

Article

Evolution and Trends of Meteorological Drought and Wet Events over the Republic of Djibouti from 1961 to 2021

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Abstract: Drought is a meteorological and hydrological phenomenon affecting the environment, agriculture, and socioeconomic conditions, especially in arid and semi-arid regions. A better understanding of drought characteristics over short and long timescales is therefore crucial for drought mitigation and long-term strategies. For the first time, this study evaluates the occurrence, duration, and intensity of drought over the Republic of Djibouti by using a long-term (1961–2021) 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-, 6-, 9-, 12-, and 24-month timescales, so as to document short-, medium-, and long-duration events. The SPEI and SPI showed a significant drying tendency for the indices computed over 12 and 24 months at Djibouti Airport. The eastern coastal region of the Republic of Djibouti was the most affected by the increased drought incidence in recent decades, with more than 80% of the extremely and severely dry events occurring within the period 2007–2017. In contrast, the western regions recorded a positive trend in their SPIs during the period 1981–2021, due to the dominance of the June–September (JJAS) rains, which tend to increase. However, in the last few decades, the whole country experienced the droughts of 2006/2007 and 2010/2011, which were the longest and most intense on record. Large-scale climate variability in the Indo-Pacific region partially affects drought in Djibouti. The SPI and SPEI are significantly positively correlated with the Indian Ocean Dipole during October–December (OND), while for JJAS the SPI and SPEI are negatively correlated with Nino3.4. The wet event in 2019 (OND) causing devastating floods in Djibouti city was linked with a positive IOD anomaly. 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 agro-pastoral populations in a precarious situation.

Keywords: drought characteristics; SPI; SPEI; CHIRPS; rainfall variability



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1. Introduction

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

In East Africa (EA), where extensive regions experience arid or 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 in 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 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 to 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 [13].

Like most countries of East Africa, the Republic of Djibouti faced an unprecedented chronic drought during 2007–2011, resulting in high rates of cattle mortality, food insecurity, and severe water and food shortages [14]. 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 [14]. This drought also caused an estimated 3.9% loss in the gross domestic product of the country [14,15]. On the other hand, drought is one of the main factors of migration for rural agro-pastoral nomads towards urban areas in Djibouti [16]. However, the long-term spatial and temporal evaluation of drought occurrences remains unexplored. This has resulted in poor preparedness and uninformed strategies for drought management in the country. Ozer and Mahamoud [17] 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 the total average rainfall. Recently, Assowe et al. [18] evaluated the 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 spatiotemporal patterns of droughts over the Republic of Djibouti.

Numerous indices have been established to measure drought events and their features. The Standardized Precipitation Index (SPI) [19] and the Standardized Evapotranspiration–Precipitation Index (SPEI) [20] are the most frequently employed drought indicators for keeping track of meteorological, agricultural, and hydrological drought. The SPI requires only precipitation data, while the SPEI requires additional potential evapotranspiration (PET) data to assess drought. Both indices can be computed over periods of time of varying lengths, enabling researchers 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 indices 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 have demonstrated that ENSO partly controls the June–September (JJAS) interannual rainfall variations in Ethiopia and that ENSO was the ultimate cause of most drought years in Ethiopia [21–23]. Other studies [24,25] based on different datasets in the 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 eastern 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 to comprehensively document the spatial and temporal variation of drought characteristics (i.e., frequency, severity, and intensity) in the Republic of Djibouti by using long-term (1961 to 2021) observed rainfall time series combined with a merged (i.e., satellite and observed) precipitation product (CHIRPS). The drought occurrences were examined based on the SPI and SPEI at 3-, 6-, 9-, 12-, and 24-month timescales, so as to document short-, medium-, and long-duration events. Seasonal and annual trends of drought were described to assess whether there was 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 [3,9,26]. The next aim was to determine the drought-prone regions and to assess whether droughts occurred simultaneously in the different parts of the Republic of Djibouti. The teleconnections between the global SSTs (e.g., IOD and ENSO) and seasonal and annual drought indices were also considered. The results of this study could greatly help concerned decision-makers to understand the spatiotemporal variation of droughts and, subsequently, to 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 indices. Section 3 presents the detailed results of the spatial and temporal variability of drought on the seasonal and annual scales. Finally, our conclusions and recommendations are presented in Section 4.

2. Study Area 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 located within latitude 11–12.5° N and longitude 42–43.5° E. The neighboring countries are Eritrea to the north, Ethiopia to the west and south, and Somalia to the southeast (Figure 1). Its coastline extends to about 372 km distributed between the Gulf of Aden (80 km), the Red Sea (38 km), and the Gulf of Tadjoura (254 km) [27]. Elevation in the country ranges from 150 m below sea level (Assal Lake) to over 2000 m above sea level (northern mountainous regions), while the east is lowland.

The Republic of Djibouti records low amounts of precipitation, with the mean annual rainfall ranging from 60 to 300 mm [18]. The local climate is regulated by the complex topographical features of the country and the proximity of the Indian Ocean. Rainfall variations in Djibouti are embedded in large-scale climate variability—particularly that associated with El Niño–Southern Oscillation and the Indian Ocean Dipole (IOD) [18]. Djibouti has two predominating seasons: a cool season (winter) from October through April, and a hot season (summer) from May through September [28]. In winter, the climate is characterized by northeasterly 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 dominate [29], and average temperatures range from 30 °C to 45 °C. The potential evapotranspiration rate is very high, amounting to 2000 mm per year [30].

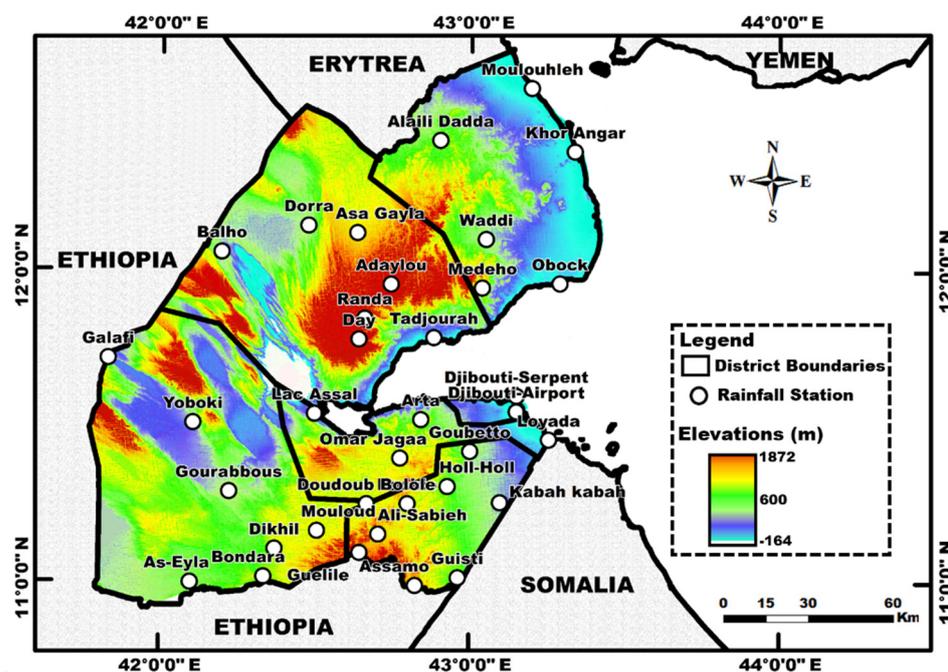


Figure 1. Map and spatial distribution of the meteorological stations and elevation. The white dots on the map represent the 35 meteorological stations across the country.

2.2. Data Sources

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 35 stations distributed across the country (Table 1). These are mainly concentrated in the southeast of the country, while the northwest (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 are 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). The monthly minimum and maximum temperatures were acquired from the ANM for the airport station during 1961–2021. Figure 1 shows the administrative boundaries, elevation, and meteorological stations used in this study.

The most fundamental barrier that hinders regional studies in fields such as drought monitoring is the long-term recording and quality of climatic data. Most ground observations in the Republic of Djibouti contain a long gap in the 1990s and 2000s. Accordingly, it is difficult to analyze the spatial distribution of drought and climatic trends. For this purpose, our study used a satellite-based rainfall estimate from Climate Hazards Group Infrared Precipitation with Stations (CHIRPS version 2.0) [31]. 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 [31]. It merges satellite data from multiple sources with ground precipitation records, used to calibrate the satellite estimates on a monthly timescale. The product is available at a high spatial resolution of 0.05° (~5 km) and on multiple timescales (e.g., daily to monthly) from 1981 to present. In a previous study of Djibouti’s rainfall variability, CHIRPS was compared to other satellite rainfall estimates and reanalysis datasets, as well as against rain gauge data, and the results revealed the good performance of CHIRPS compared to other datasets [18]. Ayugi et al. [32] also recommended CHIRPS for the examination of long-term precipitation trends and for drought analysis in Kenya. On the other hand, CHIRPS datasets are among the most used products for East Africa and display the longest time series to date [33–35]. Overall, the CHIRPS datasets can be employed as an alternative to in situ datasets in regions characterized by scarcity of ground-based datasets for drought characterization.

Table 1. Meteorological gauge station characteristics. All stations have data within the periods 1961–1991 and 2013–2021, with the exception of Djibouti Airport, which has complete data for 1961–2021.

Sites	Location	Latitude (°N)	Longitude (°E)	Elevation (m)	Average Annual Rainfall (mm)
S1	Adaylou	11.97	42.74	1130	140.7
S2	Ali-Sabieh	11.16	42.71	715	130.1
S3	Arta	11.52	42.84	705	181.6
S4	Assamo	10.99	42.83	809	136.5
S5	As-Eyla	11.00	42.10	350	144.7
S6	Asa Gayla	12.18	42.63	615	111.7
S7	Alaili Dadda	12.42	42.90	374	83.4
S8	Balho	12.06	42.20	340	75.6
S9	Bondara	11.02	42.33	488	144.9
S10	Dasbio	11.25	42.80	770	140.9
S11	Day	11.79	42.63	1456	161.0
S12	Dikhil	11.11	42.37	500	138.9
S13	Djibouti Airport	11.55	43.15	8	146.6
S14	Djibouti-Serpent	11.60	43.15	3	117.3
S15	Dorra	12.15	42.48	295	101.8
S16	Doudoub Bolole	11.25	42.67	549	132.8
S17	Galafi	11.60	41.80	519	90.1
S18	Gourabbous	11.28	42.22	310	110.2
S19	Goubetto	11.42	43.00	336	147.0
S20	Guelile	11.08	42.69	816	128.6
S21	Guisti	11.02	42.96	445	113.9
S22	Holl-Holl	11.31	42.93	470	165.7
S23	Kabah kabah	11.25	43.08	274	138.3
S24	Khor Angar	12.39	43.34	7	57.6
S25	Lac Assal	11.53	42.45	313	113.9
S26	Loyada	11.46	43.25	3	88.6
S27	Medeho	11.95	43.04	500	123.1
S28	Mouloud	11.17	42.50	3	129.0
S29	Moulouhleh	12.59	43.20	3	43.9
S30	Obock	11.96	43.29	20	70.5
S31	Omar Jagaa	11.38	42.76	571	139.4
S32	Randa	11.85	42.66	920	221.0
S33	Tadjourah	11.79	42.88	15	150.9
S34	Waddi	12.10	43.05	305	109.9
S35	Yoboki	11.51	42.11	23	132.3

2.3. Methodology

2.3.1. Drought Analysis Procedures

Drought indices with specific timescales are important elements for drought monitoring and management planning systems [36]. The Standardized Precipitation Index (SPI; [19]) and the Standardized Precipitation–Evapotranspiration Index (SPEI; [20]) are useful to assess drought events in arid-dominated regions such as East Africa [37]. 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 indices and compares the normalized rainfall with average rainfall to express the deficit and excess of rainfall for a particular time period and climate. The SPI is globally recommended by the World Meteorological Organization (WMO) for drought assessment [38]. The SPI was calculated based on long-term rainfall data for Djibouti Airport station and CHIRPS regional rainfall indices with the 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 dryness conditions [39]. The SPEI is mainly used to evaluate the role of temperature through its influence on potential evapotranspiration (PET), which relates to global warming and the occurrence of drought [40]. The SPEI is quantified using precipitation (P) and potential evapotranspiration (PET) as input variables, resulting in an index describing the water balance. PET can be calculated using various parameters, i.e., temperature, relative humidity, solar radiation, air water vapor, and sensible and latent heat flux. Due to the limited availability of data, the present study used the Hargreaves technique, which only requires precipitation, maximum and minimum temperature datasets, and the latitude of the meteorological station [41]. Comparative studies examining the suitability of different PET estimation methods have found a satisfactory performance of the PET derived from the Hargreaves equation [42]. SPEI values were estimated by fitting historical observations into log-logistic distribution. More details on the mathematical equations behind the calculations of the SPEI and SPI can be found in [41].

The present study adopts SPEI and $SPI \leq -1.0$ to represent dry conditions, while SPEI and $SPI \geq +1.0$ denote wet events over the study area. Dry events are divided into three main categories: extreme ($SPI/SPEI \leq -2.00$), severe ($-1.50 > SPI/SPEI > -1.99$), and moderate ($-1.00 > SPI/SPEI > -1.49$). Similarly, wet events are categorized as follows: extreme ($SPI/SPEI \geq +2.00$), severe ($+1.50 > SPI/SPEI > +1.99$), and moderate ($+1.00 > SPI/SPEI > +1.49$). These values for the SPI/SPEI define the characteristics of dry and wet conditions in terms of severity, intensity, and the duration of occurrence. A similar approach has been employed in a recent study to examine the spatiotemporal evolution of drought over East Africa [35,43].

2.3.2. Evaluating Drought Characteristics

In order to examine the impact of drought events in the Republic of Djibouti, this study considers the 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 [44]:

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

where n is the number of drought months and N is the total number of months over the study period. Following the dryness categorization as indicated in Table 2, drought months were defined as having an SPI (or SPEI) ≤ -1.0 , whereas SPI (or SPEI) $\geq +1.0$ represented wet events over the study domain.

Table 2. Classification of the severity of drought (or wet) events based on the calculation of SPI/SPEI [19].

SPI/SPEI Values	Categories
≤ -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

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 [45]:

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

where d_i is duration of the i th dry event and n is the total number of dry events.

The intensity (I) of drought can be defined as follows:

$$I = \frac{1}{n} \sum_{i=1}^n SPI_i \text{ or } I = \frac{1}{n} \sum_{i=1}^n SPEI_i \quad (3)$$

where n is the number of drought months (i.e., with SPI (or SPEI) < -1) and SPI_i (or $SPEI_i$) represents the actual values of the precipitation indices for these months.

Additionally, one of the most significant benefits of SPI and SPEI is that they can be computed at various timescales, allowing us to factor in the influence of the variable's previous values in the computation. To assess and characterize meteorological drought in the Republic of Djibouti, we studied both short-term SPI/SPEI (3 and 6 months) and long-term SPI/SPEI (12 and 24 months). According to [19], dry and wet levels were classified according to the seven ranges of SPI and SPEI of values presented in Table 2. These drought severity classes were used to compute time series of drought indices (i.e., SPI and SPEI) based on monthly, seasonal, and annual timescales.

In order to analyze the drought occurrence over the different regions, hierarchical agglomerative clustering (HAC) was applied on mean monthly rainfall at the 35 stations over the period 1961–2021. HAC enables the stations to be grouped step-by-step according to predefined distance metrics and a clustering algorithm (e.g., simple and complete mean links or Ward's methods) [46,47]. In this work, we used Euclidean distance and Ward's algorithm applied to standardized monthly precipitation in order to define clusters of stations with the most similar precipitation regimes. Based on the clustering, homogeneous regions were defined in which the precipitation indices were computed, enabling us to assess the spatial patterns of drought occurrence and trends in the country. Given the fact that the station data had a lot of gaps, CHIRPS was used to compute these regional indices. In the absence of temperature data at this regional scale, only the SPI was computed.

The temporal variations of drought and wet events were examined based on the SPI and SPEI at monthly and seasonal time steps. Long-term linear trends of the SPI and SPEI were computed at different timescales to assess their spatial patterns. The teleconnections between global SSTs (e.g., the IOD and ENSO) and seasonal drought indices were also considered. A summary of the research framework is shown by the flowchart presented in Figure 2.

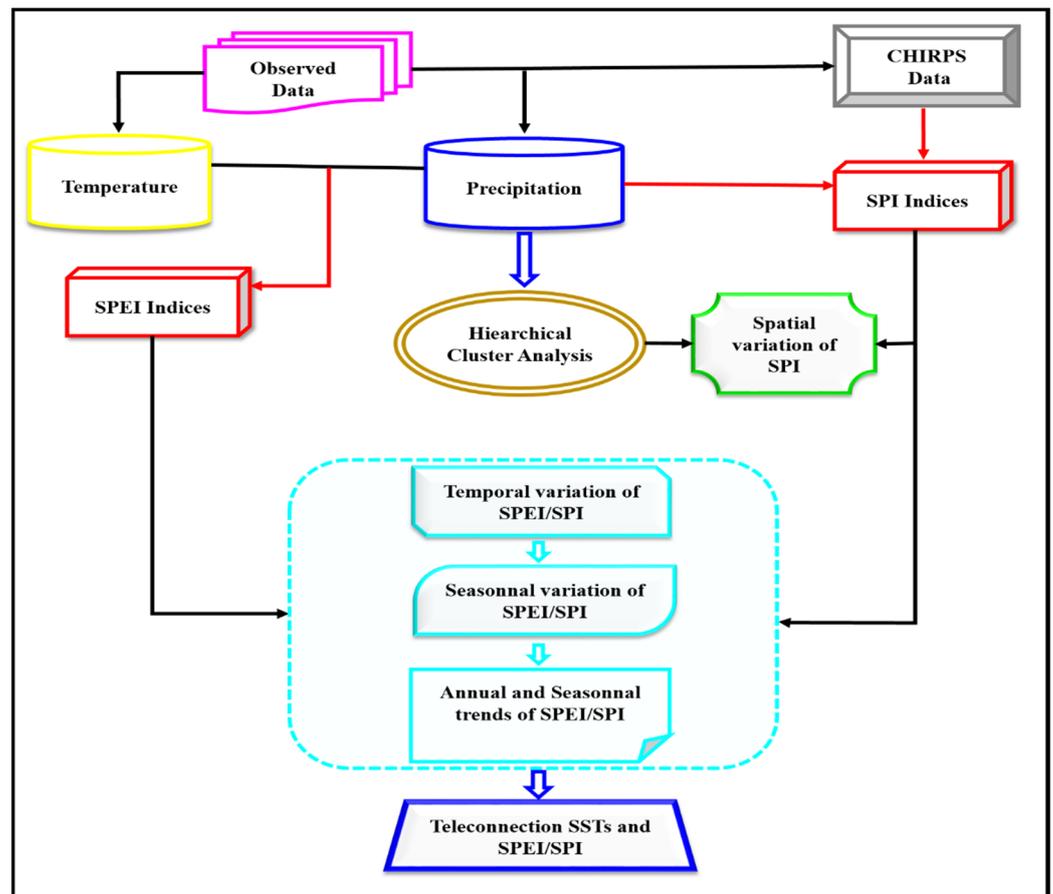


Figure 2. Flowchart of the research methodology.

3. Results

3.1. Mean Climatological Patterns

First, the spatial rainfall variability, which is the key parameter influencing the occurrence of drought events, was analyzed. Based on the 35 rain gauge stations, the annual rainfall amount over the Republic of Djibouti is presented in Figure 3. Rainfall in Djibouti is generally erratic and infrequent, and extreme wet and dry events can be observed in some years [48]. The rainfall amounts display 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 the terrain. The highest rainfall is found along a north–south discontinuous ridge (150 mm to 250 mm), while in the southeast and southwest of the country the annual rainfall is between 100 mm and 150 mm. On the other hand, the northeastern coastal regions receive less than 100 mm annually.

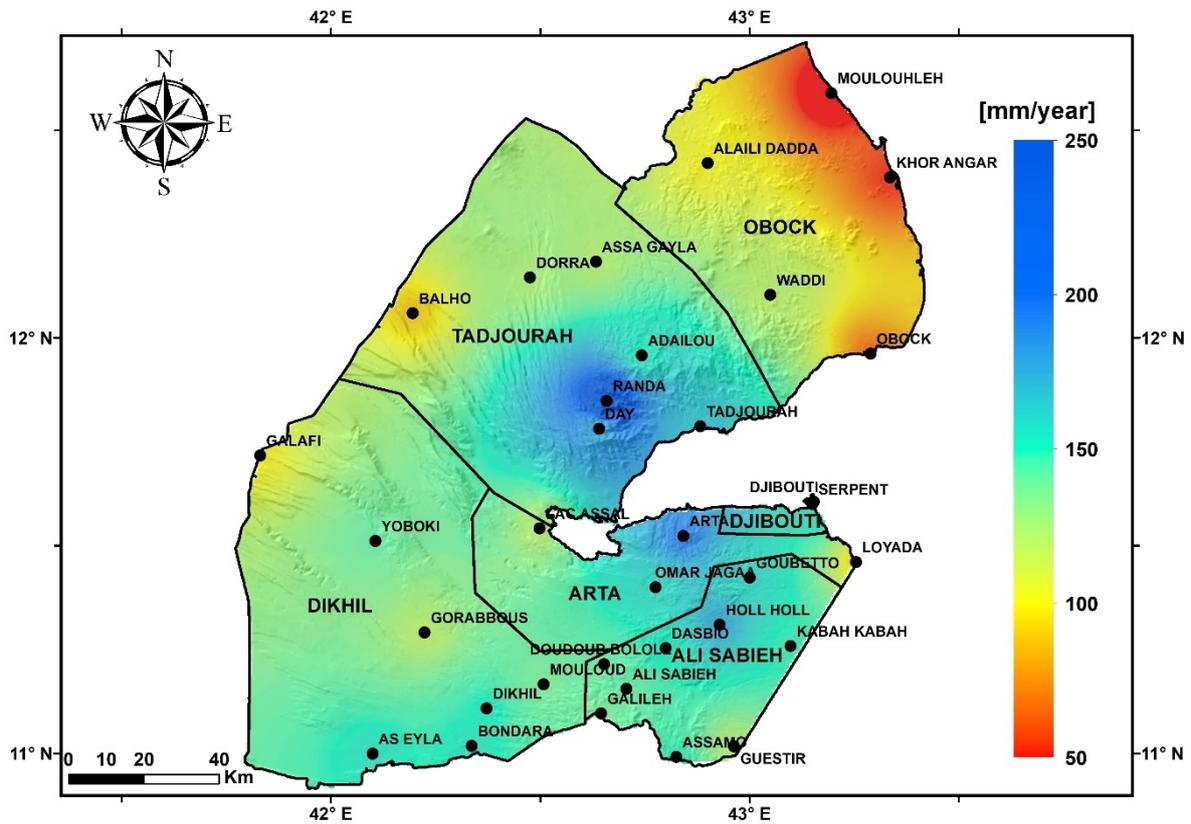


Figure 3. Spatial distribution of mean annual rainfall over the Republic of Djibouti based on 35 meteorological stations.

As a preliminary step to identify spatial patterns of dryness, a clustering method—i.e., hierarchical agglomerative clustering (HAC)—was applied on the mean monthly rainfall at the 35 stations over the period 1961–2021 (Figure 4a). The spatial variability of rainfall regimes in Djibouti reveals the existence of two regions: a coastal region (EAST) and a continental region (WEST). This regionalization (Figure 4b) is further used to study the spatial variation of drought over the whole country in Section 3.4.

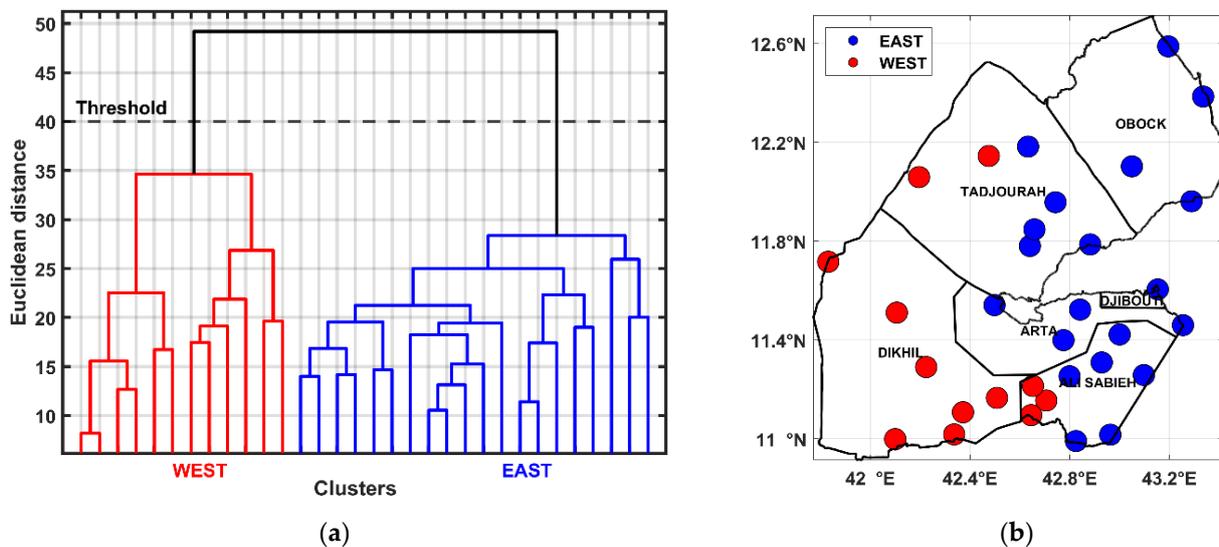


Figure 4. Dendrogram of the HAC (a) of mean monthly precipitation, and a map (b) displaying the distribution of rainfall stations belonging to the two regions (WEST and EAST).

Figure 5 shows the mean monthly precipitation regimes in the EAST and WEST regions for 1961–2021 (Figure 5a,b). The mean monthly rainfall and temperature at Djibouti Airport station, which is part of the EAST region, are presented in Figure 5c,d, respectively. A bimodal rainfall regime is found in the EAST region. Substantial rainfall is recorded during the MAM (March–May) season, with a peak in April and a decline by the end of May (Figure 5a,c). The whole country receives roughly the same amount of rainfall during this season, with an average of ~15–20 mm in April for both regions. A second peak is found in November in the eastern part of the country. This region receives higher amounts of rainfall than the western part during OND (October–December) and JF (January–February). MAM and OND are also the two main wet seasons in many parts of East Africa [44,49,50]. As indicated by Camberlin [51], the equatorial regions and most of the Indian Ocean coastal plains have double-peak regimes with rains in the transition seasons (i.e., MAM and OND).

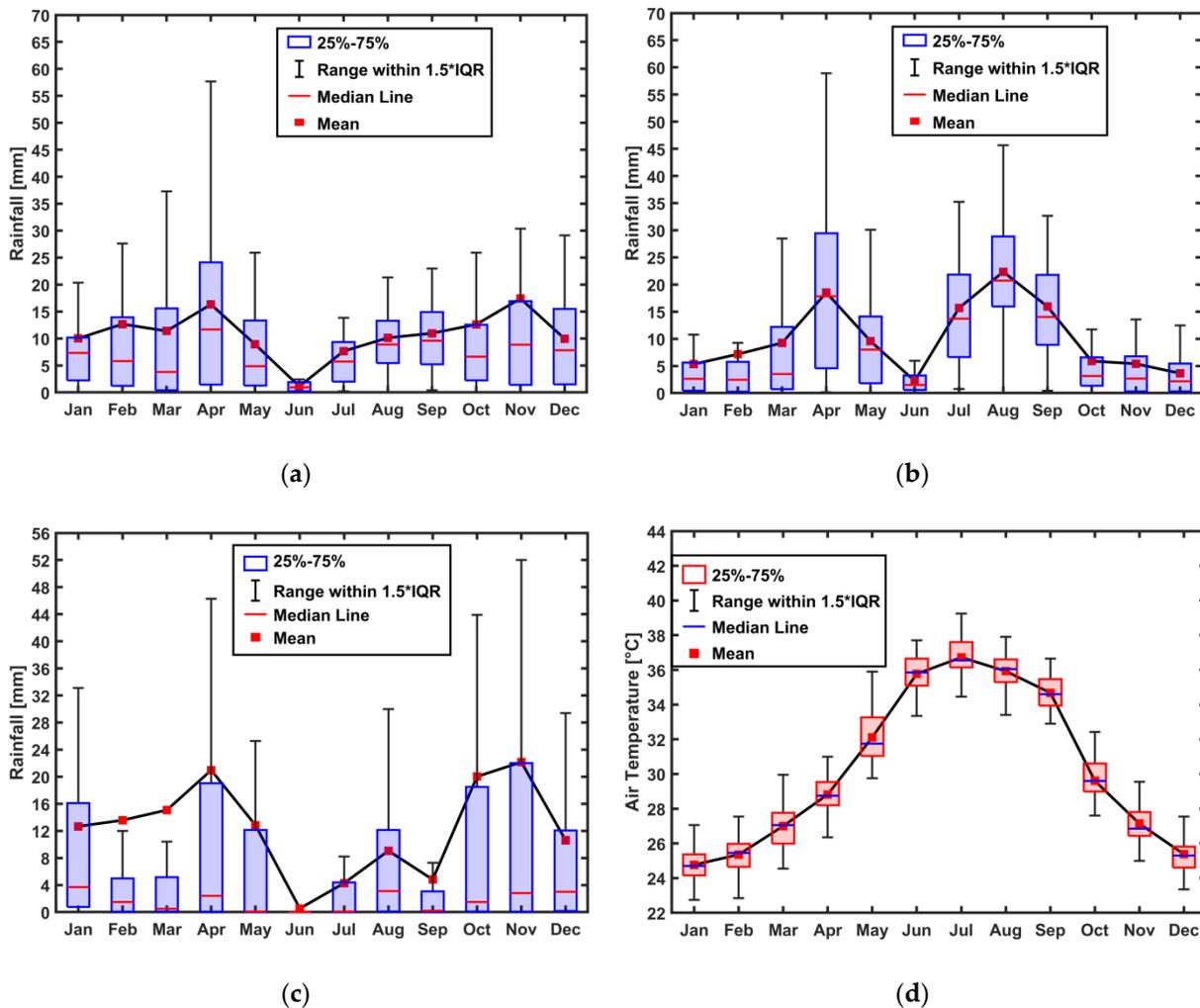


Figure 5. Monthly climatology over the Republic of Djibouti for the period 1961–2021: Panels (a,b) indicate the mean monthly precipitation regimes in the EAST and WEST regions, respectively, as presented in Figure 4. The mean monthly rainfall and mean air temperature at the airport station are presented in panels (c,d), respectively.

The western part of the country singularizes by the JJAS (June– September) season. Starting with a very dry month (June is the driest month across the country), this becomes the wettest period in the western part of the country, with rains lasting from July to September and a peak in August. In contrast, the eastern area receives a small amount of rain in July–August (Figure 5a,c). The July–September rainy season is more widespread

in neighboring Ethiopia and shows a steep gradient from northwest to southeast close to Djibouti [52].

The minimum and maximum air temperatures at the airport station are presented in Figure S1 in the Supplementary Materials. Average monthly temperatures range from 25.2 °C in January to 36.8 °C in July (Figure 5d).

3.2. Temporal Variations in the SPI and SPEI

The assessment of the short- and long-term variations in the SPI issued from Djibouti Airport station exhibited the existence of dry and wet events throughout the study period (Figure 6). The temporal variations in the SPEI for the different timescales were broadly similar and are presented in Figure S2 in the Supplementary Materials. As expected, the drought events were more frequent and with shorter durations for the 3-month and 6-month SPI compared to the 9-month, 12-month, and 24-month SPI (Figure 6). During 1961–2006, few drought events were recorded in Djibouti. For instance, moderate-to-severe drought conditions were observed in 1971, 1981, and 1986. Droughts were more severe and persistent during 2007–2018 than those during other periods, as revealed by both indices (Figure 6 and Figure S2). It was evident that the incidence of drought events increased, especially after 2007, with high intensity and duration (Figure 6d). As indicated in [53], droughts at the SPEI-12/SPI-12 or larger timescales tended to persist much longer (Figure 6d,e and Figure S2d,e). The SPEI results detected the same periods of drought, but the intensity was much higher with the SPEI than the SPI (Figure S2d,e in the Supplementary Materials). This difference between the SPEI and SPI is related to the fact that the SPEI takes into account evapotranspiration, which makes it more sensitive to the combined effects of temperature and rainfall changes. The results further showed that the most intense drought (SPI = −2.19) based on SPI-3 occurred between October and December 1981. For the 12-month SPI, the most intense drought (SPI = −1.65) occurred between January and 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 6d,e and Figure S2d,e). These drought events were found to have large-scale impacts on the environment and society in the Horn of Africa [54]. The 2010–2011 Horn of Africa drought caused a wide-ranging food insecurity situation in the region [11,12,55], and rainfall was at least 50–75% below average in the Horn of Africa region.

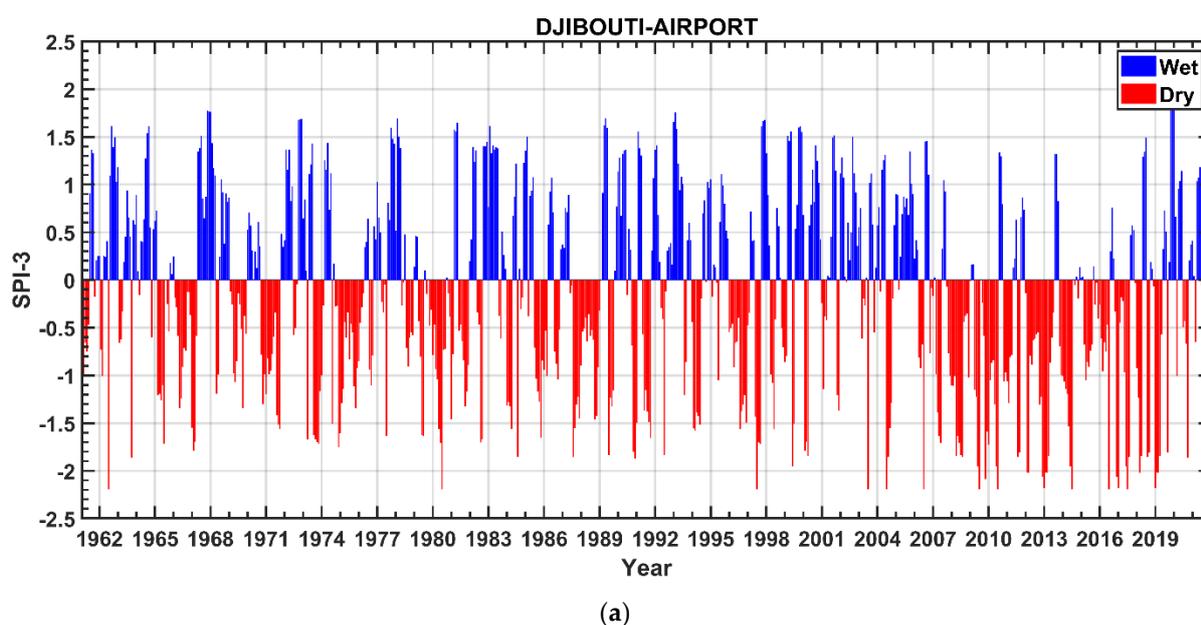
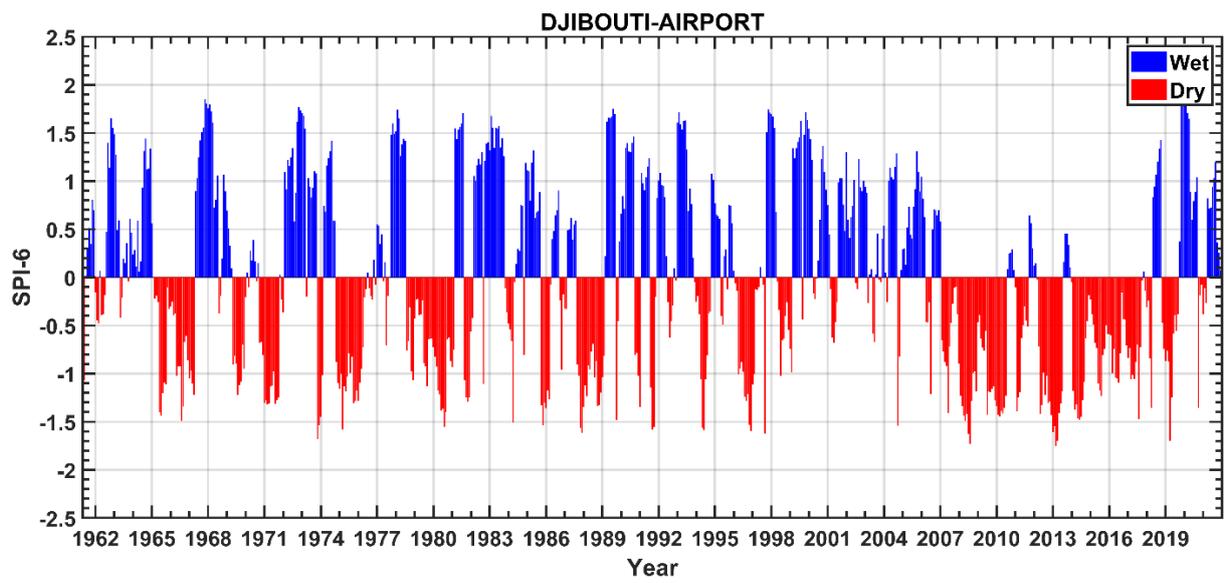
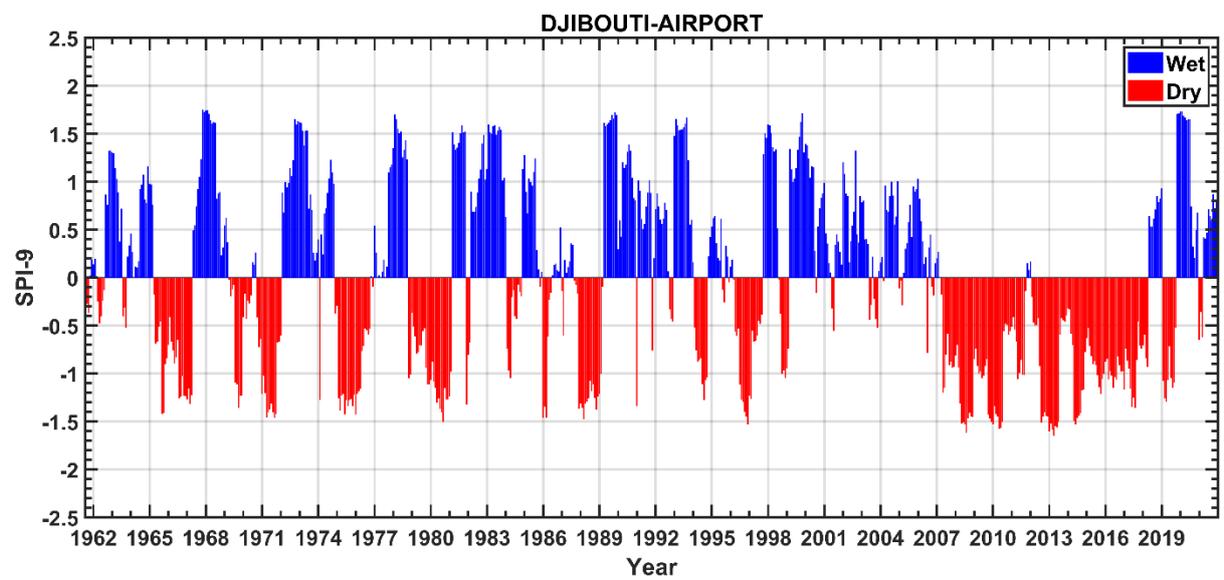


Figure 6. Cont.

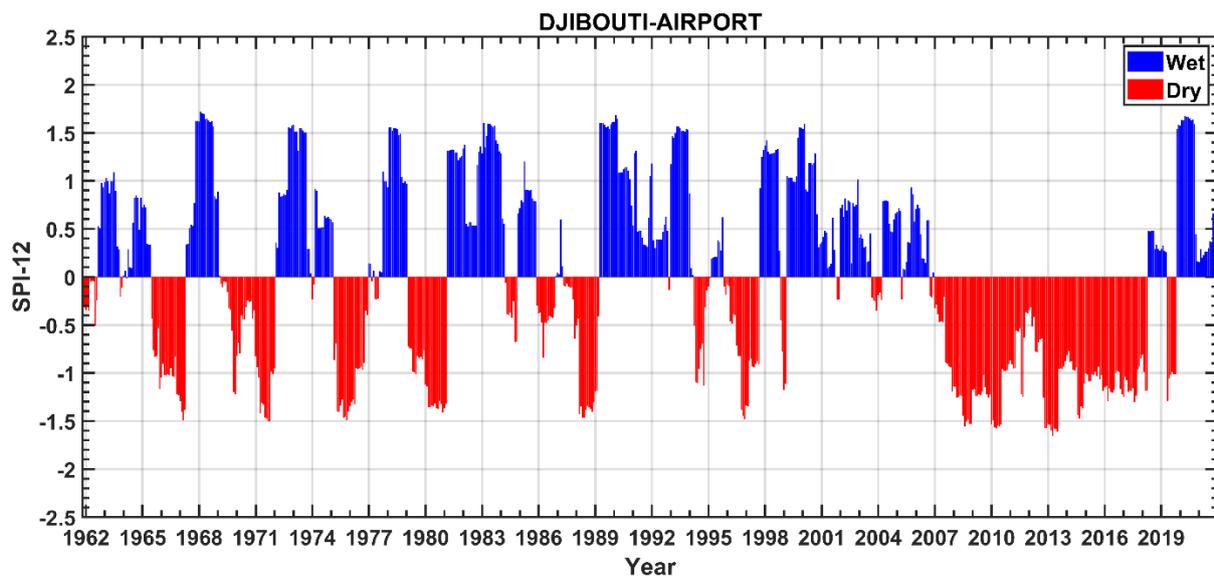


(b)

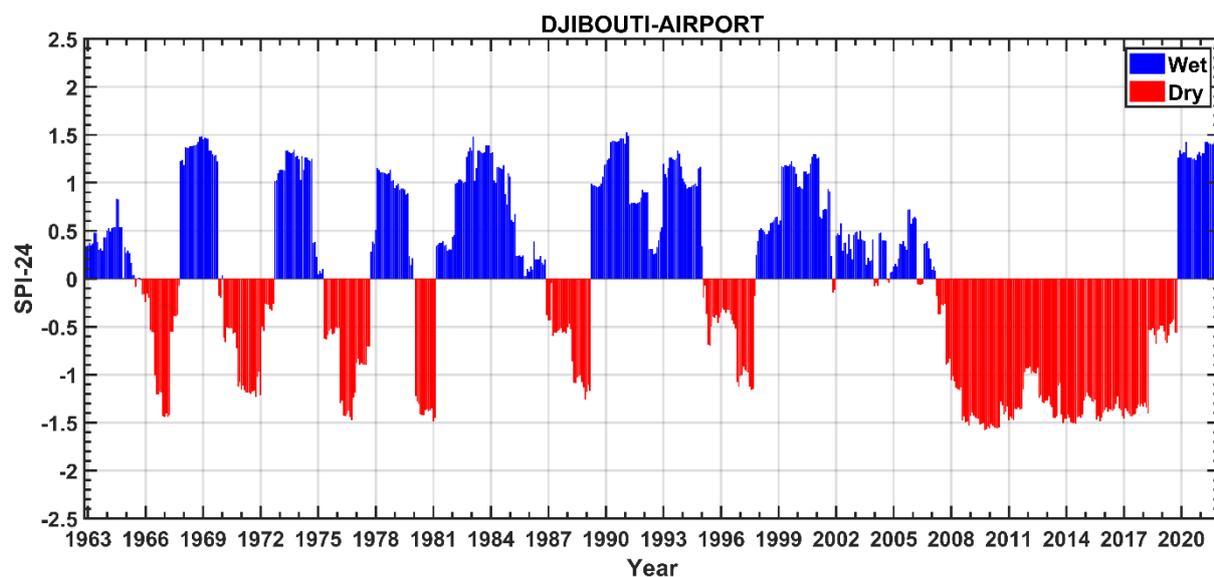


(c)

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(d)



(e)

Figure 6. Temporal evolution of dry events (red) and wet events (blue) for the short-term and long-term SPI during the period 1961–2021: (a) SPI-3, (b) SPI-6, (c) SPI-9, (d) SPI-12, and (e) SPI-24.

Drought duration, intensity, and frequency are important properties for the characterization of droughts. Table 3 presents the mean duration, frequency, and intensity of dry and wet events at various timescales over the Djibouti Airport station during 1961–2021 for both the SPI and SPEI. The duration of dry and wet events tended 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, respectively, and 2.40 and 5.63 months for SPEI-3 and SPEI-12, respectively. The SPI revealed a higher frequency of dry events than the SPEI (for instance, 26.01% and 20.59% for SPI-24 and SPEI-24, respectively; Table 3). The average drought intensity varied from -1.60 for SPI-3 to -1.28 for SPI-12. This suggests that drought intensity decreases with the timescale.

Table 3. Characterization (duration, frequency, and intensity) of dry and 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-9	4.85	22.1	−1.28	5.62	20.17	1.39
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-9	4.29	18.37	−1.37	7.43	21.55	1.41
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 7 shows the long-term temporal variation in the occurrence of dry and wet conditions 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. Based on Table 2, dry and wet events were classified as moderate, severe, or extreme at the 3-month timescale (Figure 7 and Figure S3). Analysis of SPI-3 at Djibouti Airport revealed that changes occurred in the frequency of drought events during the period 1961–2021 (Figure 7a). Moderate and severe drought cases were found between 1961 and 2000, but only three extreme dry events occurred in this period (1962, 1980, and 1997). However, the incidence of extreme drought was more frequent after 2003, yielding critical situations in Djibouti. Twelve extreme drought events were identified between 2003 and 2021 accounting for more than 80% of the total extreme dry events in Djibouti since 1961. In contrast, no severe wet conditions were recorded between 2003 and 2017, and the incidence of moderate wet events was also low, indicating a significant decrease in rainfall in this period (Figure S3). The analysis of SPEI-3 showed moderate-to-severe drought in Djibouti but did not clearly indicate the existence of extreme dry events (Figure 7b). The number of wet years remained the same for both the SPEI and SPI values (Figure S3), but the wet severity of the SPEI was higher than that of the SPI.

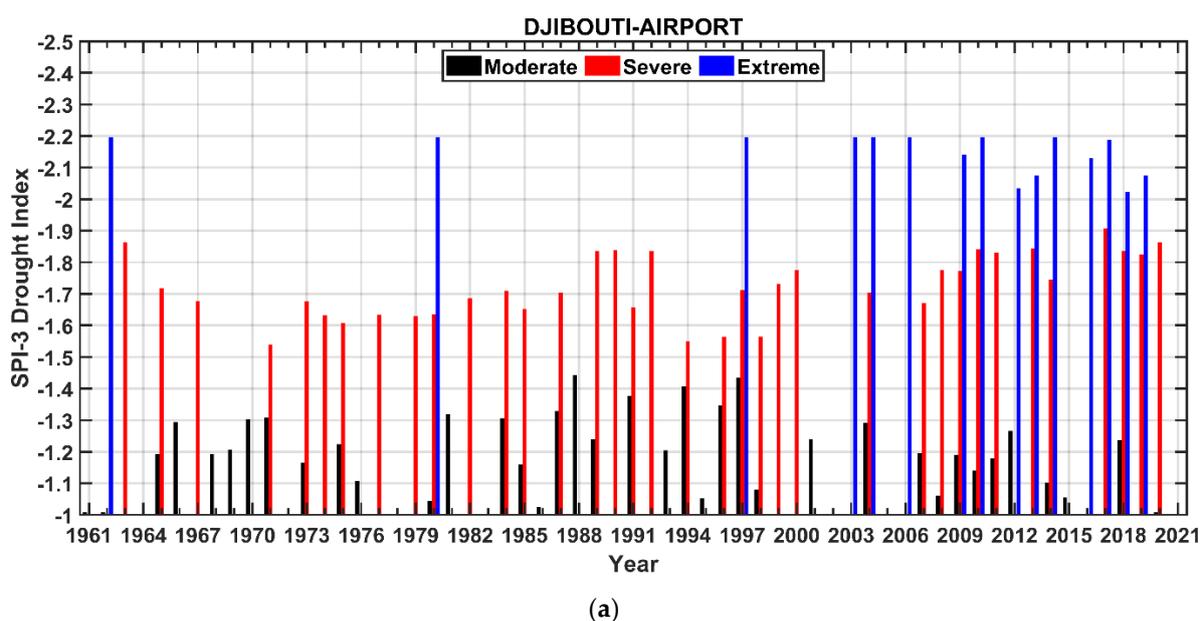


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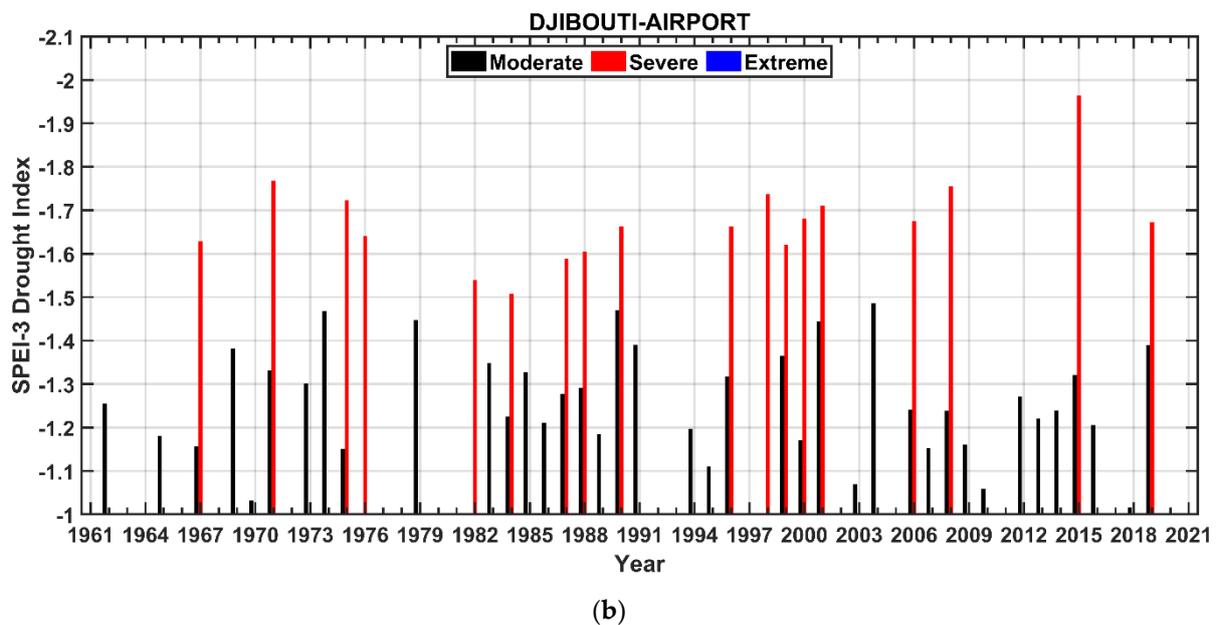


Figure 7. Temporal variation of SPI (a) and SPEI (b) at a 3-month timescale for moderate, severe, and extreme drought events at Djibouti Airport from 1961 to 2021.

3.3. Annual and Seasonal Variations in Drought

In this section, we analyze the SPI and the SPEI on a seasonal scale to assess whether the drying up of Djibouti in recent decades is associated with a specific season (Figure 8). The seasonal and annual variations in the SPEI are presented in Figure S4 in the Supplementary Materials. The analysis of the SPI and SEPI values at a seasonal scale clearly shows the existence of severe and extreme drought events in any season, although with the index being standardized it cannot be used to compare the severity of droughts between seasons. Several extreme dry events have occurred during the JF (January–February) season since 2009, indicating a strong decline in rainfall during this season (Figure 8a). The SPEI and SPI indices for the MAM season showed that moderate wet periods started from the year 1981 until 1988 (Figure 8b and Figure S4b in the Supplementary Materials). The most severe wet event was observed in 1989, which was the wettest year ever registered in Djibouti, with the annual rainfall exceeding 450 mm [18]. This period was followed by alternating wet and dry MAM seasons, and 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 8d and Figure S4b in the Supplementary Materials). Two extreme dry events occurred during OND in 2012 and 2016. However, as for MAM, moderate-to-severe dry events occurred from 2006 to 2017 in the OND season (Figure 8b–d and Figure S4b–d in the Supplementary Materials). This period was characterized by a persistent decline in rainfall during these seasons, which both contributed to the prolonged drought conditions, as displayed above in the monthly SPI. The MAM and OND seasons are actually the wettest seasons in the eastern parts of Djibouti [18]. Limited precipitation in both the October–December 2010 and March–May 2011 rainy seasons was the main cause of the 2010–2011 droughts in the Republic of Djibouti (Figure 8b–d).

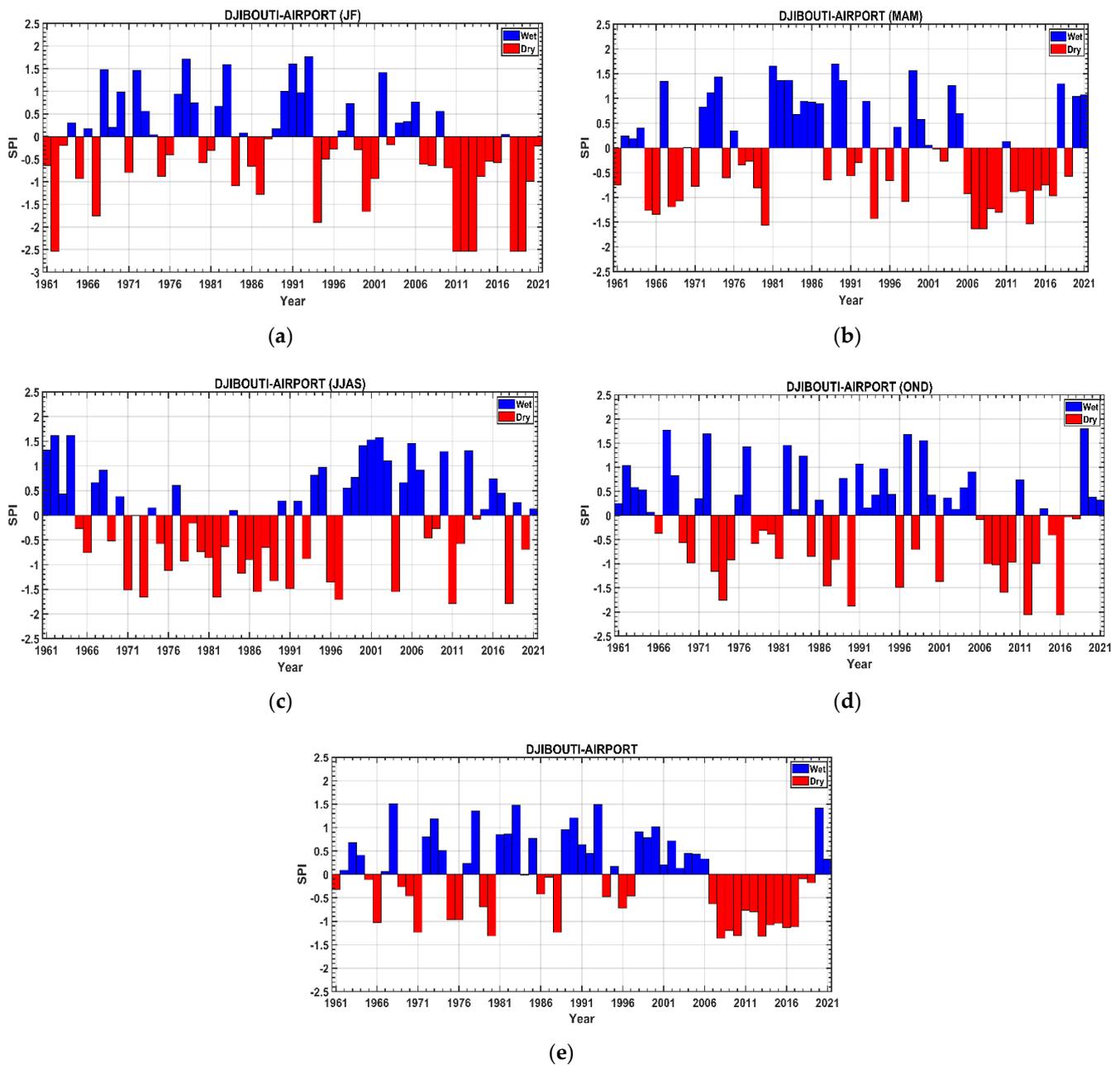


Figure 8. Seasonal ((a) JF, (b) MAM, (c) JJAS, and (d) OND) and (e) annual variability in the SPI over the period 1961–2021 at the Djibouti Airport station.

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 rainy season has had major consequences for food insecurity [9,11,24].

Some similarities between the JF, MAM, and OND seasons are found in the temporal variations in the SPI, but the JJAS season shows a strongly different evolution. The JJAS season experienced the longest recurrent drought events during the 1970s and 1980s (Figure 8c). The SPEI also indicates this long period of dryness in JJAS, but the intensity is lower than in the SPI (Figure S4c in the Supplementary Materials). Williams et al. [57] 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. This was followed

by wetter conditions, interrupted by some dry events (e.g., 1996–1997, 2004, 2011, 2018). However, a consistent decline in rainfall occurred between 2005 and 2017 (Figure 8e).

3.4. Trends and Spatial Patterns of Drought Since 1981

In view of the increased drought conditions in Djibouti in recent decades, we focused on the period 1981–2021 using both observed (Djibouti Airport station) and CHIRPS data. The aim was to quantify the linear trends of the SPI and SPEI computed at different timescales and to assess their spatial patterns by considering the two subregions defined in Section 3.1 (Figure 9 and Figure S5; Table 4). Due to the interrupted data records during 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.

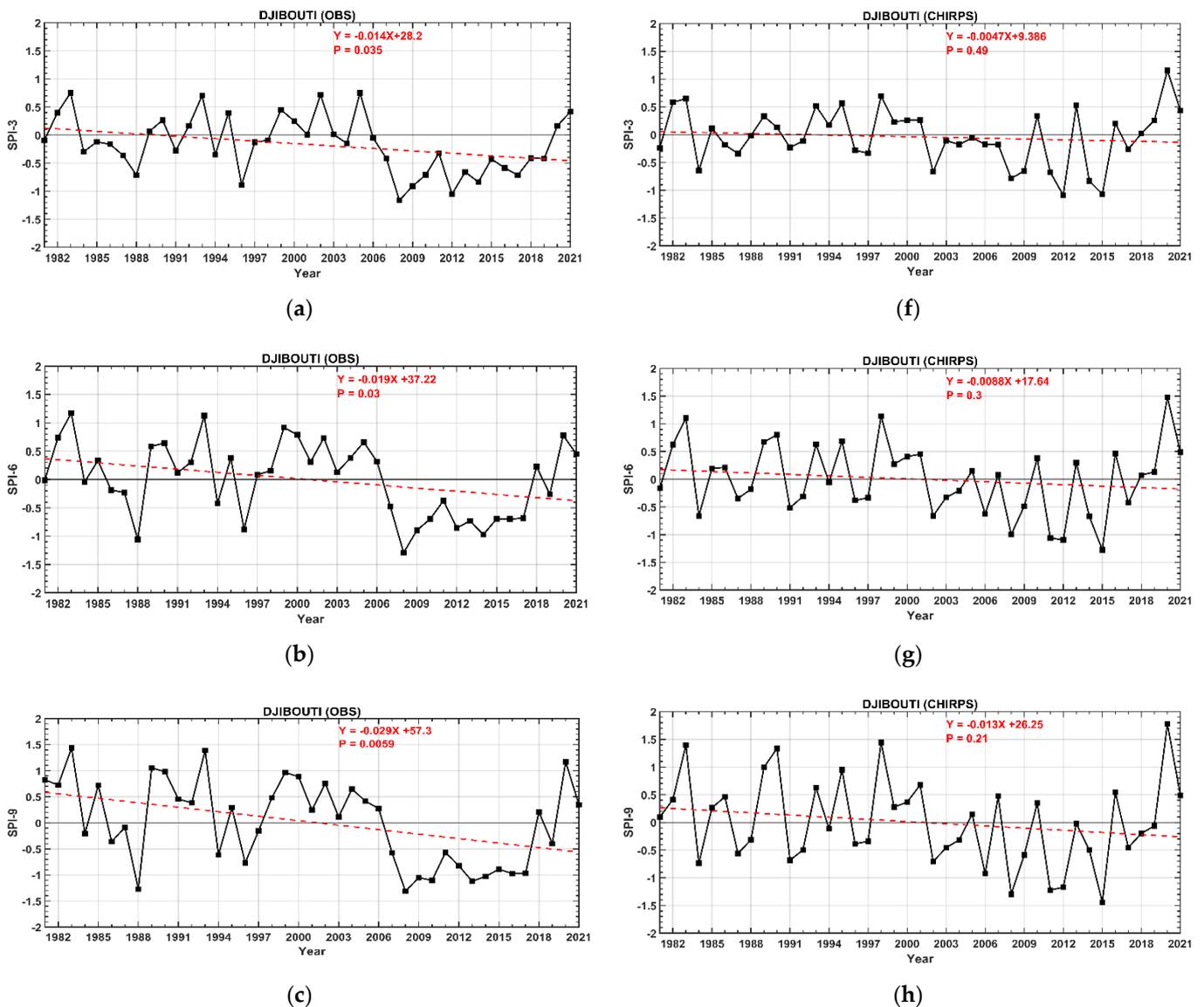


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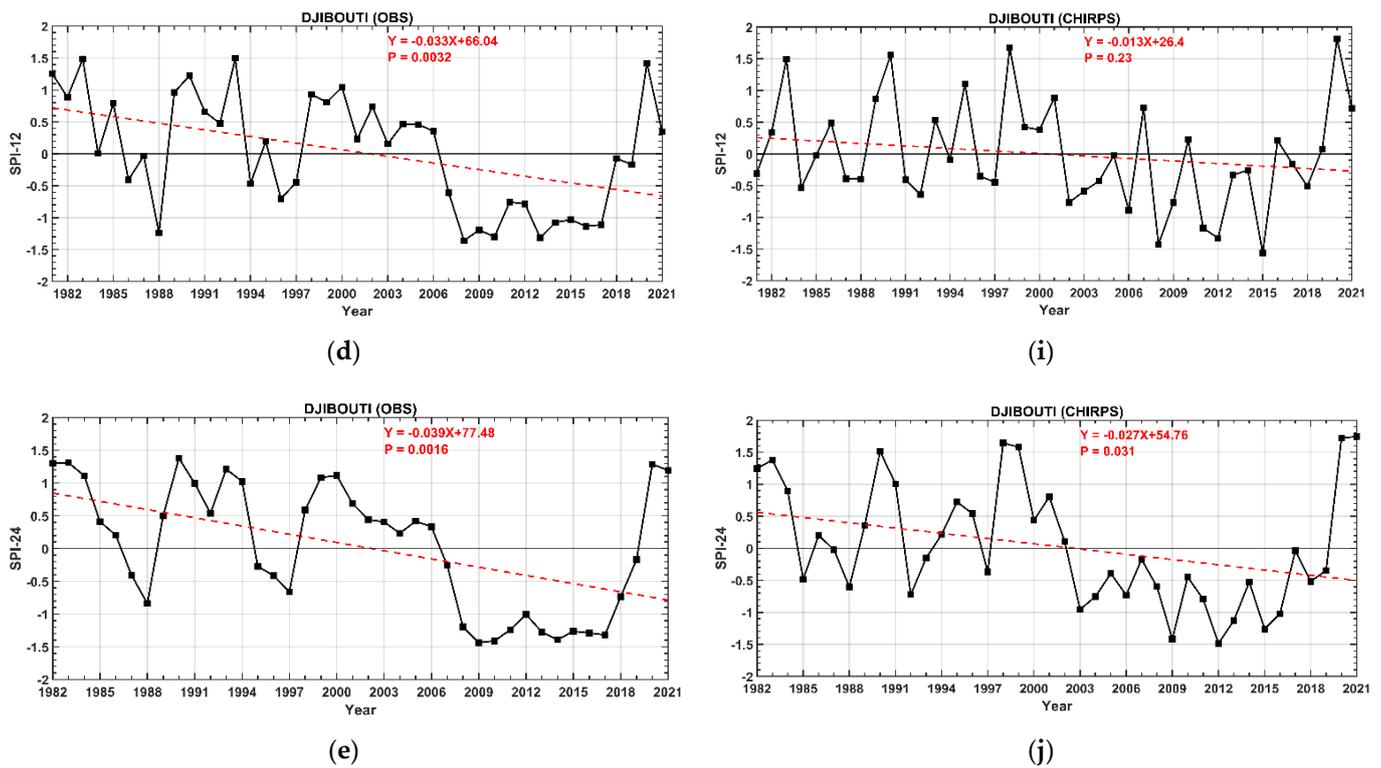


Figure 9. Interannual variations (black line) and linear trends (red line) of the annual mean of the SPI (3, 6, 9, 12, and 24 months) at Djibouti Airport station (left panels (a–e): observed data; right panels (f–j): CHIRPS data at the co-located grid point) during 1981–2021.

Table 4. Linear trend values of the SPI and SPEI (3, 6, 9, 12, and 24 months) at Djibouti Airport station (observed and CHIRPS data) and in the two subregions over the 1981–2021 period.

		3-Month	6-Month	9-Month	12-Month	24-Month
SPEI-Airport (Observation)	Trend	0.12	−0.10	−0.36	−0.56	−1.00
	<i>p</i> -Value	0.73	0.79	0.4	0.04	0.03
SPI-Airport (Observation)	Trend	−0.56	−0.76	−1.16	−1.32	−1.56
	<i>p</i> -Value	0.04	0.03	0.01	0.00	0.00
SPI-Airport (CHIRPS)	Trend	−0.19	−0.35	−0.52	−0.52	−1.09
	<i>p</i> -Value	0.49	0.3	0.21	0.23	0.03
SPI-EAST (CHIRPS)	Trend	−0.08	0.02	−0.08	−0.11	−0.40
	<i>p</i> -Value	0.75	0.96	0.85	0.80	0.45
SPI-WEST (CHIRPS)	Trend	0.44	0.56	0.8	0.96	1.32
	<i>p</i> -Value	0.11	0.11	0.04	0.02	0.01

Note: trends that are significant at the 5% level are marked with bold font.

At Djibouti Airport, the annually averaged SPI values generally showed increasingly negative values, suggesting drying trends. The observed data depicted a significant increasing drought trend ($p < 0.01$) for all of the SPI timescales (i.e., SPI-3, SPI-6, SPI-9, 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 SPEI results indicated a non-significant decreasing trend for SPEI-6 and SPEI-9. However, the SPEI displayed a significant decreasing trend for the long-term indices (i.e., SPEI-12 and SPEI-24) (Figure S5 in the Supplementary Materials). The stronger trends found for the longest SPEI and SPI timescales indicate that while there was only a moderate increase in short-duration droughts, there has been a marked increase in prolonged drought events.

Figure 10 shows the time series of the SPI at 3-, 6-, 9-, 12-, and 24-month timescales for the eastern and western regions during 1981–2021. At the 3-month timescale, moderate-to-severe droughts were observed for both climate zones. The SPI-12 and SPI-24 showed the most prominent drought years in the Republic of Djibouti. At a national scale, the analysis of the SPI-3 time series showed a non-significant decreasing trend in the eastern parts of Djibouti (Table 4; Figure 10). Likewise, the 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 have recorded much wetter conditions (Figure 10). Using the CHIRPS high-resolution dataset, Gebrechorkos et al. [34] found increasing drought in large parts of the East Africa region by analyzing the long-term trends in the 3-, 6-, and 12-month SPI, but their study was restricted to the period ending in 2016 and, therefore, did not include some wetter years that occurred later on.

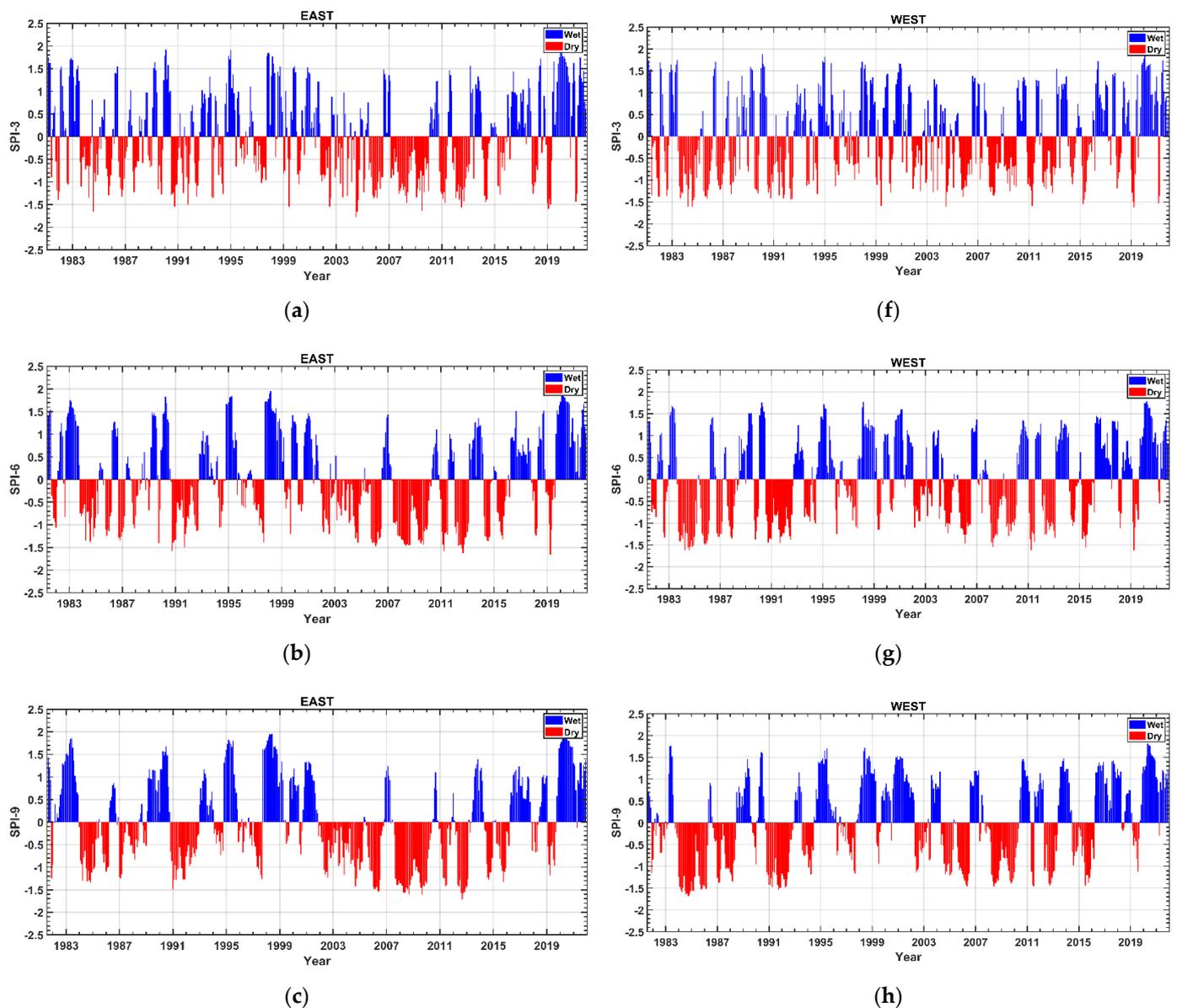


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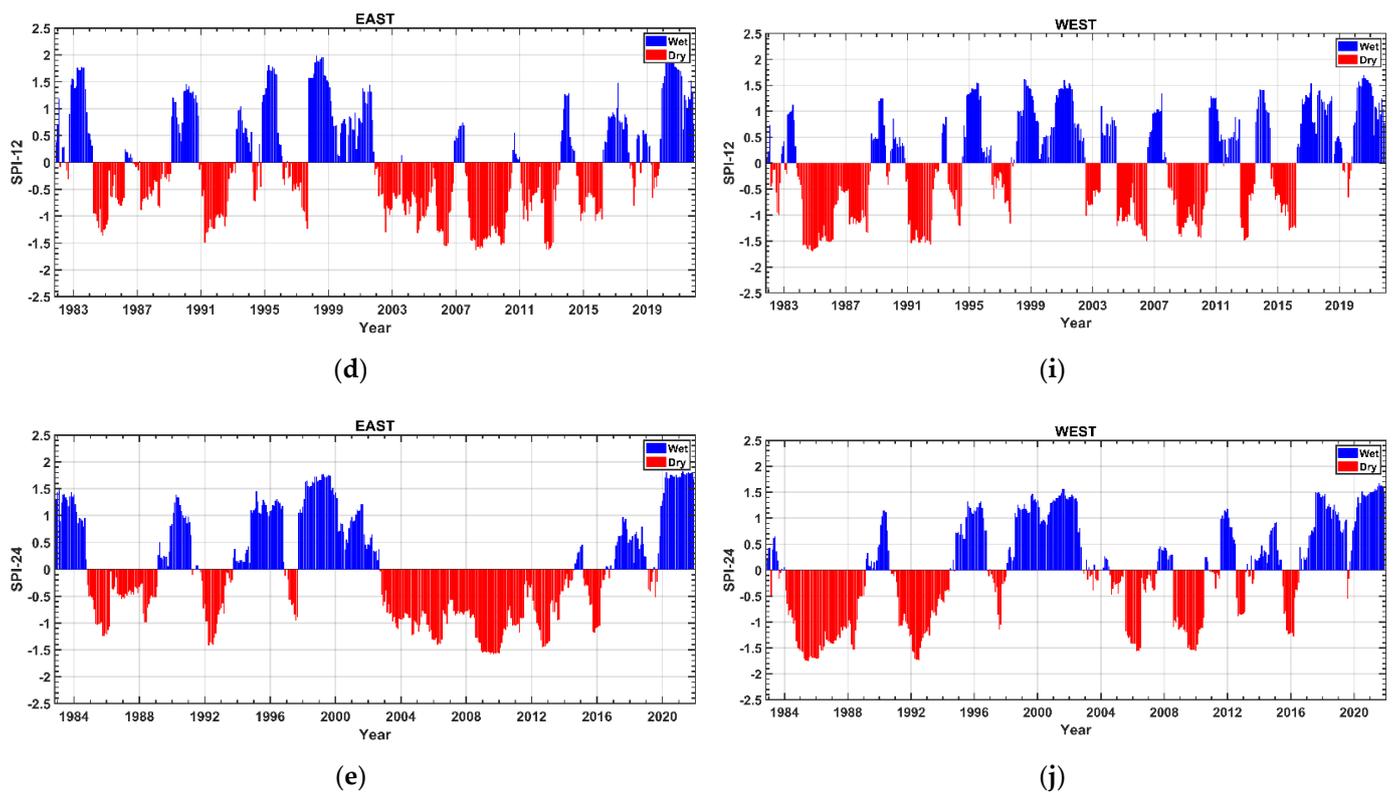


Figure 10. Spatiotemporal variation of the SPI (3, 6, 9, 12, and 24 months) for the EAST (left panels (a–e)) and WEST (right panels (f–j)) subregions computed with CHIRPS during 1981–2021.

In the western part of the country, unlike the eastern subregion, the SPI trends over 1981–2021 were positive and even significant ($p < 0.05$) for SPI-9, SPI-12, and SPI-24 (Table 4). This is due to the fact that the 1980s were particularly dry years (Figure 10), as in much of Ethiopia, Sudan, and the Sahel region. Droughts reoccurred frequently between 2003 and 2016. This correlates well with the extended drought period found in the eastern subregion, but the droughts in the west were interrupted by periods of higher rainfall. Drought conditions actually seem 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 contrasting trends for the eastern and western subregions are partially related to their different rainfall regimes, because the JJAS rains play a dominant role in the west, while in the east the OND and JF rains have a greater share of the annual rainfall. At Djibouti Airport, a significant negative trend (i.e., drier conditions) was observed with the SPI during the JF and MAM seasons (Table 5). The SPEI indicated non-significant negative trends in JF and MAM. CHIRPS also showed a negative trend in these seasons, but this was only significant ($p < 0.05$) in the JF season. For the eastern and western indices, consistent negative trends were similarly found in both JF and MAM, but none were significant. JJAS was the only season experiencing a positive trend (i.e., wetter conditions) for both the observation (SPI) and CHIRPS. This was statistically significant ($p < 0.05$) in both the western and eastern subregions, as was the SPEI at Djibouti Airport. The JJAS season is the main rainy season in the northern and northeastern parts of East Africa [58]. Teshome and Zhang [59] found a positive trend over the period 1980–2015 over most parts of Ethiopia, thereby indicating that the occurrence of drought is decreasing in the JJAS season. Using CHIRPS to compute drought indices, Brown et al. [60] 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 had a positive trend) with respect to the MAM and JF rains

(generally showing a negative trend) indicates that this region does not show the same overall evolution of the SPI as the eastern region.

Table 5. Seasonal trends of the SPI and SPEI at Djibouti Airport station (observed and CHIRPS data) and in the two subregions over the 1981–2021 period.

		JF	MAM	JJAS	OND
SPEI-Airport (Observation)	Trend	−0.72	−0.76	1.32	0.31
	<i>p</i> -Value	0.18	0.16	0.01	0.56
SPI-Airport (Observation)	Trend	−1.96	−1.51	1.02	−0.37
	<i>p</i> -Value	0.00	0.00	0.06	0.51
SPI-Airport (CHIRPS)	Trend	−1.37	−0.74	0.47	0.19
	<i>p</i> -Value	0.01	0.18	0.41	0.73
SPI-EAST (CHIRPS)	Trend	−0.85	−0.72	1.44	0.32
	<i>p</i> -Value	0.11	0.19	0.01	0.56
SPI-WEST (CHIRPS)	Trend	−0.56	−0.65	1.72	0.60
	<i>p</i> -Value	0.29	0.22	0.00	0.26

Note: trends that are significant at the 5% level are marked with bold font.

3.5. Relationship between Droughts and SST Indices

To understand the large-scale climate conditions associated with the occurrence of drought events, teleconnections with global SST (e.g., Nino3.4 and IOD) were analyzed using the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1.1) dataset [61]. Many studies [62–66] have demonstrated that the variability of large-scale climate oscillations in the Indo-Pacific region (e.g., the IOD and ENSO) is responsible for the occurrence of droughts in East Africa by modulating the rainfall patterns. Analyzing the correlation between SSTs and drought indices allows researchers to depict whether there is a relationship between the occurrence of dry and wet years in Djibouti and the IOD and Nino3.4. The correlations between seasonal (JJAS and OND) precipitation indices (both observation and CHIRPS for the SPI; observation only for the SPEI) and the IOD and Nino3.4 indices during 1981–2021 are presented in Figure 11 and Table 6. Drought indices in the OND season showed a positive correlation with both SST indices (Table 6). However, the IOD appeared to have the largest influence, with significant correlation values of 0.44, 0.36, and 0.41 for the SPEI, observed SPI and CHIRPS-SPI, respectively. For example, the wet event in 2019 (OND), which caused devastating floods in the city of Djibouti, was linked with a positive IOD anomaly (Figure 11). During MAM, there was a significant negative correlation (−0.33) between observed SPI and the IOD, although the correlation was moderate. The correlation obtained for the SPEI was also negative but statistically insignificant, while CHIRPS-SPI had non-significant correlations with both SST indices. The significant positive correlation of OND with the IOD was observed in both the eastern and western regions (Table 6). These results are consistent with the findings of 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 were only weakly related to Indo-Pacific SST anomalies. Changes in SST gradients between the Tropical Warm Pool area and nearby equatorial oceans have often been suggested to explain the protracted drought that affected East Africa in the early period of the 21st century during MAM (including the Djibouti area, as demonstrated above), but there is still much uncertainty as to its real cause(s) [3,24,67,68].

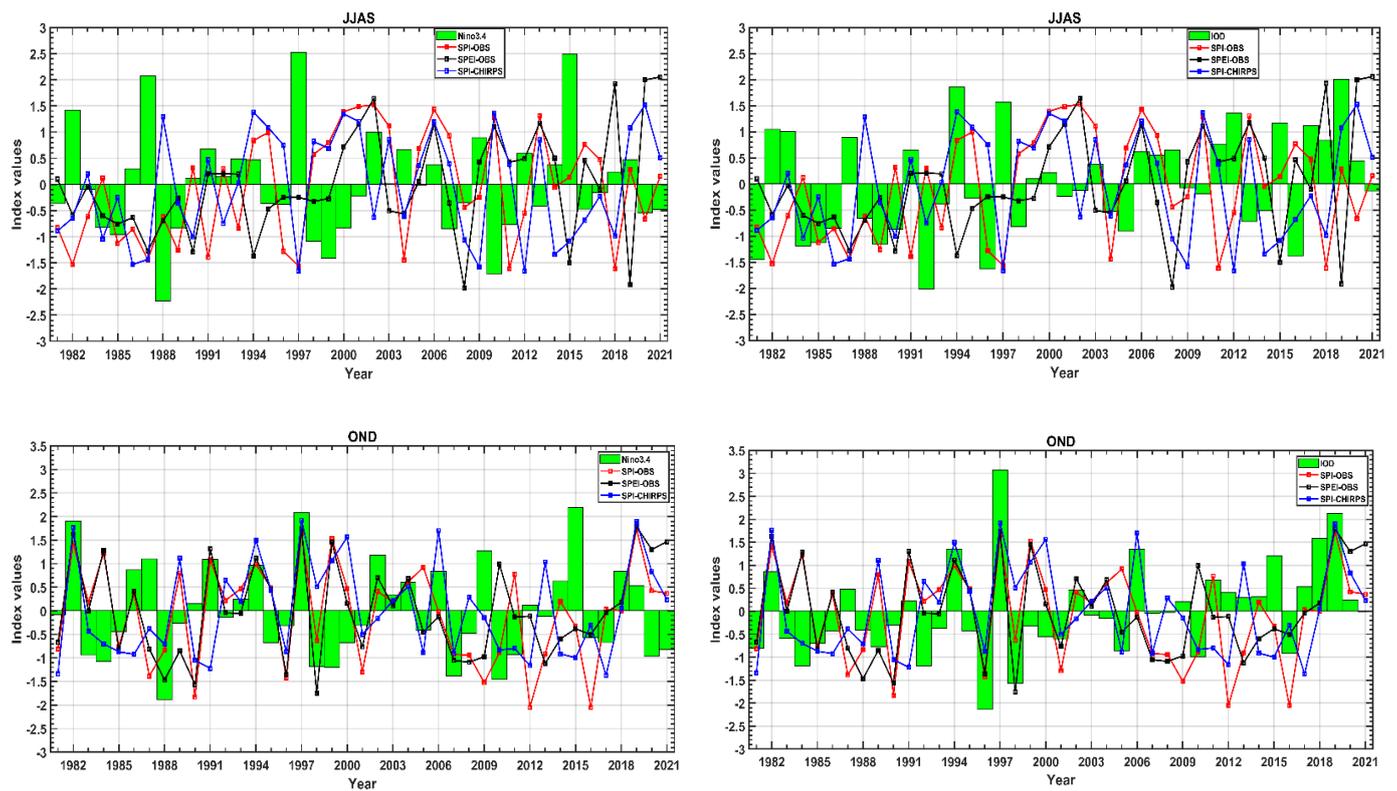


Figure 11. Time series of seasonal variability (JJAS and OND) of SPI and SPEI observations and CHIRPS (SPI) at the airport compared with the IOD and ENSO indices during 1981–2021.

Table 6. Correlation coefficient (CC) between seasonal SPEI/SPI and the SST indices (i.e., IOD/Nino3.4) over the 1981–2021 period. Statistically significant correlation ($p < 0.05$) is indicated in bold.

			JF	MAM	JJAS	OND
SPEI-Airport (Observation)	Nino3.4	CC (<i>p</i> -Value)	0.24 (0.11)	0.040 (0.81)	−0.18 (0.23)	0.24 (0.12)
	IOD	CC (<i>p</i> -Value)	−0.14 (0.36)	−0.16 (0.3)	−0.149 (0.32)	0.44 (0.00)
SPI-Airport (Observation)	Nino3.4	CC (<i>p</i> -Value)	0.30 (0.05)	−0.12 (0.43)	−0.27 (0.08)	0.19 (0.28)
	IOD	CC (<i>p</i> -Value)	−0.34 (0.03)	−0.33 (0.03)	−0.06 (0.64)	0.36 (0.02)
SPI-Airport (CHIRPS)	Nino3.4	CC (<i>p</i> -Value)	0.46 (0.002)	0.10 (0.54)	−0.55 (0.00)	0.22 (0.15)
	IOD	CC (<i>p</i> -Value)	−0.01 (0.93)	−0.20 (0.21)	0.06 (0.70)	0.41 (0.00)
SPI-EAST (CHIRPS)	Nino3.4	CC (<i>p</i> -Value)	0.47 (0.02)	0.16 (0.42)	−0.43 (0.00)	0.19 (0.09)
	IOD	CC (<i>p</i> -Value)	0.08 (0.67)	−0.18 (0.34)	0.102 (0.52)	0.40 (0.00)
SPI-WEST (CHIRPS)	Nino3.4	CC (<i>p</i> -Value)	0.46 (0.01)	0.15 (0.25)	−0.43 (0.01)	0.25 (0.17)
	IOD	CC (<i>p</i> -Value)	0.02 (0.42)	−0.15 (0.26)	0.04 (0.51)	0.41 (0.01)

During JJAS, the SPEI and SPI were negatively correlated with Nino3.4, suggesting the influence of El Niño events on the occurrence of drought in this season. CHIRPS indicated a significant negative correlation (−0.55) between Nino3.4 and the SPI at the airport station and the two subregions (−0.43). For instance, the drought incidence in 2015 (JJAS) was associated with an El Niño year (Figure 11). Droughts driven by El Niño were found to have large-scale impacts in the East African countries that record rains in boreal summer [54,69].

Recently, Anose et al. [39] indicated that the JJAS Kirmet season droughts in Ethiopia were highly correlated with global climate indices such as Nino3.4. Getachew [70] also reported that the recent El-Niño-induced drought of 2015/2016 has led to severe impacts in Ethiopia's pastoralist areas. The fact that Djibouti's rainfall is influenced by such large-scale climate drivers offers scope for the development of predictive models to better anticipate persistent droughts or devastating floods in the country.

4. Conclusions

This study provides the first description of the 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 scales through the SPI and SPEI at 3-, 6-, 9-, 12-, and 24-month timescales. Based on hierarchical agglomerative clustering, two subregions with different seasonal rainfall regimes were identified from east to west. The most important results of this work can be summarized as follows:

- The temporal evolution of the SPI and SPEI indicates the existence of moderate and severe drought incidents between 1961 and 2000 at the 3-month timescale. However, 12 extreme drought events have been detected by SPI-3 since 2003, representing more than 80% of the total extreme droughts in Djibouti since 1961.
- As expected, drought events of shorter duration (detected by the 3-month SPI) are more frequent. However, the very long drought periods detected by the 12-month and 24-month indices may have more adverse effects. The longest and most intense dry period was 2007–2017 based on both the SPI and the SPEI. Within this period, the whole country experienced the droughts of 2010–2011 and 2013–2015, but the severity of droughts was much higher in the eastern region than in the western region.
- The SPI for all timescales showed significant decreasing linear trends, while the SPEI indicated a significant decreasing trend only for the 12- and 24-month timescales at the airport station. Non-significant decreasing trends were observed with CHIRPS-SPI in the eastern subregion. Conversely, in the western part of the country, the CHIRPS-SPI trends were positive and even significant ($p < 0.05$). The contrasting trends for the eastern and western subregions are partially related to their different rainfall regimes, because the JJAS rains—which did not undergo the strong drying trend characteristic of the other seasons—play a dominant role in the west. The analysis also showed that the main drought events of the recent decades have tended to mainly 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 help 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, with more than 13 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: <https://www.mdpi.com/article/10.3390/cli10100148/s1>, Figure S1: Minimum (a) and maximum (b) mean air temperature at the airport station during 1961–2021. Figure S2: Temporal variation of dry events (red) and wet events (blue) for the short-term and long-term SPEI during the period 1961–2021: (a) SPEI-3, (b) SPEI-6, (c) SPEI-9, (d) SPEI-12, and (e) SPEI-24. Figure S3: 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 7. Figure S4: Seasonal ((a) JF, (b) MAM, (c) JJAS, and (d) OND) and (e) annual variability of the SPEI over the period 1961–2021 at the Djibouti Airport station. Figure S5: Interannual variations and linear trends of the annual mean of the SPEI (3, 6, 9, 12, and 24 months) at the Djibouti Airport observation station during 1981–2021.

Author Contributions: Conceptualization, writing—original draft, O.A.D.; preparation, methodology, A.-B.I.A.; 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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Conflicts of Interest: The authors declare no conflict of interest.

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