Integrative investigation of dust emissions by dust storms and dust devils in North Africa

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HIGHLIGHTS
• Two dust emission mechanisms in North Africa are studied and quantified.
• Dust storms mainly occur in Spring with dust emission regions in northern and north-eastern.
• Dust devils mainly occur in Summer with dust emission regions in the center of North Africa.
• The annual emissions from dust storms and dust devils contribute 61.3% and 38.7% to the total dust emission, respectively.

GRAPHICAL ABSTRACT

Dust aerosols in North Africa account for >50% of the global total; however dust emission areas are still unclear. Based on the analysis of dust storms simulated with the numerical Weather Research and Forecast (WRF) model, satellite aerosol index (AI), and the dust data observed at 300 meteorological stations over 20 years, the spatio-temporal distribution characteristics of dust storm, dust devil and AI are compared and analyzed. The results show that: 1) There are two dust emission mechanisms: the dynamically-dominated dust storm and thermally-dominated dust devil; 2) Dust storms occur most frequently in Spring and are concentrated in the areas of Grand Erg Occidental Desert to the Erg Chech-Adrar Desert, the northern part of Grand Erg Oriental, the Arouila Desert to the Ourane Desert, the Mediterranean coast, the eastern side of Nubian Desert and Bodélé Depression; 3) Dust devils occur most frequently from April to August and are mainly concentrated in the central part of North Africa, especially in the southwest of Hoggar Mountains to the west of Air Mountains, the border area of Egypt - Sudan - Libya and the vicinity of Tibesti Plateau; 4) The spatio-temporal distribution of AI is correlated more with the dust devils emission whereas the annual average contributions by dust storms and dust devils are 61.3% and 38.7%, respectively. This study discovers a new area of dust emissions by dust devils, and provides a better explanation for the spatio-temporal distribution of AI in North Africa.

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1. Introduction

Dust aerosols contribute more than half of the total atmospheric aerosols in the troposphere (IPCC, 2013), and have a significant impact on the climate through direct effect (Maley, 1982), indirect effect
come an important potential dust emission area due to the exposure of Depression. Mahowald et al. (2002) argued that the Chad Lake had been considered an important dust emission area. Goudie and Middleton (2001) considered Western Sahara also as an important dust emission area in addition to Bodélé Depression. Prospero et al. (2002) and Washington et al. (2003) further determined the Bodélé Depression as a Sahara Desert depression that is located near the Chad Lake. However, previous studies by using meteorological observations and numerical simulations of dust devil emissions in the northern deserts of China, Han et al. (2008) concluded that the Sahel was not a dust emission area, contradicting with the conclusions based on meteorological observations. Furthermore, the time of high Al values (Summer) does not exactly match that of the dust storm occurrence (Spring) time. Similar phenomenon also occurs in the deserts of Northern China, where Al remains high during the months when dust storms are rare (Wang et al., 2012). Liu et al. (2018) compared the dust emission and deposition in Tengger Desert from 2006 to 2015, and found that in most days without dust weather, the dust deposition remained high for the same period. These results suggest the existence of an additional dust emission mechanism that has been overlooked in previous studies.

Unlike the dynamically-dominated dust storms that require strong winds, the dust emission by dust devils is predominantly thermal. Dust devils occur in sunny, weakly windy weather conditions due to the uneven heating of the surface (Gu et al., 2003; Gu et al., 2010). Han et al. (2008) argued that dust devils first carry dust aerosols into the sky, and the thermal convection continuously transports the fine dust particles up to the top of the boundary layer. Through observations and simulations of dust devils in the northern deserts of China, Han et al. (2016) concluded that dust devil’s emission accounts for more than half of the annual total dust emission and was an important source of atmospheric dust aerosols. Due to the difficulty to directly observe the basic parameters of the dust devil, the study on dust devil emissions has relied mainly on numerical simulations. Klose and Shao (2016) simulated the dust devil’s distribution and their contribution to the annual dust emission in Australia using Large Eddy Simulation. The authors believed that the dust emission by dust devils was underestimated by the simulation. Jemmett-Smith et al. (2015) introduced a method to determine the occurrence of dust devils based on many meteorological factors.
thresholds. Tang et al. (2018) applied this method with modified the meteorological factor thresholds for dust devil occurrence based on the observations of the meteorological variables related to the dust devil in the deserts of Northern China. They further proposed a parameterization for the dust devil emission, and coupled it with the WRF model. The simulated dust devil occurrence pattern, region, and dust emission matched well with the observations, and the calculated dust devil emission represented 53% of the total annual emission.

Based on the previous studies, there are at least two dust emission mechanisms: by dynamically-dominated dust storms and by thermally-dominated dust devils. The meteorological observations and simulations of dust storm weather processes only reflect the dust emission driven by strong winds. However, AI is a composite index of the total amount of dust aerosols produced by the various local dust emission mechanisms and remote transports. To address the deficiencies, here we combine the three methods to conduct an integrative investigation of dust emissions. The daily AI in North Africa from 1997 to 2016 is used to determine the total dust emission. The relationship between the sum of emissions by storms and devils and AI is quantified, and the dust emission areas in North Africa are determined. Further, the contributions of dust storms and dust devils to the total emission are quantified by analyzing the observations collected at 300 stations, and simulations of WRF with the dust devil parameterization. The study reveals new dust emission areas by dust devils, and reconciles the discrepancy between the spatio-temporal distribution of AI and dust storms.

The rest of the paper is organized as follows. Section 2 describes the area of study, data sources and methods. Section 3 presents the results. Main conclusions are summarized in Section 4.

2. Study area, data sources and methods

2.1. Study area

North Africa is located on both sides of the northern tropic with flat terrains. Controlled by the subtropical high pressure zone with dry and hot sinking air, the region’s main climate types are Mediterranean and tropical desert, with the world’s largest desert — the Great Sahara Desert, consisting of nearly 17 deserts (Fig. 1). In addition, there are four large mountains: Atlas Mountains (1000-4165 m, ASL), Hoggar Mountains (3003–4627 m, ASL), Air Mountains (>1300 m, ASL) and Tihert Plateau (2000 m, ASL) with a peak of 3415 m in the central part of North Africa. A narrow strip of 320–480 km wide in the south of the Sahara Desert (about 10–15°N and known as the Sahel) experiences annual precipitation of 200 mm to 800 mm from north to south, an arid and semi-arid zone in the transition from African savannah to Sahara Desert. As shown in Fig. 1, there are a total of 300 meteorological stations in the study area, mainly distributed in southwestern North Africa with more developed river systems, the Nile Basin and northern North Africa. A few sites are located in the outer edge of the desert.


2.2. Data sources

The meteorological and dust data at the 300 meteorological stations are from the North African surface international exchange stations acquired from the National Meteorological Information Center of China. The AI data are from the NASA TOMS and OMI satellites. Reanalysis data are NCEP and NCAR (https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl). The time series of data are from January 1997 to December 2016.

2.3. Description of model and numerical setup

The Weather Research and Forecasting (WRF) model is a mesoscale prediction model system jointly developed by the environmental prediction center of the National Oceanic and Atmospheric Administration (NOAA) and the National Atmospheric Research Center (NCAR) of the
United States. We use WRFV3.6.1 in this study that considers the process of dust emission, transmission and settling. The simulation spans about two decades from January 1997 to December 2016 with outputs every 6 h. The NCEP/NCAR reanalysis data with a time resolution of 6 h and 1° × 1° are used as the initial and boundary conditions.

The model adopts one layer of nesting; the simulation domain (0°N ~ 40°N, 20°W ~ 50°E) with 60 × 150 grids and a horizontal spacing of 50 km and 33 vertical layers from the ground to 50 hPa is employed. The terrain data uses the 2 m and 30 s high-resolution LANDUSE data provided by USGS. The related physical parameterization schemes are as follows: Lin scheme for cloud microphysics, YSU scheme for boundary layer, Noah scheme for land surface, Monin-Obukhov scheme for surface layer, RRTMG scheme for both short-wave and long-wave radiation, GOCART scheme for dust storm.

A dust devil occurrence scheme based on five meteorological factor thresholds (Tang et al., 2018). The five factor thresholds are: 1) Wind Erosion Index > 0 as a dust emission area; 2) near-surface (0–2 m) adiabatic decline rate (LR) ≥ 8.5 K/m (Jemmett-Smith et al., 2015); 3) the ratio of convective buoyancy w* to friction velocity u* > 5 (Lyons et al., 2008; Oke et al., 2007; Jemmett-Smith et al., 2015); 4) ambient wind speed is between 2 and 7 m/s (Ansmann et al., 2009); 5) no dust devils when the cloud threshold > 7 or when there is precipitation (Tang et al., 2018).

2.4. Calculation of dust devil emission

The total dust devil emission (DAE_{tot}) is calculated with

\[
DAE_{tot} = \frac{D_{time}}{C_2} \frac{St}{C_2} \frac{\sigma}{C_2} \frac{F_d}{C_2} \left(1 \right)
\]

where \(D_{time}\) is the duration of the dust devil; \(S_t\) is the area where the dust devil’s instantaneous position is located (Sinclair, 1969; Balme and Greeley, 2006; Oke et al., 2007); \(F_d\) is the average dust flux in a dust devil flux of 0.7 g/(m²·s) (Metzger, 1999; Gillette and Sinclair, 1990);

The fractional area \(\sigma\) covered by a dust devil is estimated by Koch and Renno (2005):

\[
\sigma = \left( \frac{\mu}{\eta} \right)^{1/3} \left( \frac{\Delta P}{\rho_{air} g TR} \right)^{1/3} \left( \frac{F_m}{\rho_{air}} \right)^{-1/3}
\]

where \(\mu = 18\) is the dimensionless coefficient for the turbulent dissipation of mechanical energy; \(\rho_{air} = 1.29\) kg/m³ is the air density; \(g = 9.8\) m/s² is the gravitational acceleration; \(T_R \approx 9 \times 10^5\) s is the radiation time scale of the convective boundary layer; \(F_m \approx 155\) W/m² is the heat flow of the dust devil; the air pressure difference from the surface to the boundary layer top is \(\Delta P = \rho_{air} g Z_{BL}\) with \(Z_{BL}\) being the boundary layer height; the thermodynamic efficiency \(\eta\) is given by (Koch and Renno, 2005):

\[
\eta = \frac{\Gamma_{ad} Z_{BL}}{T_R}
\]

2.5. Analysis workflow

For convenience, Fig. 2 illustrates the general workflow of our analysis. First, by simulating the emissions of dust storms and dust devils at each grid point, the spatio-temporal distributions of the dust emissions from both are obtained, and compared with the number of dust storms days from 300 weather stations. Second, the spatio-temporal distributions of the emission sum by storms and devils are compared and

![Fig. 2. Illustration of analysis workflow.](image)
Fig. 3. Monthly spatial distribution of Al in North Africa averaged over the period of 1997 to 2016.
analyzed with that of AI. Finally, the contribution of dust devils to dust emission sum is obtained.

### 3. Results

#### 3.1. AI-based dust emission areas

The satellite aerosol index (AI) is used as an indicator of the total dust amount, because anthropogenic aerosols are minimal in North Africa and the data are not available. The spatial distribution of the 20-year average AI for each month in North Africa (Fig. 3) shows that the areas with AI <1.5 almost cover North Africa and can be regarded as background aerosol. In December, the high-value areas where AI is consistently >1.5 are located in both the Gulf of Guinea and Bodélé Depression at 0°–10°N. In January, the AI high-value area in the Gulf of Guinea begins to strengthen and expand northward, and connects with the high-value area in the Bodélé Depression. From February to June, this high-value area gradually extends northward and eastward to the whole Sahel region and Sahara Desert. And by June, both regional expansion and the intensity of high-value areas are maximized, forming four regional centers with AI >3.0: near the Atouila Desert and the Ouara Desert, the west of the Air Mountains, the Bodélé Depression and east of the Nubian Desert. With the expansion of the region and the increase of the intensity, the high-AI region moves northward as a whole, and the AI over the south Sahel returns to the background value. From July to November, the high-value areas begin to gradually shrink and diminish in intensity, although the areas continue to move northward. By November, AI remains high value between 2.1 and 2.4 only for the Bodélé Depression. It is noteworthy that from June to July there is an obvious small area of high AI (up to 3.0 or higher) in the northern part of Eritrea bordering Sudan, and this high-AI area begins to decrease until August. The AI value at the Bodélé Depression is above 2.1 throughout the year.

#### 3.2. Dust emission areas revealed by dust storm simulation and observation

Fig. 4 shows the spatial distribution of annual average dust emissions simulated in this study (a) and simulated by Mokhtari et al. (2015) using the ALADIN model of coupled SURFEX surface parameterization scheme from 2006 to 2010 (b). Both results show that the areas of high dust emissions are located in the Bodélé Depression, northern Western Sahara, along the Mediterranean Sea and Southeast Nubian Desert, with the dust emissions simulated in this paper is slightly lower than that of Mokhtari et al. (2015).

(a: this paper from 1997 to 2016; b: Mokhtari et al. (2015) from 2006 to 2010)

The monthly spatial distribution of the average dust storm emissions (Fig. 5) shows that the simulated areas of dust emissions are largely fixed, mainly concentrated in six independent regions: the Grand Erg Occidental and Erg Chech-Adrar, the northern part of Grand Erg Oriental, the Mediterranean coast, the eastern side of the Nubian Desert, the Atouila Desert and Ouarae Desert, and Bodélé Depression, while the Hoggar Mountain, Air Mountain, Tibesti Plateau and the southern side of Cnalscaco Desert at about 20°N have almost no dust emissions and not dust source areas. In terms of the spatial distribution by month, the dust emissions have the least amount from September to November, with the exception of the Bodélé Depression, where it is lower than 10 g/m². Dust storm emissions begin to increase gradually from December onwards, with the Bodélé Depression being particularly notable, reaching up to 30 g/m². The dust storm emissions in all regions show a significant increase trend in January, which continues to increase from February and March, with the highest emission >30 g/m². From April to May, the emissions continue to increase except in the Bodélé Depression where it decreases significantly. In June, except for the northern part of Eritrea where it increases slightly, all other regions show a decreasing trend, especially in the Bodélé Depression where the amount decreases to 14-18 g/m². In July, the emission rising in the northern part of Western Sahara is >30 g/m², while the emission increases rapidly in northern Eritrea and becomes a new high-value area, reaching above 30 g/m², as in northern Western Sahara. In addition, the emission in other areas continues to decrease. In August, the dust storm emission in North Africa begins to decrease as a whole, while the high-value zone in northern Eritrea remained with no significant change in the emission intensity. In September, this high-value region decreases sharply or even almost disappear.

Compared with the dust storm days by 300 meteorological stations and other study (Pan et al., 2020), the simulated high-emission areas roughly coincide with high dust storm days, and the simulated high-value areas are mostly located in the desert hinterland while the observed high values are on its outer edge, implying that the unobserved desert hinterland has more dust activity than its outer edge, which is consistent with common sense and implies that the simulation dust emission map is more refined. Combined the observed dust storm days and simulation results, the dust storms occur mainly north of 15°N, and their dust storm emission areas are mainly concentrated in the northern part of the Grand Erg Oriental, the Grand Erg Occidental to the Chech Desert, the Mediterranean coast, the eastern side of the Nubian Desert, the Atouila Desert to the Ouarae Desert, and the Bodélé Depression is the most important dust emission area in North Africa. However, the Hoggar Mountains, Air Mountains, Tibesti Plateau and the south side of Cnalscaco Desert at about 20°N are not dust storm emission areas.

Although Figs. 3 and 5 show some similarities between the daily dust storm emission and the daily AI from 1997 to 2016 in North Africa with a correlation coefficient of 0.29 and significance $z = 0.0001$, in depth analysis reveals more discrepancies. Firstly, high dust storm area extends southward from the northern North Africa from December to April, while the AI high-value area extends southward from the...
Fig. 5. Spatial distribution of the simulated monthly averages of dust storm emissions and days from weather stations in North Africa from 1997 to 2016.
Atmosphere dust aerosols have at least two mechanisms of dust emission, the dynamically-dominated dust storm and the thermally-dominated dust devil. Fig. 7 shows the simulated monthly spatial distribution of the mean sum of emission by dust storms and dust devils over the 20 years. Evidently, the sum of dust emission from October to November is several scattered areas, such as the Mediterranean coastline, the northern part of Western Sahara, Grand Erg Occidental to the Chech Desert and the eastern side of the Nubian Desert, where the sum is very small, and the area larger than 10 g/m² is mainly concentrated in Bodélé Depression. From December to January, the sum starts to increase, and Bodélé Depression expands above 30 g/m², but the dust emission areas are still scattered. The scattered areas begin to connect in February, and they are almost united by March, and the sum has further increased. From April to May, the sum increases significantly in the vicinity of Air Mountains, the Grand Erg Occidental to the Chech desert, the northern part of Western Sahara and along the Mediterranean. At the same time, the sum around the Tibesti Plateau has also increased significantly and is connected to the high-emission area of Bodélé Depression. June’s sum begins to decrease near the Air Mountains and Bodélé Depression, but continue to increase in the northern part of Western Sahara, and the high-emission area around the Tibesti Plateau begins to expand to the southern part of Calnascio Desert. July’s sum in the northern part of Western Sahara reaches the highest of the year, and continues to increase along the Hoggar Mountains - Tibesti Plateau - Calnascio Desert line, while a new high-emission area has been formed in northern Eritrea. There is no significant change in the dust emission area in August compared with July, but the sum of dust emission intensity is obviously weakened, and in September, the sum of dust emission area is obviously reduced towards central of North Africa, with the emission intensity decreasing to a maximum of 22 g/m², while the dust emission area in northern Eritrea have disappeared.

A comparison of the monthly spatial distribution of AI with that of the sum of dust emission in North Africa shows that, although the sum of dust emission does not move northward gradually from the Gulf of Guinea as shown by AI since December, but their spatial change along time is very similar. Both have an annual minimum from October to November, an increasing trend from December onwards, an annual maximum from June to July, and a decrease after July. The Bodélé Depression, the area from the southwestern Hoggar Mountains to the western Air Mountains and the northern Eritrea correspond very well.

Although the spatial distributions of the sum of dust emission and AI are similar in general, they still do not fully overlap in details, such as the Atouila Desert and Ouarane Desert have higher AI but smaller dust emission. Near the Tibesti Plateau, the dust emission is high from March to September, while AI is high only from April to June and in a slightly smaller range. These facts suggest that although the two dust emission mechanisms above can roughly explain the spatial distribution of the dust emission by dust devils mainly occurs from February and are mainly concentrated in the Sahel south of 20°N. In contrast to February’s a few scattered emission areas, March’s emission areas rapidly expand and become contiguous in the Sahel, with the areas concentrated in the south of Sahel, Air Mountains, Tibesti Plateau and the southeast side of Djourab Desert. The dust emissions range between 10 and 14 g/m². From April to July, the emission areas expand rapidly northward to 30°N, along with a significant increase in emission amount, and the dust aerosols are mainly concentrated in the south of the Hoggar Mountains and south of the Sahel. The area where the largest emission amount reaching 26 g/m² is located near the Air Mountains. In May, the areas continue to expand northward to the Mediterranean coast; the high-emission areas in the Air Mountains and Tibesti Plateau continue to enhance, up to 30 g/m² near the Air Mountains; but the emissions begin to decrease to lower than 14 g/m² in the southern Sahel at south of 15°N. June’s emissions do not change significantly from May, but the area in the western North Africa begins to shrink and the Djouf desert is almost no dust emission; the high-emission area near Tibesti Plateau extends eastward to the south of Calnascio Desert where emission amount reaches 10–14 g/m². In July, the emission areas and amount decrease further in western North Africa, but the areas in eastern North Africa expand to the Red Sea coast. At the same time, there is a marked increase in dust emission in northern and central North Africa, and the range above 10 g/m² has significantly increased, especially in the vicinity of the Hoggar Mountains, the western Air Mountains, the Tibesti Plateau and the Egypt - Sudan - Libya border areas, where it reaches up to 26 g/m². August’s emission areas and amounts both begin to decrease, but there is still an obvious high-emission area near the Tibesti Plateau where emission amount can reach 22–26 g/m². September’s emission areas shrink rapidly towards the center of North Africa, and the emission amount also decreases rapidly to 2–10 g/m² over most of the areas. There are only a few scattered emission areas in the west of Air Mountains and Tibesti Plateau in October, leaving only one in the western Air Mountains in November, and there is almost no dust emission area in December.

In summary, the dust emission by dust devils mainly occurs from April to August, and the dust devil emission areas are mainly concentrated in the central North Africa north of 10°N, especially in the southwest of the Hoggar Mountains to the west of the Air Mountains, the border area of Egypt - Sudan - Libya and the vicinity of the Tibesti Plateau.

Comparative study of Figs. 6 and 3 shows that the trend of the two are almost identical, and the high-value regions are both characterized by a northward expansion from southern North Africa. In particular, the dust emission regions revealed by dust devils and that by AI highly coincide with each other from April to August. In addition, the AI high-value areas occur southwest of the Hoggar Mountains to the west of the Air Mountains and near the Tibesti Plateau, where there are no dust storms but a high occurrence of dust devils, implying that the dust emission in these areas is likely to be dominated by the dust devils. In addition, the daily dust devil emissions from 1997 to 2016 have a significant positive correlation with daily AI, with the correlation coefficient of 0.69 is much higher than that of 0.29 between AI and dust storm emissions for the same sample size. The result suggests that the monthly spatial distribution of AI is more reflective of dust devil emissions than dust storm emissions.

3.4. Simulated monthly spatial distribution of sum of emission by storms and devils versus AI

The spatial distribution of dust emission by dust devils by month over 20 years in North Africa (Fig. 6) shows that the dust emission is very low from October to January, only a few regions have 2–6 g/m². The emissions begin to increase from February and are mainly concentrated in the Sahel south of 20°N. In contrast to February’s a few scattered emission areas, March’s emission areas rapidly expand and become contiguous in the Sahel, with the areas concentrated in the south of Sahel, Air Mountains, Tibesti Plateau and the southeast side of Djourab Desert. The dust emissions range between 10 and 14 g/m². From April to July, the emission areas expand rapidly northward to 30°N, along with a significant increase in emission amount, and the dust aerosols are mainly concentrated in the south of the Hoggar Mountains and south of the Sahel. The area where the largest emission amount reaching 26 g/m² is located near the Air Mountains. In May, the areas continue to expand northward to the Mediterranean coast; the high-emission areas in the Air Mountains and Tibesti Plateau continue to enhance, up to 30 g/m² near the Air Mountains; but the emissions begin to decrease to lower than 14 g/m² in the southern Sahel at south of 15°N. June’s emissions do not change significantly from May, but the area in the western North Africa begins to shrink and the Djouf desert is almost no dust emission; the high-emission area near Tibesti Plateau extends eastward to the south of Calnascio Desert where emission amount reaches 10–14 g/m². In July, the emission areas and amount decrease further in western North Africa, but the areas in eastern North Africa expand to the Red Sea coast. At the same time, there is a marked increase in dust emission in northern and central North Africa, and the range above 10 g/m² has significantly increased, especially in the vicinity of the Hoggar Mountains, the western Air Mountains, the Tibesti Plateau and the Egypt - Sudan - Libya border areas, where it reaches up to 26 g/m². August’s emission areas and amounts both begin to decrease, but there is still an obvious high-emission area near the Tibesti Plateau where emission amount can reach 22–26 g/m². September’s emission areas shrink rapidly towards the center of North Africa, and the emission amount also decreases rapidly to 2–10 g/m² over most of the areas. There are only a few scattered emission areas in the west of Air Mountains and Tibesti Plateau in October, leaving only one in the western Air Mountains in November, and there is almost no dust emission area in December.
Fig. 6. Spatial distribution of the simulated monthly averages of dust devil emissions in North Africa from 1997 to 2016.
Fig. 7. Spatial distribution of monthly averages of sum of dust emission in North Africa from 1997 to 2016.
characteristics of AI, the AI also reflects the remote transport of dust aerosol to the local area as well as possibly new dust emission mechanisms that have not been discovered.

3.5. Contribution of dust devil to dust emission

The 20-year monthly average of the dust devils in North Africa shows a single-peak distribution (Fig. 8), with a near-zero contribution in the winter months, a sharp increase after February, a contribution >50% from April to August, reaching a maximum of 60% in July, a precipitous decline after August, and almost zero after November.

Because dust devils occur most frequently from April to August, we use the spatial distribution of the dust devil’s contribution in each month during this period to determine the dominant area of dust devils in North Africa. In order to study the contribution of dust devil to the sum of dust emission by dust storms and dust devils, the regions where dust devil contributes >50% are defined as dust devil dominant regions.

It is clear from Fig. 9a–e that the dust devil dominant areas extend northward from the Tibesti Plateau, the Hoggar Mountains, the west side of the Air Mountains, near the Atlas Mountains and the south side of the Calnascio Desert, and connect with the area near the Atlas Mountains, then expand eastward to the areas near the Red Sea. In April to May, the dominant regions are concentrated in the Atlas Mountains, Hoggar Mountains, Tibesti Plateau, south side of Calnascio Desert, and Sahel area to the south of 20°N (except Bodélé Depression and Nubian Desert). The spatial distribution of contribution from June to July is similar to that in May, but the contribution rate continues to increase and reach a maximum of >90% in the middle east region of North Africa (including the Edeyen Ubari, the Edeyen Murzuq, the Calnascio Desert, the...
4. Conclusions

Based on the combined analysis of AI, numerical simulations, and dust observations at the 300 meteorological stations for the same 20-year period, the similarities and differences in the spatio-temporal distributions of AI, dust storms, and dust devil emissions are investigated to determine the dust emission areas of dust storms and dust devils in North Africa. The main findings are summarized as follows.

1) North Africa dust storms mainly occur in Spring and their emission areas are mainly concentrated from the Grand Erg Occidental to the Erg Chech-Adrar, the northern part of the Grand Erg Oriental, the Mediterranean coast, the eastern side of Nubian Desert, the Atouila Desert to the Ouarine Desert, and Bodêl Dépression.

2) Dust devils mainly occur from April to August, and their emission areas are mainly concentrated in the central part of North Africa, especially from the southwest of Hoggar Mountains to the west of Air Mountains, the border area of Egypt - Sudan - Libya and the vicinity of Tibesti Plateau.

3) The spatio-temporal distribution of AI is correlated more with that of dust devils than that of dust storms. However, most dust devils occur from April to August and the others months are dominated by dust storms, leading to an overall annual contribution of 61.3% by dust storms, only 38.7% by dust devil.

It is noteworthy that although the spatial distribution of AI and the sum of dust emission by dust storms and dust devils in each month are generally similar, detailed differences remain. The contribution from long-distance dust transports may be responsible for the remaining discrepancy, and thus merits further study in the future.

CRediT authorship contribution statement

Lin Pan: Investigation, Software, Formal analysis, Writing - Original Draft
Yongxiang Han: Ideas, formulation or evolution of overarching research goals and aims, Writing - Reviewing and Editing, Supervision
Zhenggi Lu: Software help, Validation, Data Curation
Jiaxin Li: Validation
Fei Gao: Resources
Zhaoxuan Liu: Review & Editing
Weijia Liu: Validation
Yangang Liu: Writing - Review & Editing

Declaration of competing interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted. No conflict of interest exists in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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