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The Bodélé depression: a single spot in the Sahara that provides most of the mineral dust to the Amazon forest

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Abstract
About 40 million tons of dust are transported annually from the Sahara to the Amazon basin. Saharan dust has been proposed to be the main mineral source that fertilizes the Amazon basin, generating a dependence of the health and productivity of the rain forest on dust supply from the Sahara. Here we show that about half of the annual dust supply to the Amazon basin is emitted from a single source: the Bodélé depression located northeast of Lake Chad, approximately 0.5% of the size of the Amazon or 0.2% of the Sahara. Placed in a narrow path between two mountain chains that direct and accelerate the surface winds over the depression, the Bodélé emits dust on 40% of the winter days, averaging more than 0.7 million tons of dust per day.

Keywords: Sahara, Amazon, dust, aerosols, rainforest, fertilization

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1. Introduction

Satellite observations show continuous dust transport across 5000 km from the Saharan sources to the Caribbean Sea and North America in the Northern summer and to the Amazon basin during the Northern winter [1, 2]. Due to the annual cycle in winds over the Sahara, the winter Saharan dust sources are different from the summer sources [3]. In the summer, dust fluxes reaching the Tropical Atlantic shore originate mainly from the northwest and central-west parts of the Sahara. During winter, strong surface winds (the Harmattan winds) occur along the southern border of the Sahara, activating sources on the border of the Sahel, notably the Bodélé depression in Northern Chad.

Analysis of satellite data [4] shows that out of the 240 ± 80 Tg (1 Tg $= 10^{12}$ g $=$ one million tons) of dust transported annually from Africa to the Atlantic ocean, 140 Tg are transported in the summer and 100 Tg in the winter. A total of 140 ± 40 Tg is deposited in the Atlantic ocean and 50 ± 15 Tg reach and fertilize the Amazon basin. This is four times an older estimate, explaining a paradox regarding the source of nutrients to the Amazon forest. Swap *et al* suggested [5] that while the source for minerals and nutrients in the Amazon is the dust from Africa, it was estimated that only 13 Tg of dust per year actually arrive in the Amazon. However, they pointed out that 50 Tg are needed to balance the Amazon nutrient budget.

Here we show a remarkable arrangement in nature in which the mineral dust arriving at the Amazon [6, 7] basin from the Sahara actually originates from a single source of only ∼0.5% of the size of the Amazon or ∼0.2% of the Sahara: the Bodélé depression. Located northeast of Lake

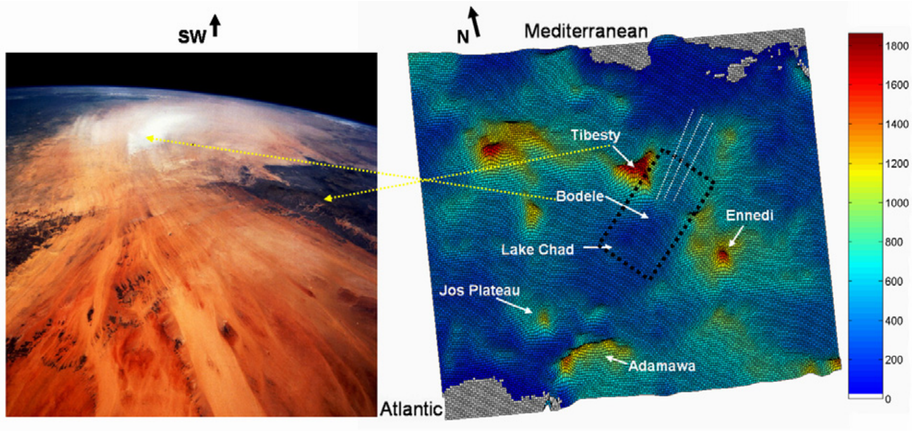

Figure 1. The surface wind focusing toward the Bodélé. Right: 3D topography of the Sahara; left: a rare shuttle image of emission from the Bodélé between the Tibesti and the Ennedi mountains (the projection of the shuttle image is marked in black on the map and the viewing direction is towards the southwest). The most significant pass between the northeast of the Sahara and the southwest is the one between the Tibesti and the Ennedi mountains. The structure of the mountains creates a caldera shape that guides and accelerates the surface winds from the northeast through the narrow pass located at the southwest. The Bodélé is located downwind directly after the pass. Several wind tunnels can be seen on the shuttle image starting as far north as 1000 km from the pass and focusing towards it, activating the Bodélé downwind from the passage (marked as white lines in the topographic map). A heavy dust storm leaving the Bodélé towards the Sahel is can be seen in the distance. The white dust emitted from the Bodélé is shown in the middle of the narrow path between the Tibesti (the black mountains on the right) and the Ennedi (left) approaching Lake Chad (see on the right near the horizon). The focusing effect can be seen as the distance between the wind tunnels become smaller near the Tibesti–Ennedi narrow path.

Chad (17°N, 18°E) near the northern border of the Sahel, it is known to be the most vigorous source for dust over the entire globe [3, 8]. Unlike most of the large sources in the Sahara that emit mainly during the summer months, the Bodélé depression emission pattern reaches its peak during the winter months. This depression is a unique dust source due to its location at a bottle neck of two large magmatic formations that serves as a 'wind lens', guiding and focusing the surface winds to the Bodélé.

The Tibesti mountains to the north and the Ennedi mountains southeast of the Bodélé form a large (more than 44 300 km^2) caldera-like valley [9]. Downwind, on the southwest corner, the caldera forms a cone with a narrow pass that accelerates the surface winds towards the Bodélé, which is located in a depression along the pass (see figure 1 right). A unique low level wind jet (LLJ) forms over the Bodélé [10, 11], and the maximum dust production occurs in the winter when the LLJ is strongest.

During the winter, the near surface winds are consistently northeasterly, making the Tibesti–Ennedi structure very efficient in focusing and guiding the winds over the Bodélé with an average of more than two days per week of winds stronger than 12 m s^{-1} [9, 11]. The surface winds over the Bodélé have a pronounced diurnal pattern, reaching the critical velocity for dust emission in the early morning and weakening toward the evening [12]. Therefore a clear 'dust parcel' forms, travelling away from the Bodélé, shown as an area covered by heavy dust with clear borders. This parcel can be detected by satellites on the day following the emission (figure 3: see the parcel in the right satellite image) and sometimes can be followed up to 3–4 days downwind, southwestward towards the Atlantic. In the same season, the Sahel biomass burning reaches its peak [13]. Therefore, the dust from the Bodélé may mix with the smoke, making retrievals of the dust properties over the Sahel much more difficult. Actual transport of a dust parcel from the Bodélé to the Atlantic ocean can be seen on an ozone monitoring instrument (OMI) [14] movie (available at stacks.iop.org/ERL/1/014005).

The rate of emission from the Bodélé depression has not been measured yet from space or otherwise, due to its remote, isolated location and difficulties in analysis of traditional satellite data of dust over the bright desert. Here we take advantage of recent advancement in satellite instrumentation to produce the first quantitative estimate of the amount of dust emitted from the Bodélé and transported across the Atlantic ocean to the Amazon. The analysis of emission combines data from two satellite instruments: MODIS (moderate-resolution imaging spectroradiometer), which provides daily observations of dust emitting days and dust parcel area but no quantitative estimates of dust concentration over the bright desert; and MISR (multi-angle imaging spectroradiometer), which provides estimates of the average dust optical depth of the parcel that in turn is used to derive the dust column mass but has only a nine-day revisit frequency.

2. Methods and results

The analysis over land is aimed at estimating the contribution of the Bodélé to the total dust flux reaching the African coast, followed by detailed analysis of dust fluxes reaching the Amazon coast, over the Atlantic ocean. Data from the MODIS blue channel (0.47 μm), with 1 km resolution, are used for detecting the area of the dust parcel emitted from the Bodélé. By using information from two satellites carrying the instrument, observing the same spot on ground 3 h apart (Terra ∼ 10:30 AM, Aqua 1:30 PM), we observed the patterns of the dust activity. The dust (wind) speed and direction are calculated from the difference in the location of the dust front in the two satellites [9]. Then the emission starting time is estimated from the wind speed, the location of the source and the location of the dust front, and the duration of the emission is extracted from the wind velocity and the length of the dust parcel along the wind direction. Similarly, these properties can be calculated when using the location of the dust parcel from satellite images of the day after the emission. The optical parameters of the dust plume are derived from MISR data [15]. Each MISR pixel is measured from nine different angles, enabling the use of the directional variability of the dust in order to retrieve optical parameters over bright surfaces. The dust flux was calculated by converting the MISR optical thickness into dust mass [4] and integrating it over the entire parcel.

Dust emission starts with saltation and blasting of the surface crust by larger particles that release and lift the finer dust particles [16]. The large particles sink relatively quickly and are not transported to large distances from the source. The aerosol optical depth near the Bodélé may contain a contribution from the large particles. Therefore, to estimate the amount of fine dust that can be transported over large distances we focus on the day following the emission, where the average dust parcel is more than 1200 km away from the source.

The mass column concentration for Saharan dust M is estimated from the dust optical depth τ_d using the following ratio:

$$\frac{M}{\tau_d} = 2.7 \text{ g m}^{-2}, \quad (1)$$

as estimated in several field experiments combined with Aeronet measurements and models [17–21]. The mass flux of a particular event over land is the product of the average mass column concentration (calculated from the average dust optical thickness) and the parcel area.

The analysis of the MODIS and MISR satellite data over the desert was complemented with calculations of the dust flux over the Atlantic ocean. To do so, we separated the satellite measurements of aerosol optical depth into dust, marine aerosol and smoke. The amount of marine aerosol is estimated using the NCEP surface winds [22]. Dust and smoke are separated by estimating the contribution of the fine particles to the optical depth derived from MODIS. The flux of dust transported from Africa to Brazil is then calculated by applying the westward NCEP winds to the dust concentration, and the longitudinal length between 20°S and 10°N of the segment through which the flux is being computed near the African and the Brazilian coasts (*the method and results are described in detail in* [4]).

All dust outbreaks over the Saharan Atlantic zone from October 2003 to October 2004 were analysed in this study. Figure 2 (blue line) shows the accumulated distribution of days that the Bodélé emitted dust form October 2003 to October 2004 defined from MODIS data. Dust emission was highest during the winter time and occurred on 50% of the days during late winter and spring (February–April). The average duration of each event is about four days. The emission decreased sharply in May–June and occurred on less than 20% of the days during July–September.

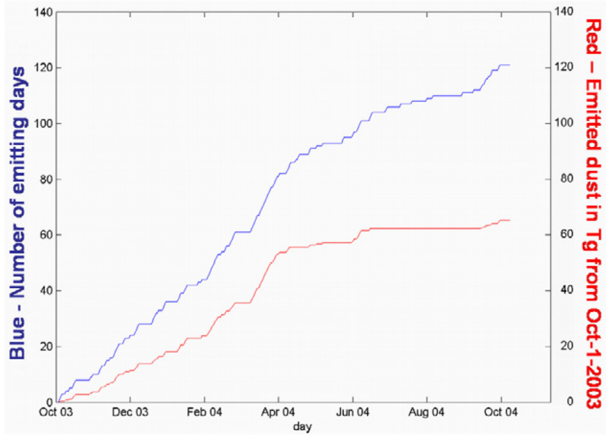

Figure 2. Dust emission from the Bodélé. The blue line shows a cumulative histogram of the Bodélé emission days between October 2003 to October 2004 and the red line is the corresponding cumulative histogram of the estimated dust mass emitted from the Bodélé. This analysis indicates that more than 60 Tg of dust were emitted during this year.

The average measured wind near the source derived from the Aqua–Terra difference for 40 cases is 13.2 ± 1 m s^{-1} with azimuth direction of $250° \pm 6°$, in line with previous measurements [7]. Moreover, during the winter–spring period the wind of the one-day-old dust parcel has a similar average wind speed of 13.0 ± 1.5 m s^{-1} and direction of $247° \pm 9°$. The average daily duration of emission is 8 ± 2 h, starting at 5 am $\pm$ 2 h. The average length of the dust package is $L = 370 \pm 100$ km, and the average width is $W = 700 \pm 300$ km.

Based on 21 cases of MISR analysis, the one-day-old dust parcel has an average optical depth of 1.1 ± 0.4 (with standard error of 0.1), and neutral spectral reflection of sunlight (Angstrom exponent of 0.2), indicating that the aerosol is pure dust [23]. The error estimate includes the error due to averaging for the entire parcel and the error of the dust retrieval [24]. The total mass of dust emitted from the Bodélé and observed by MODIS on the next day parcel is calculated as the product of the average MISR aerosol optical depth and the average parcel area covered by the dust, yielding $M_{tot} = 2.7\ \tau_{du} A$, where A is the averaged parcel area, $M_{tot} = 0.77 \pm 0.1$ Tg/day. The accumulation of emitted dust mass from October 2003 to October 2004 is plotted in red in figure 2.

The analysis of the satellite data shows that during the winter–spring time of 2003–2004 more than 58 ± 8 Tg of dust were emitted from the Bodélé, as measured 1300 km downwind from the source. At this distance the dust parcel is mostly free of the large particles that were removed earlier by gravitational settling. The estimates of dust flux emitted from the Bodélé depression are compared here to the dust fluxes across the Atlantic ocean to the Amazon [4]. In figure 3, we show the results of calculation for average of two years (2003–2004) of emissions and two cross section of the Atlantic ocean, one next to the African coast (brown frame) and one next to the South American coast (yellow frame). Out of 80 ± 8 Tg of dust transported to the ocean from Africa (between 20°S and 10°N), 40 ± 13 Tg arrive at South America. If we assume that the

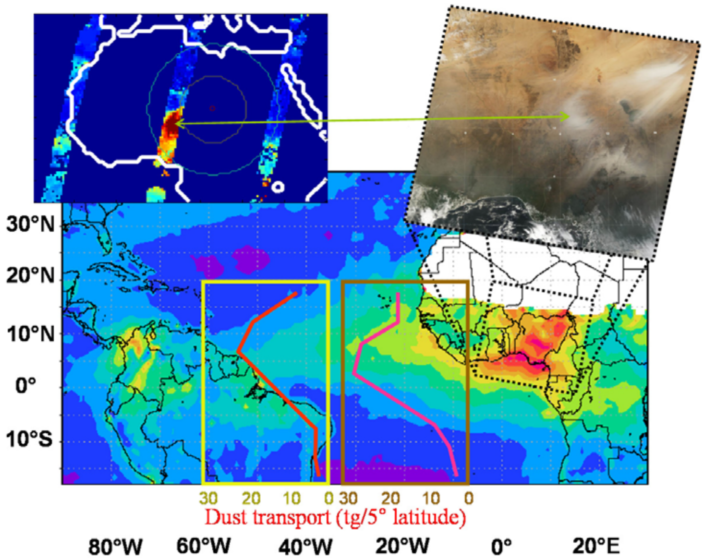

Figure 3. Dust production and transport across the Atlantic ocean from the Bodélé depression northeast of Lake Chad (17°N, 18°E) to the Amazon basin. Main image: distribution of the average aerosol optical depth as a measure for the column aerosol concentration derived from MODIS data for January 2003–March 2003 (http://g0dup05u.ecs.nasa.gov/OPS/Giovanni/). The upper right MODIS true colour image shows a huge dust plume leaving the Bodélé depression in the top right corner. The dust parcel emitted on the previous day, 1300 km downwind from the Bodélé, is shown closer to the ocean. The parcel is marked with an arrow connecting to the parcels optical depth measured by the MISR instrument (upper left). High dust concentrations follow all the way to the Amazon, with cross section profiles of dust western transport flux shown as a function of latitude (averaged for 5° of latitude and longitude) centred at 17°W and 37°W.

deposition rates over West Africa are similar to those over the Atlantic ocean we find that out of the 58 ± 8 Tg of dust emitted from the Bodélé depression, about 45 ± 6 Tg are loaded on the westward trade winds to be transported across the ocean. This amounts to 56% of the total annual burden, all coming from a single source.

3. Discussion

Using satellite data and reanalysis wind fields we have identified a remarkable connection between the Amazon forest and a single dust source in the Sahara: the Bodélé depression and its wind regime. A unique combination of global wind pattern and topography forms a vigorous dust source that emits an average of more than 0.7 Tg of dust per emission day and is active mostly during the winter–spring, which is different from most other Saharan dust sources. We estimate that between November and March, the Bodélé depression sends more than half of the dust that is deposited annually in the Amazon forest. Our direct measurements are consistent with a recent modelling study showing that the Bodélé is responsible for >40% of dust optical depth over the Amazon in the winter season [25].

The soil of the Amazon tropical rainforest is shallow, poor in nutrients and almost without soluble minerals. Heavy rains have washed away the nutrients in the soil obtained from weathered rocks. The rainforest has a short nutrient cycle, and due to the heavy washout, a stable supply of minerals is required to keep the delicate nutrient balance [26]. Kimmins [27] showed that any change in the nutrient supply will convert tropical forests to ‘wet deserts’.

Despite the insight we gained into the role of the Bodélé in fertilization of the Amazon forest, some key questions remain open. What is the relationship of the mineralogical content of the dust to the local surface mineralogy? What is the size of the reservoir of mineral dust there? And since when has the Bodélé emitted such a huge amount of dust, and for how long will it continue to do so?

Such questions, among others, were the motivation for the BoDEx Field Experiment [28]. An expedition to the Bodélé during the spring of 2005 aimed at collecting *in situ* measurements of the emitted dust, and characterizing the local meteorology and the surface properties [29]. Answers to these questions are needed to understand the nature of the emissions in the past, and the future capability of the Bodélé to fertilize the Amazon.

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