Impact of sunspot activity on the rainfall patterns over Eastern Africa: a case study of Sudan and South Sudan
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ABSTRACT
The relation between sunspots and rainfall patterns is still obscure in Africa, especially for Sudan and South Sudan. This research explores the response of rainfall to solar activity in eastern regions of Africa, with a case study in Sudan and South Sudan. Rainfall varies with time; therefore, skillful monitoring, predicting, and early warning of rainfall events is indispensable. Severe climatic events, such as droughts and floods, are critical factors in planning and managing all socioeconomic activities. Similar trends for the sunspot activity (sunspot number and sunspot groups) changes and rainfall variations for different stations in East Africa during the years 1910–2018 were not found. Correlation analysis carried out for the above period indicated a weak negative correlation between the total rainfall and the average number of sunspots over the long-term scale for selected stations in Sudan and South Sudan. The overall result of the paper indicated no significant relationship between sunspot numbers and rainfall in temporal and spatial scales in Sudan and South Sudan.

Key words | rainfall, South Sudan, statistical analysis, Sudan, sunspot numbers

HIGHLIGHTS
- This paper analyzed the rainfall variability of Sudan and South Sudan.
- Many statistical measures were employed to evaluate the rainfall trend.
- The paper specified the link between sunspot numbers and groups with rainfall variability.
- The paper assessed the impact of climate change on rainfall annually and seasonally.

INTRODUCTION
Rainfall is usually considered the most important meteorological variable throughout the world, and especially for African countries. It is the most important part of the hydrological cycle (Nazari-Sharabian et al. 2019a). The surface runoff is majorly dependent on rainfall, among other factors (Nazari-Sharabian et al. 2018, 2019b). Rainfall is necessary to support the Sudan and South Sudan populations’ livelihoods, where agriculture in the majority of these countries is heavily dependent on rainfall (El Tom 1972). Sudan’s ecological conditions vary greatly, from the northern desert region, the central arid and semi-arid regions to the southern tropical rainforests. The average annual rainfall varies from almost zero in the north to more than 1,000 mm in the south (Rhodes 2012). The study focuses on solar activity (SA) in terms of sunspot numbers. The solar cycle (SC) influence on climate is a research subject of high scientific importance due to the rigorous need to estimate and distinguish between natural
variability and climate change. The lack of understanding of the atmosphere’s physical mechanisms of the response to SA changes is a major challenge (Chiodzi et al. 2012). The overall measured change in solar radiation during SC of 11 years is about 0.1%. This change leads to a radiative forcing of intensity of about 0.2–0.3 W/m² in total solar radiation (TSI). Although the net forcing in TSI is small, space measurements indicated significant differences (4–8%) in the UV range of 200–250 nm solar minimum to maximum conditions (Lean et al. 1997). The ultraviolet light fabricates propellant gases from small amounts of water vapor, sulfur dioxide, and ozone. The increase in propellant gases made by gamma sources’ ionization is fixed from nucleation to above 50 nm diameter. That is suitable for cloud condensation nuclei (Svensmark et al. 2013). The mass-flux of small ions may enhance the neutral molecules’ condensation. The increase from ions may represent many percents of the neutral increase (Svensmark et al. 2017). Solar radiation is one of the fundamental natural driving forces of the Earth’s atmosphere. Due to this energy varying temporally and spatially, its impact on the climate is never zero. The climate response must be fully defined to improve our understanding of the climate system and the impact of human activities (El-Mahdy et al. 2016). However, despite all the efforts made, whether subtle differences in solar radiation affect climate and weather or not remains a mystery (Fan et al. 2019). One of the main elements often taken as evidence of response is the similarity of periodicities between several indicators of SA and different meteorological parameters (Nazari-Sharabian & Karakouzian 2020). Some previous studies include a long history of negative or positive correlations between climate and weather factors, such as temperature, rainfall, drought, etc. and SA cycles like the 27-day cycle, the prominent 11-year sunspot cycle, the 22-year Hale cycle and the Gleissberg cycle of 80–90 years (Xu et al. 2008). However, doubts about these relationships will remain as long as the indisputable physical mechanism, which may work to produce these relationships, is not available (Kakad et al. 2019; Michalek et al. 2019). All results show that the most visible feature of global temperature change in the 20th century was the sudden and strong warming that has occurred since the early 1970s and beyond (Tapley et al. 2019). Moreover, over the course of the 20th century, global warming did not occur steadily, as different periods of change were identified (Solomon et al. 2007). Climate change may occur in many remarkable aspects. The precipitation rate increased by 0.05% to 0.1% per annum in the 20th century in the majority of the middle and high latitudes in the northern hemisphere, while it increased by 0.02% to 0.03% per annum in tropical areas (10°S to 10°N). On the other hand, the precipitation rate decreased over most of the northern sub-tropical areas (10°N to 30°N) by about 0.03% per annum in the 20th century (El-Tantawi 2005; Zhang et al. 2019). For the last 30–40 years, climate data for Africa showed that global warming had taken a firm hold. Variation has increased between the years since the late 1960s. In particular, drought has become more intense and widespread (Gommes & Petrassi 1996; Yang et al. 2018; Jiao et al. 2019; Gebrechorkos et al. 2020; Peng et al. 2020). There is plenty of circumstantial evidence that SA changes influence climate over the longer term on regional scales worldwide (Solomon et al. 2019). Recent research has focused primarily on the tropics of eastern Africa; however, the rainy season resulting from the convergence zone’s passage between the tropics penetrates as far north as the Sahel, affecting the area that suffers from severe water stress (Audu & Okeke 2019). The temperature gradient from the pole to the equator, which is maintained by differential absorption of solar radiation, is the driving force of the atmospheric dynamics and the general circulation (Haigh 1996). Accordingly, differences in SA may significantly influence the Earth’s climate (Ndebele et al. 2020). Assessing the impact of solar change on climate is an important step in the task of understanding natural and anthropogenic forced climate fluctuations and change (Haigh 1996; Hathaway et al. 2002; Haigh et al. 2010; Chiodzi 2014; Falchetta et al. 2019). The most useful variable for determining the impact of SA fluctuation on the climate is TSI; i.e., the spectrally integrated shortwave energy flux density in units W/m² reaching the top of the atmosphere (Federov 2019). The record shows a clear 11-year oscillation of roughly 1 W/m², which makes up a relative change of 0.1% in the TSI. This is called the 11-year solar cycle, and will be referred to as ‘solar cycle’ (SC) throughout this study. Strong fluctuations in the TSI also occur at shorter time scales. They are related to the 27 days’ rotational cycle of the sun.
While the short-term changes of the rotational cycle can surpass the 11-year SC (0.3%), the latter is more important for climatic research (Chiodo 2014). The SC is also called ‘the sunspot cycle’ because it can be traced by the sunspot number (SSN). The sunspot is defined as a dark area seen on the surface of the Sun. The SSN reaches from 100 to 200 units in the peaks of the 11-year SC. Figure 1 shows the Sun’s surface in the years 2000 and 2009, representing the maximum and minimum of cycle number 23 (Chiodo 2014). In 2000, the surface was covered by more than 100 sunspots, while it was utterly spotless in 2009. The increase in the SSN leads to a reduction of the visible light emitted by the Sun. Sunspots are usually ringed by brighter zones, called ‘faculae’, that are obvious at extreme ultraviolet images (EUV) of the Sun, as shown in Figure 2. On the 27 days’ solar rotation cycle, the sunspots cause abrupt reductions in the TSI (Fröhlich & Lean 2004). This impact occurs primarily around the maxima of the SC, which is caused by SSN maximization. TSI and sunspots are highly correlated on decadal time scales (Chiodo 2014). Geomagnetic activity and galactic cosmic rays’ phenomena are related to SA.

A connection among the Sun, cosmic rays, and rainfall exists worldwide (Svensmark et al. 2009). The UV in the stratosphere has no impact on rainfall; but, the Forbush decrease influence on rainfall is proven, possibly by ions (Svensmark et al. 2016). The occurrence of the geomagnetic storms and galactic cosmic rays’ peak mostly occurs through the descending phase of the 11-year SC (Steinhilber et al. 2012). The SA periodicity has been investigated by many researchers. The amelioration in data analysis methods has led to more rigorous results on the variation of SA over time (Zhao et al. 2004). The link between SA and rainfall is not new. Laurenz et al. (2019) studied the influence of the changes of SA on precipitation over Europe. The results proved that February rainfall has the strongest relationship with SA in western and central Europe. The correlation between SA and rainfall in central Europe represents positive trend on a decadal scale. Many multidecadal studies on central Europe found a negative correlation coefficient between the precipitation and SA. This may be attributed to the fact that short time lags are small on timescales above the 11-year SC. The flood frequency typically expands through times of low SA (Czymzik et al. 2016). This study’s main objective was to assess the impact of SA on rainfall variation in the study region. The rainfall is the most essential part of the hydrologic cycle. This is critical in the short-, medium- and long-term planning phases for the socio-economic development of the study region and management of water resources.

**STUDY REGION**

Sudan and South Sudan extend over a large area with diverse climate conditions and vegetation cover. The desert surrounds the area in the north with a hot, dry climate and almost no vegetation cover. The region also includes the African Sahel zone in the center (arid to semi-arid climate) with its light and dense savanna. Finally, there is the subtropical region in South Sudan with heavier rains and thick tree cover. It occupies about 2.5 million km² extending between 3° and 22° north latitudes and 22° to 38° east longitudes (El-Tom 1969; Elagib & Mansell 2000). Its north–south extent is about 2,000 km, while its farthest east–west length is about 1,500 km. The boundary of the area from the
north-east is the Red Sea. Nine countries border the study region. Ethiopia and Eritrea surround it from the east. It is bordered by the Democratic Republic of Congo, Uganda, and Kenya from the south. Its boundary from the west is the Central African Republic, the Libyan Arab Jamahiriya, and Chad. In addition, Egypt is located in the north of the area. Temperatures do not vary greatly with the seasons in Sudan and South Sudan; however, rainfall and the rainy season length are severely decreasing. There is almost no rainfall countrywide from January to March due to dry north-easterly winds (Elagib 2010; Chen et al. 2013). By early April, the rainy season starts from South Sudan as the moist south-westerlies reach South Sudan, and by August, the south-westerly flows extend to northern Sudan limits. The dry north-easterlies begin to strengthen in September and push south and cover all of Sudan by the end of December (Jones & Lindesay 1993; Elhag 2006; Chen et al. 2013).

### EXTREME EVENTS

Drought is considered one of the worst natural phenomena that Sudan suffers from. The recurring consecutive dry years in the Sudano-Sahelian region have become usual. There are two types of droughts: the first is widespread drought, which is caused by below-normal rainfall across the country; the second is localized drought that affects only some parts of the country. Between 1961 and 1998, episodes of drought had various intensities in Sudan (Elagib & Elhag 2011). In this period, the two most severe widespread droughts in the century occurred from 1967 to 1973, and from 1980 to 1984, with the latter being the severest. A series of drought events occurred in the years 1987, 1989, 1990, 1991, and 1993, mostly in Darfur and Kordofan in western Sudan, in addition to some parts of the country’s central region. A key example of localized drought is that which affected Geneina and Nyala in western Sudan in 1996. This region reported below normal rainfall while rainfall in central and eastern Sudan was above normal (Mohamed et al. 2014). The drought phenomenon is threatening the agriculture of about 30 million acres of mechanized rainfed lands besides about 16.5 million acres of traditional rainfed lands. Also, nomadic and pastoral groups living in the Sudanese semi-arid zones are affected. Despite the prevalence of drought hazards, floods also affect Sudan. As with drought, two types of floods affect the country: localized floods, caused by exceptionally heavy rainfall, and runoff (flash flood) and widespread floods caused by the overflow of the River Nile and its tributaries (Guha-Sapir et al. 2004; Zhang et al. 2012b). Floods in both forms are highly unpredictable due to the nature of rainfall variability in time and space. In the last 38 years, floods caused by localized heavy rainfall affected parts of central, eastern, and western Sudan during the years 1962–1965, 1978–1979, 1988, 1994, and 1998. The most vulnerable groups to both forms of flooding are people who live in low lands and along the riverbanks. Of the most severe floods recorded for the River Nile (1878, 1946, 1988, 1994, 1998, and 2020), three occurred within the past 30 years. Between April and October, severe sandstorms, or ‘Habouns’, blow frequently in the northern part of the country (ElSiddig 2003).

### Table 1 | Specification of meteorological stations in the study area

| No. | WMO Nr. | Station     | Latitude (N) | Longitude (E) | Altitude (m) |
|-----|---------|-------------|--------------|---------------|--------------|
| 1   | 62640   | Abu Hamed   | 19° 32’      | 33° 20’       | 314          |
| 2   | 62680   | Atbara      | 17° 42’      | 33° 58’       | 348          |
| 3   | 62750   | Ed Deim     | 13° 59’      | 32° 20’       | 379          |
| 4   | 62771   | El Obeid    | 13° 10’      | 30° 14’       | 575          |
| 5   | 62781   | En Nahud    | 12° 42’      | 28° 26’       | 565          |
| 6   | 62752   | Gedaref     | 14° 02’      | 35° 24’       | 599          |
| 7   | 62941   | Juba        | 04° 52’      | 31° 36’       | 458          |
| 8   | 62810   | Kadugli     | 11° 00’      | 29° 43’       | 499          |
| 9   | 62730   | Kassala     | 15° 28’      | 36° 24’       | 501          |
| 10  | 62721   | Khartoum    | 15° 36’      | 32° 33’       | 389          |
| 11  | 62772   | Kosti       | 13° 10’      | 32° 40’       | 382          |
| 12  | 62840   | Malakal     | 09° 33’      | 31° 39’       | 389          |
| 13  | 62641   | Port Sudan  | 19° 35’      | 37° 13’       | 3             |
| 14  | 62762   | Sennar      | 13° 33’      | 33° 37’       | 418          |
| 15  | 62751   | Wad Medani  | 14° 23’      | 33° 29’       | 408          |
| 16  | 62760   | El Fasher   | 13° 38’      | 25° 20’       | 730          |
| 17  | 62660   | Kareima     | 18° 33’      | 31° 51’       | 250          |
| 18  | 62671   | Tokar       | 18° 25’      | 37° 45’       | 19           |
| 19  | 62880   | Wau         | 07° 42’      | 28° 01’       | 439          |

Source: Sudan Meteorological Authority.
DATA

Data from 19 meteorological stations covering different parts of the study region have been compiled to study their datasets’ variability. The specifications of stations are listed in Table 1 and Figure 3. The climate data are composed of mean monthly and annual records of the total rainfall. The rainfall seasons were categorized as four seasons. The dry season occupies the period from December to February. The rainy season extends from June to September. The advancing season lasts through March to May. The retreating season is from October to November (ElSiddig 2003; Funk et al. 2011; Zhang et al. 2012a). The monthly SSNs during the period of 1910 to 2018, which were obtained from Solar Geophysical Data (SGD) of the National Oceanic and Atmospheric Administration (NOAA), were used for SA analyses.

METHODS

Simple linear regression model (SLRM)

Regression analysis is the most widely used statistical technique for examining and modeling the relationship
between variables, and it is the more commonly used statistical technique (Draper & Smith 1998; Brook & Arnold 2018).

**T-test for significance**

The t-test is a statistic utilized to explore if the difference between the means of two datasets is significant (Helsel & Hirsch 2002).

**RESULTS**

**Climatic parameters**

A wide range of climate variations characterizes Sudan and South Sudan. It varies from the northern desert of Sudan, where it scarcely rains through a southward belt of varying summer rainfall. However, in the extreme south-west, almost an equatorial type of rain exists, where the dry season is abridged (ElSiddig 2003). Rainfall in northern Sudan varies annually from zero near the Egyptian border to about 200 mm around Khartoum. The rainy season is about two or three months only, while the rest of the year is almost dry. Moreover, the rain usually comes in isolated showers, which are highly variable in time and location. In the quarter south of the country’s center, the rainfall rarely exceeds 700 mm annually. Rains in that quarter are concentrated in less than four months of the year. In the southernmost quarter, the rainfall exceeds 800 mm annually, as shown in Figure 4(b). The third climatic region, according to Köppen climate classification, is found in the north of Sudan and extends from 15° north latitude approximately to the northern boundaries. This region can be called a desert climate. This region’s most important characteristics are dry climate and rainfall less than 250 mm annually, as shown in Figure 4(b). Rainfall is influenced by the behavior and nature of the Intertropical Convergence Zone (ITCZ) controlled by atmospheric pressure over and near the African continent (Issa Lélé & Lamb 2010; Zhang et al. 2022a). The ITCZ is the zone that separates the dry

![Figure 4](http://iwaponline.com/jwcc/article-pdf/12/5/2104/923300/jwc0122104.pdf)
northerly wind from the moist south to south-westerly winds. It oscillates north and south, following the superficial movement of the Sun. South of the ITCZ, the weather is humid with occasional rainfall (Alia & Mohamed 2014).

The distribution of the mean annual rainfall (MAR) over the study area

The term MAR refers to the average amount of rainfall that may be received during the course of a year. The MAR trend distribution over the study area follows a fairly simple pattern in which the amounts decrease northward in a very marked negative correlation with the latitude. Over the southern parts, the MAR may exceed 1,500 mm, while along the northern frontiers of the country, the yearly average is less than 3 mm. The general decrease in the rainfall amounts is from south-west to north-east which is quite understandable if the direction of the rain-producing winds is taken into consideration. MAR in the northern half of Sudan varies from close to zero near the border with Egypt, to about 200 mm around Khartoum city. The rainy season ranges from two to three months while the rest of the year is almost dry. Moreover, the rain usually falls in isolated showers, which are highly variable in time and location, with a relative standard deviation ranging between 40 and 60% (Huber 2018). In the quarter south of the country’s center, the rainfall rarely exceeds 700 mm annually. Rains in that quarter are concentrated in less than four months of the year with a relative standard deviation between 20 and 40%. In the southernmost quarter, the MAR exceeds 700 mm annually, as shown in Table 2. Therefore, the MAR over Sudan trend is to decrease gradually from south to north, as shown in Figure 5.

Trends analysis of annual rainfall over the study area

In this study, the long-term trend of rainfall was investigated at 18 stations in the study region with a full record of 108 years and a minimum record of 98 years. Results showed that there was a negative trend in rainfall in most of the stations. There were three trend zones for rainfall in the study region, i.e., positive trend, negative trend, and no

Table 2 | Mean annual and seasonal rainfall in the study area

| Station     | Annual (Jan-Dec) | Winter (Dec–Feb) | Summer (Jun–Sep) | Advancing (Mar-May) | Retreating (Oct–Nov) |
|-------------|------------------|------------------|------------------|---------------------|----------------------|
| Abu Hamed   | 13.2             | 0.1              | 12.3             | 0.7                 | 0.1                  |
| Atbara      | 73.5             | 0.1              | 62.8             | 5.7                 | 5                    |
| Ed Dueim    | 277.2            | 0.1              | 254.2            | 13.3                | 9.5                  |
| El Obeid    | 365.1            | 0.1              | 328.3            | 19.1                | 17.5                 |
| En Nahud    | 387.4            | 0                | 345.2            | 22.3                | 19.9                 |
| Gedaref     | 629.9            | 0.1              | 566.8            | 32.2                | 30.8                 |
| Juba        | 976.8            | 26.9             | 493              | 295.4               | 161.5                |
| Kadugli     | 722.9            | 0.3              | 556              | 89.7                | 76.9                 |
| Kassala     | 295.3            | 1.3              | 224.3            | 16.1                | 56.3                 |
| Khartoum    | 160.7            | 0                | 150.1            | 4.8                 | 5.9                  |
| Kosti       | 390.5            | 0                | 349.3            | 22.8                | 18.3                 |
| Malakal     | 783.9            | 0.8              | 564.9            | 129.9               | 88.2                 |
| Port Sudan  | 97.8             | 25.5             | 8.3              | 2.9                 | 60.9                 |
| Sennar      | 453              | 0.1              | 406.4            | 24.1                | 22.5                 |
| Wad Medani  | 344.8            | 0                | 310.8            | 18.3                | 15.6                 |
| El Fasher   | 263.9            | 0.2              | 239.9            | 16.3                | 7.6                  |
| Kareima     | 25.6             | 0                | 24.5             | 0.5                 | 0.6                  |
| Tokar       | 91.2             | 39.2             | 12.8             | 5.2                 | 32.9                 |
| Wau         | 1,120.9          | 5.4              | 757.4            | 218.7               | 139.4                |

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The results were supported by the least-square method test. Climate data were analyzed to investigate observed climate change in the study region through rainfall trends in the study periods (1910–2018). According to the least-square method test for trend, negative trends of the annual rainfall (long period) were observed at all study stations except Abu Hamed (north). The negative trends ranged between $-1.505$ and $-0.039$ (mm/year) at Kassala and Abu Hamed (north), respectively. According to the least-square method test for trend, the trends at most of the studied stations were not significant. The trends at stations Ed Dueim, Kassala, Kosti, and Wad Medani were very highly significant at a 0.001 level of significance. The stations of Atbara, En Nahud, Khartoum, and El Fasher had a highly significant trend at a $P$-value of 0.01. The trends at stations Kadugli and Kareima were weakly significant at a 0.05 level of significance. El Obeid station had a very low significance at a $P$-value of 0.1, and the trend of the rest of the stations is not significant, as tabulated in Table 3 and shown in Figure 6.

Figure 5 | Distribution of total annual rainfall in the study area.
Table 3 | Annual and summer rainfall trends (mm/year) over the study area

| Station  | Annual trend | Sig. | Summer trend | Sig. |
|----------|--------------|------|--------------|------|
| Abu Hamed| –0.039       |      | 0            |      |
| Atbara   | –0.378       | **   | –0.584       | **   |
| Ed Dueim | –0.651       | ***  | –1.242       | **   |
| El Obeid | –0.132       | +    | –0.75        |      |
| En Nahud | –0.570       | **   | –0.866       | *    |
| Gedaref  | –0.100       |      | –0.124       |      |
| Juba     | –0.563       |      | –0.177       |      |
| Kadugli  | –0.860       | *    | –0.443       |      |
| Kassala  | –1.505       | ***  | –1.463       | ***  |
| Khartoum | –0.501       | **   | –1.103       | **   |
| Kosti    | –0.705       | ***  | –1.325       | **   |
| Malakal  | –0.358       |      | –1.476       | **   |
| Port Sudan| –0.465       |      | –0.016       |      |
| Sennar   | –0.135       |      | –0.278       |      |
| Wad Medani| –0.933       | ***  | –1.685       | ***  |
| El Fasher| –1.009       | **   | –1           |      |
| Kareima  | –0.170       | *    | –0.167       | *    |
| Tokar    | –0.302       |      | –0.032       |      |
| Wau      | –1.148       |      | –0.238       |      |

*Significant at 5% significance level; **significant at 1% significance level; ***significant at 0.1% significance level.

The summer season result showed negative trends of the rainfall at all study stations except Abu Hamed station in the north. The negative trends ranged between –1.685 and –0.016 (mm/year) at Wad Medani (middle) and Port Sudan, respectively. The trends at all stations were not significant, except that Kassala (east) and Wad Medani (middle) were very highly significant at a 0.001 level of significance. Also, the trend at Atbara, Ed Deim, Khartoum, Kosti, and Malakal was highly significant at the 0.01 level. In addition, Kareima, En Nahud, and El Fasher had a weak significance at a P-value of 0.05. Rainfall varies both temporally and spatially with extreme rainfall conditions, such as floods and droughts. In general, between 30°N and 70°N, a rise in rainfall has been observed. This is also true for the area between 0° and 70° southern latitude. In the area between 0° and 30° northern latitude, a general decrease was seen in rainfall. Rainfall has very likely increased during the 20th century by 5–10% over most of the high mid-latitudes of northern hemisphere continents, but in contrast, rainfall has likely decreased by 3%, on average, over much of the subtropical land areas (Dai et al. 1997; Dore 2005). The climate and the environment in the study region have shown localized changes during the course of this century, and recurrent droughts in the last 30 years. Sixty per cent of the study region is affected by desertification. In 1984 and 1985, particularly severe drought and famine resulted in widespread deaths (Kassa 1999).

Through the period of the study, it is noted that substantial depletion of rainfall through the period (1910–2018) has occurred. Annual precipitation has witnessed a 20% decline in magnitude. This has been accompanied in the center of the study region by a contraction of the wet season by about 3 weeks and a southward displacement of rainfall zones of between 50 km and 100 km. Such a migration represents approximately 25% of the fluctuation in precipitation resources which are estimated to have occurred during the last 20 years. These changes have been most evident in the semi-arid zone of the central area of the study region (Hulme 1990). These results are a good match with the findings of Salih et al. (2018) and Mahgoub & Abd Allah (2017).

Time series analysis was conducted using monthly and long-term MAR for four stations in the study region. The results showed that there has been a gradual decrease in the monthly and annual rainfall during the period of 1940–2016 for Shambat and Wad Medani and from 1970 to 2016 for Halfa. In contrast, Gadaref shows a gradual increase in both monthly and annual rainfall. The statistical analysis of the trend for annual and monthly rainfall of Wad Medani and Shambat shows a significant decline, while for Halfa and Gadaref, the trend does not significantly decline or increase. These findings support the results in the papers of Elhag (2006) and Adam (2006).

Analyses for data indicate that there was a decreasing trend of the annual rainfall in Shambat and Wad Medani from 1968 to 1994. After this period, the rain is close to the long-term mean. In Gadaref, there is a decrease during the 1950s until the beginning of the 1970s; however, this decrease recovered from 1975 to 1982 when the station received rainfall higher than the long-term mean. There is another turning point from 1988 to 1994, while in Halfa there is a decrease from 1982 to 1995. This result agrees with the investigation of annual rainfall series for the western and central areas by Eltahir (1989), for a record period of 1928–1986.
Trends analysis of total sunspot number and sunspot group

The linear regression t-test statistical method was used to analyze the SSN periods from 1910 to 2018 to check the periods' variation. The relative SSNs have four clear periods of about 11, 22, 33, and 78 years (Xu et al. 2008). Through these periods, the 11-year period has the most robust amplitude, while the 22-year period has the lowest. Both the intensity and extent of these periods vary from one time to

Figure 6 | Scatter plot of rainfall (mm) for the interval 1910–2018. (Continued).
Figure 6 (Continued).
another. The 11-year period may be less than 11 years, as happened around 1950, or greater than 11 years as occurred around 1900. The 11-year period may range from 10.01 years up to 11.78 years with a mean value of 10.75 years (Zhao et al. 2004). For the 22-year period, the variation ranges from 18.81 to 25.02 years, and the mean is 22.85 years. The 33-year period ranges from 30.67 to 33.28 years, with a mean of 31.97 years. The 78-year period ranges from 76.05 years up to 79.77 years, with a mean of 78.31 years (Xu et al. 2008). Numerical climatic models predict that a change in the sunspot numbers of only 1% per century would alter the Earth’s average temperature by 0.5–1.0 °C (Wade 1995). A 1% change of solar constant results in a change in equilibrium temperature of 0.6 °C, while a 2% increase causes up to a 10% increase in the rate of precipitation, and evaporation as well. Change in precipitation rate resulting from changes in the solar constant is not uniform in all latitudes, but it is small in low latitudes and relatively large in mid and high latitudes (El-Tantawi 2005).

Table 4 | Minimum and maximum parametric values of total sunspot number

| Cycle | SSNmin (yr) | SSNmax (yr) | ASC | PER | Gmin (yr) | Gmax (yr) | SSAmin (yr) | SSAmax (yr) | NSDmax (yr) |
|-------|------------|------------|-----|-----|----------|----------|-------------|-------------|-------------|
| 12    | 3.4 (1878) | 63.7 (1883) | 5   | 11  | 0.22 (1878) | 5.57 (1884) | 22.2 (1878) | 1,149.8 (1883) | 280 (1878) |
| 13    | 6.3 (1889) | 85.1 (1893) | 4   | 12  | 0.52 (1889) | 8.42 (1893) | 76.7 (1889) | 1,460.6 (1893) | 212 (1889) |
| 14    | 2.7 (1901) | 63.5 (1905) | 4   | 12  | 0.22 (1901) | 5.35 (1907) | 27.9 (1901) | 1,195.9 (1905) | 287 (1901) |
| 15    | 1.4 (1913) | 105.9 (1917) | 4   | 10  | 0.17 (1913) | 9.62 (1917) | 7.5 (1913) | 1,533.9 (1917) | 311 (1913) |
| 16    | 5.8 (1923) | 77.8 (1928) | 5   | 10  | 0.67 (1923) | 7.14 (1928) | 54.7 (1923) | 1,388.9 (1928) | 200 (1923) |
| 17    | 5.7 (1933) | 114.4 (1937) | 4   | 11  | 0.62 (1933) | 10.15 (1937) | 91.3 (1933) | 2,072.8 (1937) | 240 (1933) |
| 18    | 9.6 (1944) | 151.6 (1947) | 3   | 10  | 1.01 (1944) | 11.78 (1947) | 124.7 (1944) | 2,634.1 (1947) | 159 (1944) |
| 19    | 4.4 (1954) | 190.2 (1957) | 3   | 10  | 0.45 (1954) | 13.74 (1957) | 34.6 (1954) | 3,048.5 (1957) | 241 (1954) |
| 20    | 10.2 (1964) | 105.9 (1968) | 4   | 12  | 1.07 (1964) | 9.29 (1967) | 53.9 (1964) | 1,601.3 (1970) | 112 (1964) |
| 21    | 12.6 (1976) | 155.4 (1979) | 3   | 10  | 1.16 (1976) | 14.90 (1979) | 166.4 (1975) | 2,283.3 (1982) | 105 (1976) |
| 22    | 13.4 (1986) | 157.6 (1989) | 3   | 10  | 1.10 (1986) | 13.06 (1990) | 124.7 (1986) | 2,579.2 (1989) | 129 (1986) |
| 23    | 8.6 (1996) | 119.6 (2000) | 4   | 12  | 0.83 (1996) | 9.81 (2000) | 81.9 (1996) | 1,828.7 (2002) | 165 (1996) |
| 24    | 2.9 (2008) | 64.9 (2013) | 5   | –   | 0.33 (2008) | 5.80 (2013) | 22.8 (2008) | 860.8 (2013) | 265 (2008) |

SSNmin (yr): minimum sunspot number; SSNmax (yr): maximum sunspot number; ASC: ascent duration in years; Gmin (yr): minimum number of sunspot groups; PER: period or cycle length (from SSNmin to next cycle SSNmin); Gmax (yr): maximum number of sunspot groups; SSAmin (yr): minimum sunspot area; SSAmax (yr): maximum sunspot area; NSDmax (yr): maximum number of spotless days.

Figure 7 | Annual variation of SSN and SSG for the interval 1910–2018.
Table 4 shows the minimum and maximum parametric values of the total sunspot numbers. The years 1957 and 1979 are identified because of their large deviations from the regression line, as shown in Figure 7. The year 1957 represents the highest observed annual SSN to date (\(190.2\), associated with cycle maximum for SC19). Its observed value is 4.06 SE higher than what one would have predicted for SSN given the observed \(13.3\). Similarly, the years 1978 and 1979 (associated with SC21) have large deviations from the regression line, but now in the opposite sense (i.e., their predicted SSNs are too high). For 1978, given \(11.05\), one would have expected SSN = 130.5; however, the observed SSN measured only 92.5, a difference of \(-4.7\) SE. Similarly, for 1979, given \(14.9\), one would have expected SSN = 176.7; the observed SSN instead measured only 155.4, a difference of \(-2.6\) SE.

As depicted in Table 5, the standard deviation is 68.5 for the total annual sunspot number, the skewness 0.6 (\(P = 0.007^{**}\)), predominantly positive skewness with an average around 89.1, indicating that annual sunspot number during the period is asymmetric and it lies to the right of the mean. The coefficient of kurtosis for the period is \(-0.5\) (\(P = 0.104\)) and the coefficient of variation (CV) is 76.9%. During the study, the total annual sunspot groups were 4.7 with 3.3 standard deviations and 70.4% CV. The minimum ever recorded sunspot group was 0.13 per year in 1913, while the maximum was 12.9 per year in 1959. Kolmogorov–Smirnov and Shapiro–Wilk tests are used to assess the normality for the distribution type. The analysis indicated that annual sunspot number and sunspot group data of the area are not normally distributed at a significance level of 1% (\(P = 0.007^{**}\) and \(P = 0.005^{**}\), respectively). The regression equation analysis is shown in Table 6 and Figure 8.

The trend analysis test result revealed a non-significant increasing trend for the mean annual sunspot number and sunspot groups through the studied period. The sunspot number and sunspot groups’ rate of change were found to be 0.039 and 0.013 per decade, respectively.

## Analysis of correlation between total rainfall and sunspot number

The total rainfall dataset in the study region from 1910 to 2018 was obtained from the Sudan Meteorological

### Table 5 | Statistical analyses of total sunspot number and groups in the period 1910–2018

|                           | Annual (1910–2018) = 109 | Rainy season (1910–2018) = 109 | Total annual sunspot groups (1910–2018) = 109 |
|---------------------------|--------------------------|-------------------------------|-------------------------------------------|
| Sample size               |                          |                               |                                           |
| Lowest value              | 2.4 (1913)               | 1.3 (1913)                    | 0.13 (1913)                               |
| Highest value             | 268.8 (1957)             | 276.8 (1957)                  | 12.9 (1959)                               |
| Mean                      | 89.1                     | 91.9                          | 4.7                                       |
| Coefficient of variation  | 76.9%                    | 79.4%                         | 70.4%                                     |
| Coefficient of variation  | 68.5                     | 73.1                          | 3.3                                       |
| Standard error            | 6.55                     | 6.9                           | 0.31                                      |
| Coefficient of skewness   | 0.6 (\(P = 0.007^{**}\)) | 0.6 (\(P = 0.006^{**}\))     | 0.5 (\(P = 0.030^{**}\))                 |
| Coefficient of kurtosis   | \(-0.5\) (\(P = 0.104\)) | \(-0.6\) (\(P = 0.077\))     | \(-0.7\) (\(P = 0.015^{**}\))           |
| Normal distribution       | Reject normality (\(P = 0.007^{**}\)) | Reject normality (\(P = 0.005^{**}\)) | Reject normality (\(P = 0.005^{**}\)) |

*\(P\)-value < 0.05 (significant); **\(P\)-value < 0.01 (significant); P-value > 0.05 (non-significant)

### Table 6 | Regression equation of total sunspot number and sunspot group

|                           | Total sunspot number | Total sunspot group |
|---------------------------|----------------------|---------------------|
| Sample size               | 109                  | 109                 |
| Regression equation       | \(y = 12.4 + 0.039 x\) | \(y = -22.7 + 0.013 x\) |
| Constant                  | 12.4                 | -22.7               |
| Slope                     | 0.039                | 0.013               |
| \(R^2\)                   | 0.003                | 0.018               |
| \(t\) test                | 0.18                 | 1.4                 |
| \(P\) value               | 0.852                | 0.164               |

\(R^2\): Coefficient of determination.

*\(P\)-value < 0.05 (significant); **\(P\)-value < 0.01 (significant); P-value > 0.05 (non-significant).
Administration. The particular annual SSNs for the same periods were acquired from the National Oceanic and Atmospheric Administration (NOAA) and Solar Geophysical Data (SGD). In the present work, it was decided to use the Pearson method for analyzing the correlation coefficient (CC) and t-test for significance. The CC between annual SSNs and total annual rainfall (TAR) in the study area was calculated. This method was applied because of its ability to detail the correlation values besides the relationship direction (positive or negative) (El-Mahdy 2014; Giang et al. 2016).

The analysis results are shown in Table 7 and Figure 9. The CC between SSNs and TAR in the study region was computed at 18 stations, from 1910 to 2018. The analysis proved a non-significant CC between SSNs and TAR at all stations except Khartoum and Sennar stations. The CC is negative for Khartoum station, while it is positive for Sennar station ($r = -0.20$ and 0.20, respectively). Significant CCs were not found between SSNs and TAR at any station except for Khartoum and Sennar stations at $P$-value of 0.039° and 0.043°, respectively, as shown in Figure 9. The correlation between SSNs and the rainy season TAR is shown in Table 7 and Figure 10. There are negative significant CCs between summer sunspot number and rainy season rainfall at Khartoum and Port Sudan stations ($r = -0.18$ and $-0.21$, respectively). However, positive CCs have been found between summer sunspot number and rainy season at Sennar station ($r = -
Figure 11 shows the correlation between the TAR and the total sunspot groups. The only significant CCs between the total annual rainfall and the total sunspots groups were found at the stations of El Obied, Khartoum, and Tokar. In any location, the solar radiation rate that reaches the Earth’s surface relies on the time of the day, cloud cover, the season, and the concentration of the aerosol particles in the atmosphere. Thus, it is evident that the increase in sunspot number has led to a reduction in total annual rainfall in the study region. SC has a direct impact on tropospheric precipitation patterns (Rind et al. 2008; Svensmark et al. 2013). The SC impact on rainfall in model simulations results from two distinguished mechanisms; the first includes UV changes, while the other comprises the total solar irradiance (Gachari et al. 2014). During maximum solar conditions, the rise of incident UV rays raises the stratospheric ozone generation in the stratosphere layer. That maximizes ozone in the layer of the tropical lower stratosphere. This warms the area by absorbing short and long waves. In response to a stable vertical profile for tropical tropospheric processes, tropical convection preferentially shifts off the equator, which favors monsoonal effects during the summer of the northern hemisphere and on the annual average (Rind et al. 2008). The changes in the total solar irradiance appear to influence sea surface temperatures (SSTs). This influence is mainly visible in abundant irradiance zones with small cloud cover, such as the summer season in the northern hemisphere subtropics. Far from the subtropics, the augmented SSTs assist in condensing the circulations, supporting the equator’s rainfall. Thus, both the TSI and UV forces produce similar effects but TSI helps to intensify

| Total sunspot number | Total annual | Rainy season | Total annual sunspot groups |
|----------------------|-------------|-------------|-----------------------------|
|                      | r          | P-value     | r                          | P-value    | r            | P-value     |
| Abu Hamed            | – 0.01     | 0.899       | 0                          | 0          | – 0.02       | 0.835       |
| Atbara               | 0.00       | 0.974       | – 0.04                     | 0.684      | – 0.07       | 0.476       |
| Ed Dueim             | – 0.11     | 0.246       | – 0.07                     | 0.445      | – 0.08       | 0.404       |
| El Obeid             | – 0.08     | 0.395       | – 0.13                     | 0.174      | – 0.22       | 0.024*      |
| En Nahud             | 0.11       | 0.270       | 0.14                       | 0.155      | – 0.02       | 0.874       |
| Gedaref              | – 0.01     | 0.908       | 0.00                       | 0.985      | – 0.08       | 0.441       |
| Juba                 | 0.11       | 0.250       | 0.16                       | 0.097      | 0.07         | 0.469       |
| Kadugli              | – 0.05     | 0.614       | – 0.11                     | 0.265      | – 0.12       | 0.232       |
| Kassala              | – 0.03     | 0.760       | – 0.04                     | 0.661      | – 0.14       | 0.145       |
| Khartoum             | – 0.20     | 0.059*      | – 0.18                     | 0.040*     | – 0.22       | 0.024*      |
| Kosti                | 0.03       | 0.733       | – 0.02                     | 0.833      | – 0.02       | 0.862       |
| Malakal              | 0.16       | 0.100       | 0.16                       | 0.088      | 0.02         | 0.864       |
| Port Sudan           | – 0.06     | 0.530       | – 0.21                     | 0.028*     | – 0.16       | 0.098       |
| Sennar               | 0.20       | 0.045*      | 0.25                       | 0.018*     | 0.04         | 0.650       |
| Wad Medani           | – 0.06     | 0.572       | – 0.04                     | 0.688      | – 0.10       | 0.317       |
| El Fasher            | 0.01       | 0.890       | 0.00                       | 0.998      | – 0.02       | 0.852       |
| Kareima              | 0.11       | 0.273       | 0.09                       | 0.379      | 0.02         | 0.812       |
| Tokar                | – 0.05     | 0.649       | 0.02                       | 0.849      | – 0.22       | 0.024*      |
| Wau                  | 0.03       | 0.768       | 0.06                       | 0.524      | 0.05         | 0.639       |

r: Correlation coefficient; P-value: probability value.
*Correlation is significant at the 0.05 level.
the response (Ineson et al. 2015). During the last decades, SSTs have been affected by other factors such as greenhouse gases (Li et al. 2017). These changes have affected the solar cycle impacts. Similarly, the gradual cooling conditions result from increased carbon dioxide, so the UV influences the stratospheric circulation. The solar influence now competes with the prospects of stronger disturbance, thus its effect may well decrease with time (Maycock et al. 2015; Schwander et al. 2017).

**DISCUSSION AND CONCLUSION**

This study investigated the relation between sunspot numbers and groups on the rainfall patterns of eastern Africa, especially in Sudan and South Sudan. The correlation analysis results showed low significant relationships between rainfall and sunspot numbers and groups. A weak linkage between the average SSNs and seasonal rainfall pattern is attained from the analysis. Therefore,
Figure 10 | Correlation between total rainy season (June–September) and total sunspot number (June–September) in the study area.
Figure 11 | Correlation between total annual rainfall and total sunspot groups in the study area.
the sunspot data alone cannot be used to predict rainfall over the study region. In general, the Sudan and South Sudan annual rainfall does not follow the same trend as the average number of sunspots. These less significant correlation results may be due to the likelihood of rains depending more strongly on processes internal to the Earth–atmosphere system such as ENSO, El Niño, La Niña, and atmospheric–oceanic circulation mechanisms. Further analysis of other phenomena and their relation with sunspots and rainfall is required. Linking the current study with El Niño and La Niña studies will enhance both.

**DATA AVAILABILITY STATEMENT**

Data cannot be made publicly available; readers should contact the corresponding author for details.

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