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Evaluation of meteorological drought events and trends over the Republic of Djibouti from 1961 to 2021 (Horn of Africa)

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Abstract: Drought is a meteorological and hydrological phenomenon affecting environment, agriculture, and socio-economic conditions, especially in the arid and semi-arid regions. A better understanding of drought characteristics at short and long timescales is therefore crucial for drought mitigation and long-term strategies. This study evaluates for the first time the drought occurrence, duration and intensity over the Republic of Djibouti by using a long-term (1961 to 2021) rainfall time-series at Djibouti-Airport, completed by the CHIRPS precipitation product and local records from 35 weather stations. The drought is examined based on the Standardized Precipitation Evapotranspiration Index (SPEI) and the Standardized Precipitation Index (SPI) at 3-, 12-, and 24-months timescales, to document short, medium and long duration events, respectively. The analysis revealed that the Eastern coastal region of the republic of Djibouti was the most affected by an increased drought incidence in the recent decades, with more than 80% of the extremely and severely dry events occurring within the period 2007–2017. By contrary, the Western regions recorded a positive trend of its SPI indices during the period 1981–2021, due to the dominance of the June–September (JJAS) rains which tend to increase. However, in the last decades, the whole country experienced the droughts of 2006/2007 and 2010/2011, which were the longest and most intense. Large-scale climate variability in the Indo-Pacific region partly affects drought in Djibouti. SPI is significantly positively correlated with the Indian Ocean Dipole during October–December (OND), while for JJAS it is negatively correlated with Nino3.4. This study provides essential information on the characteristics of drought in the Republic of Djibouti for decision makers to better plan appropriate strategies for early warning systems to adapt and mitigate recurrent droughts that put the country's agropastoral populations in a precarious situation.

Keywords: Djibouti; drought characteristics; SPI; SPEI; CHIRPS; Trends

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1. Introduction

Drought is a complex phenomenon that affects natural environments and socio-economic systems in the world, which is characterized by abnormally dry weather over a period of time long enough to cause a serious hydrological imbalance [1]. It usually consists in a reduction of soil moisture content, groundwater level and volume of surface runoff that may induce crop failure, food shortage, and in the worst cases famine, epidemics and mass migration.

In East Africa (EA), where extensive regions experience arid to semi-arid conditions, drought manifests itself as a natural endemic phenomenon [2, 3]. This region exhibits

some of the largest interannual rainfall variations in the world, resulting into large magnitude droughts [4, 5]. Drought has been one of the main causes of socioeconomic instability in various nations, including Somalia, Kenya, and Ethiopia [6]. There have been a number of drought-related events that have occurred in the EA region in the recent decades, resulting in massive crop failures, livestock deaths, and human casualties [7, 8]. During the past few decades, the frequency of droughts in EA has increased from once every six years to once every three years and become widespread [6, 9]. There have been eight boreal spring droughts in the EA region in the last 16 years. Over 13 million people in EA were affected by the drought from 2008 to 2010 [10]. Recent catastrophic events in the area were brought on by the Horn of Africa drought that lasted from 2010 to 2011 [11, 12]. In 2022, due several consecutive failed rainy seasons, it is forecasted that 16 million people will be in need of immediate food assistance, particularly in Somalia where the situation is catastrophic.

Like most countries of East Africa, the Republic of Djibouti has been facing an unprecedented chronic drought during 2007-2011 resulting into high rates of cattle mortality, food insecurity, severe water and food shortages [13]. More than 120,000 people in rural areas (i.e., 50% of the rural population and 15% of the total population) are estimated to be victims of drought hazards in Djibouti [13]. This drought also caused an estimated 3.9% loss in Gross Domestic Product of the country [13, 14]. On the other hand, drought is one of the main factors of migration for rural agropastoral nomads towards urban areas in Djibouti [15]. However, the long-term spatial and temporal evaluation of drought occurrences remain unexplored. This has resulted in poor preparedness and uninformed strategies for drought management in the country. Ozer and Mahamoud [16] analyzed changes in extreme precipitation between 1980 and 2011 in Djibouti based on annual statistics from the single station of Djibouti Airport. They found a strong decline in precipitation (73%) during 2007-2011 compared to total average rainfall. Recently, Assowe et.al, [17] evaluated spatiotemporal variability of rainfall over the republic of Djibouti by using monthly data from 14 weather stations and high-resolution long-term satellite rainfall products. These two studies analyzed overall rainfall variability and trends in Djibouti, but no known study has ever attempted to assess the countrywide pattern of drought incidence. Therefore, there is a need for a critical investigation of long-term historical spatio-temporal patterns of droughts over the Republic of Djibouti.

Numerous indices have been established to measure drought events and their features, including the Standardized Precipitation Index (SPI; [18]), Standardized Precipitation Evapotranspiration Index (SPEI; [19]), Palmer Drought Severity Index (PDSI; [20]), and the Soil Moisture Deficit Index (SMDI; [21]). Each of these indices takes into account one or more environmental factors including rainfall, temperature, and soil moisture, among others. SPEI and SPI, however, are some of the most often employed drought indicators for keeping track of meteorological, agricultural, and hydrological drought. SPI is globally recommended by the World Meteorological Organization (WMO) for drought assessment [22] and can be used to determine the anomalously wet or dry events on a particular time scale for any locations where precipitation records are available. SPI requires only precipitation data, while SPEI require additional potential evapotranspiration (PET) data to assess drought. Both indices can be computed over periods of time of varying lengths, thus enabling to account for both short-term droughts (mostly meteorological droughts) and long-term events (generally of major hydrological and ecosystemic significance). Thus, the key aim of this research is to study meteorological drought and its characteristics using the SPI and SPEI drought indexes over the Republic of Djibouti.

In addition, to the best of our knowledge, the large-scale climate variability associated with the occurrence of drought in Djibouti has not been specifically evaluated to date. El Niño-Southern Oscillation (ENSO), one of the prominent natural modes of climate variability originating from the tropical Pacific Ocean, impacts rainfall variability over East Africa [3]. Many studies demonstrated that ENSO partly controls June-September (JJAS) interannual rainfall variations in Ethiopia and ENSO was the ultimate cause of most

drought years in Ethiopia [23–25]. Other studies [26, 27] based on different datasets in East Africa region showed a strong connection between rainfall variability during the October–December (OND) season and the Indian Ocean Dipole (IOD), a seesaw in sea-surface temperature (SST) anomalies between the western and the western Indian Ocean. However, there is still an absence of any systematic analysis on the part of Djibouti's drought variations explained by climate drivers such as ENSO and the IOD. Based on this fact, this study also examined the link between seasonal and annual drought occurrence in the Republic of Djibouti and SST indices associated with global-scale climate variations.

The present study is therefore the first one to comprehensively document the spatial and temporal variation of drought characteristics (frequency, severity, and intensity) in the Republic of Djibouti by using long-term (1961 to 2021) observed rainfall time-series combined with a merged (satellite and observed) precipitation product (CHIRPS). The drought occurrences are examined based on SPI and the SPEI indices at 3-, 12-, and 24-months timescales, to document short, medium and long duration events, respectively. Seasonal and annual trends of drought were described to assess whether there is any long-term change in drought characteristics in the country, as suggested by several studies indicating a decrease in the boreal spring (March–May) rains over parts of East Africa since the 1980s [3, 9, 28]. The aim is next to determine the drought-prone regions and to assess whether droughts occur simultaneously in the different parts of the Republic of Djibouti. The teleconnection between the global SSTs (e.g., IOD and ENSO) and seasonal and annual drought indices are also discussed. The results of this study could greatly help concerned decision makers to understand the spatiotemporal variation of droughts to subsequently design appropriate drought mitigation and early warning systems in the Republic of Djibouti.

This study is organized as follows; Section 2 provides a description of the study area, data, methods, and drought index. Section 3 presents the detailed results of the spatial and temporal variability of drought at seasonal and annual scales. Finally, conclusion and recommendation are presented in Section 4.

2. Materials and data collection

2.1. Study area

The Republic of Djibouti is geographically located in the Horn of Africa facing the Red Sea and the Gulf of Aden (Figure 1). It is found within latitude 11–12.5° N and longitude 42–43.5° E. The neighboring countries are Eritrea in the north, Ethiopia in the west and south, Somalia in the southeast (Figure 1). Its coastline is extended to about 372 km distributed between the Gulf of Aden (80 km), the Red Sea (38 km), and the Tadjoura Gulf (254 km) [29]. Elevations in the country range from 150 meters below the sea level (Asal Lake) to over 2000 meters above the sea level (northern mountainous regions), while the east is lowland.

The Republic of Djibouti has a low precipitation regime, with the mean annual rainfall ranging from 60 to 300 mm [17]. The local climate is regulated by the complex topographical features of the country and the proximity of the Indian Ocean. Rainfall variation in Djibouti is embedded in large-scale climate variability, particularly that associated with the El Niño Southern Oscillation and the Indian Ocean Dipole (IOD) [17]. Djibouti has two predominating seasons which are a cool season (winter) from October through April and a hot season (summer) from May through September [30]. In winter, the climate is characterized by northeast trade winds coming from the eastern Arabian Peninsula and the Gulf of Aden and an average temperature between 20 °C and 30 °C. In summer, westerly winds associated with the African-Asian monsoon circulation dominates [31] and average temperatures range from 30 °C to 45 °C. The potential evapotranspiration rate is very high, amounting to 2000 mm per year [32].

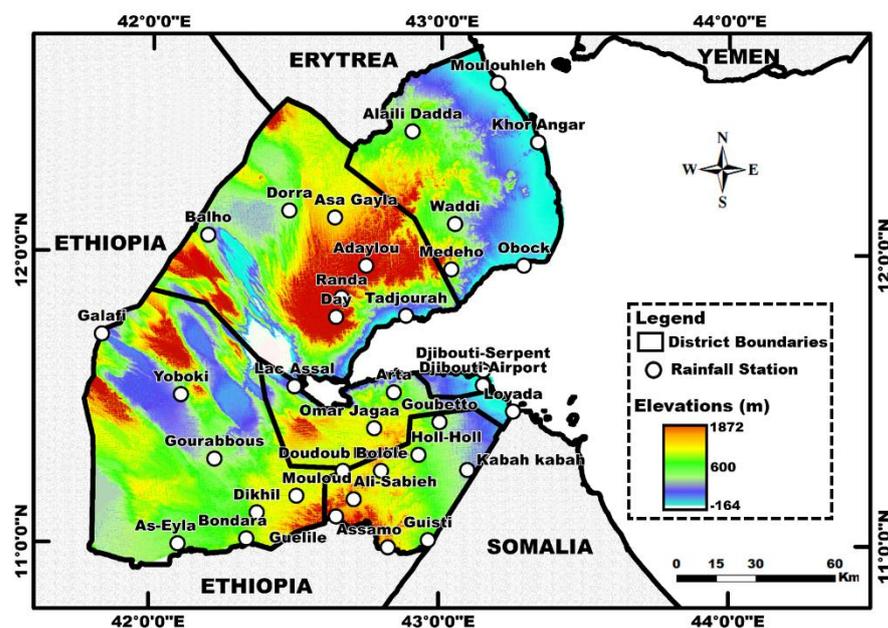


Figure 1. Map and spatial distribution of the meteorological stations and elevation. The white dots in the map represent the 35 meteorological stations across the country.

2.2. Data source

The availability of climate data in the Republic of Djibouti is limited. Monthly precipitation from the “Agence Nationale de la Météorologie (ANM)” is recorded at Thirty-five (35) stations distributed across the country. They are mainly concentrated in the south-east of the country while the Nord-west (complex and rugged terrain) is less covered (Figure 1). Most records started around 1961 and are analyzed here until 2021, but contain many gaps, and no data at all is available between 1991 and 2012 except at the Djibouti-Airport station which contains the most complete meteorological data available in the country, uninterrupted for the whole period of study (1961-2021). Figure 1 shows the administrative boundaries, elevation, and meteorological stations used in this study.

The most fundamental barrier that hinders regional studies such as drought monitoring is the long-term recording and quality of climatic data. Most ground observation in the Republic of Djibouti contain a long gap in the 1990s and 2000s. Accordingly, it is difficult to analyze the distribution of drought and climatic trends in space. For this purpose, the study used a satellite-based rainfall estimate from Climate Hazards Group Infrared Precipitation with Station observation (CHIRPS version 2.0). CHIRPS is a quasi-global (ranging from 50°S to 50°N) precipitation dataset mainly designed for monitoring droughts and other global environmental changes in data scarce regions such as East Africa [33]. The product is available at a high spatial resolution of 0.05° (≈ 5 km) and on multiple time scales (e.g., daily to monthly) from 1981 to present. More details of the product can be found from [33].

CHIRPS was compared to other satellite rainfall estimates and reanalysis datasets in our previous study and the results revealed the good performance of CHIRPS compared to other datasets [17]. Ayugi et al. [34] also recommended CHIRPS for examination of long-term precipitation trends and for drought analysis in Kenya. On the other hand, CHIRPS datasets are among the most used products over East Africa and display the longest time-series to date [35-37]. Overall, the CHIRPS datasets can be employed as an

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alternative to in-situ datasets in a region characterized by scarcity of ground-based datasets for droughts characterization.

2.3. Methodology

2.3.1. Drought Analysis Procedures

Drought indices with specific time-scales are important elements for drought monitoring and management planning system [38]. The Standardized Precipitation Index (SPI; [18]) and the Standardized Precipitation Evapotranspiration Index (SPEI; [19]) are useful to assess drought events in arid-dominated regions such as East Africa [39]. In this study, the SPI and SPEI drought indices were used to identify the anomalous dry and wet conditions in the Republic of Djibouti.

The SPI was developed to describe long-term meteorological drought. It is one of the most commonly used drought indexes and compares the normalized rainfall with average rainfall to express the deficit and excess of rainfall for a particular time period and climate. SPI is globally recommended by the World Meteorological Organization (WMO) for drought assessment [22]. The SPI was calculated based on long-term rainfall data for Djibouti-Airport station and CHIRPS regional rainfall indices with gamma distribution estimation method. The SPEI is an improved index for regional drought monitoring because of its ability to identify the effects of temperature on drought conditions [40]. The SPEI is mainly selected to evaluate the role of temperature through its influence on potential evapotranspiration (PET), which relates to global warming and the occurrence of drought [41]. The SPEI is quantified using precipitation (P) and potential evapotranspiration (PET) as input variables resulting in an index describing the water balance. Due to the limited availability data, the present study used the modified Hargreaves technique, which only requires precipitation, maximum, and minimum temperature datasets [42]. SPEI values were estimated by fitting historical observations into log-logistic distribution. More details on the mathematical equations behind the calculations of SPEI and SPI can be found in [42].

2.3.2. Evaluating drought characteristics

In order to examine the impact of drought events in the Republic of Djibouti, the study considers drought components of drought duration (D), drought frequency (F) and drought intensity (I). These parameters were used to detect the potential effects of climate change on drought characteristics in the context of global warming.

To determine how frequently there are droughts (drought frequency of occurrence, F) in a given area, the following formula can be used [43].

$$F (\%) = \frac{n}{N} \times 100 \quad (1)$$

where n is the number of drought events ($SPI/SPEI < -1.0$) and N is the total number of the months over the study period. The average drought duration (D) is the length of a drought episode (months) during which the drought index is consecutively above or below a truncation value. It can be calculated as follows [44]:

$$D = \frac{\sum_{i=1}^n d_i}{n} \quad (2)$$

Where d_i is duration of i th drought event and n is the total number of drought events. The intensity (I) of drought is used to measure the overall intensity of drought events and can be defined as follow:

$$I = \frac{1}{n} \sum_{i=1}^n SPI \setminus SPEI_i \quad (3)$$

With n is number of drought occurrences in months with SPI/SPEI < -1.

Additionally, one of the most significant benefits of SPI and SPEI is that they can be computed at various time scales, allowing us to factor in the influence of the variable's previous values in the computation. To assess and characterize the meteorological drought in the Republic of Djibouti, we have studied both short-term SPI/SPEI (3 and 6 months) and long-term SPI/SPEI (12 and 24 months). According to [18], drought levels were classified according to the seven SPI and SPEI range of values as presented in Table 1. These drought severity classes were used to compute time series of drought indices (SPI and SPEI) based on monthly, seasonal annual timescale.

Table 1. Classification of the severity of drought (or humidity) events on the calculation of SPI/SPIE [18].

SPI/SPEI classifications	Catégories
≤ -2.0	Extremely Dry
- 1.99 – -1.5	Severely Dry
- 1.49 – -1.0	Moderately Dry
- 0.99 – 0.99	Near Normal
1.0 – 1.49	Moderately Wet
1.5 – 1.99	Severely Wet
≥ 2.0	Extremely Wet

3. Results

3.1. Mean climatological patterns

The spatial rainfall variability which is the key parameter influencing the occurrence of drought events is first analyzed. Based on the 35 rain-gauges station, the annual rainfall amount over the republic of Djibouti is presented in Figure 2. Rainfall in Djibouti is generally erratic, infrequent and extreme wet and dry events can be observed in some years [45]. Rainfall amounts displayed high spatial variability which is largely associated with the altitudinal variation within the country. Orographic effects appear most prevalent in the highlands, where the rainfall gradient broadly follows terrain. The highest rainfall is found along a north–south discontinuous ridge (150 mm to 250 mm) while in the south-east and southwest of the country annual rainfall is between 100 mm and 150 mm. On the other hand, northeastern coastal regions receive less than 100 mm annually.

In order to identify spatial patterns of droughts, a clustering method, the Hierarchical Agglomerative Clustering (HAC), is applied on mean monthly rainfall at the 35 stations over the period 1961–2021 (Figure 3). The spatial variability of rainfall regimes in Djibouti reveals the existence of two regions, that is a coastal region (EAST) and a continental region (WEST). This regionalization (Figure 3) is further used to study the spatial variation of drought over the whole country in section 3.4.

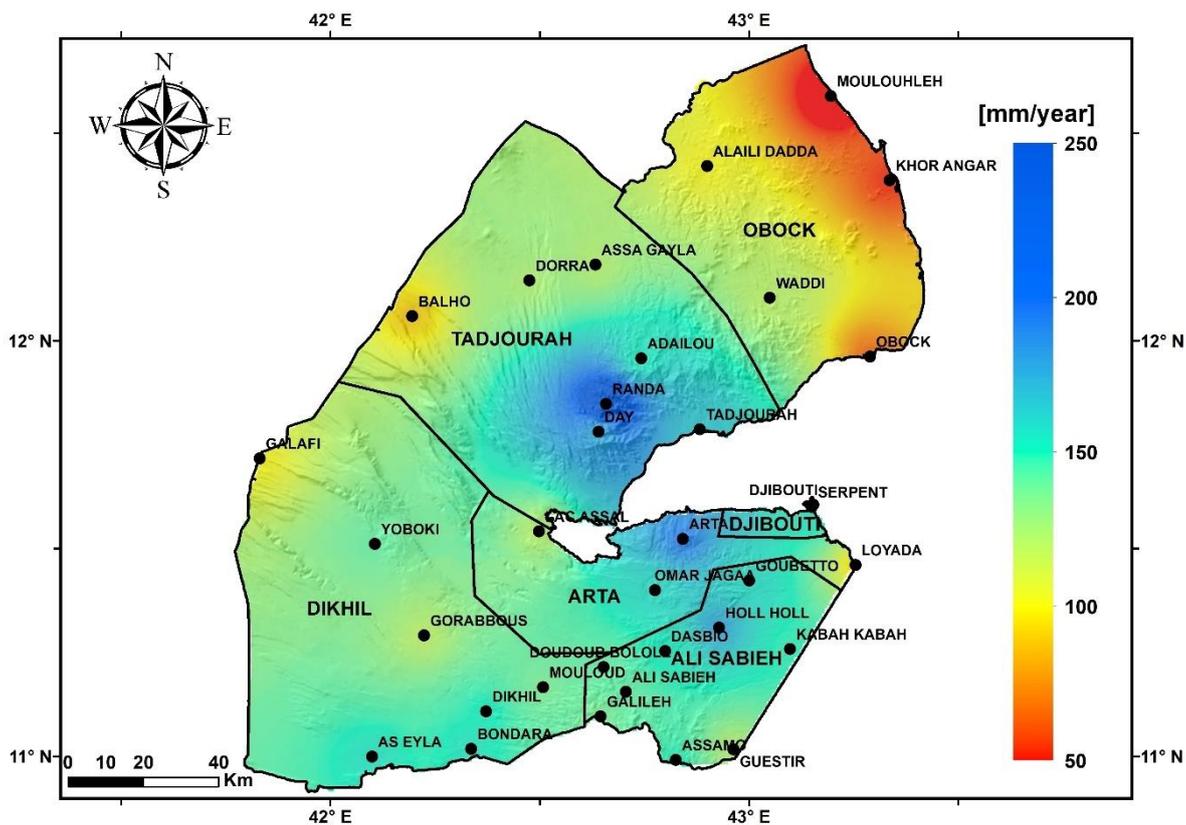


Figure 2. Spatial distribution of mean annual rainfall over the Republic of Djibouti based on 35 meteorological stations.

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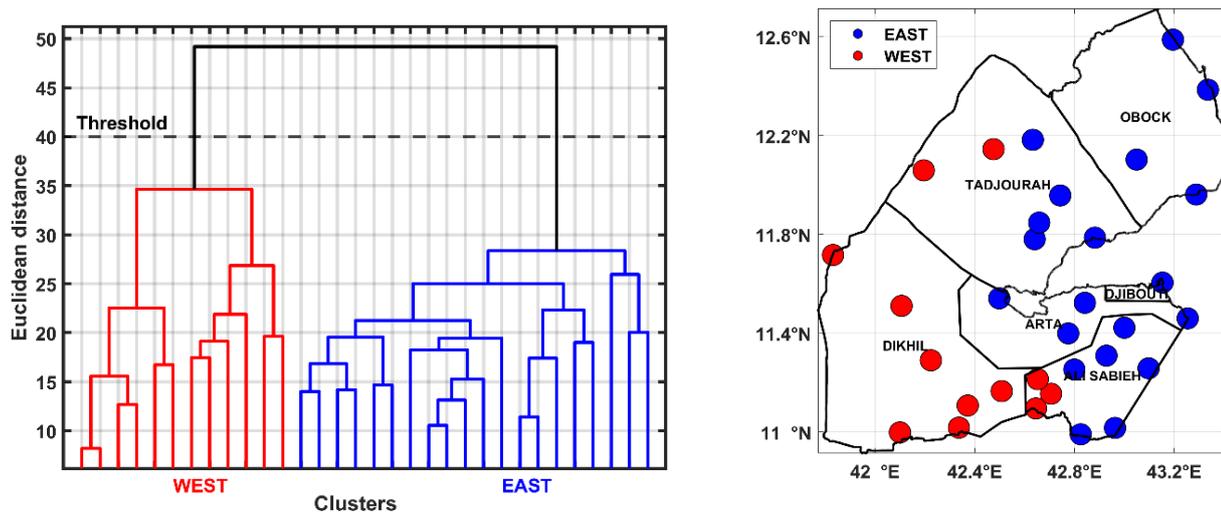


Figure 3. Dendrogram of the HAC of mean monthly precipitation, and map displaying the distribution of rainfall stations belonging to the two regions (WEST and EAST).

Figure 4 show the mean monthly precipitation regime in the EAST and WEST regions averaged during 1961-2021 (Figure 4a and Figure 4b). The mean monthly of rainfall and temperature at Djibouti-Airport station which is part of the eastern region are presented

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in (Figure 4c, Figure 4d). More rainfall is recorded during the MAM (March-April-May) season with a peak in April and decline by the end of May for the EST region (Figure 4a and Figure 4c). The whole country receives about the same amount of rainfall during this season (Figure 4a, Figure 4b and Figure 4c). The monthly rainfall peaks in April during MAM with ~15 mm is observed for both regions. June is the driest month across the country.

The Eastern part of the country receives more rainfall amounts than western part during OND (October-November-December) and JF (January-February). The MAM and OND are the two main wet seasons in most part of the East Africa countries [44, 46-47]. As indicated by Camberlin [48], the equatorial regions and most of the Indian Ocean coastal plains have double-peak regimes with rains in the transition seasons (MAM and OND). JJAS (June-July-August-September) includes the wettest period in the western part of the country lasting from July to September with a peak in August. By contrast, the Eastern area receives a small amount of rain in July–August (Figure 4a and Figure 4c). The July–September rainy season is more widespread Ethiopia and covers the entire country with a steep gradient from north-west to south-east close to Djibouti [49]. The minimum and maximum air temperatures at the airport station are presented in Figure S1 in supporting information files. Average monthly temperatures range from 25.2°C in January to 36.8°C in July (Figure 4d).

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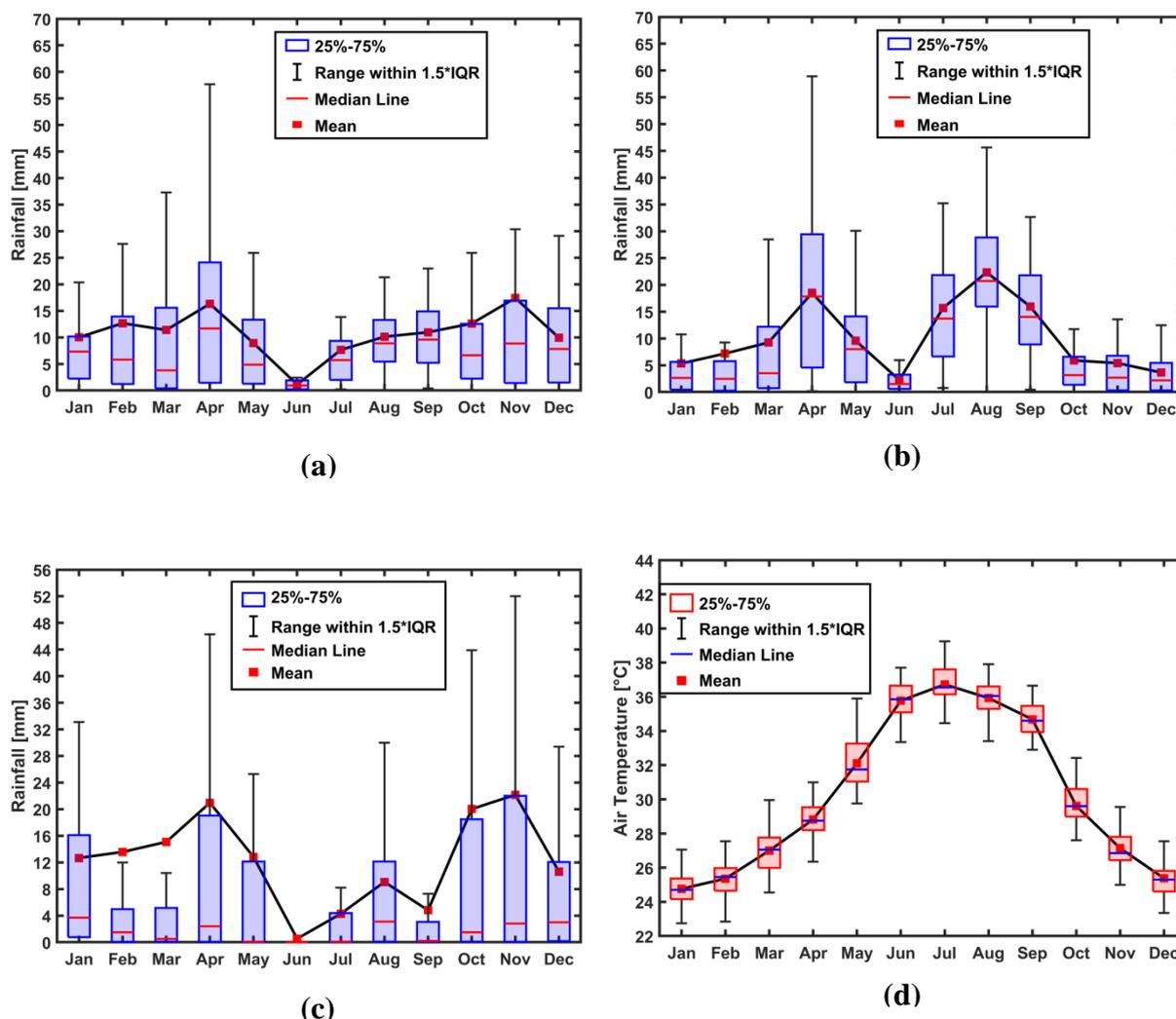


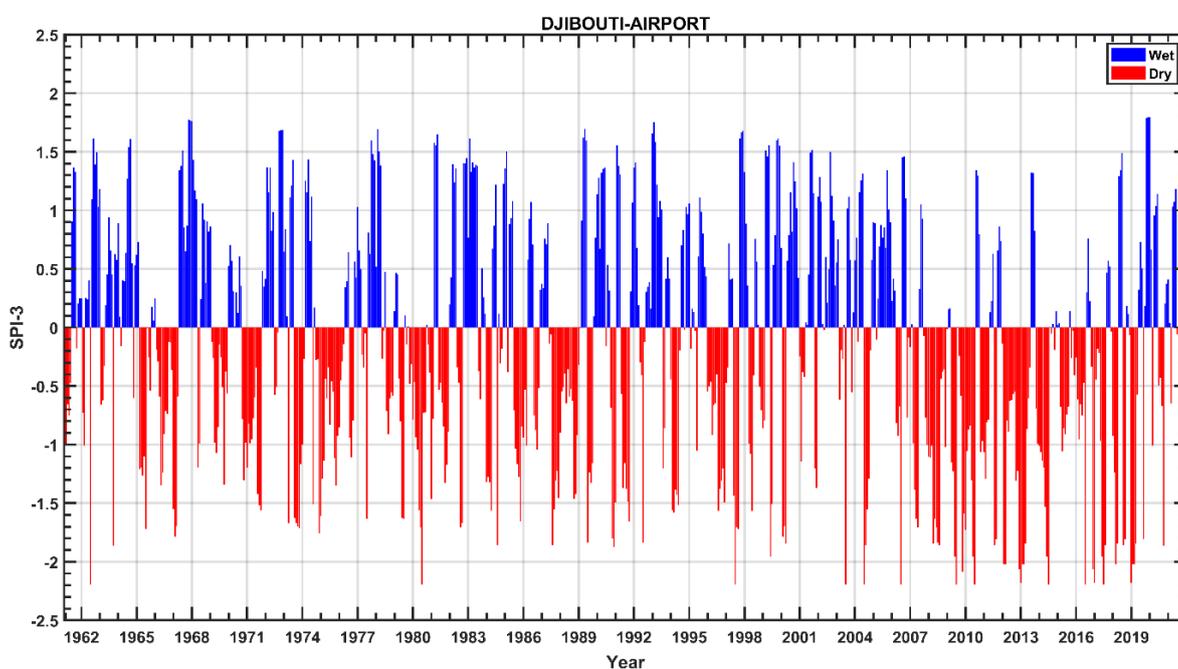
Figure 4. Mean monthly climatology over the Republic of Djibouti averaged during 1961–2021: (a) and (b) indicate the mean monthly precipitation regime in the EAST and WEST regions as presented in Figure 3. The mean monthly rainfall and mean air temperature at the airport-station are presented in (c) and (d) respectively. The box and whiskers indicate the interquartile range of the observed changes in rainfall and temperature climatology. The red horizontal line in each box represents the median. The bottom and top of the boxes denote the 25th and 75th percentiles, respectively, while the top of the whiskers shows the most extreme values.

3.2. Temporal variation of SPI and SPEI

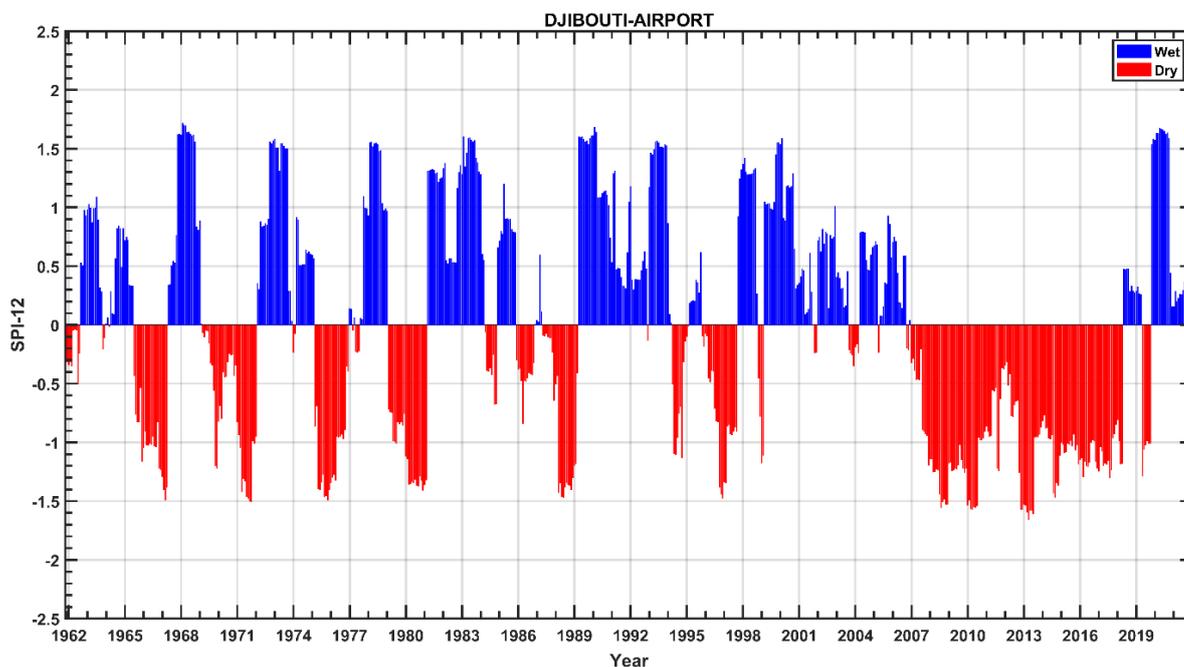
The assessment of the short and long-term of SPI index issued from Djibouti-airport station exhibited the existence of dry and wet events throughout the study period (Figure 5). The temporal variations of SPEI for the different time scale are presented in Figure S2 in supporting information files. As expected, the drought events are more frequent with shorter durations for 3-month SPI compared to the 12-month, and 24-month SPI (Figure 7a). These results agree with those of [50] who found a decreasing trend in frequency of the wet and dry periods with increase in SPEI and SPI timescales. During 1961–2006, few drought events were recorded in Djibouti. For instance, moderate to severe drought conditions were observed in 1986, 1971 and 1981. Droughts were more severe and persistent during 2007–2018 than those during other periods, as revealed by both indices. It was evident that drought events increasingly occurred, especially after 2007 with high

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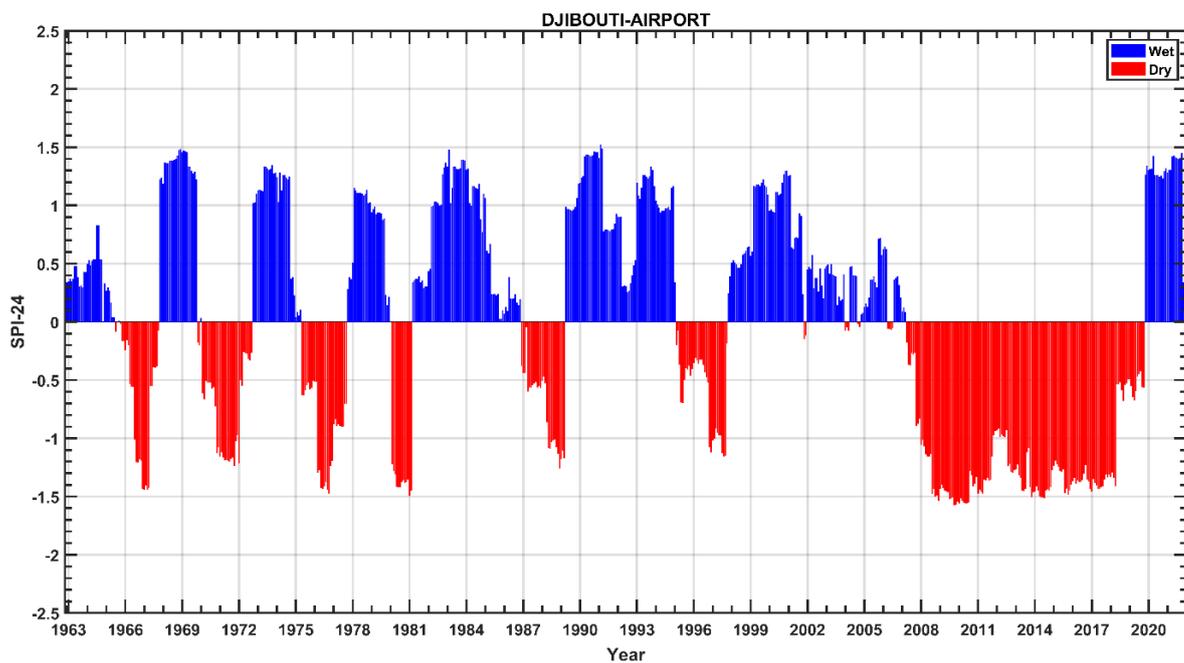
intensity and duration (Figure 5b). As indicated by [51], droughts at the SPI-12 or larger timescales tended to persist much longer. The SPEI results detected the same period of drought, but the drought is much more pronounced with the SPEI than with the SPI (Figure S2 in supporting information files). Because SPEI takes into account evapotranspiration, it is more sensitive to changes in drought, so there are some differences with SPI results further shows that the most intense drought (SPI = -2.19) based on SPI 3 occurred between October to December 1981. For the 12-month SPI, the most intense drought (SPI = -1.65) occurred between January to December 2013. On the other hand, based on SPI-12 and SPI-24 (as well as SPEI-12 and SPEI-24), the 2010-2011 and 2013-2015 drought events were the most severe experienced in Djibouti (Figure 5b, Figure 5c). These drought events were found to have large scale impacts in the Horn of Africa on the environment and society [52]. The 2010–2011 Horn of Africa drought caused a wide range of food insecurity situation in the region [12, 53-54]. Rainfall was at least 50% to 75% below average in the Horn of Africa regions.



(a)



(b)



(c)

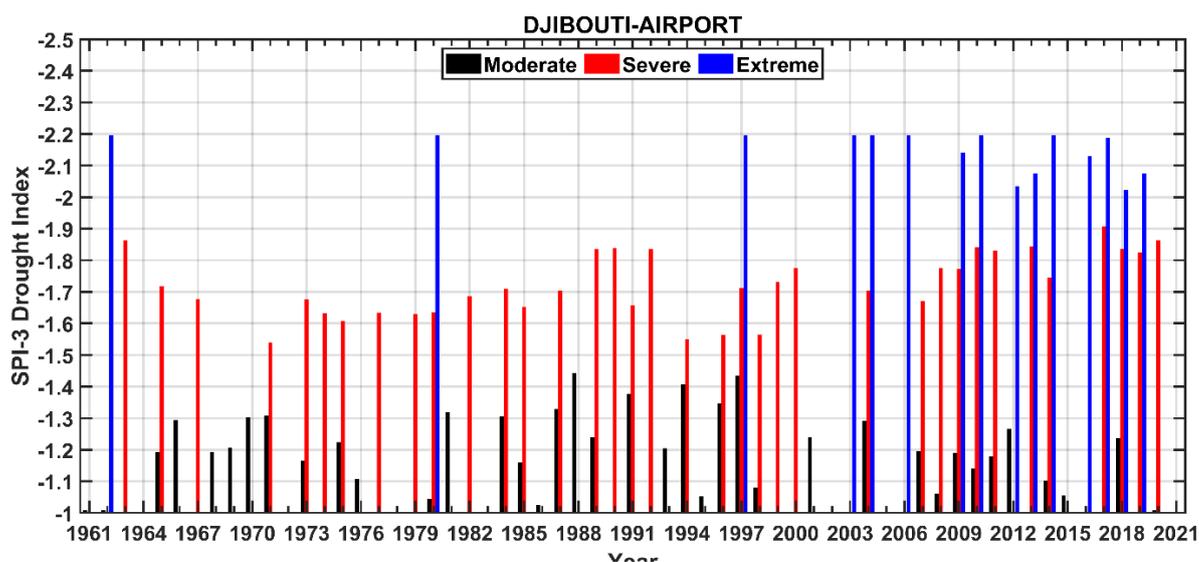
Figure 5: Temporal evolution of dry events (red color) and wet event (blue color) for SPI short-term and long-term during the period 1961–2021: (a) presents short dry periods at three months scale (SPI-3), (b) shows wet and dry periods at 12-month scale (SPI-12) and (c) represents a long-dry period at 2-year scale (SPI-24).

Drought duration, intensity and frequency are important properties for droughts characterization. Table 2 present the mean duration, frequency and intensity of droughts at various timescales over the Djibouti-airport station during 1961–2021 for both SPI and SPEI indexes. Drought and wet duration tend to increase with the SPI and SPEI timescales. The average drought durations were 2.77 and 6.93 months for SPI-3 and SPI-12 and 2.40 and 5.63 months for SPEI-3 and SPEI-12 respectively. SPI index revealed high frequency of drought than SPEI ranging between 20.53% and 26.01% (Table 2). The average drought intensity varies between -1.68 for SPI-3 to -1.28 for SPI-12. This suggests that drought intensity decreases with the timescale.

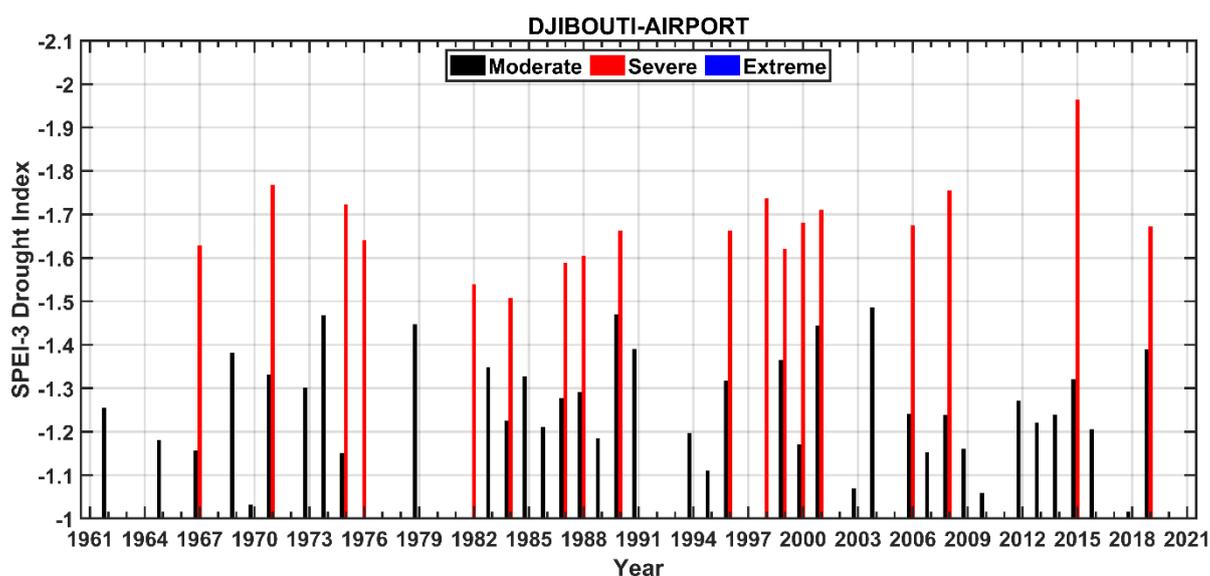
Table 2. Drought characterization (duration, Frequency and intensity) of occurrence for dry ad wet events at Djibouti airport station over the period 1961-2021.

	Dry			Wet		
	Duration	Frequency	Intensity	Duration	Frequency	Intensity
SPI-3	2.77	24.89	-1.60	2.40	18.16	1.32
SPI-6	3.34	20.53	-1.32	3.62	20.12	1.38
SPI-12	6.93	21.62	-1.28	8.03	20.16	1.39
SPI-24	20.33	26.01	-1.30	12.23	23.45	1.23
SPEI-3	2.40	19.04	-1.39	2.94	19.73	1.45
SPEI-6	3.56	19.12	-1.38	5.32	20.51	1.42
SPEI-12	5.63	18.72	-1.34	8.72	21.78	1.41
SPEI-24	9.73	20.59	-1.35	11.69	21.44	1.36

Figure 6 shows the long-term temporal variation in the occurrence of drought in the district of Djibouti-ville, the country's capital, where the meteorological station at Djibouti airport, which contains the most comprehensive meteorological data in the country, is located. According to table 2, the evaluation of drought and wet events were classified as moderate, severe, and extreme at 3-months timescales (Figure 6 and Figure S3). Analysis of SPI-3 at the Djibouti-airport exhibited recurrent drought events during the period 1961-2021 (Figure 6a). The SPI-3 results show that the existence of moderate and severe drought cases between 1961 and 2000. Only three extremes drought events occurred in this period (1962, 1980 and 1997). However, the extreme drought incidences were intensified since 2003, yielding critical situations in Djibouti. 12 extremes drought events were identified between 2003 and 2021 accounting more than 80% of total extreme drought in Djibouti since 1961. In contrast, no severe wet conditions were recorded between 2003 and 2017 and the moderate wet events were still low indicating significant rainfall decrease in this period (Figure S3). The analysis of SPEI-3 showed moderate to severe drought in Djibouti but does not clearly indicate the existence of extreme dry events (Figure 6b). The number of wet years remained the same both for SPEI and SPI values (Figure S3), but the wet severity of the SPEI was higher than SPI.



(a)



(b)

Figure 6. Temporal variation of SPI and SPEI at 3-month timescale for moderate, severe, and extreme drought events at Djibouti-airport from 1961 to 2021. Drought event is considered only for the period in which the $SPEI/SPI \leq -1$ for 3-months timescale. Drought events are divided into three main categories, namely: extreme ($SPI/SPEI \leq -2.00$), severe ($-1.50 > SPI/SPEI > -1.99$) and moderate ($-1.00 > SPI/SPEI > -1.49$).

3.3. Annual and seasonal variations of drought

In this section we analyzed the SPI index on a seasonal scale to assess whether the drying up of the recent decades in Djibouti is associated with a specific season (Figure 7). The analysis of SPI values at a seasonal scale clearly shows the existence of severe and extreme droughts events in any season, although the index being standardized it cannot be used to compare the severity of droughts between seasons (Figure 7a). Several extreme

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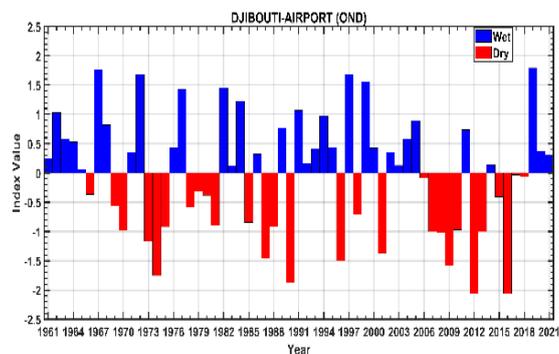
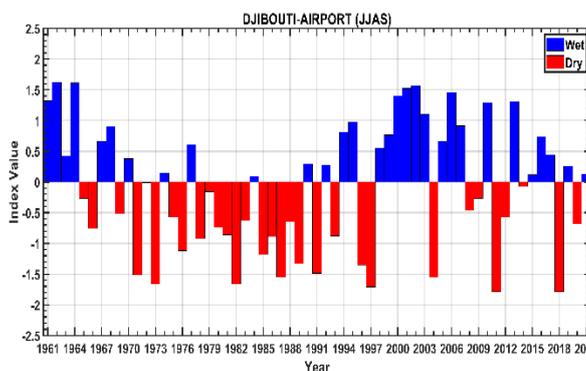
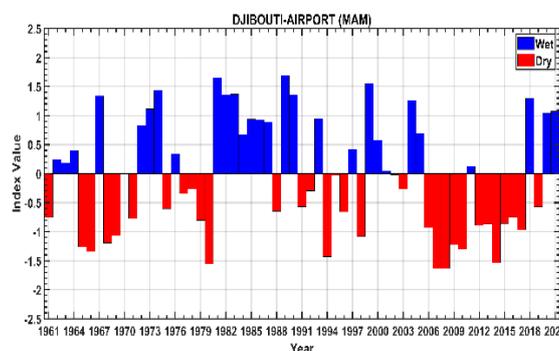
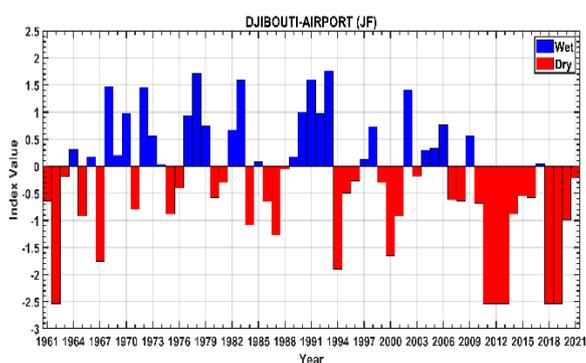
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dry events have been occurring since 2009 during the JF (January-February) season, indicating a strong rainfall decline in this season. The JJAS season experienced the longest recurrent drought events during 1970s and 1980s (Figure 7c). Williams et al. [55] documented a decline in JJAS rainfall in the Horn of Africa from 1970 to 1989, which they attributed to the warming of the southern tropical Indian Ocean. It was followed by wetter conditions, interrupted by some dry events (e.g., 1996-97, 2004, 2011, 2018). However, a consistent rainfall decline occurred between 2005 and 2017 (Figure 7e).

The SPI index at MAM season showed that moderate wet periods started from the year 1981 until 1988 (Figure 7b). The most severe wet event is observed in 1989 which is the wettest years ever registered in Djibouti, with rainfall amount exceeding 450 mm/year [17]. This period was followed by alternating wet and dry MAM seasons, then an extensive, almost uninterrupted drought period from 2006 to 2017. On the other hand, the OND season experienced a more regular alternation between severe dry events and wet events (Figure 7d). Two extremes dry events occurred for OND at 2012 and 2016. However, as for MAM, moderate to severe dry events occurred from 2006 to 2017 in the OND season (Figure 7b-7d). This period was characterized by a persistent rainfall decline in these seasons, which both contributed to the prolonged drought conditions as displayed above in the monthly SPI index. The MAM and OND seasons are actually the wettest seasons in the eastern parts of Djibouti [17]. Limited precipitation in both the October–December 2010 and March–May 2011 rainy seasons were the main causes of 2010-2011 droughts in the Republic of Djibouti (Figure 7b-7d).

In the larger East African region, the MAM long rains season is the primary rainy season [9, 56]. Nicholson [9] indicated that the greatest changes in drought appear to have occurred during the long rains (MAM). As agriculture in the region is largely dependent on rainfall, the decline in the MAM rains season has had major consequences for food insecurity [9, 11, 26].



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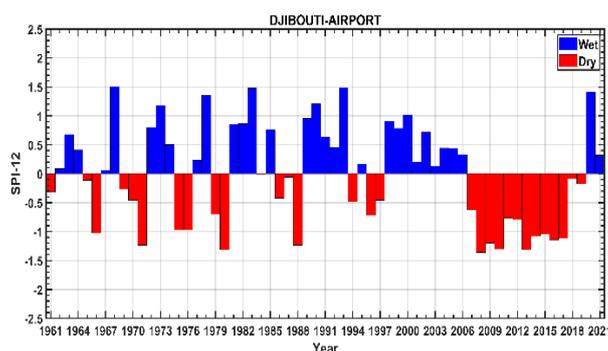


Figure 7. Annual and seasonal variability of the SPI index over the period 1961-2021 at the Djibouti Airport station.

3.4. Trends and spatial patterns of drought since 1981

In view of the increased drought conditions of the recent decades in Djibouti, a focus is made on the period 1981-2021 using both observed (Djibouti-Airport station) and CHIRPS data. The aim is to quantify the linear trends of the SPI computed at different timescales and to assess their spatial patterns by considering the two sub-regions defined in section 3.1 (Figure 8, Table 3). SPEI is not presented here since it was shown to broadly display the same evolution. Due to the interrupted data records during the 1991-2012 in all stations of the country (except for Djibouti-airport station), CHIRPS datasets were used to evaluate the spatial variability of drought and its trends over the whole country.

At Djibouti-Airport, the annually-averaged SPI values generally show negative values, suggesting drying trends. The observed data depicted a significant increasing drought trend ($P < 0.01$) for all the SPI timescales (SPI-3, SPI-12 and SPI-24). However, CHIRPS showed an insignificant drying tendency for SPI-3 and SPI-12 but a significant trend for the long-term SPI-24 index. The stronger trend found for the longest SPI timescales indicate that while there was only a moderate increase of short duration droughts, there has been a marked increase in prolonged drought events.

Figure 9 shows the time series of SPI index at 3-, 12- and 24-months for the east and west during 1981-2021. In 3-months, moderate to severe drought were observed for both climate zones. The SPI-12 and SPI-24 show the most prominent drought years in the Republic of Djibouti. At a country scale, the analysis of the SPI-3 time series showed a non-significant decreasing trend in the eastern parts of Djibouti (Table 3, Figure 9). Likewise, SPI-12 and SPI-24 time series exhibited a non-significant drying tendency over the eastern regions. This seems to indicate that the coastal region may be the driest area in Djibouti. This absence of significant trends is due to the fact that, while there has been a prolonged drought between about 2002 and 2016, more recent years recorded much wetter conditions (Figure 9) Using the CHIRPS high resolution dataset, Gebrechorkos et al. [36] found increasing drought in large part of East Africa region by analyzing the long-term trend in the SPI 3, 6, and 12-month but their study was restricted to the period ending in 2016, therefore not including some wetter years which occurred later on.

In the Western part of the country, contrary to the Eastern sub-region, the SPI trends over 1981-2021 are positive, and even significant ($P < 0.05$) for SPI-12 and SPI-24 (table 3). This is due to the fact that the 1980s were particularly dry years (figure 9), as in much of Ethiopia, Sudan and the Sahelian region. Droughts reoccurred recurrently between 2003 and 2016. This well correlates to the extended drought period found in the Eastern sub-region, but the droughts in the West were interrupted by periods of higher rainfall. Drought actually seems to affect the whole country at the same time (e.g., 1984, 2006, 2009, 2013 and 2015) but the severity is higher in the eastern part on a regional scale. In addition, drought durations are much longer in the east than in the west as demonstrated by SPI-24.

The contrasted trends for the Eastern and the Western sub-regions are partly related to their different rainfall regimes, because the JJAS rains have a dominant part in the West, while in the East the OND and JF rains have a bigger share of the annual rainfall. At Djibouti-Airport, a significant negative trend (drier conditions) is found during the JF and MAM seasons in the observation (table 4). CHIRPS also shows a negative trend in these seasons but it is only significant ($p < .05$) in JF season. For the Eastern and Western indices, consistent negative trends are similarly found in both JF and MAM, but none is significant. JJAS is the only season experiencing a positive trend (wetter conditions) for both observation and CHIRPS. It is statistically significant ($P < 0.05$) in both the Western and Eastern sub-regions, though not at Djibouti-Airport. The JJAS season is the main rainy season in the northern and northeastern parts of East Africa [57]. Teshome and Zhang [58] found a positive trend over the period 1980-2015 over most parts of Ethiopia, thereby indicating that the drought occurrence is decreasing in the JJAS season. Using CHIRPS to compute drought indices, Brown et al. [59] found that, over the period 1982–2014 in northeastern Ethiopia (near Djibouti), there were strong but contrasting trends between March–June (increasing drought) and June–September (increasing precipitation). These mimic the trends found over the Republic of Djibouti. The greater share of the JJAS rains in the West (which have a positive trend) with respect to the MAM and JF rains (generally showing a negative trend) explain that this region does not show the same overall evolution of the SPI than the Eastern region.

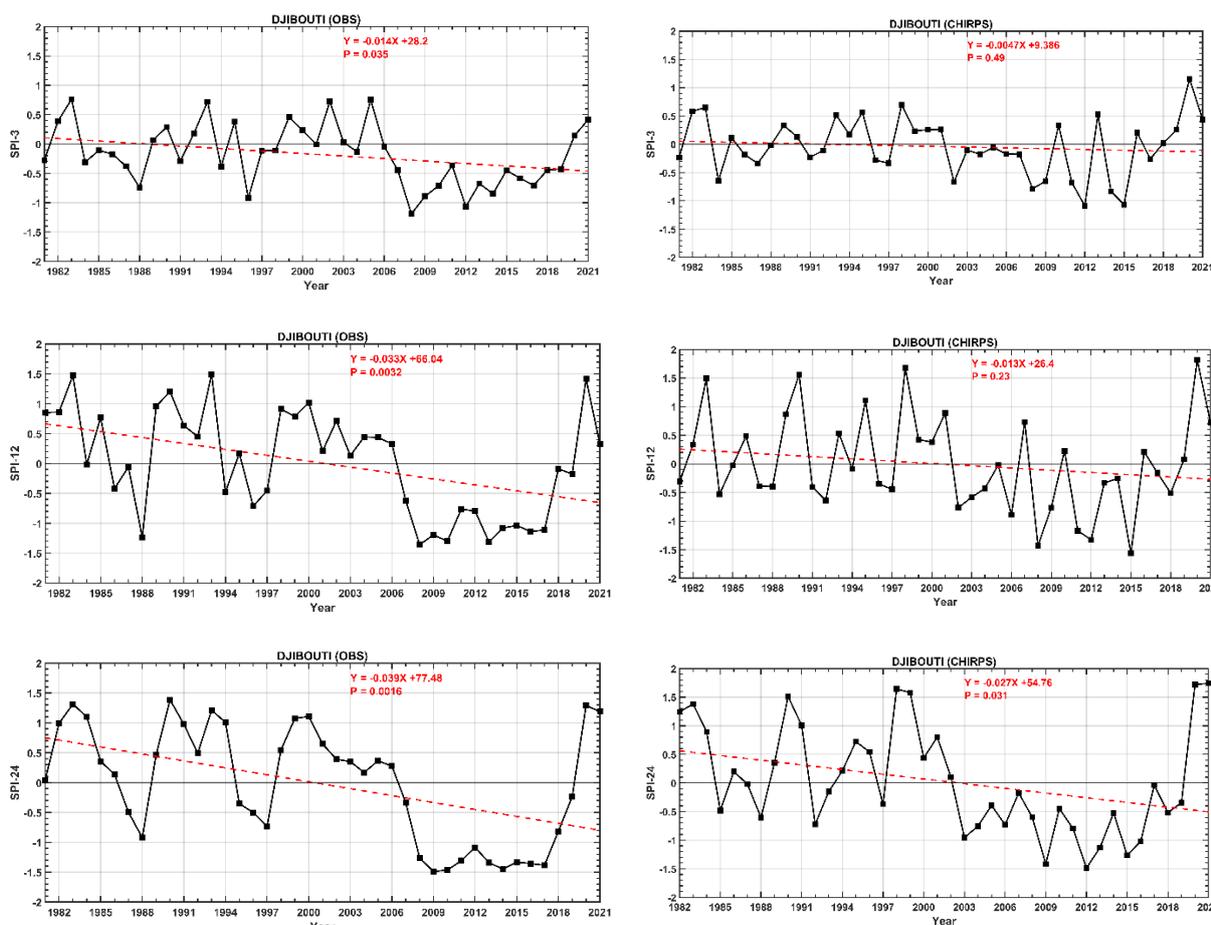


Figure 8. Interannual variations and linear trends of the annual mean of the SPI-3, SPI-12 and SPI-24 indices at the Djibouti-airport (left panels: observed data; right panels: CHIRPS data at the co-located grid-point) during 1981-2021.

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Table 3. Linear trend values of SPI-3, SPI-12 and SPI-24 at Djibouti-Airport station (observed and CHIRPS data) and in the two sub-regions over 1981-2021 period.

		SPI-3	SPI-12	SPI-24	JF	MAM	JJAS	OND
Airport-Observation	Trend	- 0.60	-1.42	- 1.68	- 1.96	- 1.51	1.02	- 0.37
	P-values	0.028	0.002	0.000	0.003	0.004	0.06	0.51
Airport-CHIRPS	Trend	- 0.19	-0.54	- 1.09	- 1.37	-0.74	0.47	0.19
	P-values	0.49	0.24	0.03	0.01	0.18	0.41	0.73
East-CHIRPS	Trend	-0.08	-0.11	-0.40	-0.85	-0.72	1.44	0.312
	P-values	0.75	0.80	0.45	0.11	0.19	0.005	0.56
West-CHIRPS	Trend	0.44	0.96	1.32	-0.56	-0.65	1.72	0.60
	P-values	0.11	0.019	0.006	0.29	0.22	0.000	0.26

Note: A trend significant at the 5% level is marked with bold font.

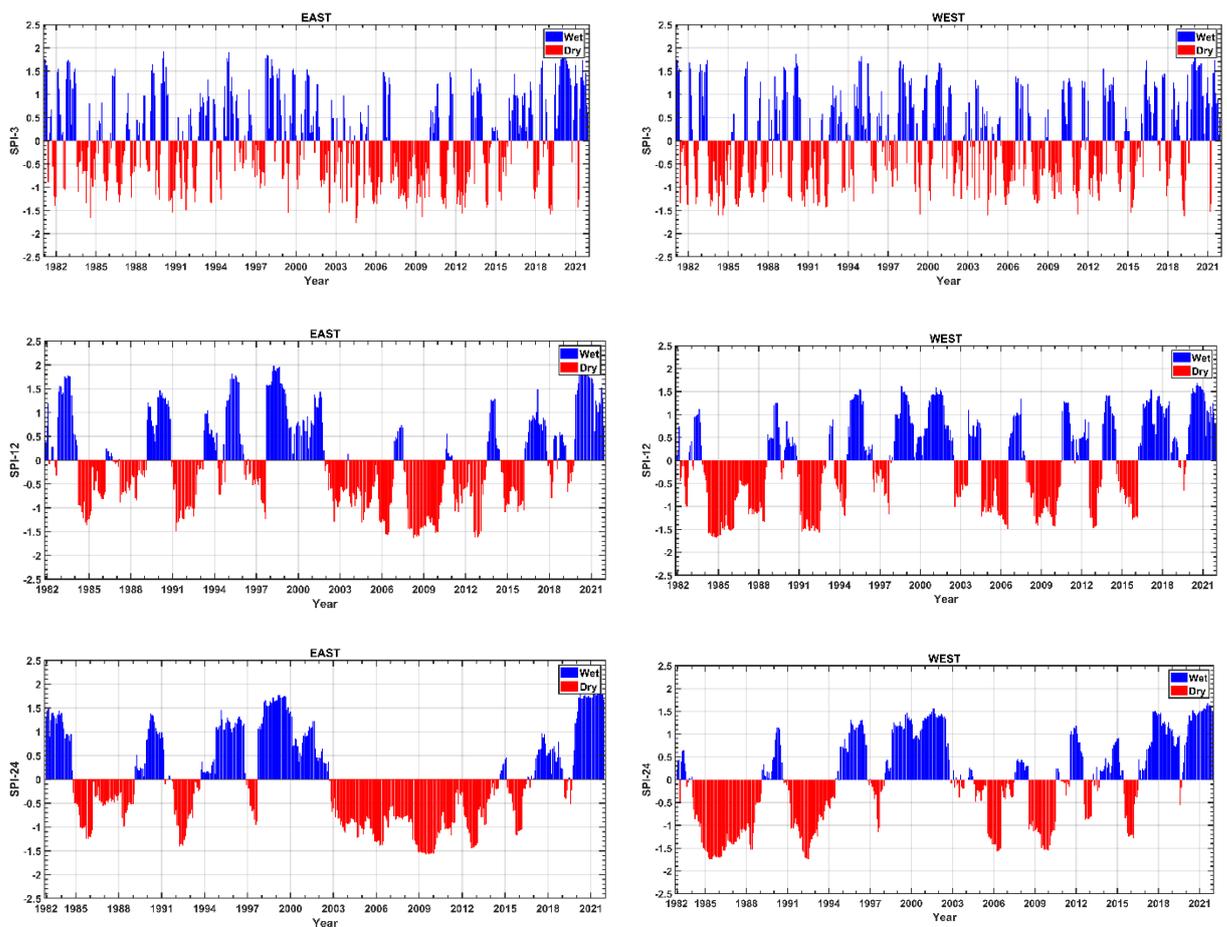


Figure 9. Spatiotemporal variation of SPI index for EAST (left panels) and WEST (right panels) sub-regions computed with CHIRPS during 1981-2021.

3.4. Relationship between droughts and SST indices

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To understand the large-scale climate conditions associated with the occurrence of drought events, teleconnections with global SST (Nino3.4 and IOD) are analysed using the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1.1) dataset [60]. Many studies [61-65] demonstrated that the variability of large-scale climate oscillations in the Indo-Pacific region (e.g., IOD and ENSO) is responsible for the occurrence of droughts in East Africa by modulating the rainfall patterns. Analysing the correlation between SSTs and drought indices allows to depict whether there is a relationship between the occurrence of dry and wet years in Djibouti and IOD and Nino3.4. The correlations between seasonal (JJAS and OND) SPI for both observation and CHIRPS with the IOD and Nino3.4 indices during 1981-2021 are presented in Figure 10 and Table 4. Drought indices in OND seasons show a positive correlation with both SST indices (Table 4). However, IOD appears to have the largest influence with significant correlation values of 0.36 and 0.41 for SPI observation and CHIRPS respectively. As an example, the wet event in 2019 (OND) causing devastating floods in Djibouti city is linked with a positive IOD anomaly (Figure 10). During MAM, there is also a significant negative correlation (-0.33) between SPI and IOD, although the correlation is moderate. SPI indicate non-significant negative correlation in both SST indices. Significant positive correlation with IOD is observed in the eastern and western region (Table 4). These results are in agreement with the previous studies showing a strong forcing of the OND seasonal rains further south in Equatorial East Africa by ENSO and the IOD, while the MAM rains are only weakly related to Indo-Pacific SST anomalies. Changes in SST gradients between the Warm Pool area and nearby equatorial oceans have often been suggested to explain the protracted drought which affected Eastern Africa in the early period of the twenty-first century during this season (including the Djibouti area as demonstrated above), but there is still much uncertainty on its real cause [3, 26, 66-67].

During JJAS, the SPI is negatively correlated with Nino3.4, hereby suggesting the influence of El-Niño events on drought occurrence in this season. CHIRPS indicate a negative significant correlation (-0.55) between Nino3.4 and SPI at the airport station and the two sub-region (-0.43). For instance, the drought incidence in 2015 (JJAS) is associated with an El Niño year (Figure 10). Droughts driven by El Niño were found to have large scale impacts in the East Africa countries [50, 51]. Recently, Anose et al [68] indicated that the JJAS Kirmet season droughts in Ethiopia was highly correlated with global climate indices such as Nino3.4. Getachew [68] also reported that the recent El Niño-induced drought of 2015/2016 has led to severe impact in Ethiopia pastoralist area. The large-scale climate variability in which Djibouti is influenced are meaningful to develop in the future to better anticipate persistent droughts or devastating floods in the country.

Table 4. Correlation between Seasonal SPI and the IOD and Nino3.4 indices over 1981-2021 period. A statistically significant correlation ($P < 0.05$) is indicated in bold.

	Variables	JF	MAM	JJAS	OND
SPI-Airport (observation)	Nino3.4	0.30	-0.13	-0.27	0.19
	IOD	-0.34	-0.33	-0.06	0.36
SPI-Airport (CHIRPS)	Nino3.4	0.46	0.10	-0.55	0.22
	IOD	-0.01	-0.21	0.06	0.41
SPI-EAST (CHIRPS)	Nino3.4	0,47	0,16	-0,43	0,19
	IOD	0,08	-0,18	0,1	0,4
SPI-WEST (CHIRPS)	Nino3.4	0,46	0,15	-0,43	0,25
	IOD	0,02	-0,15	0,04	0,41

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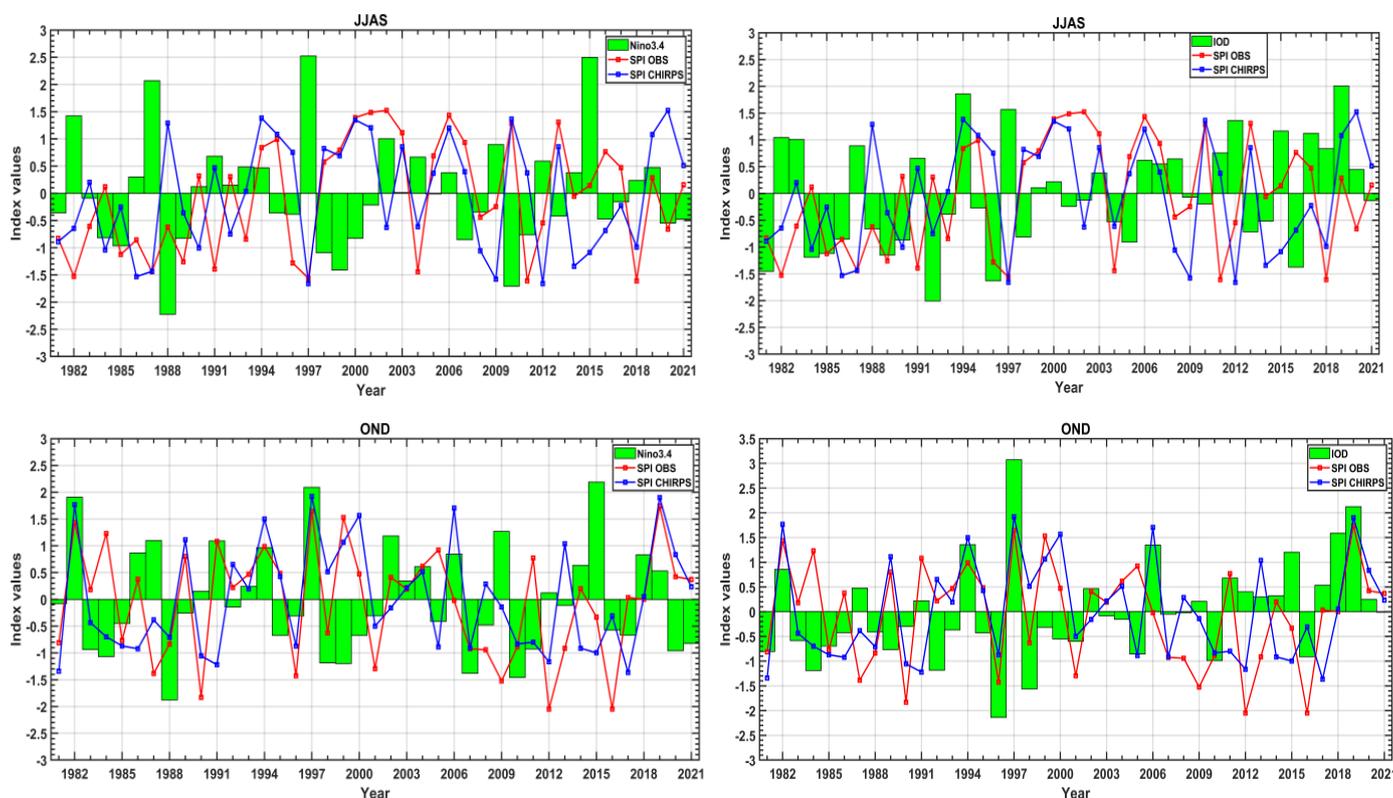


Figure 10. Time series of seasonal variability (JJAS and OND) of SPI observation and CHIRPS at the Airport compared with IOD and ENSO indices during 1981-2021.

4. Conclusions

This study provides for the first time a description of temporal and spatial variation of drought in the Republic of Djibouti for the period of 1961–2021. The dryness and wetness patterns were assessed by characterizing the trends, intensity, duration, and frequencies at seasonal and interannual level through the SPI and SPEI indexes at 3-, 12- and 24-month time series. Based on the Hierarchical Agglomerative Clustering, two sub-regions with different climate variability were identified from east to west. The most important results of this work can be concluded as follow:

- The results of temporal evolution of SPI and SPEI indexes indicate the existence of moderate and severe drought incidences between 1961 and 2000 at 3 months timescale. However, 12 extremes drought events have been detected by SPI-3 since 2003, representing more than 80% of the total extreme drought in Djibouti since 1961,

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- As expected, drought events of shorter duration (detected by 3-month SPI) are more frequent. However, the very long drought periods detected by 12-month, and 24-month indices may have more adverse effects. The longest and most intense dry period was 2007–2017 for both SPI and SPEI index, but the drought is much more pronounced with SPEI than with the SPI. Within this period, the whole country experienced the droughts of 2010–2011 and 2013–2015 but, the severity of drought was much higher at eastern region than western regions.

- SPI results from all timescales showed decreasing trends for both observation and CHIRPS rainfall estimate in the eastern part. In the Western part of the country, contrary to the Eastern sub-region, the SPI trends are positive and even significant ($P < 0.05$). The contrasted trends for the Eastern and the Western sub-regions are partly related to their different rainfall regimes, because the JJAS rains have a dominant part in the West. The analysis also shows that the main drought events of the recent decades tend to affect the MAM and OND rainy seasons.

This study on drought in the Republic of Djibouti, which is the first of its kind, would be very useful to the country's policy and decision makers as well as to the UN Resident Coordinator in Djibouti to better understand the drought cycles in the country for a better coordination of efforts to help the victims of these droughts. This is especially relevant as there is an urgent need to consider the development of a drought early warning system for better drought mitigation in the country as well as the implementation of long-term strategies for better resilience of the agro-pastoral communities most affected by recurrent droughts in this part of the world. In addition, a devastating drought is currently affecting the Republic of Djibouti and the Horn of Africa regions with more than thirteen million people already affected by the drought. Therefore, this first study of drought in the Republic of Djibouti will contribute very strongly to the national strategy for resilience to recurrent droughts that is being developed.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: Minimum (a) and maximum (b) mean air temperature at the airport-station during 1961–2021 at the airport station.; Figure S2: Temporal variation of dry events (red color) and wet event (blue color) for SPEI short-term and long-term during the period 1961–2021: (a) presents short dry periods at three months scale (SPEI-3), (b) shows wet and dry periods at 12-month scale (SPEI-12) and (c) represents a long-dry period at 2-year scale (SPEI-24). Figure S2: Temporal variation of SPI-3 and SPEI-3 for moderate, severe, and extreme flood events at Djibouti-airport from 1961 to 2021, as presented in Figure 6.

Author Contributions: Conceptualization, Writing—Original draft, O.A.D.; preparation, methodology, A.A.I.; validation, data curation M.M.A.; formal analysis, writing—review and editing M.O.A.; investigation, preparation, visualization M.M.W.; contributed through consistent discussion of Methodology and results, provided good supervision, P.C.; discussion, writing—review and editing B.P.; resources, funding acquisition, J.M All authors have read and agreed to the published version of the manuscript.

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