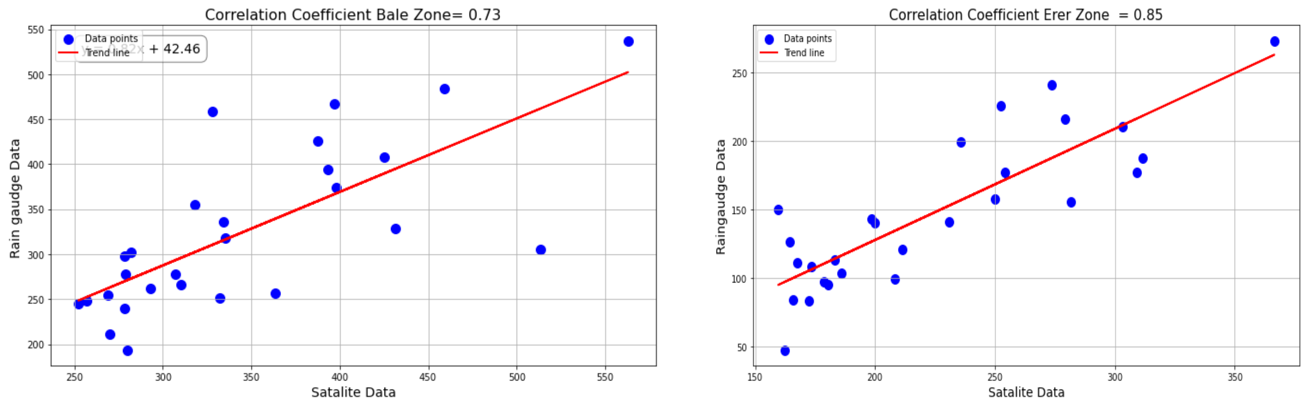
Apendix Figur 3 The Association between ENSO , IOD and SPI-3



Appendix Figure 4 IOD and ENSO neutral Year



Appendix Figure 5 Belg season Monthly coefficient of variation



Appendix Figure 6 Figure the data validation