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Research Article

# Satellite-Based Analysis of Meteorological Droughts in the Case of Wolaita Zone, South Ethiopia

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## Abstract

Drought is a climate danger that hurts rural lives, water supply and farming especially where farms rely on rain. This study looks at drought in Wolaita Zone, Southern Ethiopia from 1991 to 2020. It uses the TAMSAT/TARCAT satellite rainfall product and daily rain data from five weather stations of the Ethiopian Meteorology Institute. The study measures rain shortfalls with the Standardized Precipitation Index (SPI) for the Belg and Kiremt seasons and on a scale (SPI-3). Results from the stations show that meteorological drought is very specific to season and place. A few stations had extreme or severe meteorological drought in some years while moderate meteorological drought happened most often. The Kiremt record shows an event at Billate in 2003 (SPI = –2.0). The station summary shows the Belg-season meteorological drought at Gesuba in 2015 (SPI = –2.0). In meteorological drought conditions varied across the two wet seasons and the five stations. The station data can help prepare for and watch drought in Wolaita Zone. The final methods and findings should help people use the satellite product in SPI calculation and check it against station observations.

## Keywords

Meteorological Drought, Standardized Precipitation Index, SPI-3, Rainfall Variability, Belg, Kiremt, Wolaita Zone

## 1. Introduction

### 1.1. Background

Drought is a climate danger that affects people's well-being the economy and the environment. The frequency, severity and duration of drought vary from one region to another and from one year to the next [1-3]. Meteorological drought happens under weather and social conditions and no single definition can describe all meteorological drought situations [4]. Meteorological drought is usually seen as a period when rainfall is less than normal in a particular area. It can be hard to say when meteorological drought starts or ends and its effects can last after the rain pattern returns to normal. The effects of drought depend on the intensity, duration, frequency and spatial extent of the precipitation deficit [5, 6]. High temperatures, winds and low relative humidity can make the lack of rain even worse.

Ethiopia is recurrently affected by drought, which can reduce crop and livestock production and place pressure on household food security. A 2015 humanitarian figure cited in the original manuscript reports that more than 10.2 million people required food assistance [7]; the exact OCHA report and the definition of this figure must be confirmed before publication. Wolaita Zone is also exposed to rainfall variability and recurring dry conditions. The extent and timing of drought

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impacts, however, vary within the Zone and require assessment using locally relevant rainfall records.

This study examines the occurrence and characteristics of meteorological drought in Wolaita Zone using the Standardized Precipitation Index (SPI). It focuses on the period 1991–2020 and considers the possible relationship between identified drought years and El Ni ño–Southern Oscillation (ENSO) conditions. The analysis is intended to provide information that can support drought monitoring and preparedness in the Zone.

## 2. Materials and Methods

### 2.1. Description of the Study Area

Wolaita Zone is located approximately between 6°45′00″N and 7°00′00″N latitude and 37°35′00″E and 37°53′00″E longitude. The town lies at the foot of Mount Damota and serves as the administrative center of Wolaita Zone and Sodo Zuria Woreda. The manuscript reports a total Zone area of 4,537.5 km ²and an elevation range of approximately 900 – 2,600 m above sea level. It also describes Wolaita as comprising twelve districts: Boloso Sore, Damot Gale, Damot Weyde, Humbo, Kindo Koysha, Offa, Boloso Bombe, Duguna Fango, Damot Pulasa, Damot Sore and Sodo Zuria. These administrative and geographic details should be checked against an authoritative Zone or regional profile before submission. The lowland areas are generally described as hotter and drier, while the highlands are relatively cooler and more humid [8].

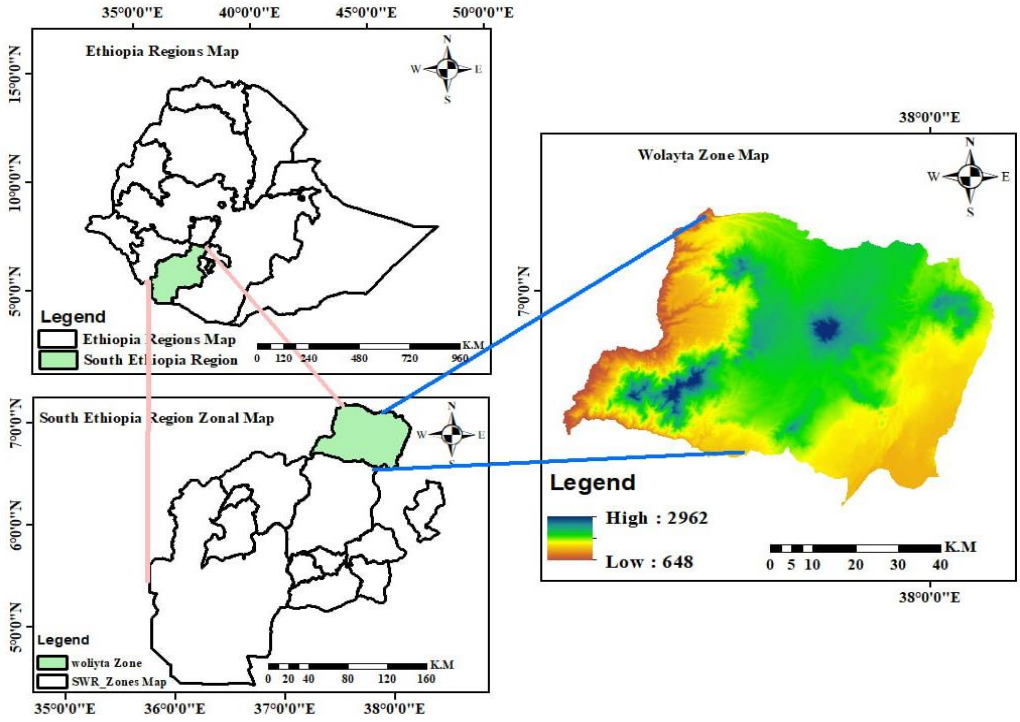



***Figure 1.*** *Location of the study area.*

#### 2.1.1. Climate

Local temperature, rainfall and farming conditions are influenced by altitude. The manuscript identifies two main rainy seasons, the Belg season which is described here as lasting from about mid-February to mid-May, and the Kiremt season which is described here as the summer months. Kiremt is the main growing season, but Belg rainfall is also important for household food production and livelihoods. The manuscript reports mean annual rainfall ranging from 803 mm at Abela Faracho in the lowlands to 1,189 mm at Sodo in the highlands. These seasonal definitions and rainfall totals should be supported by station climatology or an official meteorological source [8]. The Belg and Kiremt month ranges must also be made consistent with the months used in the SPI calculations.

#### 2.1.2. Soil Types and Agricultural Activities

The manuscript describes the major soil groups of Wolaita as Nitisols, Haplic Yermosols, Eutric Cambisols, Orthic Andisols and Calcaric Fluvisols. It also identifies declining soil fertility, due to continuous cultivation, removal of organic matter and inadequate soil management practices as a constraint on agricultural production. Crop farming is described

as the main livelihood activity, alongside livestock rearing for food, income, draught power and household security. Cereal crops, root crops and perennial crops are reported in the highlands, while the hotter and drier lowlands support a narrower range of crops. The soil classifications and agricultural descriptions are subject to verification by a soil survey or other appropriate agricultural publication. Wolaita is said to be a food deficit and famine prone area [9]. This source should be checked for the context of the particular claim.

### 2.1.3. Population Density

The original manuscript reported that the population density of Wolaita was an average of 380 persons per km ²in 2006. The values of population density ranged from 167 persons per km ² in Humbo to 746 persons per km ² in Damot Gale. The figures are compared with the national average of 68 people per square kilometer for the same year. These historical statistics and statements about population growth, reduction of farm-size and landlessness need to be checked with a verifiable source of statistics or population census [10]. These are not to be reported as current population estimates.

## 2.2. Data Sources and Types

Daily precipitation records for five meteorological stations covering the study period 1991–2020 were obtained from the Ethiopian Meteorology Institute (EMI). The stations were selected to represent different agro-climatic settings within Wolaita Zone. Seasonal rainfall totals were derived from the daily station records. The length and completeness of the available record varied among stations and should be reported for each station. The manuscript also identifies TARCAT version 3.1, produced by the Tropical Applications of Meteorology using Satellite and Ground-Based Observations (TAMSAT) project, as a satellite rainfall product. TARCAT was developed using archived Meteosat thermal-infrared imagery calibrated with rain-gauge observations [11]. The product was selected because it provides a long-term rainfall record with broad spatial coverage. The exact TARCAT version, temporal aggregation, spatial resolution, download source and method of use in the present analysis should be stated clearly. The current methods section does not yet explain whether SPI was calculated from station rainfall, TARCAT rainfall, or both.

***Table 1.*** *Meteorological stations used in the study.*

| No. | Station name | Longitude (℉) | Latitude (℻) | Altitude (m) |
|---|---|---|---|---|
| 1 | Billate | 38.08 | 6.8 | 1361 |
| 2 | Bodity | 37.85 | 6.95 | 2043 |
| 3 | Gesuba | 37.55 | 6.72 | 1552 |
| 4 | H/tebela | 37.76 | 6.71 | 1618 |
| 5 | W/sodo | 37.72 | 6.83 | 1854 |

## 2.3. SPI Methodology

The Standardized Precipitation Index (SPI) was selected to characterize precipitation deficits over a defined accumulation period. The SPI expresses precipitation anomalies as standardized values and can be calculated for different time scales [12]. The method described in the original analysis fits a probability distribution to precipitation totals and transforms the cumulative probability into a standard normal variate. The manuscript uses a gamma distribution for this purpose. The equations and parameter definitions below should be checked against the actual calculation procedure and the software or code used in the study. The WMO-recommended SPI guidance should also be cited if it was followed. The original manuscript cites [13] for SPI use; retain that citation only where it directly supports the relevant methodological statement.

$$f(x) = \frac{1}{\beta^{\gamma}\Gamma_{(\gamma o)}} x^{\gamma-1} \; e^{\frac{-x}{\beta}}, x > 0$$

Here, β and γ represent the parameters of the fitted gamma distribution. The cumulative probability is evaluated for the precipitation total in the selected accumulation period.

Where zero precipitation occurs, its probability is accounted for separately. In the expression shown, m represents the number of zero-precipitation observations and n represents the total number of observations. Confirm that this treatment matches the calculation code used in the study.

$$\mathrm{f}(x < xo) = \int_0^{\infty} f(x)dx$$

The cumulative probability is then transformed to the standard normal distribution to obtain the SPI value.

$$f(x < xo) = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} e^{-x/2} d_x$$

The transformation is calculated using the approximation shown below. The equation and notation should be checked against the original SPI algorithm used in the analysis.

$$SPI = s \frac{t-(c2t+c1)+co}{[(d3t+d2)t+d1]t+1}$$

Where: $t = \sqrt{\ln \frac{1}{\sqrt{2}}}$

$c_0 = 2.515517$, $c_1 = 0.802853$, and $c_2 = 0.010328$.

$d_1 = 1.432788$, $d_2 = 0.189269$, and $d_3 = 0.001308$.

S is the sign coefficient used in the transformation: S = 1 when F > 0.5 and S = −1 when F ≤ 0.5. Confirm that the definition of F and the sign convention match the equations retained in the manuscript.

***Table 2.*** *SPI-3 categories used to describe wet and dry conditions.*

| drought Index values of (SPI_3) | Drought severity classes description |
|---|---|
| +2.0 and above | Extremely wet |
| +1.5 to+1.99 | Very wet |
| +1.0 to+1.49 | Moderately wet |
| +0.5 to+0.99 | Mild wet |
| −0.49 to+0.49 | Normal condition |
| −0.5 to −0.99 | Mild drought |
| −1.0 to −1.49 | Moderate drought |
| −1.5 to −1.99 | Severe drought |
| −2.0 and below | Extreme drought |

Source: The original manuscript attributes this classification to [13]. Because that publication concerns the Standardized Precipitation Evapotranspiration Index (SPEI), the source of the SPI thresholds must be verified. Do not retain this attribution unless the original source explicitly supports the table.

# 3. Results and Discussion

## 3.1. Temporal and Station-Level Analysis of Drought in Wolaita Zone

Drought variability in Wolaita Zone was examined using the SPI-3 series for five meteorological stations. The analysis considered the temporal behavior of the index and compared the occurrence of dry conditions between the Belg and Kiremt seasons. The original results identify years with the lowest SPI values at each station as drought years and classify drought severity using the thresholds presented in Table 2. For Belg, the manuscript reports the use of March–May precipitation totals. The period of analysis is defined in this revised manuscript as 1991–2020. The source text and some figure annotations include years outside this interval, including 1990 and 2021; these values are retained in the original figures or tables pending confirmation and must be excluded or recalculated before the manuscript can be considered internally consistent. The methods should specify whether the SPI-3 series represents rolling three-month totals or fixed seasonal totals.

## 3.2. Belg-season Drought Characteristics

The Belg season is important for agricultural activities in Wolaita Zone. At Billate, the original time series identifies 2010 as the strongest positive anomaly, at approximately +2.2. A positive anomaly of about +1.3 is also reported for 2020. The manuscript describes 2005–2006 as a relatively wet period, with anomalies above +1.0, and identifies 1999 as the driest year, with an anomaly near −1.8. Dry anomalies are also reported for 2000–2002 and for 2008 and 2019. These descriptions are based on the values reported in the original figure and should be checked against the plotted series and the fixed 1991–2020 analysis period.

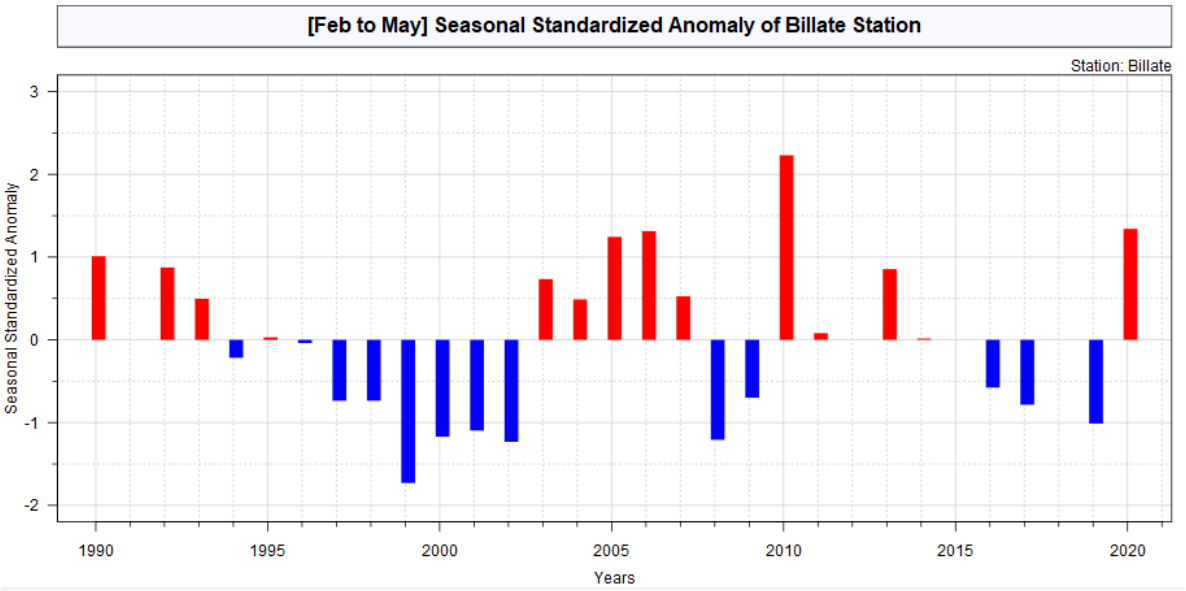



***Figure 2.*** *Belg Season time series of SPI Standardized Anomaly of Billate Station.*

At Bodity, the original Belg-season series shows a positive anomaly of approximately +3.0 in 1990 and about +1.5 in 1998. A positive anomaly of around +1.0 is reported for 2010. The strongest negative anomaly is reported in 2008 (approximately −1.6), followed by a negative anomaly of about −1.4 in 2015 and approximately −1.3 in 1999. The 1990 value lies outside the stated study period and should be removed from the analysis or explained if it is an erroneous figure label. The interpretation linking 1998 to El Niño should not be retained without a season- and location-specific supporting reference.

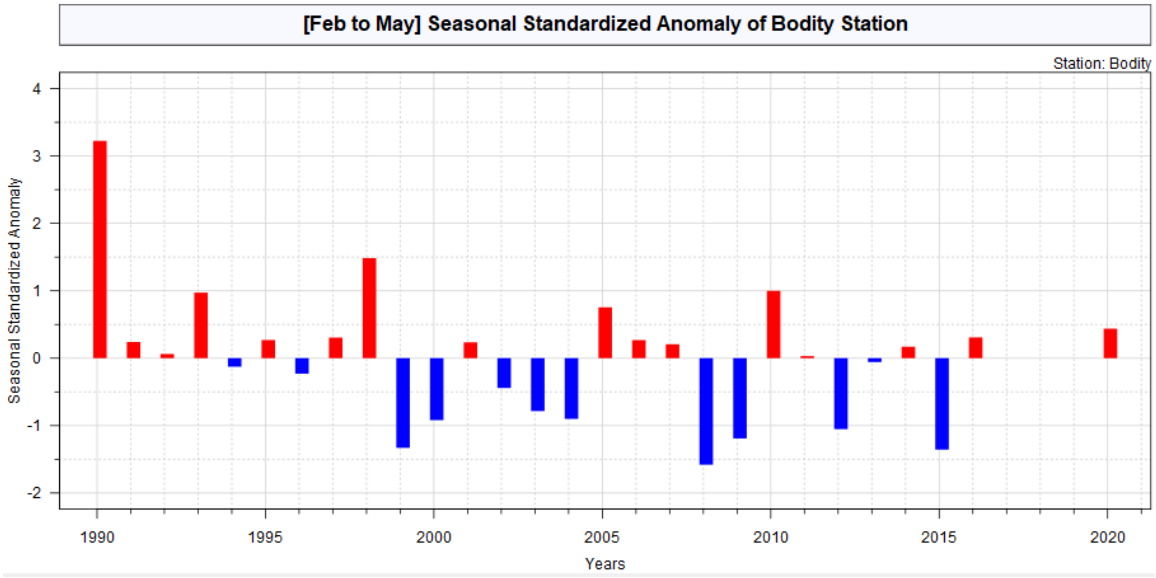



***Figure 3.*** *Belg Season time series of SPI Standardized Anomaly of Bodity Station.*

At Gesuba, the original Belg-season series identifies 2010 as the strongest positive anomaly, at approximately +1.8. Other positive anomalies are reported for 1996 (about +1.4) and 2014 (about +1.3). The most pronounced negative anomaly occurs in 2015 (approximately −2.0), which falls in the extreme drought category under the thresholds shown in Table 2. Negative anomalies are also reported for 2002 (approximately −1.8) and 2012 (approximately −1.5). These values should be checked against Figure 4 and the station data before final publication.

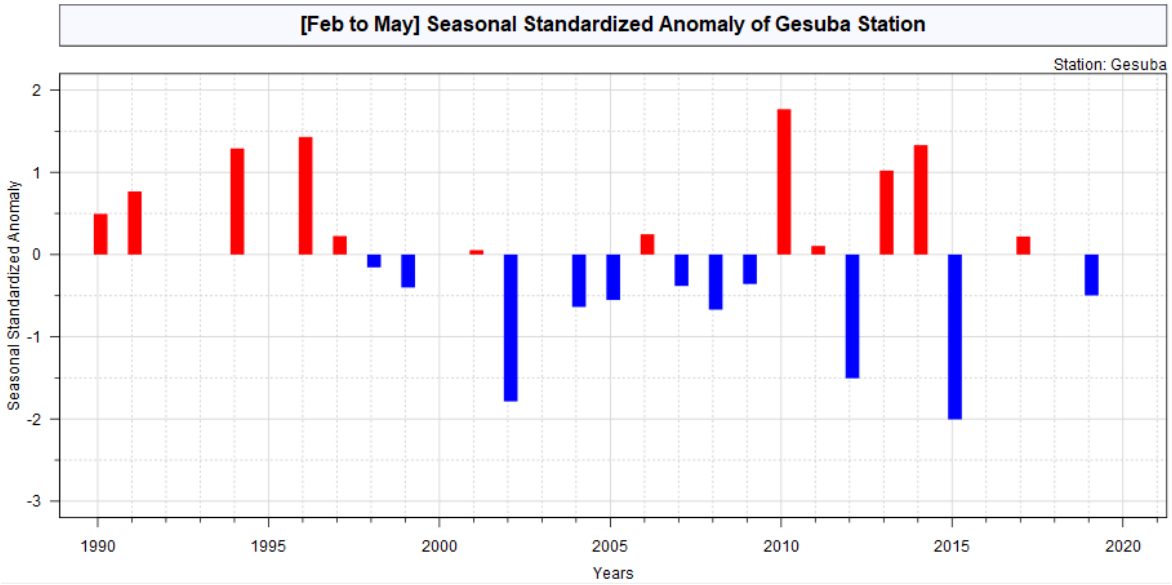



***Figure 4.*** *The Belg Season time series of SPI Standardized Anomaly of Gesuba Station.*

At Gesuba, the original Belg-season series is described as having a positive anomaly of approximately +2.5 in 2010. Positive anomalies of around +1.5 are reported for 1996 and 2018, and approximately +1.2 for 2005. Negative anomalies are reported for 1999 (approximately −1.6), 2019 (approximately −1.5), and 2004 and 2012 (at or below −1.0). The text and figure caption currently identify this station inconsistently in the manuscript; confirm whether the figure refers to Gesuba or another station before submission.

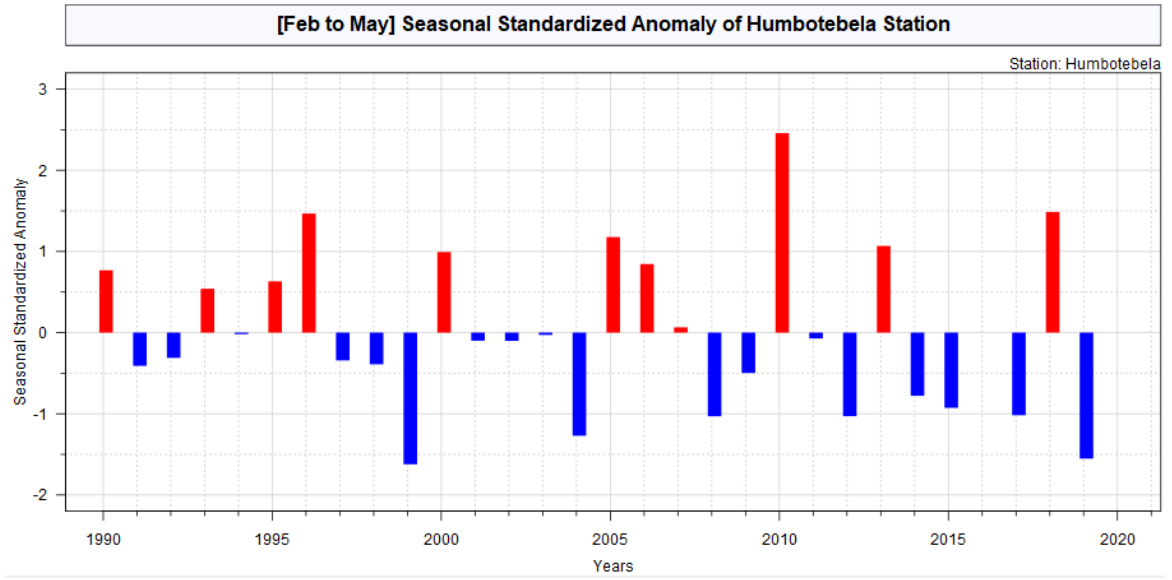



***Figure 5.*** *The Belg Season time series of SPI Standardized Anomaly of Humbotebela Station.*

For Humbotebela, the original Belg-season series reports positive anomalies of approximately +2.1 in 2005, +2.0 in 1993 and +1.7 in 2010. Negative anomalies are reported for 2008 (approximately −1.6), 1999 (approximately −1.4) and 2003 (approximately −1.3). Confirm the station name and figure number, and check these values against the plotted time series.

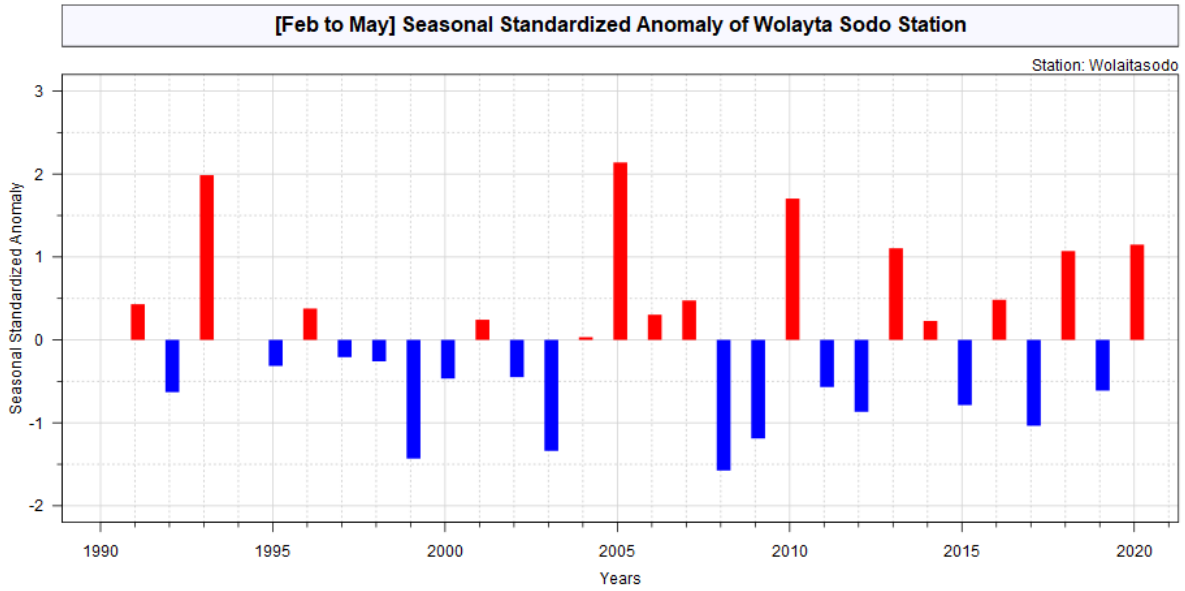



***Figure 6.*** *Belg Season time series of SPI Standardized Anomaly of Wolaita Sodo Station.*

The Belg-season station comparison identifies the lowest reported SPI value at Gesuba in 2015 (SPI = −2.0), which falls in the extreme drought category under the classification in Table 2. Table 3 summarizes the years and SPI values identified as extreme, severe and moderate drought at each station. The original manuscript indicates El Niño and La Niña years using different colours. The ENSO-year labels and their colour coding should be supported by a clearly identified ENSO chronology source.

***Table 3.*** *list of station and year of each station experiences extreme, severe and moderate drought for Belg season.*

| St.no. | Station Name | Year of extreme drought | SPI | Year of severe drought | SPI | Year of moderate drought | SPI |
|---|---|---|---|---|---|---|---|
| 1 | Billate | No | - | 1999 | -1.7 | 2000, 2001, 2002 and 2008 | -1.2 and -1.1, -1.25 and -1.25 |
| 2 | Bodity | No | - | 2008 | -1.6 | 1999, 2009 and 2015 | -1.4, -1.2 and -1.4 |
| 3 | Gesuba | 2015 | -2.0 | 2012 | -1.5 | 2003 | -1.3 |
| 4 | Humbotebela | No | - | 1999 | -1.75 | 2004 | -1.35 |
| 5 | W/sodo | No | - | 2008 | -1.55 | 1999, 2003 and 2009 | -1.4, -1.35 and -1.25 |

The original discussion associates some Belg-season drought years with ENSO variability, drawing on Bekele (1997) and Glantz (1996). These relationships should be interpreted cautiously because ENSO impacts can differ by season and location. According to the station results reported in Table 3, Gesuba experienced an extreme drought in 2015 (SPI = −2.0). Severe droughts are reported at Billate in 1999 (−1.7), Bodity in 2008 (−1.6), Gesuba in 2012 (−1.5), Humbotebela in 1999 (−1.75), and Wolaita Sodo in 2008 (−1.55). Moderate droughts are reported at Billate in 2000, 2001, 2002 and 2008; Bodity in 1999, 2009 and 2015; Gesuba in 2003; Humbotebela in 2004; and Wolaita Sodo in 1999, 2003 and 2009. In general, the table indicates that moderate drought was reported more frequently than severe or extreme drought. However, some year and SPI-value combinations in the prose do not match Table 3 exactly; the table and station series must be reconciled. The original statement that different stations respond differently to ENSO should be treated as a hypothesis unless supported by a formal statistical analysis.

### 3.3. Kiremt-season Drought Characteristics

The Kiremt season is an important rainy season for agricultural production in Wolaita Zone. The original manuscript states that it contributes approximately 30% of annual production in the Zone. This percentage requires a supporting agricultural source. The seasonal SPI or rainfall-anomaly series was examined to describe year-to-year variability during Kiremt.

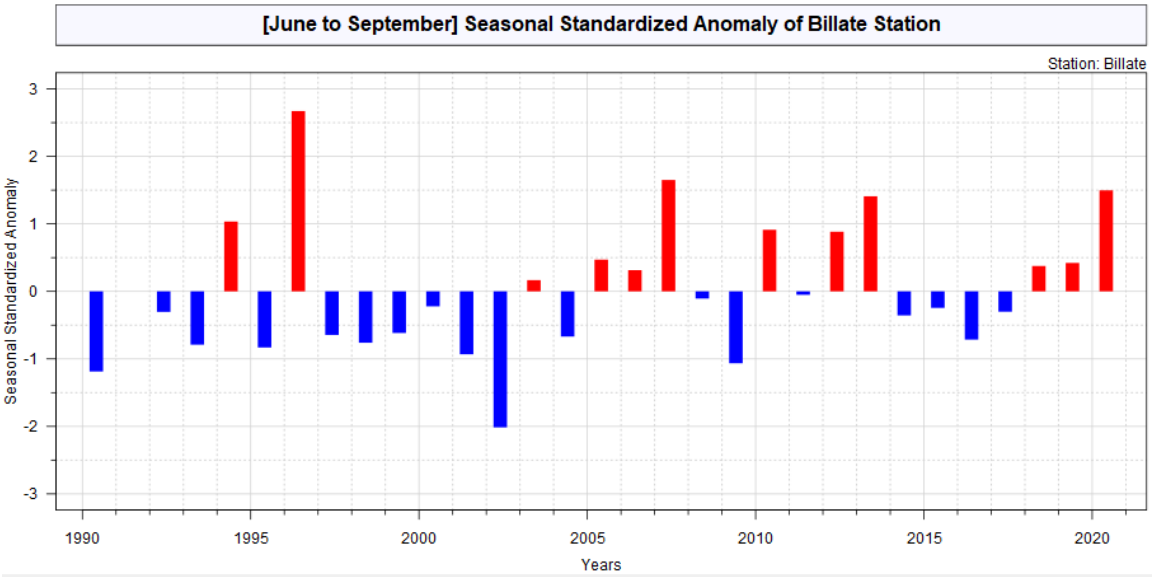



***Figure 7.*** *Kiremt Season time series of SPI Standardized Anomaly of Billate Station.*

At Billate, the Kiremt series shows substantial interannual variability, with alternating positive and negative rainfall anomalies. Negative anomalies are reported during parts of the early 1990s, late 1990s, 2001–2003, 2008–2009 and 2014–2018. The lowest value is reported in 2002 (approximately −2.0). Positive anomalies are reported in 1994, 1996, 2005–2007, 2010, 2012–2013 and 2019–2021, with the largest value in 1996 (approximately +2.7). The 2021 value lies outside the defined 1991–2020 study period and must be excluded or recalculated. Within the stated period, the series is described as fluctuating around the long-term mean, without a clear persistent upward or downward trend. The repeated negative anomalies indicate periods of reduced seasonal rainfall that may have affected agricultural production and water availability in the Billate area.

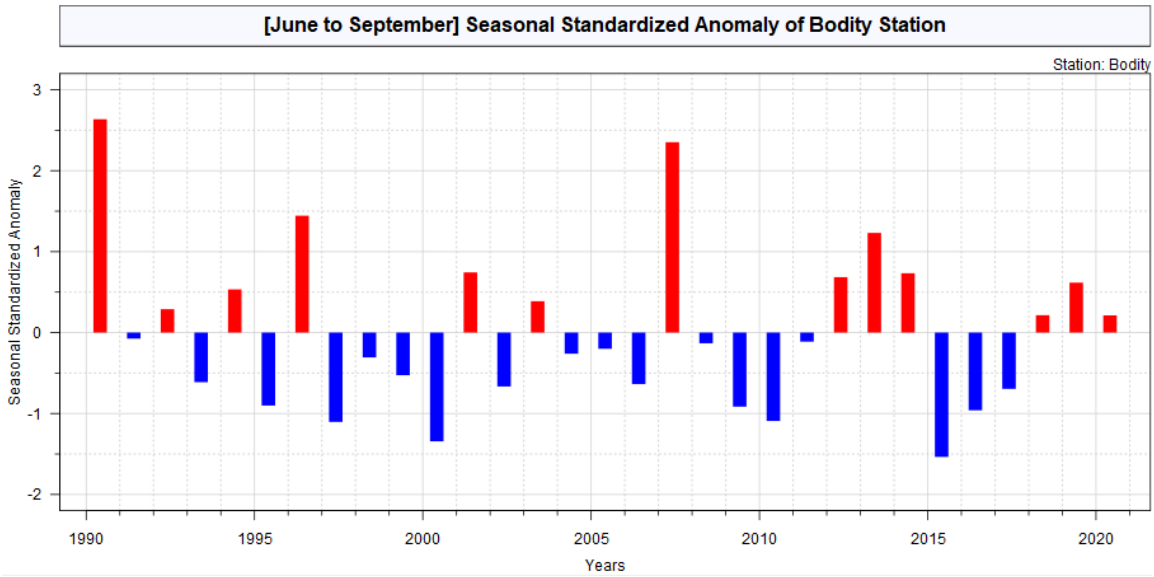



***Figure 8.*** *Kiremt Season time series of SPI Standardized Anomaly of Bodity Station.*

At Bodity, the June–September Kiremt rainfall-anomaly series for the period shown in the original figure exhibits substantial year-to-year variability. Positive anomalies exceeding +2.0 are reported for 1991 and 2008. Negative anomalies are reported for 2000 and 2015. Additional positive anomalies are listed for 1994, 1996, 2001, 2003, 2013–2015 and 2019–2021, while negative anomalies are reported for 1997–2000 and 2009–2010. The 2021 observation is outside the specified study period and should be removed or recalculated. The remaining pattern indicates alternating wet and dry Kiremt seasons rather than a clearly established long-term trend.

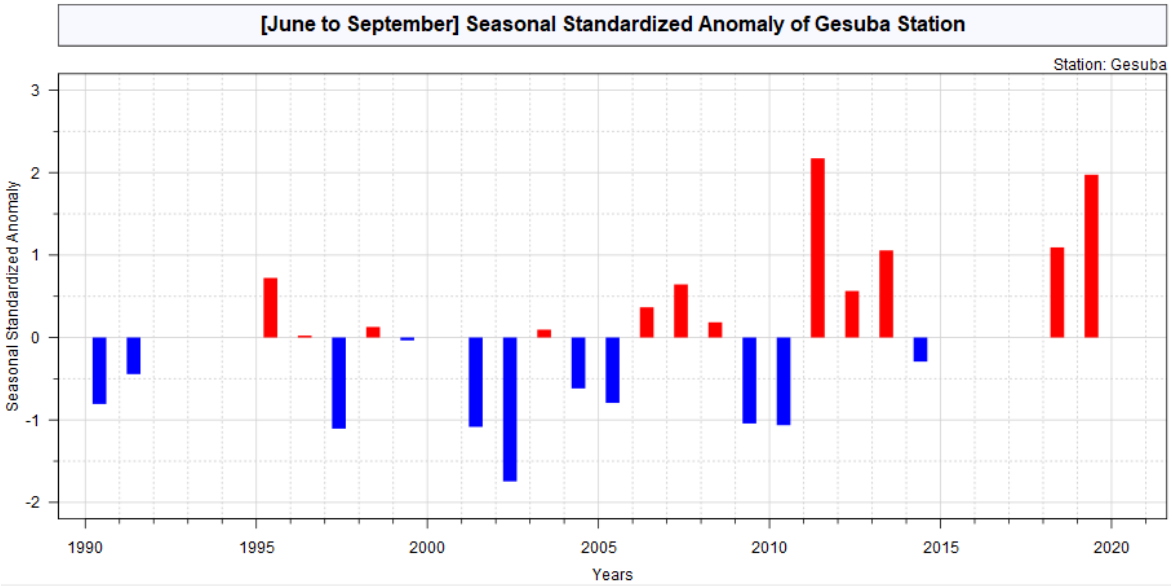



***Figure 9.*** *Kiremt Season time series of SPI Standardized Anomaly of Gesuba Station.*

At Humbotebela, the June–September rainfall-anomaly series shows marked interannual variability. The largest positive anomaly is reported in 1996 (approximately +2.9), with other positive anomalies in 2007, 2012, 2014 and 2019. The strongest negative anomalies are reported in 1993 and 2009 (approximately −1.6), while relatively dry conditions are also identified in 1991, 2004, 2016 and 2020. The series therefore indicates alternating wetter- and drier-than-normal Kiremt seasons. These values should be checked against the figure and the station record.

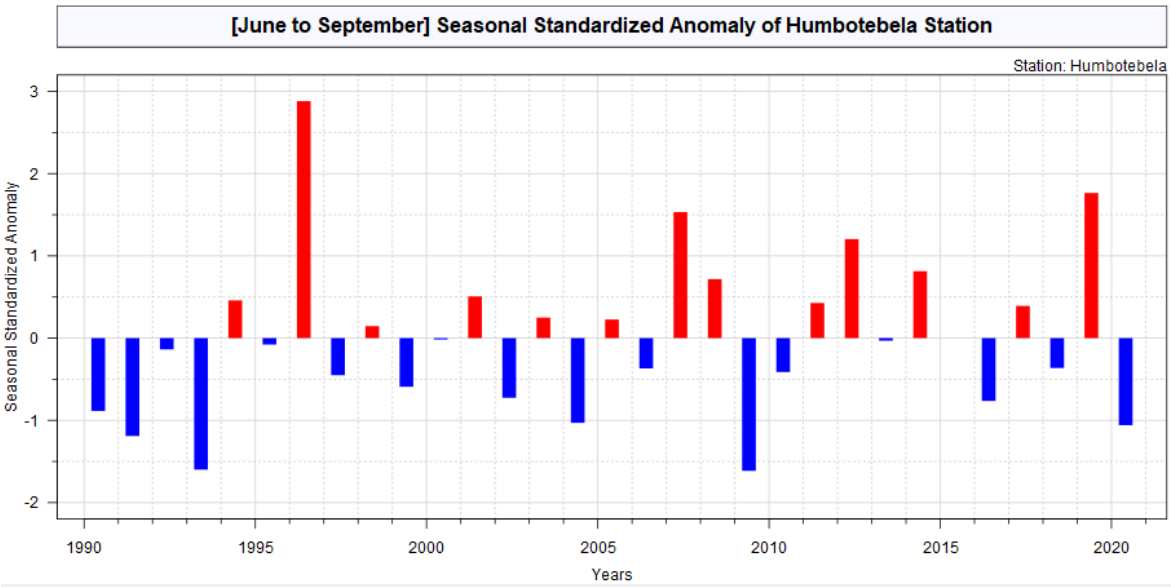



***Figure 10.*** *Kiremt Season time series of SPI Standardized Anomaly of Humbotebela Station.*

At Wolaita Sodo, the June–September series shows alternating wet and dry Kiremt seasons. The most pronounced negative anomaly is reported in 2009 (approximately −1.5). Positive anomalies are reported in 1996, 2007, 2008, 2012–2015 and 2019–2020, with the largest value in 2007 (approximately +2.1). The text also describes negative anomalies in 2016–2017 followed by positive anomalies in 2018–2020. Overall, the series indicates considerable interannual variability. The year ranges and individual values should be checked against the station plot before publication.

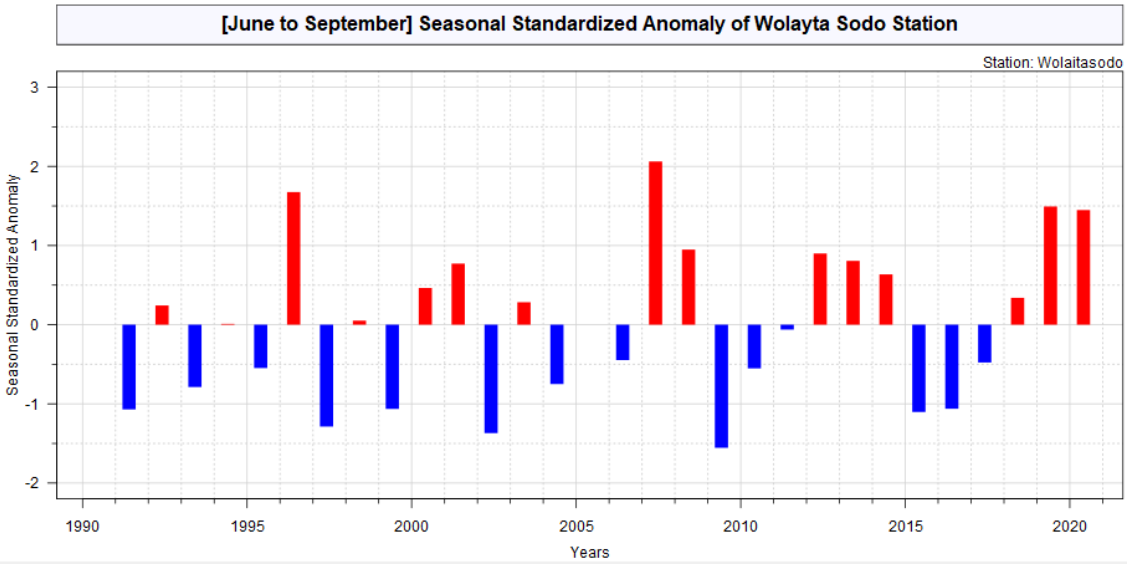



***Figure 11.*** *Kiremt Season time series of SPI Standardized Anomaly of Wolaita Sodo Station.*

The original manuscript discusses a possible relationship between ENSO and Kiremt rainfall in Wolaita Zone, citing Cassidy and Pearce (2013). The bibliographic details supplied for that citation appear inconsistent with the claimed ENSO–rainfall discussion and must be verified. The manuscript also associates above-normal Kiremt rainfall in 1996 and 2007 with La Niña conditions. These interpretations should be retained only if the ENSO chronology and local rainfall evidence support them. Table 4 summarizes the drought categories reported for the Kiremt season. The table's color coding for El Niño and La Niña years should be accompanied by a complete source for the ENSO classification.

***Table 4.*** *list of station and year of each station experiences extreme, severe and moderate drought for Kiremt season.*

| St. no. | Station Name | Year of extreme drought | SPI | Year of severe drought | SPI | Year of moderate drought | SPI |
|---|---|---|---|---|---|---|---|
| 1 | Billate | 2003 | -2.0 | - | - | 1990 and 2009 | -1.25 and -1.2 |
| 2 | Bodity | - | - | 2015 | -1.5 | 1997, 2000 and 2010 | -1.2, -1.2 and -1.4 |
| 3 | Gesuba | - | - | 2002 | -1.6 | 1997, 2001 and 2010 | -1.2, -1.1 and -1.1 |
| 4 | Humbotebela | - | - | 1993 and 2009 | -1.6 and -1.65 | 1991 and 2020 | -1.2 and -1.1 |
| 5 | W/sodo | - | - | 2009 | -1.55 | 1991, 1997, 2002 and 2015 | -1.1, -1.3, -1.35 and -1.1 |

According to Table 4, Billate is the only station listed as experiencing an extreme Kiremt drought, in 2003 (SPI = −2.0). Severe droughts are reported at Bodity in 2015 (−1.5), Gesuba in 2002 (−1.6), Humbotebela in 1993 (−1.6) and 2009 (−1.65), and Wolaita Sodo in 2009 (−1.55). Moderate droughts are reported at Billate in 1990 and 2009, at Bodity in 1997, 2000 and 2010, at Gesuba in 1997, 2001 and 2010, at Humbotebela in 1991 and 2020, and at Wolaita Sodo in 1991, 1997, 2002

and 2015. The 1990 entry is outside the stated study period and must be checked. The text should also be reconciled with the SPI category thresholds: a value of −1.5 is at the boundary between moderate and severe drought under the table's stated ranges SPI≤-2.

## 4. Conclusions and Recommendations

### 4.1. Conclusion

The study analyzed the temporal characteristics and station level variation of meteorological drought using SPI-3 computed for five meteorological stations in Wolaita Zone. The results indicate that during the study period the conditions were moderate, severe and in some cases extreme droughts. Moderate drought was more frequently reported than severe and extreme drought. The station summaries identify severe and moderate drought conditions at Humbotebela and Wolaita Sodo, while Gesuba recorded the most severe Belg-season event in 2015 (SPI = −2.0). The Kiremt results identify an extreme event at Billate in 2003. The findings demonstrate that drought occurrence varied among stations and between the Belg and Kiremt seasons. Because the analysis is based on five stations, the results should be interpreted as station-based evidence and should not be generalized to a fully gridded spatial pattern without additional spatial analysis.

### 4.2. Recommendations

Findings of this study indicate that there is a need to strengthen drought monitoring and preparedness in Wolaita Zone. Regular tracking of rainfall and SPI would be useful in detecting emerging rainfall deficit and providing useful information for water resource management and agricultural planning. The analysis also points to the value of keeping long, quality-controlled station records and extending the observational network where possible. The study was limited by the availability of long-term rainfall records from five stations. A denser and more complete network would provide for a better assessment of spatial variability. Future work could explore the relationship between meteorological drought and hydrological or agricultural drought, evaluate remote-sensing indicators such as the Normalized Difference Vegetation Index (NDVI), and assess methods for mapping drought conditions across the Zone. Any future interpolation or gridded analysis should be based on an explicit method and validation.

## Abbreviations

| | |
|---|---|
| EMI | Ethiopia Meteorology Institute |
| ENSO | El Niño–Southern Oscillation |
| OCHA | Office for the Coordination of Humanitarian Affairs |
| SPEI | Standardized Precipitation-Evapotranspiration Index |
| SPI | Standardized Precipitation Index |
| TAMSAT | Tropical Applications of Meteorology using Satellite |
| TARCAT | African Rainfall Climatology and Time-series |
| WMO | World Meteorological Organization |

## Author Contributions

**Adugna Arba Altaye:** Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

## Conflicts of Interest

The author declares no conflicts of interest.

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