Sahel dust zone and synoptic background

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Present weather reports from synoptic station data from 1983 to 2008 are analyzed to establish the climatological existence of a zone of frequent dust events and high dust concentration over the Sahel. This zone, to be referred to as the “Sahel dust zone” (SDZ), is situated between 10°N and 16°N, and is most prevalent during the period between December and April, stretching almost over the entire North African continent from west to east. SDZ corresponds well to the convergence zone located to the north of the African monsoon trough, and the dust is primarily transported from the Sahara. Using the ERA-Interim Reanalysis data, we examine the synoptic patterns in February and March, which generate dust emission from the Sahara and subsequently transport the dust to the Sahel. Three synoptic patterns are found to be mainly responsible for the formation of SDZ. Citation: Klose, M., Y. Shao, M. K. Karremann, and A. H. Fink (2010), Sahel dust zone and synoptic background, Geophys. Res. Lett., 37, L09802, doi:10.1029/2010GL042816.

1. Introduction

North Africa is recognized as the largest dust source on Earth. By means of satellite data analyses, Prospero et al. (2002) identified the Bodele Depression and the western Sahara as the most important dust sources in North Africa. Several studies on Saharan dust have been carried out in recent years [e.g., Laurent et al., 2008]. The Sahel region is of considerable interest concerning the dust investigation. Goudie and Middleton [2001] pointed out that the Sahel is an area of net dust deposition and dust storm frequency increased during the Sahel drought in the 1970s and 1980s [N’Tchayi Mbourou et al., 1997]. Shao et al. [2010] conducted a numerical study on the intense dust episode of 1–10 March 2004 and found that a persistent zone of high dust concentration existed over the Sahel, which stretched from west to east across the whole of North Africa. The existence of this dust zone during that episode was confirmed by satellite data, and can also be seen on many other occasions. We therefore hypothesize that a Sahel dust zone (SDZ) exists in a climatic sense. Cavazos et al. [2009] showed that the radiative effect of Saharan dust can be profound with a shortwave radiative forcing of ~140 Wm⁻² per unit aerosol optical thickness (AOT) and of ~10 Wm⁻² per unit AOT at top of the atmosphere. Thus, the existence of the SDZ can have a large radiative effect on the tropical atmosphere, the formation of clouds, and precipitation. The atmospheric dust load also influences regional circulation systems. Tompkins et al. [2005] showed that changing the aerosol climatology in the ECMWF weather forecast model resulted in the removal of a forecast bias in the location and strength of the African Easterly Jet.

This study aims to detect SDZ by analyzing synoptic station data from 1983 to 2008. In some previous studies, only synoptic visibility data were used to document the spatial and temporal characteristics of Saharan dust [Engelstaedter et al., 2006]. In this study the present weather code is analyzed. This technique has been applied to Asia and Australia [e.g., Shao and Dong, 2006], but not to North Africa. Present weather conditions are subjectively determined by observers and reported every three to six hours to the “Global Telecommunication System” (http://www.wmo.int/pages/prog/www/TEM/GTS/index_en.html). This type of “in-situ” information is available for decades. In contrast, satellite data are indirect assessments of dustiness available for shorter periods with higher spatial density. Aerosol Index (AI) data are therefore used complementary to the surface data. Using the ERA-Interim Reanalysis data, we examine the characteristic synoptic patterns for the formation of SDZ during February and March when it is most pronounced.

2. Climatological Verification of the Sahel Dust Zone

To detect SDZ, we used MIDAS Land Surface Observation Stations data from 1983 to 2008 available from the British Atmospheric Data Centre (http://badc.nerc.ac.uk/data/ukmo-midas). All significant dust weather reports with the present weather code (ww) of (1) “dust in suspension” (ww = 6), (2) “blowing dust” (ww = 7), (3) “dust storm” (ww = 9 or 30–32) and (4) “severe dust storm” (ww = 33–35) were considered. Stations which report less than once a day on average were excluded from the analysis. Also excluded were the reports of dust weather accompanied by a visibility exceeding a threshold, which has been derived by calculating the visibility probability density functions under the reported ww of either 6, 7, 9 or 30–35. The corresponding threshold visibilities are 10 km for “dust in suspension” and “blowing dust” and 4 km for “dust storm” and “severe dust storm”.

After eliminating the above described inconsistencies, the relative frequencies of the dust-event types were computed, defined as ratios between the numbers of particular dust-event types to the total number of observations. The relative frequency of all dust events and that of dust in suspension for North Africa during 1983–2008 are shown in Figure 1. As can be seen, the Sahel, its western part in particular, has a high frequency of dust events and the dominant dust-event type is dust in suspension. To detect the seasonal variations of the dust patterns, the monthly relative frequency of all dust events were analyzed (Figure 2). While

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SDZ is visible for all months, it is most prominent between December and April and is strongest in February and March. SDZ is most prevalent in the western parts, but stretches eastward to the western boundary of the Ethiopian Highlands. The weakest activity is between July and October.

3. Synoptic Analysis

Two important observations can be made from the above-presented analysis. First, dust events over the Sahel are mostly dust in suspension, implying that the dust is predominantly transported from the Saharan interior. Based on the case study of Shao et al. [2010], much of the dust in the Sahel during the 1–10 March 2004 event originated from Chad, Sudan, and Egypt. Second, the seasonal variation of SDZ is closely related to that of the monsoon trough (also West African Heat Low). Also shown in Figure 2 are the monthly mean $8 \times 10^{-6} \, \text{s}^{-1}$ contours of horizontal convergence and the monthly mean positions of the lowest 925 hPa geopotential heights between the Equator and 28°N from

![Figure 1](image1.png)

**Figure 1.** (a) Relative frequency of dust events (including dust in suspension, blowing dust, dust storms and severe dust storms) for 1983–2008 in North Africa. (b) As in Figure 1a, but for dust-in-suspension events.

![Figure 2](image2.png)

**Figure 2.** Relative frequency of dust events over the period 1983–2008 for individual months. The topographic height is shaded in black. The blue areas represent the $8 \times 10^{-6} \, \text{s}^{-1}$ level of horizontal convergence and the black dashed lines the position of the lowest 925 hPa geopotential height between the Equator and 28°N (an indication of the ITD position) as derived by Lavaysse et al. [2009]. Yellow and orange areas indicate regions of monthly averaged TOMS/OMI AI for the analysis period exceeding 1.8 and 3.
Lavaysse et al. [2009], to indicate the locations of the monsoon trough. Although there is a lack of surface measurements in the Sahara, it can be seen that the zone of maximum dust event activity is located to the north of the monsoon trough and is closely linked to its spatio-temporal evolution [see also Engelstaedter and Washington, 2007]. This is especially evident for the months between November and March. These observations suggest that SDZ is a convergence zone of dust transported from the Saharan interior. On the northern side of the monsoon trough, relatively weaker winds and stronger convergence prevail. The vertical mixing in the monsoon trough area enables the dust to remain suspended for relatively long time before it is deposited to the ground or transported by the easterlies toward the Atlantic. The frequent dust activities south of the monsoon trough in summer are probably related to synoptic-scale easterly waves, meso-scale dust fronts (haboobs) generated by cold air outflows from convective events, and small-scale phenomena such as dust devils or the breakdown of the nocturnal low-level jet [Knippertz and Todd, 2010]. Due to the lack of surface measurements in the Sahara, AI data of the Total Ozone Mapping Spectrometer (TOMS) for 1983 to 2004 (not available for May 1993–July 1996) and of the Ozone Monitoring Instrument (OMI) for 2005 to 2008 were used to verify the results derived from the surface data. The satellite data confirm the relationship between SDZ and the monsoon trough and reveal that SDZ stretches further over the Atlantic. As expected, the upper level dusty zone seen from AI covers a larger area and can extend further south than the surface dust zone. The AI maximum in summer in central west Sahara appears to be unlikely. It cannot be ruled out that the AI maximum is overestimated in the heat low area compared to the Sahel due to sensitivity of AI to boundary layer height [Engelstaedter and Washington, 2007].

To better understand the reasons why dust accumulates over the Sahel, the synoptic patterns of representative dust episodes were examined. As SDZ is most prominent in early spring [N’Tchayi Mbourou et al., 1997], synoptic data for February and March of the 26 years were used to analyze the synoptic background of SDZ. To detect the most outstanding dust episodes during these years, we created the daily time series of relative dust frequency. Peaks in this time series (Figure 3) represent the major dust episodes over North Africa.

Using this method, 37 SDZ events from the historical data were selected, all of which were accompanied by the occurrence of SDZ. The synoptic patterns associated with these events were analyzed by using the mean sea-level pressure and 10m wind to characterize the surface pattern and by using the geopotential heights and wind vectors to characterize the 700 and 500 hPa patterns. The most recent generation of atmospheric reanalyses, ERA-Interim data [Simmons et al., 2007] with a horizontal resolution of T255, were used for this purpose. ERA-Interim data are available from 1989 and thus dust events before 1989 were not considered. We identified the similarities and differences in the flow fields between the selected events and found that the synoptic patterns can be roughly grouped into three categories. The first category has two stages, both of which result in a large amount of floating dust in the Sahel. A composite analysis was carried out by averaging the flow fields of all events in each category to identify the characteristics of the corresponding synoptic pattern. An objec-

Figure 3. (top) Time series of ratio between the number of dust-event observations to the total number of observations in North Africa for February during the period from 1983 to 2008. (bottom) As in the top plot but for March. The horizontal dashed line indicates the chosen threshold value of 0.8.
Figure 4. Illustration of the types of synoptic situations that lead to a SDZ. (left) The flow pattern and dust source regions. Blue and red shaded areas indicate the positions of cyclones and anti-cyclones and the yellow shaded areas represent the possible dust source regions. Black dashed arrows represent the basic flow fields. The SDZ is represented by a yellow ellipse. The occurrence frequency for each type is shown in percentage. (right) Examples for all types, i.e., 22 February 2007 12 UTC, 20 March 2002 12 UTC, 25 February 1992 12 UTC and 07 February 1991 12 UTC for Type 1a, 1b, 2 and 3, respectively.
tive analysis using the Euclidian distances of a particular event to each composite confirmed the validity of the classification. Figure 4 shows a schematic illustration of the surface weather pattern for each category together with a real event as example. The indicative dust source regions are also shown in Figure 4, which were identified as follows: The potential dust source regions were first determined on the basis of (1) remotely-sensed leaf area index (LAI), (2) topographical height (H) and (3) surface type (S) as described by Shao et al. [2010]. Potential dust sources are defined as the regions which satisfy the criteria of LAI < 0.3, H < 500 m and S being an erodible surface (continental surface excluding water, salt-lake and stony surfaces). The indicative dust sources for each sketched category were defined as the potential dust source areas where mean surface wind speed exceeded 6 ms⁻¹.

[9] The main features of the three categories of synoptic patterns can be summarized as follows.

[10] Type 1: 49% of all analyzed cases belong to this category. This percentage can be split into 19% associated with Type 1a and 30% with Type 1b. Type 1b can be considered to be a later stage of Type 1a.

[11] The main feature of Type 1 is the extension of the Azores High into Northwest Africa accompanied by a cyclone over Northeast Africa. North Africa to the east of about 15°E is dominated by a low-pressure system centered over Libya and Egypt. The western part of North Africa is influenced by the Azores High. This situation produces a northerly flow over central North Africa, turning toward the monsoon trough, which is usually located at around 10°N in early spring [Lavaysse et al., 2009]. In this case, the dust lifted from the source areas in Libya, Chad, Mali and Niger is transported toward the convergence zone over the southern Sahel, resulting in floating dust in that region. The dust can remain suspended for several days and is then transported westward over the Atlantic or deposited to the surface.

[12] In case of Type 1b, the low pressure is centered over the Arabian Peninsula and the Azores High is displaced northeasterward and extends farther east into North Africa. A north-westerly flow parallel to the coast of the Red Sea is prevalent over Northeast Africa. It then turns toward the monsoon trough, and becomes an easterly flow at about 10 to 20°N. The dust source areas are now mainly located in Egypt, Sudan, Niger, and Chad. The transport of dust to the Sahel region is similar to that of Type 1a.

[13] Type 2: 19% of the analyzed dust episodes can be classified as Type 2. The surface synoptic situation in these cases shows high pressure over southern Europe extending to most of North Africa. A cyclone is found over Mali and Mauritania and low pressure dominates the vicinity of the Ethiopian Highlands. Contrary to Type 1, the northern part of the Arabian Peninsula shows high surface pressure. This situation produces a northerly or north-easterly flow over Northeast Africa, which carries dust lifted from Egypt and Sudan to the SDZ. Contemporaneously, dust transported around the cyclone over Mali and Mauritania increases the dust load in the westernmost part of the Sahel.

[14] Type 3: 14% of the analyzed dust episode can be classified as Type 3. Three interacting synoptic systems build the surface pattern of this type. An anti-cyclone located west of the African coast and a cyclone centred over Spain result in a westerly to north-westerly flow toward the African continent around Morocco. Another high pressure system is located over Egypt, which produces north-easterly winds over Sudan and easterly winds over central Africa. The interactions of these systems result in a strong convergence zone stretching from Liberia to Tunisia. In relation with the monsoon trough, the strong convergence and weak winds provide excellent conditions for SDZ formation. In Type 3, many different origins of dust are involved, including Mauritania, Mali, and Algeria from the west and Sudan, Niger, and Chad from the east.

[15] Seven of the analyzed 37 events (19%) can neither be classified into one of these three types nor have enough similarities to be classified as an additional type.

4. Summary and Conclusions

[16] This study presents a climatological analysis of dust pattern in North Africa based on present weather reports. For the period under investigation (1983–2008), in terms of the relative dust event frequency, we found SDZ exists in a climatic sense between 10 and 16°N and stretches over the Sahel from west to east, reaching the western boundary of the Ethiopian Highlands. Satellite data show that SDZ stretches further over the Atlantic. This may result in increased dust deposition in tropical Atlantic, an interesting observation which may impact upon the research on the relationship between Atlantic sediment and North African aridity.

[17] SDZ is in excellent agreement with the convergence zone to the north of the African monsoon trough, and their spatio-temporal evolutions are closely related. The dust events reported in SDZ are mostly dust in suspension, and hence its formation is primarily due to dust transported from the Saharan interior, rather than local dust emission. The dynamic conditions to the north of the African monsoon trough are such that dust emitted from the Saharan interior is forced to converge frequently to the Sahel region and is probably allowed to float there for relatively long time. The frequent presence of dust over the Sahel may significantly affect the radiation balance on the synoptic scale [e.g., Milton et al., 2008] and thereby the regional circulations [e.g., Tompkins et al., 2005, Knippertz and Fink, 2006]. The quantification of radiative effect arising from the SDZ on synoptic scale atmospheric circulation waits for more detailed investigation.

[18] Based on the 37 major dust events between 1989 and 2008, three characteristic synoptic patterns that contribute to the formation of SDZ at its annual peak intensity (February and March) have been identified, together with indicative dust source regions. The identification of SDZ and the most important responsible synoptic patterns provided an overview of dust activities in North Africa. The understanding of the seasonal cycle of SDZ in relation to the monsoon trough, and the understanding of the contributions of the typical weather patterns to the development of SDZ are also unique results obtained in the present study.

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References


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