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# The Investigation Of Dust Storm's Frequency And Its General Trend In Arid And Semi-Arid Sudan

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## Abstract

*Dust /sand storms are common meteorological phenomena in the arid and semi-arid regions of Sudan. The Sahara and drylands in North Africa are the main dust storm sources. It is usually caused by thunderstorms, and strong pressure gradients associated with cyclones, which increase wind speed over a wide area, lifting large amounts of dust storm from the barren ground, the site of low converge vegetation into the atmosphere. The location of the study area is in the arid and semi-arid zones, where dust storm frequency has often been regarded as one of the most important manifestations of desertification, fragile ecosystems, and frequent droughts, and thus, the interest in this phenomenon has increased in recent years.*

*The main objectives of this study, are first, to identify temporal and spatial dust storm distribution and characteristics of dust storms over the study area during the 11 years (2004-2014). Second, to investigate dust storm frequency and its general trend in the mentioned period. Finally, to obtain correlation coefficient values to reveal rainfall variability that reduces and increases dust storm frequency.*

*There are a variety of methods used such as, (i) an average of dust storms was obtained to consider the monthly, seasonal, and annual distribution of this phenomenon across the study area, while the annual average rainfall was used to determine the variations of rainfall amount between the stations. (ii) The Pearson Correlation Analysis method was applied to determine the correlation coeffi[1]cient between the two variables. (iii) both deviations of dust storm from its arithmetic mean and Simple Liner Regression analysis are used to identify the general trend of a dust storm, based on dust storm values.*

*These methods are based on two meteorological variables, namely dust storm days and monthly rainfall amount. These data were collected from the Archive of Meteorological Authority in Sudan for seven stations during the period of 11 years (2004-2014).*

*The outlines of this study showed that Khartoum station has the highest annual dust storm frequency with a number of about 145 dust days, while Abu Hamad station has the lowest dust storm with 33 days. Generally, Kassla and Al Fasher stations experience fewer dust storm days than the mean of all stations (81 dust storms per 11 years).*
*The monthly averages of dust storms increased during the summer season (June-August), whilst, it decreased in the winter season (December-February).*
*The general trend of dust storm frequencies showed an increase in six stations out of seven during the entire period, with an exception for the Khartoum station which showed a decrease in the general trend.*

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## 1. Introduction

Dust storms and sand storms are common meteorological hazards, occurring in arid and semi-arid and desert areas in the world (Knippertz, 2014) and are defined as massive quantities of dust raised into the air by surface winds and reduced visibility to less than 1000 m(Fattahi Masrour & Rezazadeh, 2022). They are caused by thunderstorms or strong air pressure gradients, which increase wind speed over a wide area(Sissakian et al., 2013). The dust storm distribution depends on surface characteristics such as vegetation cover, soil surface, dry lakes, riverbeds, and surface wind speed (Bullard et al., 2016).
These storms are hazardous for transportation systems, and polluted air causes negative impacts on the human respiratory and cardiovascular systems(Opp et al., 2021).
The largest and most persistent sources of mineral dust are located in the subtropical Northern Hemisphere, known as the "dust belt" ranging from North Africa, across the Middle East, Central and South Asia, to China, and including major global deserts (Prospero et al., 2002). According to Total Ozone Mapping Spectrometer (TOM) data the most profile dust source region in the world is the Sahara Desert, particularly, the Bodélé Depression in Chad (more active source in spring), with a large path of the country covering the states of Mauritania, Mali and southern Algeria. It also suggests that the Horn of Africa and the Nubian Desert in southern Egypt and Northern Sudan are important sources(Middleton & Goudie, n.d.2001). Moreover, some studies stated that Sudan is the dustiest area in the Sahara and North Africa with a very high frequency of dust emission and transport (Cowie et al., 2014).
The impact of dust storms on the atmosphere's radiative balance(Tanré et al., 2003) includes the direct effects on scattering and absorption and indirect effects related to the aerosols on clouds microphysics, by altering the atmospheric temperatures(Notaro et al., 2013). Dust storms can affect convective activities, cloud formation, and precipitation(Tao et al., 2012).

The studied area is situated in the arid and semi-arid region, facing severe climate change challenges, and it has inherently, fragile ecosystems, frequent droughts, continuous desertification, and vulnerability of soils to erosion, which in turn, has raised dust storm frequencies in recent decades (Goudie & Middleton, 1992).

As has been noted that drought is relatively frequent in Sudan, and episodes of drought are spreading. For example, one of the most severe dust storms occurred earlier on the 21st of September 2008; monitored by the Sudan Meteorological Authority recorded a visibility of less than 50 m during the storm(Elsheikh et al., 2017). Another severe dust storm occurred from 27 to 30 March 2018 over Sudan and was characterized as a heavy dust storm, which had been hitting Sudanese capital Khartoum, and other states, crippled traffic, and caused Khartoum international airport to suspend all domestic and international flights due to the lack of visibility(Ragab et al., 2021).

There are many studies written to monitor dust variability(Prospero et al., 2002; ), using satellite imagery and ground-based meteorological data for fifty years made in 28 synoptic stations of Senegal, Mauritania, Mali, and Niger, to study the dust storm variability and land degradation in the Sahel (Ozer, 2002). In the last method based on meteorological data pointed out that dust production in West Africa was a synthetic climatic indicator of the global environmental degradation process in the arid, semi-arid, and even in dry humid regions.

meteorological data used such as total rainfall amount, visibility, and wind speed and direction, to study the effects of rainfall quantity on the frequency of severe dust storms in Iraq, by comparing annually severe dust storms with rainy and drought seasons. They found that there was a reverse relationship between rainfall and severe dust storms during the period from 2001 to 2017(Mohammed & Hassoon, 2019). Dust storms are becoming most frequent mainly in arid and semiarid regions of Africa and the Middle East owing to the reoccurrence of dry conditions and climate change phenomenon(Sharif et al., n.d.). Further studies are done by using WRF-Chem for simulating and evaluating the dust three-emission schemes during the severe dust storm 27 to 30 March 2018 over Sudan. They used some meteorological aspects of dust emission and transport, such as changes in the quantities of winds, temperature, pressure, and relative humidity. Their results showed that all schemes of the model reproduced dust emission very well compared to MODIS and MERRA-2 satellite and WRF-Chem can be used for dust forecast over the Sahara regions, including Sudan(Ragab et al., 2021).

There are several research questions, concerning dust storms in central Sudan that need to be addressed. These include, what are the causes of the reoccurrence of dust storms in arid and semi-arid regions; whether or not there is a trend in dust frequency and where the dust goes; what the most properties of the temporal and spatial distribution of dust storms in the same area; and is there any impacts of droughts or a lack of rain during the recurrence of dust storms in central Sudan.

## 2. Study Area

The Republic of Sudan lies between latitudes (8.4–23.3) º North and longitudes (21.5–39.0) º East, covering an area of 1.87 million $km^2$.  It is located in tropical east Africa and has all the general characteristics of the tropical region concerning climate and its general determinants, except for local differences.

The general topography of Sudan is characterized by a broad plain valley of the river Nile and its branches with moderate slopes from south to north with the maximum in the Alnuba mountains in the far south, the Red Sea hills as an extension of Ethiopian highlands in the east, and Jabal Marra mountains in the west of Sudan(Alriah et al., 2021)

Soil in Sudan is described as a great plain resulting from ancient alluvial depositions and soils of volcanic origin in the Nile Basin in addition to clay plains and sandy or rocky soils in the rest of the country. The semi-desert and Red Sea soils differ in respect to particular topography found in the extreme east; the shallow Rea Sea soils on steep slopes are calcareous and sandy fluvisols. Further, fertile soils of the plateau and higher slopes are found in the Nuba Mountains, and volcanic soils in Jebal Marra besides the erosive plain in Darfur. Qoz soils are poor but free draining, deep and loamy sand even along drainage lines (CIRAD (Organization (Ede, 1993)

The climate of Sudan is a tropical climate from true desert with no rainy month to the tropical type of the southern frontier with a dry season of only three or four months.

The most significant climatic variables are rainfall and temperature values. Rainfall varies, from north to south, by (25-700) mm and falls in a few months between June and October, in comparison with the Sahel zone, which receives between 250 and 450 mm of rainfall in total in an average year(Klose et al., 2010). The north of the country is characterized as largely desert, shifting progressively to semi-desert, low rainfall savannah, and high rainfall savannah towards the south. In the semi-arid zones, inter-annual rainfall varies from 20-50% with averages of up to 700 mm. while, the dry sub-humid areas receive higher amounts of rainfall than the other categories of drylands which can reach more than 800 mm annually.  Temperature degrees range from (30-40) ºC in summer and (10-25) ºC in winter. Drylands are characterized by high maximum temperatures and large temperature differences between day and night. Other climatic characteristics include strong winds, and low humidity(Abdi et al., 2013)

Some studies linked between upper tropospheric synoptic flows of Tropical Easterly Jet (TEJ) and surface rainfall in Sudan during summer. It was noticed that the dynamic flows of TEJ exert some control towards moisture transport from the South Atlantic to Africa and Sudan. As a result, it induces rainfall anomalies(Alriah et al., 2021).

Sand-dust storms occurred and developed in central Sudan, mainly in the spring and early summer seasons forming three types: a) dust storms associated with cumulus clouds, which occur during the period April-September; b) dust storms caused by steep pressure gradients for south\southwesterly wind south of Inter-Tropical zone (ITCZ) occur in the period May-October; and c) dust storm due to strong dry winds behind cold fronts as spring is the season with frequent cold fronts in the northern hemisphere (February-March).

## 3. Material and Methods

Surface observation data have been collected from the archive of the Sudan Meteorological Authority, in the capital Khartoum; which includes almost seven stations, which have been shown in Table (1), covering the area of arid and semi-arid regions in the Sudan during the period from 2004 to 2014. The data consisted of the monthly average of rainfall and mean dust storm days for 11 years. This data was used for obtaining the monthly, seasonal, and annual dust storm frequency as well as to analyze a trend of dust storm frequencies too, for the overall research period.
The meteorological stations are shown in Figure (1), most of them are located in arid regions, such as Port Sudan, Dongola, Abu Hamad, and Atbara; while Khartoum station is in the marginal area between two zones, and Kassala and El Fasher in the semi-arid regions. These stations are classified according to the study of the classification of drought conditions in Sudan (khadiga et al., 2021).
The two methods used in this study are analytical approaches, such as correlation and regression analysis. These methods are commonly used and the most important tools applied in atmospheric sciences. The basic idea of correlation/regression analysis is to predict the behavior of one variable based on fluctuations in one or more related variables. First, Pearson's Correlation Analysis is applied to show the characteristics of dust storms over this area, and the most important drivers for its occurrence. Duststorm and daily rainfall data are permitted to obtain the correlation coefficient from this equation:

$$R = \frac{n \sum xy - \sum x \sum y}{\sqrt{\{n \sum x^2 - (\sum x)^2\}\{n \sum y^2 - (\sum y)^2\}}} \qquad \textbf{Eq. (1)}$$

The value of (R) is known as a factor of correlation, which measures the significance of the correlation between the two variables, exactly, dust storm (X) and average rainfall (Y) during the study period. This value (R) ranges between (1) and (-1), where 1 indicates a positive correlation and -1 indicates a negative one. As a result, the value of the correlation factor ranges between $-1 \leq r \leq +1$. Further, when r=zero, we may not assert that there is no correlation at all between X and Y (Hauke & Kossowski, 2011).
There are two ways to determine the general trend for the study area. The first analysis of the deviation between the average of dust storm frequency from its arithmetic mean. Second, simple linear regression analysis is used based on annual dust storm frequency data, to calculate the general trend of dust storm frequencies throughout the study period. The linear regression analysis was applied to estimate the general trend of dust storms in the study area. Simple linear regression equation as below:

$$Y = a + bx \qquad \textbf{Eq. (2)}$$

Where $\hat{y}$= general trend of dust storm values

$\hat{y} = \hat{a} + \hat{b}x$ --------------- **eq. (2.1)**

$\hat{a} = \bar{y} - \hat{b}\bar{x}$ ________________ **eq. (2.2)**

a^ indicates the time parameters

$\bar{y} = \frac{\sum y}{n}$

$\bar{x} = \frac{\sum x}{n}$

$\hat{b} = \frac{\Sigma xy}{\Sigma x^2}$

These indicators mean: ˆa = time parameter; xi = time; and bˆ= absolute range.

**Table (1): List of Meteorological Stations in the Study Area**

| No | Stations | Longitude | Latitudes | Elevation (m) |
|---|---|---|---|---|
| 1 | El Fasher | 25.35 | 13.63 | 700 |
| 2 | Khartoum | 32.56 | 15.60 | 382 |
| 3 | Atbara | 33.98 | 17.71 | 360 |
| 4 | Port Sudan | 37.21 | 19.61 | 2 |
| 5 | Dongla | 30.47 | 19.17 | 226 |
| 6 | Abu Hamad | 33.32 | 19.53 | 290 |
| 7 | Kassala | 36.40 | 15.45 | 500 |

Source: (Sudan Meteorological Authority, 2020)

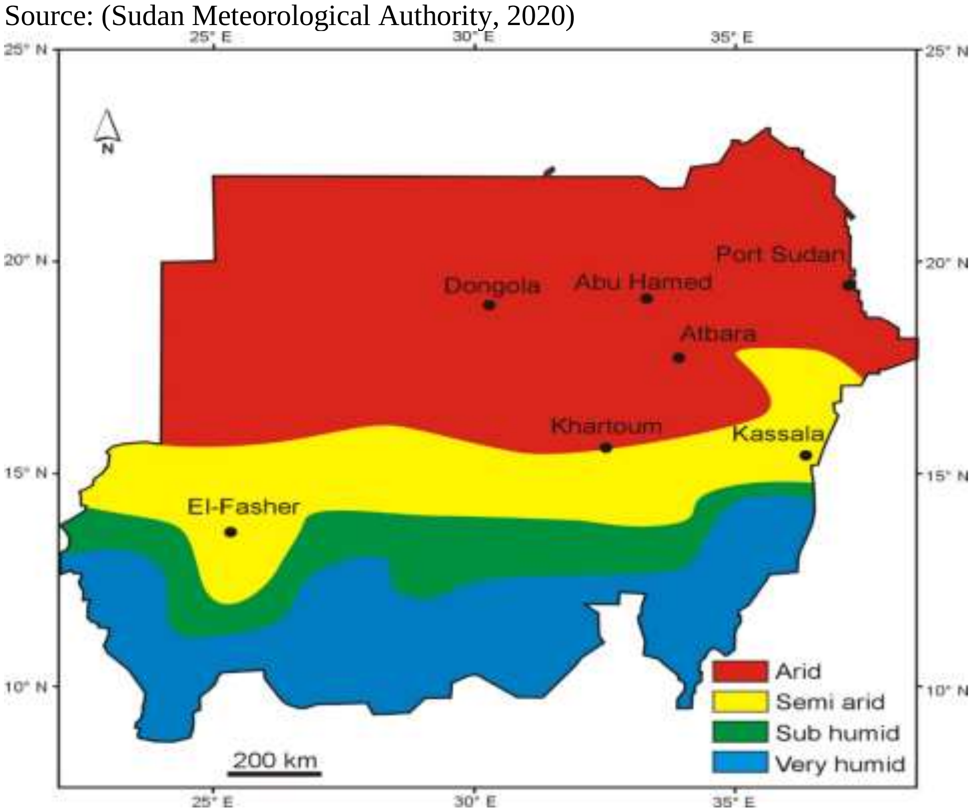


**Figure (1): meteorological stations in central Sudan**

**Source: developed by** (Khadiga et al., 2021)

## 4. Results and Discussions:

### 4.1 Monthly distribution of dust storms in the study area:

Figure (2) shows the monthly distribution of dust storms over the study area, with some variations in their occurrence from one month to another during the entire period. During July, the occurrence of dust storms had the highest frequencies reaching 92 storms (18.1%) of the total storms, mainly in the stations, which are located in arid areas, such as Dongola, Abu Hamad, and Port Sudan. As evidence, poor management of the Earth's dry lands is increasing sand or dust storm frequency from desert margins.

August recorded a frequency of 84 storms (16.5%), while December and January recorded 11 and 12 storms respectively, as the less frequent months of the year, with six storms and a rate of less than 2.2%. It should be noticed that there is a monthly variation throughout stations, where the highest frequency was observed in Khartoum in August with 25 storms. However, during August rainfall belt accompanying the Inter-Tropical Convergence (ITCZ) moves northwards associated with large pressure depressions northwest of Sudan with a southwest humid air stream. Usually, the occurrence of dust storms is more frequent than during the other seasons. Port Sudan station recorded about 24 storms in July. Some stations such as Kassla and El Fasher observed less frequent storms occurring during months of the year figure (2). The range between the highest and lowest frequency of storms was 81 storms during the study period, indicating the great variation and fluctuation in the occurrence of dust storms during the months of the year. As evidence, the North and Northeast of Sudan, where dust particles are derived from the Sahara Desert in Africa, it is an area where the most frequent of all types of dust events occur. The highest frequency of dust events (22.3%) in this region is observed at Abu Hamed Station (33 °N,19.5 °E) in northern Sudan(Fattahi Masrour & Rezazadeh, 2022).

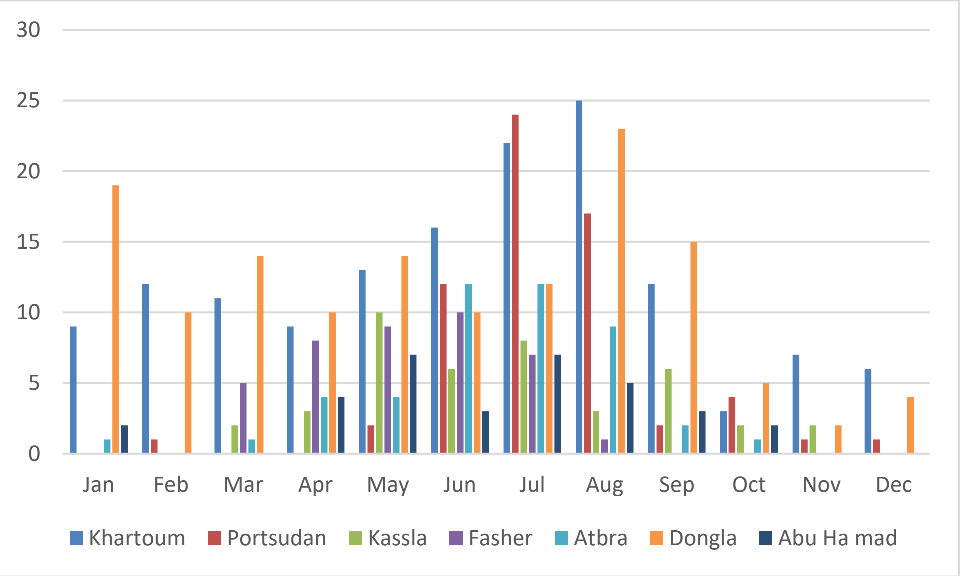


Figure (2) monthly distribution of dust storms during the study period (2004 - 2014)

### 4.2 Seasonal distribution of dust storms in the study area

Seasonal patterns show great variability in the dust storms table (2). Dust activities appear to be very limited over the entire area, in Kassla, Al Fasher, Abu Hamad, Atbra, and Port Sudan in winter season. Occasionally, thunderstorms and showers occur over the Red Sea coast, which reduces dust storm frequency as shown over the Port Sudan area, which coincides with continental Polar air reaching Sudan as a cold front associated with strong eastern depressions in the last winter (February) and early spring (Aril). Dongola station recorded 38 dust storms frequency as the highest one in the spring season (March-May) due to steep pressure gradients for southwesterly wind south of the intertropical front that occur during this period, following the Sun movement northwards. Comparing the incidence of dust storms, in Khartoum and Dongola during the spring, Khartoum has the second highest occurrence of dust storms with an average of 33 days at the same time.

In all stations, there is a remarkable number of dust storms during summer, reaching a maximum of 244 days 48% of the total number of dust storms during the entire period. Dust storms' presence is greater in the summer season, especially over the Khartoum area lies under the influence of dry conditions, with a number of 63 days of dust storms. The Station of Port Sudan recorded the second number of storms in about 53 days. It's one of the moderate dust occurrence areas in the vicinity of the Red Sea and western Saudi Arabia. In addition, the gap between the Red Sea hills and the hills of Eritrea, in the vicinity of Tokar, provide a tunnel effect to the southwesterly wind this increase wind speed that leads this area to be most frequent with long period of blowing sand and dust storm mainly in July and August, figure 3.

Kassla and Al Fasher stations showed some dust storms between 17 to 18 days respectively during summer. Dongla station is located in the northern frontier of Sudan and reaches some 45 days of dust storms. As evidence, north of 16° N has become a large dust-raising area. It seems clear that the effect of drought, reducing soil moisture and vegetation cover, is mainly responsible for this new geographical distribution of wind erosion processes (Pierre O. 2002). Over the studied area, the average dust frequency has increased by at least 18 storms in winter to more than 80 in summer, figure (3). Dust frequency decreases southwards, as in Al Fasher station in autumn due to the dominance of the moist southwest wind. In the other seasons, the more frequent is the spring season, which registered 33 days of dust storms over the Khartoum area, winter season is about 27 days of dust storms. Khartoum, Port Sudan, and Dongola are recorded for the highest dust storm frequencies in summer (June-August).

**Table(2) Seasonal distribution of dust storms in study area (2004-2014)**

| Stat/Seasons | winter | spring | summer | autumn |
|---|---|---|---|---|
| Khartoum | 27 | 33 | 63 | 22 |
| Portsudan | 2 | 2 | 53 | 7 |
| Kassla | 0 | 15 | 17 | 10 |
| Al Fasher | 0 | 22 | 18 | 0 |
| Atbra | 1 | 9 | 33 | 3 |
| Dongla | 33 | 38 | 45 | 22 |
| Abu Hamad | 2 | 11 | 15 | 5 |

| | | | | |
|---|---|---|---|---|
| Total | 65 | 130 | 244 | 69 |

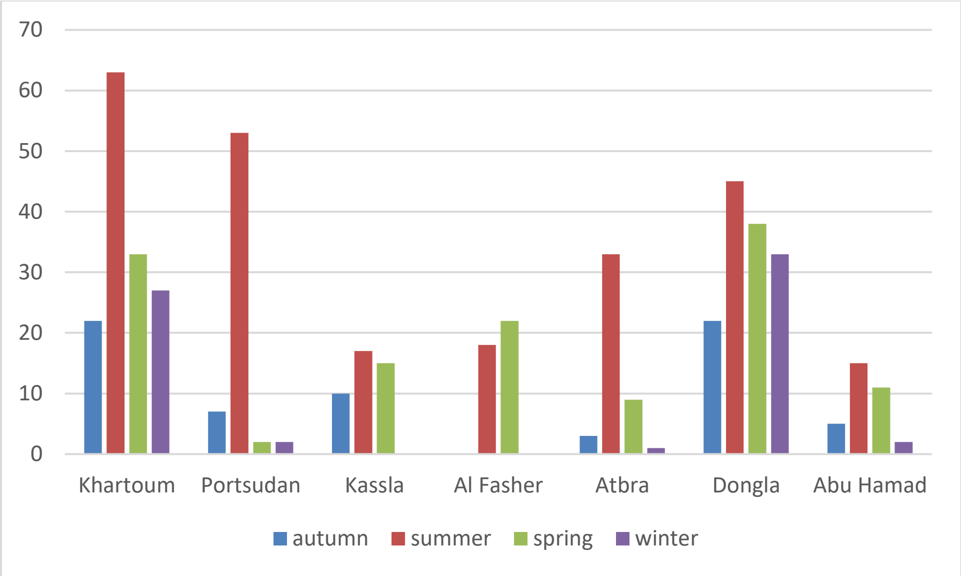


**Figure (3) Seasonal distribution of dust storms over the study area (2004 – 2014)**

**4.3 Inter-annual distribution of dust storms during the study period:**

The annual frequency of dust storms over the study area varies over a wide range of less than 3 to more than 24 days \year, which allowed the region to be among the highest dust storm areas in the world. In the Sahel-Sudan region earlier in (1971-1973), dust storm occurrences reached more than 81days/year (Indoitu., 2009). Table (3) shows the most frequent years 2005, 2006, 2007, and 2009, which recorded 60, 66, 61, and 64 dust storm days respectively. Khartoum station has recorded the highest number of dust storms of about 145 days during 11 years. The most important cause of dust storm frequency over this area is the destruction of the vegetated area around the rapidly growing urban centers, where the circle of deforested land gets largely every year (Pierre, O. 2002). Moreover, these results are also associated with the study conducted by Elsheikh et al., (2017) about a severe dust storm monitored on 21st September 2008, which occurred over Khartoum, and reduced the visibility to less than 50 m during this storm.

**Table (3) Annual frequency of dust storms over study area (2004- 2014)**

| Yea/stat | Khartoum | Port Sudan | Kassla | Al Fasher | Atbra | Dongola | Abu Hamad | Total |
|---|---|---|---|---|---|---|---|---|
| 2004 | 8 | 4 | 6 | 0 | 1 | 3 | 2 | 24 |
| 2005 | 11 | 9 | 4 | 9 | 1 | 20 | 6 | 60 |
| 2006 | 21 | 10 | 7 | 2 | 5 | 19 | 2 | 66 |
| 2007 | 15 | 3 | 4 | 4 | 7 | 24 | 4 | 61 |
| 2008 | 16 | 7 | 0 | 0 | 5 | 26 | 2 | 56 |
| 2009 | 21 | 6 | 0 | 7 | 5 | 18 | 7 | 64 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2010 | 19 | 6 | 3 | 11 | 5 | 3 | 0 | 47 |
| 2011 | 1 | 2 | 0 | 3 | 6 | 3 | 0 | 15 |
| 2012 | 21 | 7 | 8 | 1 | 6 | 14 | 0 | 57 |
| 2013 | 7 | 5 | 2 | 1 | 5 | 2 | 1 | 23 |
| 2014 | 5 | 5 | 8 | 2 | 0 | 6 | 9 | 35 |
| Total | 145 | 64 | 42 | 40 | 46 | 138 | 33 | 508 |

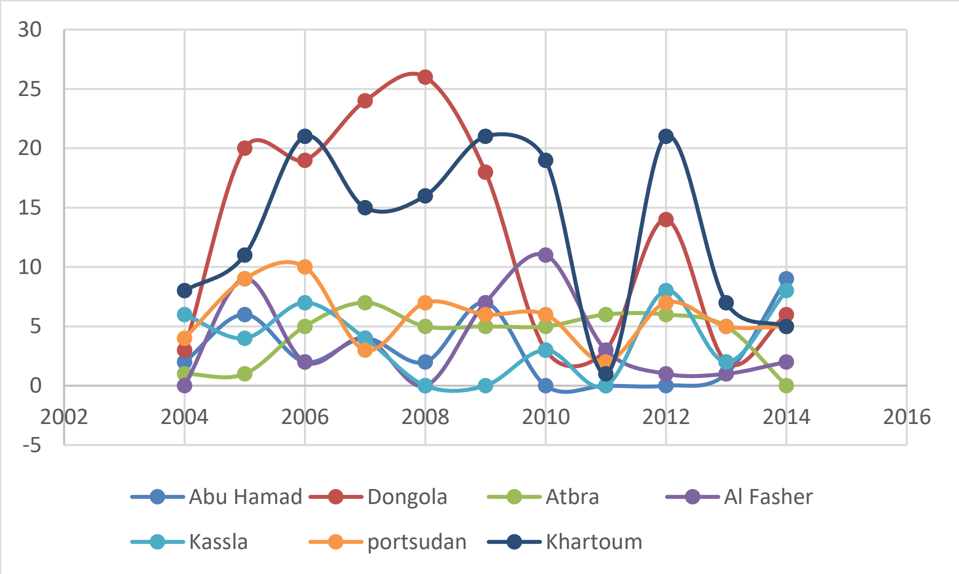


**Fig (4) Annual dust storm frequency over study stations (2004-2014)**

### 4.4 Relationship between dust storm frequency and annual rainfall:

To verify the existence of a positive statistically significant correlation between the number of reoccurrences of dust storms and the amount of rainfall, the Pearson correlation coefficient was calculated. The results of this procedure are illustrated in Table (4), where the significance of the correlation showed that there was no statistically significant correlation.

It was obvious that the phenomenon of drought might not be directly related to the amount of rainfall in a specific year, as drought results from a number of different factors, the most important of which is the amount of rainfall. Al-Qasim (1996), studied the correlation between drought and intensifications and frequency of dust storms in the arid and semi-arid environments of the Khartoum area, and his findings are likely the same as of this study. The highest average of rainfall over Khartoum station was in 2007 with a number of 178 mm, whilst in Kassala was in the same year with an average of 394 mm as well as in Al Fasher with an average of 265 mm. The highest average of rainfall was recorded in Al Fasher in 2005, 2012, and 2014 with a number of (317, 300, and 288) mm respectively. Kassala station represented the highest averages of rainfall during the studied period mainly in 2005 and 2007 with a number of 378 mm and 394mm, whereas the lowest averages are shown in Dongola, Abu Hamad, and Port Sudan, table (5). The last station receives limited rainfall between December and February in the coastal regions due to the effects of cold air blowing from the Mediterranean frontal system over the Red Sea (warm-moist) air mass in winter (Alriah et al., 2021). The other stations receive rainfall during the rainy monsoon season (June-September), influencing, the Inter-Tropical Convergence Zone (ITCZ) moves towards the north Sudan. It moves steadily until it reaches the northern borders of Sudan in mid-August. The amount, intensity, and length of the rainy season depend on the amount of moist southwesterly wind, which decreases northwards as shown in the northern stations' rainfall averages, table (5). The average annual rainfall was higher in stations, which are located in semi-arid areas, such as Kassala and Al Fasher, through the aforementioned years, than in stations lying in the arid areas.

**Table (4) Probability values and Coefficient factors (2004-2014)**

| **stations** | Probability Values | Sample size | coefficient Factor | result (R) |
|---|---|---|---|---|
| Abo Hamad | 0.837 | 11 | -0.070 | Lack of correlation |
| Al -Fasher | 0.384 | 11 | 0.292 | Lack of correlation |
| Atbara | 0.284 | 11 | -0.355 | Lack of correlation |
| Dongola | 0.888 | 11 | -0.048 | Lack of correlation |
| Kassala | 0.301 | 11 | 0.343 | Lack of correlation |
| Khartoum | 0.843 | 11 | 0.068 | Lack of correlation |
| Port-Sudan | 0.721 | 11 | 0.122 | Lack of correlation |

**Table (5) Annual rainfall average in Study Stations (2004- 2014)**

| Years/stations | Khartoum | Port-Sudan | Kassla | Al-Fasher | Atbra | Dongola | Abu Hamad |
|---|---|---|---|---|---|---|---|
| 2004 | 109.7 | 111.9 | 197 | 116.5 | 15 | 0 | 0 |
| 2005 | 140.7 | 38.2 | 378.9 | 317.3 | 74.9 | 13.4 | 2.2 |
| 2006 | 133.7 | 78 | 246.1 | 242.2 | 53.2 | 0.8 | 18.3 |
| 2007 | 178 | 34.4 | 394.4 | 265.2 | 63.1 | 26 | 39.9 |
| 2008 | 82.2 | 0 | 179.2 | 159.1 | 15.7 | 0 | 11.5 |
| 2009 | 135.7 | 29 | 101.9 | 166.7 | 32.3 | 0 | 1 |
| 2010 | 54.1 | 97.6 | 170.8 | 240.3 | 19.8 | 14.8 | 16.4 |
| 2011 | 50.4 | 19.9 | 121.8 | 147.1 | 41.1 | 0 | 0 |
| 2012 | 87.1 | 30 | 154.4 | 289.9 | 1 | 8.5 | 0 |
| 2013 | 97.1 | 2.1 | 62.2 | 252.5 | 51 | 11 | 24 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2014 | 166.4 | 23.4 | 219.8 | 287.9 | 77.8 | 31.8 | 8.1 |

**4.5. The general trend and dust storm variability over the study area:**

The importance of this study is to identify the behavior of dust storms and the changes that occurred according to the general trend during the entire period. To verify positive and negative signs were used to clarify the change and differences in the frequency of dust storms and their deviation from the arithmetic mean of its occurrence, as well as calculating and drawing the general trend line for dust storms by applying the simple regression model.

The positive and negative signs indicate the deviations of the dust storm phenomenon in the studied stations during the study years from the arithmetic mean. The highest positive deviation for the frequency of dust storms reached 72.7% in Atbara, and the lowest in both El Fasher and Abu Hamad by 36.4%. In the Khartoum station, the positive frequency was 63.6%, and in Port Sudan, Kassala and Dongola were 54.4%.

(Khartoum - + + - + + + - + - - )
( Portsudan - + + - + + + - + - - )
( Kassla + + + + - - - - + - + )
( Al Fasher - + - + - + + - - - - )
( Atbra - - + + + + + + + + - )
( Dongola - + + + + + - - + - - )
( Abo Hamad - + - + - + - - - - + )

The results in table (6) showed an increasing trend of dust frequency, without any abrupt changes during the study period mainly in Dongla station, with some exceptions for Khartoum station, which showed a significant decrease through 11 years, according to the application of the simple regression model, some explanations could be suggested that the weaken wind patterns over this area due to the spread of planned fruit farms as well as expansion of residential areas. It must be noted that a great disparity in the rates of increase between the different stations. Dongola has the highest rates, followed by Port Sudan and Atbara. By virtue of the location of the stations, we found that the general trend of dust storms increases in the stations located in the arid zone at a higher rate than in the semi-arid zone**.** The trend of dust frequency in the last three stations (Kassala, Al Fasher, and Abu Hamad, throughout the study period) was broadly stable or slightly increasing as shown in Figure (5).

**Table (6) the general trend of dust storms over study area (2004-2014)**

| Stations / years | Khartoum | Port Sudan | Kassla | Al Fasher | Atbra | Dongola | Abu Hamad |
|---|---|---|---|---|---|---|---|
| 2004 | 15.7 | 2 | 1.1 | 0 | 1.2 | 5.5 | 1 |
| 2005 | 15.2 | 2.7 | 1.6 | 0.6 | 1.8 | 6.9 | 1.4 |
| 2006 | 14.7 | 3.5 | 2.1 | 1.1 | 2.4 | 8.3 | 1.8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2007 | 14.2 | 4.3 | 2.7 | 1.7 | 3 | 9.7 | 2.2 |
| 2008 | 13.7 | 5 | 3.3 | 2.2 | 3.6 | 11.1 | 2.6 |
| 2009 | 13.2 | 5.8 | 3.8 | 2.8 | 4.2 | 12.5 | 3 |
| 2010 | 12.6 | 6.6 | 4.4 | 3.3 | 4.8 | 13.9 | 3.4 |
| 2011 | 12.1 | 7.4 | 4.9 | 3.9 | 5.4 | 15.3 | 3.8 |
| 2012 | 11.6 | 8.1 | 5.5 | 4.4 | 6 | 16.7 | 4.2 |
| 2013 | 11.1 | 8.9 | 6 | 5 | 6.6 | 18.1 | 4.6 |
| 2014 | 10.6 | 9.7 | 6.5 | 5.5 | 7.2 | 19.5 | 5 |

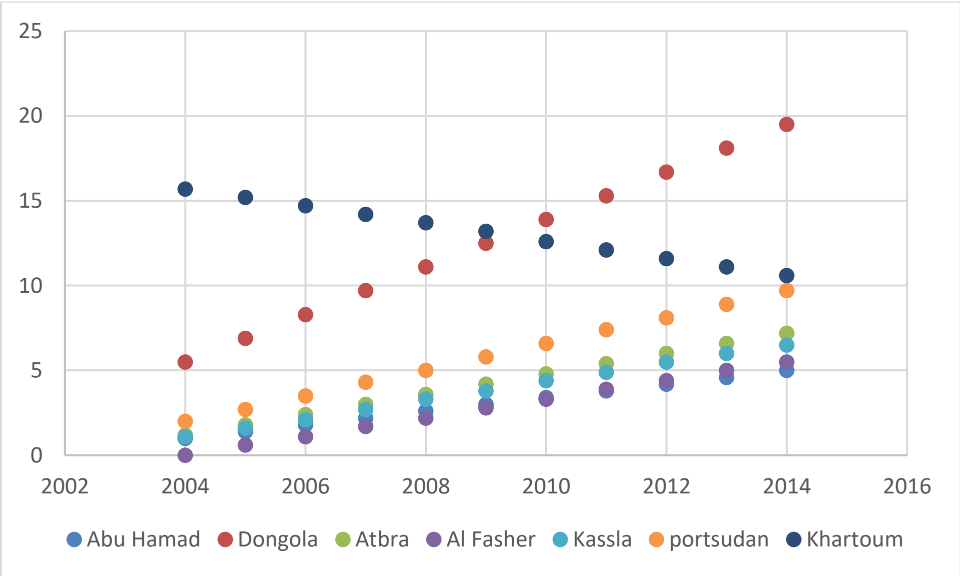


**Figure (5) the general trend of dust storms in the study stations (2004-2014)**

## 5. Conclusion

Sand and dust storms' frequency and severity have increased in recent decades in some areas but decreased in other areas. However, previous studies showed a result of the global mean of near-surface dust concentration decreased by 1.2 percent per year. This decrease is mainly due to reduced dust activities in North Africa, and other active areas in the world. For instance, the major dust storm event in 2015 in the Middle East has been attributed to the wind and arid conditions in the area rather than man-made factors. Besides wind speed, other landform characteristics also determine wind erosion. Considering these factors, the biggest dust sources are therefore, usually in land drainage basins or depressions in arid and semiarid areas such as the Bodélé Depression in the Sahara and the Taklamakan Desert in China.

Aridity in Sudan is one of the dust storms main drivers along the country and it could be explained through the potential evapotranspiration, as very high everywhere ranging between (1600-3000 mm/year) on account of high temperatures leading to humidity index negative over most the country, considering to be the boundary between the arid and semi-arid regions. For example, when light rain falls during the hottest hours of the day evaporates immediately and adds nothing to the soil water bank. Likewise, most of the stations in this study are receiving rainfall less than 800 mm/year (table (5), e.g. Atbara, Dongola, Abu Hamad, Khartoum, Port Sudan) and only 20-30% of rainfall provides water useful for plants.

The results of this study concluded that monthly dust storm distribution records the highest frequency in July with a rate of 18.1%, followed by August with 16.5%. December and January showed less frequency with 2.2%. The study also confirmed the large monthly fluctuation, which amounted to 81 storms.

At the seasonal level, the most frequent dust storm days are in the spring and summer seasons. Dust storms over all stations increased in summer (June-August). For instance, Khartoum station recorded the highest number of 25 dust days in August. And Port Sudan station registered the second number of 24 days of dust in spring, due to the Sudan's thermal low accompanied by the southern low-pressure cell forming a deep trough over the eastern Red Sea.

On an annual basis, dust storm frequency ranges between 33-145 days/year, placing the region among the highest dust storm areas affected in the world. Additionally, Kassla and Al Fasher stations recorded less than the mean dust storm days for all stations (81 dust storm days per 11 years). Also, the stations, which are located in the arid areas have the highest number of dust storm days more than the stations that are found in the semi-arid region showing a relatively low number of dust storm days.
Further, regarding the correlation between dust storms and rainfall, the results in table (5) showed that there was no statistically significant correlation between the two variables.

The study concluded that the general trend of dust storms in the study stations tended to increase clearly in Dongola station but gradually decreased in the Khartoum station with stable or slightly increasing the remaining stations.

Decreasing dust storm frequency could be possibly explained by the recovery of vegetation cover around the urban cities in the arid and semiarid regions of Sudan.

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