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THE BODÉLÉ DEPRESSION (CHAD): WHEN THE VENTURI EFFECT PROPELLES DUST FROM THE SAHARA TOWARDS THE AMAZON BASIN

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ABSTRACT

This paper answers the question: How can a region as small as the Bodélé Depression continuously supply large amounts of dust to the Amazon Basin? To answer this question, you must know that millions of tons of dust to fly over more than 4000 km must first be lifted into the upper atmosphere. Such a criterion can only be satisfied by the existence of very violent winds that last several days. This condition was dictated by the geography and geomorphology of the Bodélé region. The adequate layout of the Tibesti and Ennedi mega-obstacles upstream of the Bodélé offers the most beautiful Venturi on the planet. In a very rare case, 3 pass areas participate at the same time to increase the wind speed. These are the passes of Tibesti (south-east), Ennedi (north-west) and Bembéché (under the Venturi effect). The harmattan wind from Libya and Egypt rushes into the Borkou tunnel and escapes from Bembéché (the pass) with much greater speed. The detachment of the air streams from the obstacles takes place in the detachment area (Largeau), which is accompanied by gigantic vortices, thus lifting the dust into the atmosphere. Thus, during the last 20 years, approximately 503 dust uplifts have been recorded at the level of the Bodélé depression, i.e., 58% of the total number of uplifts recorded in the Sahara. The great storms we have called effective upheavals. These are long-lasting dust lifts that exceed 7 days. These storms can send fine particles toward the Amazon. Each year, 2 to 3 effective uprisings per year are recorded in the Bodélé depression.

Keywords: Amazonia, Sahara, Dust rising, Dust plume, Bodélé, Tibesti-Ennedi.

INTRODUCTION

Each year and more particularly during the spring period, a plume of dust invades northern Algeria. These millions of tons of fine particles that camouflage the sky and the clouds degrade the quality of the air and irritate the eyes and the lungs. This meteorological event is not limited to the neighboring regions of the Sahara, but these dust clouds fly over the Mediterranean to cover the skies of European countries, including Portugal, Spain, France and Switzerland. In addition, since 2014 and thanks to NASA satellites, it turns out that the sand of the Sahara travels much farther and can even exceed 8000 km. Plumes of dust from the Sahara Desert cross the Atlantic Ocean to cover the skies and sprinkle the soils of the Amazon, the Caribbean and Central America as well as the southern United States. The quantities of fine particles from the Sahara blown by the winds to reach the atmosphere are estimated at more than 180 million tons per year. The transatlantic journey of dust from the Sahara to the continents of America did not divulge all these secrets. Sahara dust is a natural fertilizer, since the 27.7 million tons of dust that dust the Amazon every year contain 22,000 tons of phosphorus (Aline, 2016; Gray, 2015; Souto, 2014; Barthélémy, 2015), a very beneficial fertilizer for the plant (Remini, 2017; Remini, 2018). Recent research on the transatlantic journey of sand from the Sahara, in particular the work of Hangin et al. (2015) on the quantification of phosphorus, which made the journey from the Sahara to the Amazon, prompted me to take up this axis. Based on data collected between 2007 and 2013 by the CALIPSO remote sensing satellite and the CloudSat radar satellite, the results obtained by Hangin et al. (2015) showed that the amount of phosphorus lost by water erosion each year is compensated by that transported by dust storms from the Sahara. The crossing of the Atlantic by the sand of the Sahara takes place on average at a rate of 10 episodes per year. The amount of dust depends on the duration of the dust plume propelled by the Sahara, which can vary from 2 to 15 days. For example, an exceptional phenomenon occurred during the month of June 2020. The largest dust trip recorded for more than half a century is that which took place during the period from June 4 to 26 2020. There is an air bridge between the Sahara and the American continent to ensure the transfer of several million tons without interruption for 3 weeks (Remini, 2020). If today, we have an idea on the diffusion of dust from the Sahara toward the oceans and the continents, however the mechanism of departure of the fine particles from the Sahara remains unanswered. In the first approach, three sources of dust emissions were located (Remini, 2017; Remini, 2018). The Bodélé depression has been identified as an area that propels more than 58% of Saharan dust into the atmosphere (Remini, 2017; Remini, 2022). This confirms what was mentioned by Washington et al. (2006), who found that the Bodélé depression is the largest source of dust on the planet. According to Koren et al. (2006), approximately 40 million tons of dust are transported each year from the Sahara to the Amazon basin. More than 20 million tons of dust comes from the Bodélé depression alone. This article is a continuation of the studies begun at the end of the 1990s. This study attempts to provide more explanations of the dust lifting mechanism in the Sahara Desert.

STUDY REGION AND WORK METHODOLOGY

Study area

Covering an area of 9 million km², the Sahara is the largest hot desert in the world out of the 11 deserts in the world. The Sahara is the most sand-exporting desert to the exterior. Bodélé, an arid region located in the southeast of the most beautiful desert in the world. Bodélé is located 600 km northeast of the capital N'Djamena of the Chadian state. Covering an area of the Bodélé region represents only 0.2% of the Sahara. It is located in the middle of Chad, and more precisely, it is located in the middle of the triangle of dust formed by the two mega-obstacles: Tibesti and Ennedi as well as Lake Chad. Located 300 km downstream from the Tibesti and L'Ennedi massifs and 500 km upstream from Lake Chad, Bodélé is considered the dustiest region on the planet (Remini, Remini, 2017; Remini, 2022). Approximately 58% of the total dust lifts that occurred in the Sahara took place in the Bodélé area (Remini, 2017; Remini, 2022).

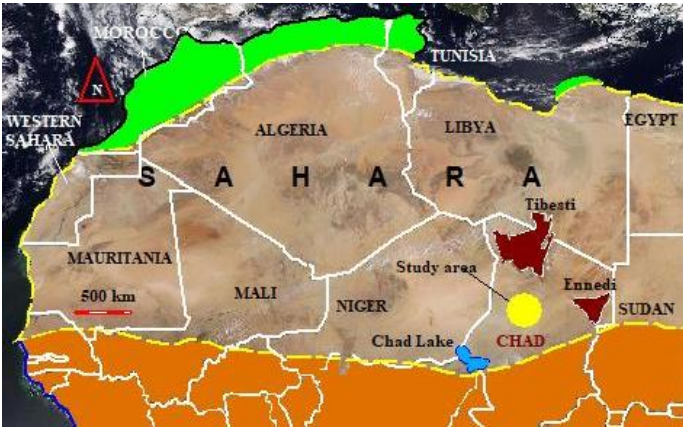


Figure 1: Geographic location of the study area (Remini, 2022)

Methodology of work

I had the chance and the privilege of working with Professor Monique Mainguet from the University of Champagne Ardenne – Reims (France) on the phenomenon of silting up during the 1990s. It was in 2001 that I defended my doctoral thesis in geography on the subject: "the influence of mega-obstacles on wind dynamics, Ergs and the silting up of oasis spaces". It is for the first time that we have introduced fluid mechanics to explain certain phenomena in geography and more particularly in the field of silting up in the Sahara, which is a component of desertification. At the time, we explained how ergs are formed and shaped. Sandstorms and dust storms are exceptional phenomena that attract our scientific curiosity on the formation of these meteorological events. We were convinced that high winds can trigger dust storms. We find that these exceptional winds at the level of the collar areas obtained wind circulation at the level of the mega-obstacles under the Venturi effect, but we have not continued our work. We had to wait until 2014 to see the first spectacular video made by NASA on the transatlantic journey of sand from the Sahara to the Amazon. In addition, the bibliographical research that we have started on the dust of the Sahara has never highlighted the mechanism of uplift of dust in the atmosphere. This prompted us to resume our research on the impact of mega-obstacles on wind dynamics and to locate the formation foci of recirculation rollers. Based on previous studies, we have located 3 foci of dust risings. That of Bodélé seems the largest diffuser of dust toward the Atlantic, with 58% of the total number of uprisings that took place during the period 2001-2021. This study answers the questions emanating from the bibliography on the importance of the dust sent by the Bodélé region to the Amazon.

RESULTS AND DISCUSSION

The Sahara, a desert like no other

As we mentioned in our previous works (Remini, 2017; Remini, 2018, Remini, 2020; Remini, 2022), fluid dynamics are generated by the presence of obstacles at the laboratory level. This results in the appearance of deposition, erosion, pass and shelter areas. The same result can be obtained at the synoptic scale. The Sahara Desert is the largest hot desert in the world, covering an area of over 9 million km^2. More than 20% of the area is occupied by sand dunes, and 10% of the area is occupied by 11 mega obstacles (fig. 3). These rock masses, by their adequate arrangement, generate very active wind dynamics, which makes it possible to erode, transport and deposit the sand. This is how we find the wind circulation author of a mega obstacle and winds transporting sand passing through a mega Venturi see their speed accelerated.

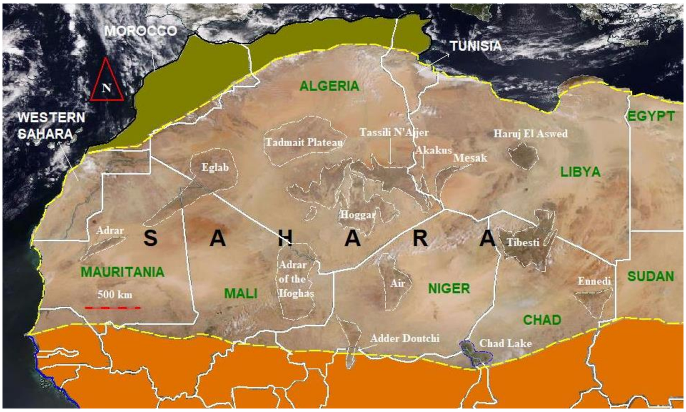


Figure 2: The Sahara with these mag-obstacles is an open-air laboratory (Remini, 2020)

How does dust from the Sahara fly over the Atlantic?

The journey of dust from the Sahara outside its territory is a complex operation and requires two phases. The first stage concerns the raising of dust in the air. In the second part, these fine particles are transported in the air in suspension.

The first stage concerns the raising of dust in the air. Scientists agree that this phase requires very high winds to lift dust into the atmosphere. It should be remembered that it is not the sand of the dunes that generates the dust, but the most violent winds are capable of raising the dust (Borunda, 2020). According to Chenil (1951), dust to be lifted requires faster winds than fine sand. The minimum velocity in a supported soil is that required by fine sands of 100 micrometers. The sandstorm that occurs on clayey-sandy soil promotes the uplift of fine particles (Mainguet and Chemin, 1990).

In the second stage, which concerns the transport of these particles once they rose in the high atmosphere, we quote some works. Once millions of tons of particles are lifted and propelled into the Saharan air layer (an extremely hot mass that forms approximately 1600 m from the Earth's layer). The layer can exceed 3 km in thickness (Borunda, 2020). In these higher atmospheres, dust can float for days or even weeks depending on how dry the air is. It is the trade winds that somehow push this plume of dust that crossed the Atlantic toward the Caribbean and the southern United States. These dust clouds can still move at low altitudes (Borunda, 2020). Other scientists say that sand is lifted by sandstorms into the upper atmosphere and then carried to the Amazon by air currents (Haug, 2015). A recent study was carried out on the famous Sahara dust plume "Godzilla", which crossed the Atlantic Ocean to reach the southern United States from June 4 to 26, 2020. According to Bing and Qinjian (2021), the transatlantic journey of millions of tons of dust from June 4 to June 26, 2020, was carried out according to 3 different systems. The East African jet exports dust from the Sahara to the Atlantic. Then, the Azores Anticyclone, a high-pressure system located over the subtropical North Atlantic, can carry this dust even further toward the Caribbean. Once the dust reaches this region, the Caribbean low-level jet (this is another system) in association with the subtropical high pressure may eventually transport the dust from the Caribbean region to the United States. A well-oiled mechanism that resembles a relay race (Altendorf, 2021). It should be recalled that the East African jet stream is located at approximately 7.8° north latitude and is oriented from east to west. It originates from a strong temperature and humidity gradient. The African Jet Stream is an area of continuous strong winds at altitudes of 600,700 hectopascals (approximately 4 kilometers) (Cook, 1999).

The propitious places of dust rising in the Sahara

Several tons of dusts from the Sahara cross the Atlantic Ocean every year. The large particles fall into the Atlantic Ocean during their crossing. Only fine particles continue their journey to reach the Amazon basin (Remini, 2017), the Caribbean and even Florida (USA), i.e., a distance of approximately 8000 km (Remini, 2020). For example, approximately 182 million tons of dust leaves the Sahara each year, and only 28 million tons of particles arrive in the Amazon (Remini, 2022). This massive departure of fine material from the Sahara is not due to chance but is due to a very active wind dynamic caused by an adequate layout of mega-obstacles. To fly over the ocean, particles must first be lifted into the atmosphere as high as possible. For this purpose, the wind must blow very strongly for a long time. Once the dust reaches the atmosphere, it will be picked up by currents to carry it as far as possible. This mechanism can only take place in very specific places. In this case, the contribution of fluid mechanics to geography becomes essential to locate the sources of dust rise. It is at the level of the pass areas that the speed increases. The wind circulation around a mega-obstacle causes a tightening of the air streams at the level of the collar zones (located on either side of the obstacle). This generates a depression and consequently an increase in the wind speed. Therefore, it is at the level of the collar areas that the uplift of fine particles will take place. Three foci of dust rising have been identified. These are the regions of Bodélé (Chad), Tamenrasset (Algeria), and Air (Niger) (Remini, 2022; Remini, 2017; Remini, 2018).

The Bodélé Depression, the dustiest region on the planet

As we mentioned in the previous paragraph, three dust lifting zones were located in the Sahara. The Bodélé region is the most favorable place for dust to rise. Several authors confirm that the Bodélé depression is the first source of dust on the planet. Each year, approximately 260 million tons of dust escapes from the Sahara Desert. Approximately 60 million tons return there, 150 million fall into the Atlantic Ocean, and tens of millions of tons arrive in Europe or America (Giles, 2005). The Bodélé depression is the first source of dust emissions in the world, propelling approximately 120 million tons of dust each year, which represents 20% of all global dust (RFI, 2014). According to the GonsonGlobe website, more than 100 million tons of dust per year is transported by the wind from the Bodélé depression to the Amazon in South America. A recent study revealed that 58% of dust lifts took place in the Bodélé depression (Remini, 2022).

In our opinion, it seems to us that the Bodélé depression located in northern Chad is the only place in the world that has all the conditions necessary to generate large dust storms. The Bodélé depression, with an area of 22,000 km^2, or 0.25% of the surface area of the Sahara, is considered the dustiest place on the planet, as we mentioned earlier. In addition, the dust from the Sahara and, more particularly, the Bodélé region is very rich in organic matter. Several authors consider Saharan dust to be a natural fertilizer. Moreover, the Bodélé Depression is widely considered to be the greatest source of minerals (Washington et al, 2006). It should be remembered that the Bodélé depression was an old lake bed that contains deposits of old skeletons of fish that have died for several centuries and that are too loaded with phosphorus elements (Haug, 2015). More than 5000 years ago, a fish-filled mega-lake looked like a closed mother that occupied the central Sahara. Today, due to climate change, which has an effect on evaporation, the body of water of this large lake has shrunk to end up in the current Lake Chad. The

Bodélé depression, an area peripheral to Lake Chad, which is now dry and bare, has become a hyperarid area. According to Washington et al. (2006), the Bodélé depression is located in an environment devoid of any vegetation. Bodélé is a white chalk desert on the ground consisting of a compact crust. Very hard, the ground is not composed of sand or stones, but most of the Bodélé is covered with diatomaceous rock (Gilles, 2005). Therefore, the absence of macroroughness decreases the effect of friction and therefore promotes an increase in wind speed.

Why is the Bodélé depression the dustiest region on the planet?

How can a region as small as that of the Bodélé depression continuously supplies large quantities of dust for the planet and more particularly for the Amazon basin? Before answering this question, we can say that the Bodélé depression has a rather planetary role, that of sprinkling the continents, the oceans and the seas with Saharan dust; it is an excellent natural fertilizer. A particular and surprising relationship exists between the Bodélé depression and the great Amazonian Forest, which owes its life to the natural fertilizer coming from Bodélé. To answer the question in the subtitle, it must be understood that for dust to fly over more than 8000 km, it must first be lifted into the upper atmosphere. So, you need very strong winds. Sending a significant amount of dust into the air requires a very violent wind that lasts several days. This condition was dictated by the geography and geomorphology of the region. A recent study was conducted on the foci of dust uplifts in the Sahara. Three sources of dust emissions have been identified, of which the Bodélé depression was ranked first, with 58% of dust lifts (Remini, 2017; Remini, 2018; Remini, 2022).

The answer to this question lies in the geography and geomorphology of the entire Bodélé region and its margins. On the geographical map of Chad, three geographical elements arranged in the form of an isosceles triangle attract our attention. As luck would have it, the Bodélé depression is located at the level of the center of gravity of the isosceles triangle, whose peaks are the Tibesti, Ennedi and Lake Chad massifs (fig. 3). Driven by very active wind dynamics, this triangle, which we have called the dust triangle (Remini, 2018), can be considered a single wind unit. The answer to the previous question can only be done with the contribution of fluid mechanics. Two problems can be studied. This is the Venturi effect and wind circulation around an obstacle.

The Venturi effect, a phenomenon resulting from the dynamics of fluids, was highlighted by the Italian physicist Giovanni Battista Venturi. This is a narrowing of the fluid streams creating a depression and increasing the speed of the flow (Fig. 4). The Venturi effect is a direct consequence of Bernoulli's theorem, which occurs when there is a narrowing of the flow under load in a convergent pipe. For free surface flow, the Venturi effect can result in a narrowing of the flow when passing a constriction caused by two obstacles. This phenomenon of the Venturi effect also applies to air fluids. The wind that blows between two hills causes the tightening of the air streams, which produces a depression and therefore an increase in the speed of the wind.

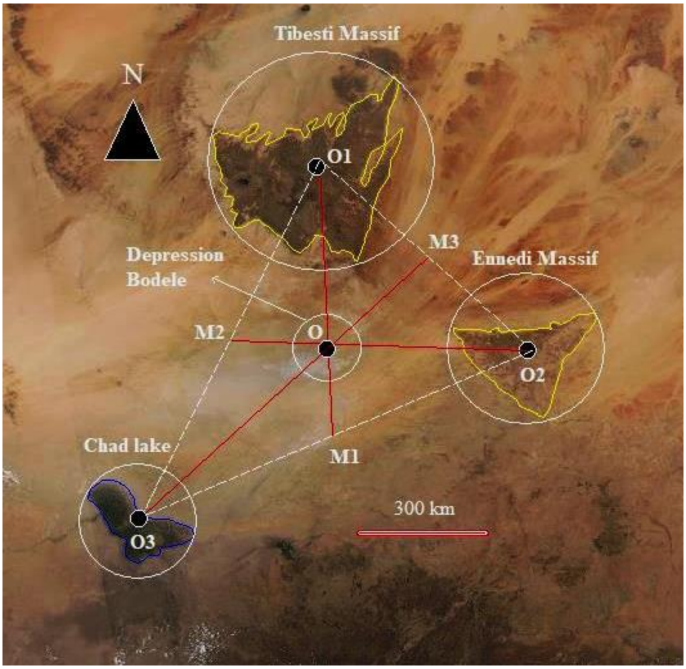


Figure 3: The isosceles triangle shape layout of 3 geographical features: Tibesti, Ennedi and Lake Chad (Remini, 2022)

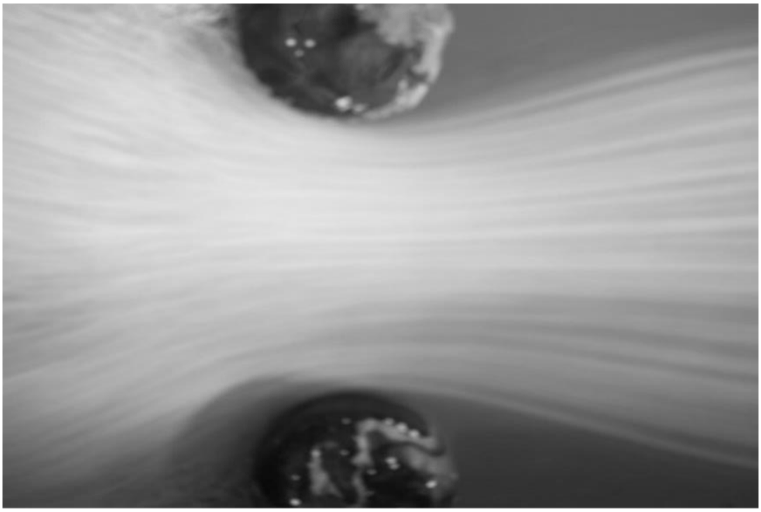


Figure 4: Venturi effect, narrowing of the flow section generated by the two obstacles (Photo. Remini, 2022)

Figure 5 shows that the flow around an obstacle generates slowing and accelerating areas. Upstream of the obstacle, it is rather the flow slowing and braking area. In the case of wind circulation, this area is the seat of a sandy deposit. On either side of the obstacle, the threads of the fluid tighten, which is the area of the pass. It is an area of erosion and transport. Downstream and just after the obstacle, the boundary layer detaches from the wall, forming the wake area. In the case of wind circulation, we are talking about the shelter area, which does not contain a deposit. Downstream of the wake area is the reattachment area, which constitutes the beginning of the sandy deposit area.

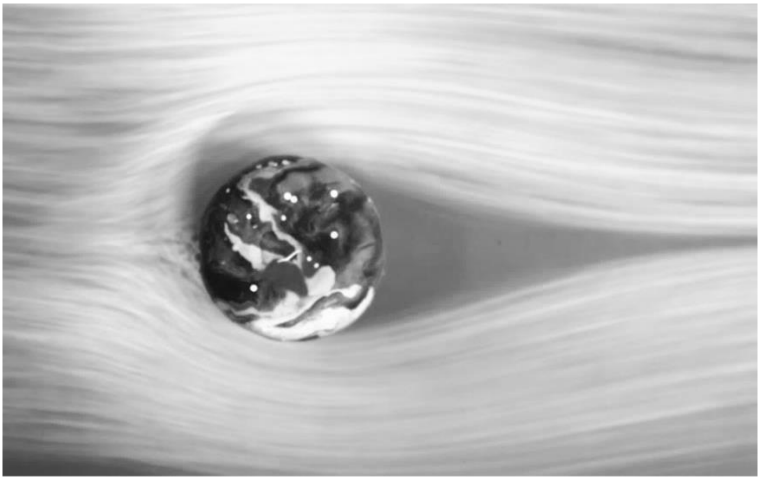


Figure 5: Flow around a circular obstacle (photo. Remini)

Starting from this idea, we can say that at the synoptic scale, the same phenomenon occurs. In the Sahara and more precisely in the Bodélé region and these margins, the wind dynamics are ensured by the wind, sand and mega obstacles. The mega-barriers of the Sahara strongly influence the wind circulation and the formation of ergs. The distribution of topographic massifs across the Sahara has created corridors and Venturi, which have favored erosion and sand deposition as well as negative and positive sedimentary budgets.

The Tibesti, Ennedi and Lake Chad complex: a single wind turbine unit

Considered the dustiest place on the planet, the Bodélé Depression is located in a place conducive to wind dynamics and lifting dust into the air. The Bodélé depression is located at the center of gravity of the triangular arrangement of the whole Lake Chad and the two Tibesti and Ennedi massifs, which we nicknamed the dust triangle (Remini, 2018). All three geographical elements, Lake Chad and the Tibesti and Ennedi massifs, form a single wind unit. Once the trade winds from Libya, Egypt and Sudan blow over the dust triangle, four wind phenomena can occur at once:

- Wind circulation around the Tibesti massif,
- The Venturi effect on wind circulation in the Borkou tunnel,
- Aeolian circulation around the topographic relief of Ennedi
- The effect of Lake Chad on the subdivision of the Alizé wind into two branches.

The topographic relief of Tibesti offers one of the best Saharan examples of the effect of a mega obstacle on wind circulation at the ground-atmosphere interface. With areas of 100,000 km^2 and 161,700 km^2 according to Mainguet et al. (1983), the Tibesti massif has an average altitude of 1800 m (Mainguet et al., 1983) (fig. 7). The great topographic relief of Tibesti, such as those of Eglab and the Hoggar-Tassili N'Ajjer ensemble, plays an important role in the wind dynamics in the Sahara. The images taken by NASA satellites on the sites of these reliefs clearly show the aeolian deflection of the wind around these mega obstacles. This is how the Tibesti massif (Chad) divides the harmattan coming from Libya into two branches: one bypasses the massif from the east, then the south; the other bypasses the massif from the north and the west (fig. 7).

Figure 6: Subdivision of the wind flow from Libya into two branches to form two mountain pass areas (Remini, 2017) (diagram taken from NASA Earth worldview satellite images)

Figure 7 shows the aggressiveness and violence of sand-carrying winds under the effects of the area of the pass (east) of the topographic relief of Tibesti and the Mega-Venturi of Borkou. The importance of wind speed is reflected in the sculpture of traces of corrosion in the form of streaks or corridor ridge systems.

Figure 7: Traces on the ground of the saltation testifying to the circumvention of wind currents by the topographic relief of Tibesti (Remini, 2017) (diagram taken from NASA Earth worldview satellite images)

Several authors have been interested in this impressive hydrodynamic phenomenon, which manifests itself on a synoptic scale, such as the Sahara Desert, an open-air laboratory. This is how Durand de Corbiac H. (1958), using aerial photographic coverage, made an overall sketch of the peri-tibestian system of ridges and corridors (fig. 8). For the first time, such a vast unit of aeolian shaping (covering 650,000 km^2) whose layout shows both how the sands coming from Libya by the northeast and the northwest of the massif meet to the southwest of it to form the erg of Bilma is described in the geographical literature. The forms of accumulation of sand only underline the same unity in the forms of corrosion.

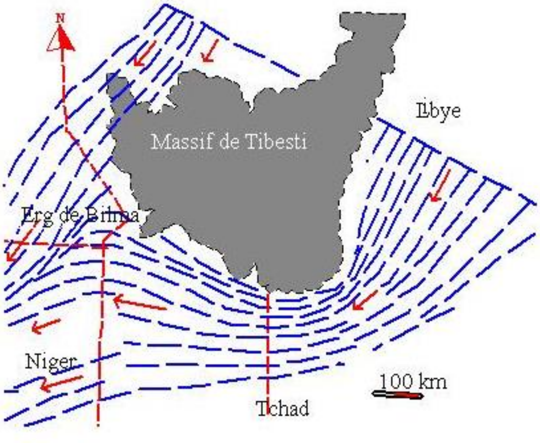


Figure 8: Overall sketch of the peri-Tibestian system (Durand de Corbiac, 1958)

In 1970, Vertappen H. Th and Van Zuidam R.A. attempted to tackle the problem using images taken by the Appollo-Gémini satellites. Their map leads to the same conclusions as Durand de Corbiac H. (1958), confirming the aeolian deflection of the wind around Tibesti (Fig. 9).

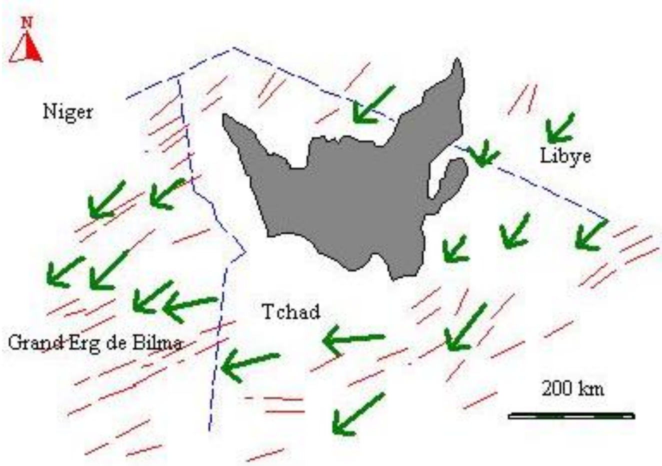


Figure 9: Overall sketch of the peri-Tibesti system (Verstapen Th., 1970)

For the first time in the history of geography by introducing fluid mechanics, Mainguet et al. (1980) confirmed from Meteosat images how the great topographic relief e Tibesti divides the harmattan into two branches: l 'one circumvents the massif by the East, then the South; the other circumvents the North and West. As we mentioned previously, a circular obstacle placed in a flow divides the latter into two branches and thus creates a dynamic whose consequences are the formation of areas of slowing down and acceleration of the flow (fig. 6). This result can also be obtained for wind circulation around an obstacle. At the synoptic scale, such as the Sahara, the topographic reliefs considered mega-obstacles create a wind dynamic that generates the birth of the following areas: the deposit area upstream of the obstacle, the pass areas that are erosion areas, and the shelter area just downstream of the obstacle known by the absence of sand deposits. Just downstream of this zone is the reattachment area, which constitutes the beginning of the sandy deposit area. The mega obstacle of Tibesti is located in an ideal place for the division of the harmattan coming from Libya into two wind flows and creates a wind circulation around the rocky massif. Upstream of the Tibesti massif, it is rather the braking area for wind currents carrying sand. With a wind speed practically equal to zero, the wind releases the sandy particles to form the Erg of Rebiana; we speak of the obstacle Erg (Mainguet et al, 1984). On both sides of the Tibesti massif, the mountain pass areas are characterized by a tightening of the air streams, thus causing a depression and consequently an increase in the speed of the wind. These two areas contain ergs of erosion, which are ergs with a negative sedimentary balance. Based on images taken by NASA satellites over the Chad Desert, we schematized the different areas obtained by the wind dynamics created around the mega obstacle of Tibesti in Figure 10.

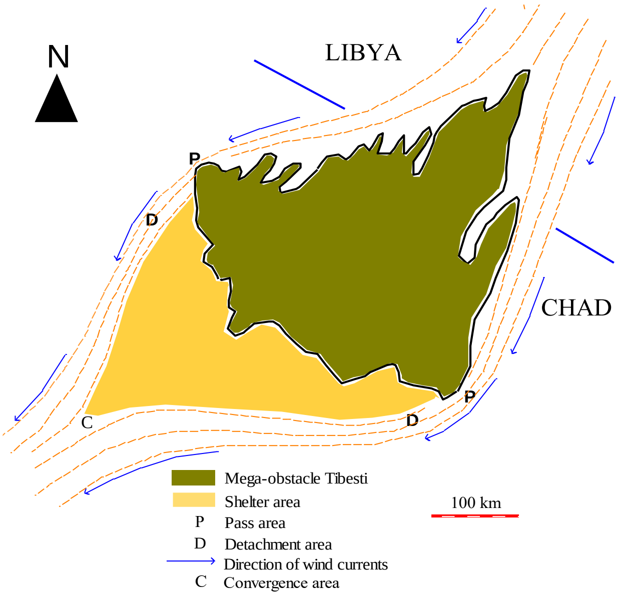
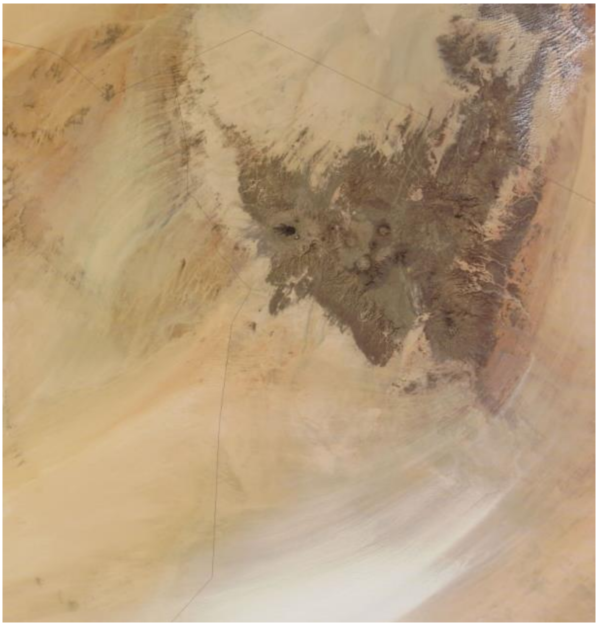
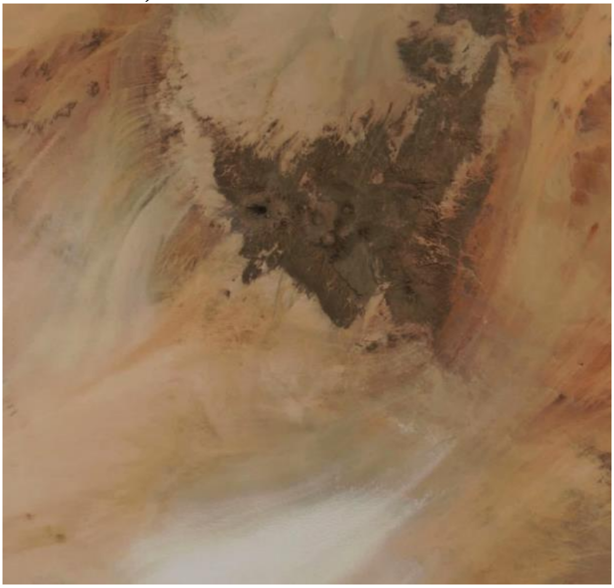


Figure 10: Traces on the ground of the saltation testifying to the circumvention of wind currents by the Tibesti

The Grand Erg of Fachi Bilma is located downstream of the Tibesti massif. It is formed at the point of convergence of the two branches of wind currents obtained by the harmattan subdivision from Libya. In addition, this place of reattachment, which is a place of deposits, represents at the same time the obstacle area upstream of the Aïr massif and which is a deposit zone. The most impressive phenomenon for this massif remains the circumvention of the branch of the harmattan, which runs along the Tibesti from the east and bends to the southwest in an arc in the Bembéché. With a length of 600 km, this arc has a radius of 300 to 450 km (Mainguet and Chemin, 1990). The shelter area with an area equal to 37,000 km^2 and 30,000 km^2 according to Mainguet et al. (1983) was formed by the circumvention of the two wind flows, which plays the same role as topographic relief. The shelter area, which is characterized by the absence of sandy deposits, represents the seat of lively, disordered movements where the speeds are very variable in time and space. On the other hand, it is at the level of the places of detachment that are located just downstream of the neck areas, which are characterized by the detachment of the streams of air from the walls of the obstacle and which is accompanied by the formation whirlpools, thus causing dust to rise in the air and which are then driven by violent winds (fig. 11). It is an original approach that explains the mechanism of the phenomenon of propulsion of dust from the Sahara toward the Atlantic.



a) Dust storm of December 9, 2011



b) Dust storm of November 30, 2015

Figure 11: Dust uprisings created by the effect of the Tibesti massif on wind circulation @NASA Erath worldview

Wind circulation around the rocky massif of Ennedi

Wind flows from Libya and Sudan are divided into two wind current bundles by the topographic relief of Ennedi. Covering an area equal to 33,000 km^2, the Ennedi mega-obstacle has a triangular shape, one of the peaks of which is directly facing the wind currents (fig. 12). The division of the wind flow into two branches is carried out with less pressure drop. However, the effect of the passes forces the air streams to tighten, thus causing depression and an increase in speed. In these areas, deflation is great due to the violence of the winds. In addition to these areas, a special sector is formed downstream of the sand-free massif called a shelter area with an area equal to 25,000 km^2. The export of sand particles is much more important than the input of sand. However, at the pass area on the west side, the wind speed is much higher due to the effect of the Ennedi pass and the effect of the contracted section of the Venturi. Just downstream of the mountain pass areas, the places of detachment of the area nets from the wall of the obstacle are located. These are accompanied by whirlpools, thus causing dust to rise in the air (fig. 13). Contrary to the sources of dust exportation that appear under the Tibesti effect, the dust uplifts show little in the detachment area south of the Ennedi relief. Wind flows from Libya and Sudan are split into two wind current bundles by the Ennedi topographic relief. Of a triangular shape, one of the vertices is directly facing the wind currents. The division of the wind flow into two branches is carried out with less pressure drop. Only the effect of the collars forces the air nets to tighten. In these areas, deflation is great due to the violence of the winds. The export of sand particles is much more important than the input. However, at the pass area on the west side, the wind speed is much higher due to the effect of the Ennedi pass and the effect of the contracted section of the Venturi. In this case, it is at the level of these areas (passes) that dust storms are triggered (Fig. 14). Contrary to the three sources of dust exportation mentioned above, dust storms do not manifest themselves much in the southern pass area of the Ennedi relief.

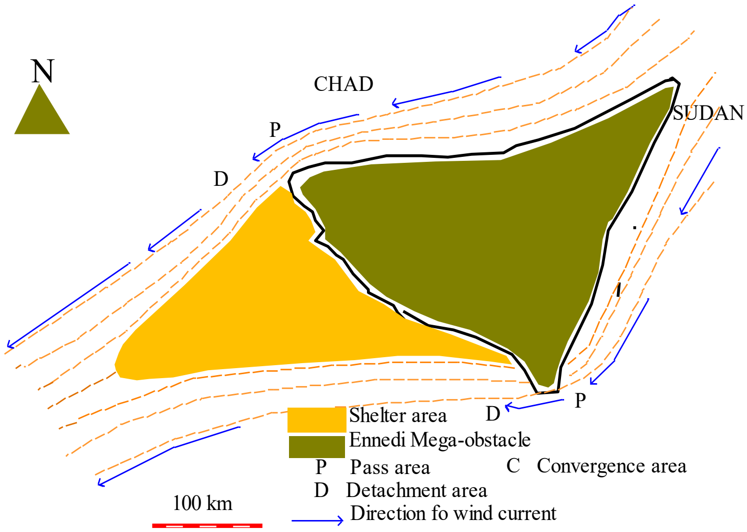


Figure 12: Subdivision of the wind flow from Libya into two branches to form two mountain pass areas (Remini, 2022) (diagram taken from NASA Earth worldview satellite images)

Figure 13: Birth of a dust storm of February 2, 2017 at the East col of Ennedi @NASA Erath worldview

The Borkou Venturi formed by the Tibesti and Ennedi massifs

Upstream of the Bodélé depression, there is a mega-Venturi obtained by the natural arrangement of the volcanic massifs Tibesti and Ennedi. A Venturi in the Sahara; it is located in the territory of Chad; it is formed by the layout of the mega-obstacles: Tibesti and Ennedi. Trapezoidal in shape, the convergent has an average length of 300 km, a width at the entrance equal to 700 km and a width at the exit (Bembéché) equal to 300 km (fig. 15). It can be considered the most beautiful mega-venturi in the Sahara. When the wind blows, arriving between these two obstacles, the streams airtighten and converge toward the corridor formed by the obstacles; then, the streams of air diverge. This scenario is presented in northern Chad by the volcanic massif of Tibesti (3415 m) and the sandstone massif of Ennedi (1400 m) separated by the Borkou corridor (mega-Venturi). This set of massifs is considered a single unit. It cannot be studied separately, as it has been described by several authors. For example, the shelter area as well as the recovery area downstream of the Tibesti massif is influenced by the mega-Venturi Tibesti – Ennedi pass.

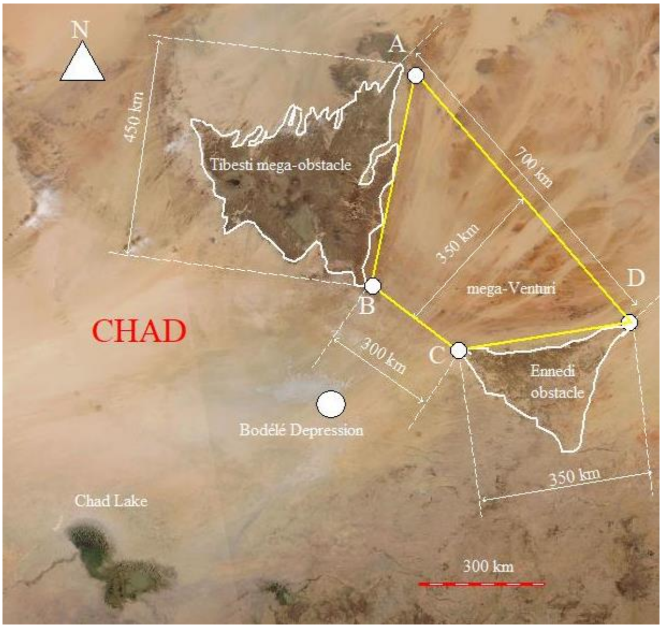


Figure 14: Dimensions of the Mega-Venturi of the planet (Remini, 2001; Mainguet and Remini, 2004)

Strong winds cause dust to rise

As we have already mentioned in our previous works (Remini, 2017; Remini, 2018; Remini, 2020; Remini 2022), dust lifting takes place near mega-barriers. In addition, strong winds cause dust to rise in the air. In the case of the Bodélé depression, the site is exceptional; the wind is so violent that each year a quantity of 2000 million tons is propelled toward the Amazonian Forest. Upstream of Bodélé, the presence of two mega-obstacles, Tibesti and Ennedi, form three pass areas. It is at this neck area that the air streams tighten, creating a depression, and therefore, the wind blows very hard. The wind causes detachment of the air streams from the wall of the obstacle, which is accompanied by the appearance of vortices. This phenomenon accelerates according to the wind speed and more precisely according to the Reynolds number (Re = VL/ν). The wind accelerates when it passes through the neck area, where the air streams tighten, creating a depression and therefore the wind speed increases. Therefore, the geographical layout of the rocky massif of Tibesti, the rocky plateau of Ennedi and the tunnel of Borkou constitute the most beautiful venturi on the planet. In this case, three pass areas participate at the same time to increase the wind speed. These are the passes: Tibesti (south-east), Ennedi (north-west) and Bembéché (under the Venturi effect) allow the harmful wind from Libya and Egypt to rush into the Borkou Tunnel (Fig. 15). As it escaped from Bembéché, the wind was blowing very hard, the speed of which exceeded 7/3 of the speed of the wind at the entrance to the Borkou tunnel. Corrosions in corridor ridges were sculpted on the ground at the level of the neck areas by sand winds whose tight air nets have greater erosive efficiency (fig. 16).

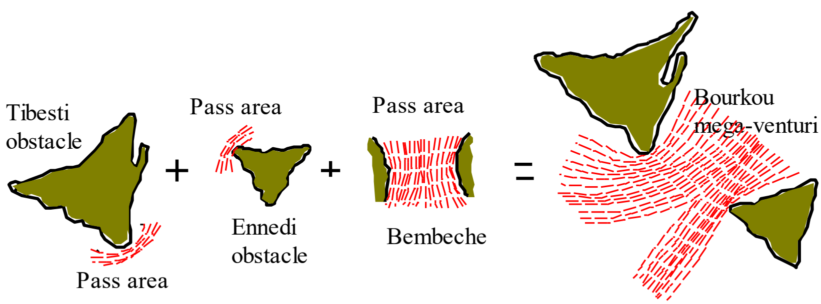


Figure 15: Three pass areas occur at the exit of the Borkou tunnel (Remini, 2022)

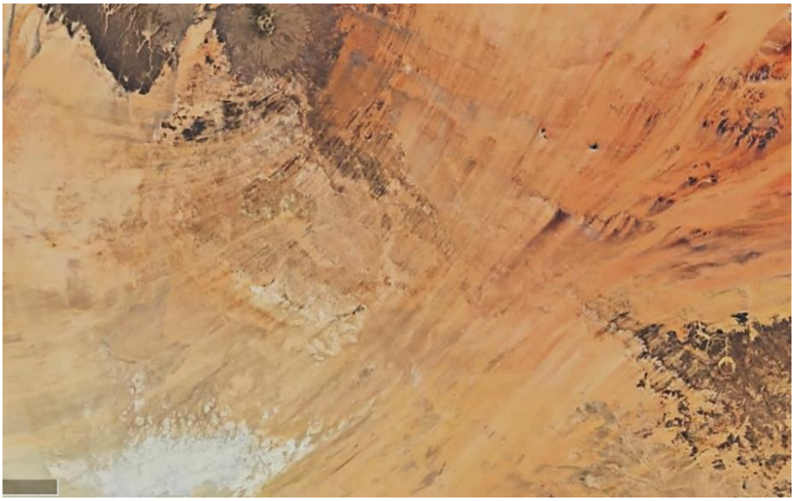


Figure 16: Effects of violent sand-carrying winds on ground corrosion (Google Earth)

Tibesti-Ennedi-Lake Chad: the dust triangle

Located at the center of gravity of the dust triangle, the Bodélé depression is the dustiest region on the planet. Contrary to some authors who have studied the wind circulation around the Tibesti and Ennedi massifs separately, our study considers that the three geographical elements Tibesti, Ennedi and Lake Chad form a single wind unit. This geographical arrangement of triangular shapes is very favorable for creating an active wind dynamic at the level of the Bodélé depression and its margins (fig. 17). Two situations of wind dynamics emerge:

- A situation concerning the movement of medium and coarse particles inside the Bodélé depression and its margins. We are witnessing a very active wind dynamic that has an impact on erosion, transport and deposition and its impact on the formation of dunes and the shaping of Ergs.
- A situation that concerns the movement of fine particles outside the Bodélé region and the Sahara. There are episodes of dust rising in the air and the propulsion of fine particles outside the borders of the Sahara.

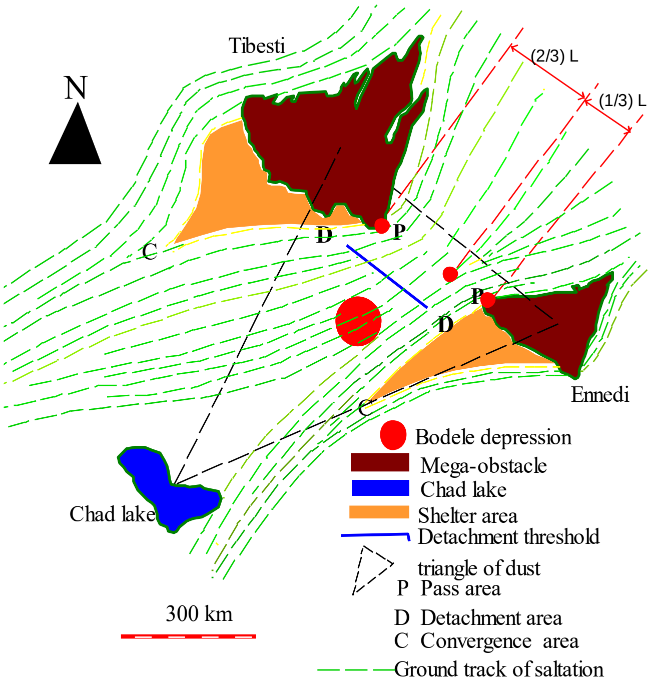


Figure 17: Geometric configuration of the Tibesti – Ennedi – Lake Chad complex

The movement of coarse particles at the level of Bodélé and these margins

The harmattan from Libya and Egypt rushes into the great portal of the mega-Venturi of Bourkou with a length of 700 km formed by the arrangement of the Tibesti and Ennedi massifs. The harmattan is made up of two branches of wind currents: one coming from Libya (which is diverted south of the Tibesti massif) and the other coming from Egypt (which is diverted north of the Ennedi massif) (Fig. 18).

The total air flow is animated by a high speed in the region of Bembéché at the exit of the Mega-Venturi. It is the consequence, on the one hand, of the effect of the pass to the southeast of Tibesti and to the west of Ennedi and of the narrowing of the section of the mega-Venturi of Borkou. Violent sand-carrying winds erode, carve and leave corrosion on the ground. After going around the obstacle, the two currents meet downwind of the massif at the level of the reattachment area. This point of convergence explains the birth of Fachi Bilma's Grand Erg (fig. 18). In the convergence area, the branch that passes to the east of the massif is the most vigorous. Erg de Rebiana, upwind of Tibesti, as well as the small ergs to the east of the Tibesti massif, can be defined as obstacle ergs (fig. 18). In the western sector, where the bend in the wind circulation around the massif begins and where a pass effect is evident, the sand-laden wind has sculpted a landscape of ridges - periodic corridors of the kalout type (Mainguet et al, 1980 Mainguet, 1978; Mainguet, 1992). The shelter area bypassed by the two branches of wind finds the reattachment area after a length of 150 km from the side oriented from SE to NW. Immediately downwind of the massif, the Grand Erg of Bilma begins with convergent Ghourdic chains expressing the convergence of wind currents and the various turbulences that result in this area. The wind is indeed more powerful there than in the southern branch, which travels a longer route to circumvent the Tibesti.

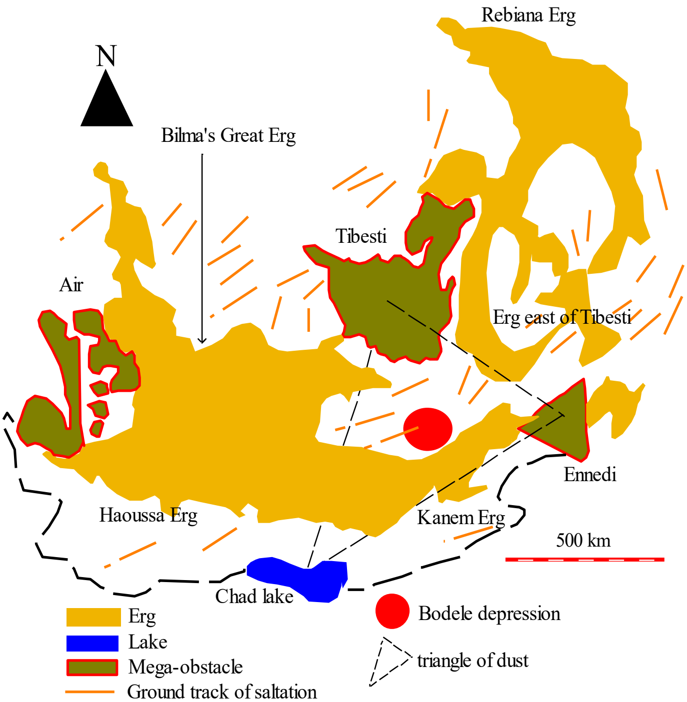


Figure 18: Wind currents around the Tibesti-Air-Ennedi complex (Mainguet M. and Chemin M. Ch., 1990; Mainguet M. et al., 1980)

In contrast to the wind flow from Libya and Egypt, the Ennedi massif divides the wind flow into two branches. However, the effect of the passes forces the air streams to tighten, thus causing depression and an increase in speed. In these areas, deflation is great due to the violence of the winds. In addition to these areas, a particular sector is formed downstream of the massif devoid of sand called a very elongated shelter area with a length of 400 km and an area equal to 30,000 km^2. The Erg de Kanem was formed at the point of convergence of the two branches of the harmattan deflected by the Ennedi plateau. The reattachment zone is characterized by a slowdown in speed and an increase in pressure. The western branch of the harmattan deviated by the Ennedi massif accelerates at the level of the pass. Under the Venturi effect, the wind speed of the western branch increases. Therefore, at the level of the pass area, the very violent wind causes intense erosion and a departure of sand toward the reattachment area. The neck area is an area with a negative sediment balance.

It is interesting to note that the Tibesti massif, with an area equal to 100,000 km^2 and 161,700 km^2 according to Mainguet (1980), has the shape of an equilateral triangle circumscribed in a circle with a diameter of 480 km. The sides of the Tibesti are 450 km apart. The Ennedi massif, with an area of 22,500 km^2, also has the shape of an equilateral triangle, circumscribed in a circle with a diameter of 250 km. The extreme points are 280 km apart on average. We note that the sides of the Tibesti triangle are approximately twice those of the Ennedi massif. Lake Chad is circumscribed in a circle with a diameter of 290 km. The centers of the three circles (O1, O2, and O3) form an isosceles triangle whose OO1 and OO2 sides are 950 km. The circulation of the carrier wind from Libya is via the southwest and west of Tibesti. The mega-Venturi, which is the Borkou corridor formed by the Tibesti and Ennedi massifs, is of an average length equal to 350 km between the entrance and the exit of the convergent. This trapezoidal shape (BADE) is the seat of high deflation, mainly due to a depression that occurred in the region of Bembéché (exit section). This leads to an increase in wind speed, which can reach 7/3 of the entry speed (Remini, 2018). Mainguet M. (1990) showed that the main branch of the harmattan runs along the Tibesti to the east and bends to the southwest in an arc (600 km) in the Bembéché. The presence of Lake Chad, the longest shore of which measures 275 km, is similar to an obstacle facing the wind, which causes a division of the harmattan into two branches. The orientation of the DE front of the Ennedi massif (east–west) forces the wind to move toward the northwest. The narrowing of the section between the Tibesti and Ennedi obstacles increases the wind speed and decreases the air pressure, which generates a zone of strong erosion and gives rise to forms of corrosion; the sediment balance is negative. On the other hand, once this wind flow has arrived in the Tibesti - Lake Chad area, where the section of the corridor increases (formation of a divergent), its speed decreases and its pressure increases, which gives a transport area to the center of the corridor, the formation of barkhanic edifices, the sedimentary budget in equilibrium and a deposition area formed by transverse dunes upstream of Lake Chad, with a positive sedimentary balance.

The movement of fine particles outside the Bodélé and Sahara regions

With regard to the movement of fine particles, a very active wind dynamic manifests itself in the Bodélé depression, thus causing a massive departure of dust toward the outside of the Sahara. As we showed at the beginning of this study, the dust triangle generates strong winds, so it is able to propel dust toward the atmosphere. Images taken by NASA satellites over the Chad Desert during the period 2001-2021 showed that 850 episodes of dust lifting occurred in the territory of the dust triangle. We have established an approach to the mechanism of the uplift and propulsion of dust from the Bodélé depression toward the Atlantic (Fig. 19). We are talking about the dustiest region of the planet; more than 50% of particles are exported from this arid zone.

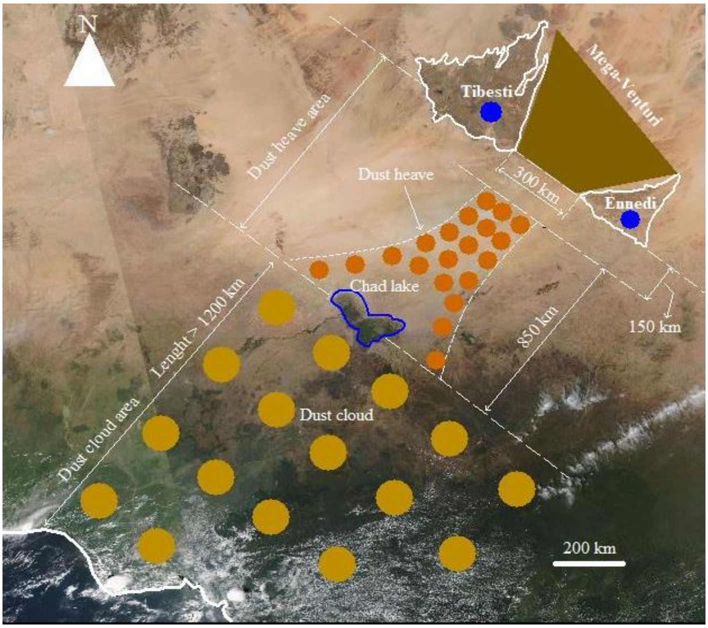


Figure 19: An approximate map of the dust uplift and propulsion mechanism in the Bodélé depression (Remini, 2022)

The map in figure 19 summarizes our approach to the Bodélé dust lifting and propulsion mechanism toward the Atlantic. Three distinct stages emerge:

- The first phase concerns the appearance of violent winds. It is dictated by the presence of the mega-Venturi called the Borkou Tunnel, formed by the proper arrangement of the mega-obstacles of Tibesti and Ennedi. With an area equal to approximately 165,000 km^2, the convergence plays a very important role in increasing the wind speed at the exit of the Tunnel (Bembéché) under the Venturi effect. The birth of dust storms in this region is due to the existence of the most beautiful Venturi on the planet. This is the originality of Bodélé's depression. As we have just shown previously that the harmattan coming from Libya and Sudan rushes into the Borkou tunnel with a speed V. At Bembéché, the wind flow leaves with a speed equal to 7/3 V. We note in the processed satellite images that two very distinct branches separate: one takes the SO direction with a width equal to (2/3) L, and the other branch with a width equal to (1/3) L goes in the SE direction. As shown in figure 20, this wind architecture sculpted and drawn by the very violent winds remains practically the same for all the dust storms that occur during the period 2001-2021.

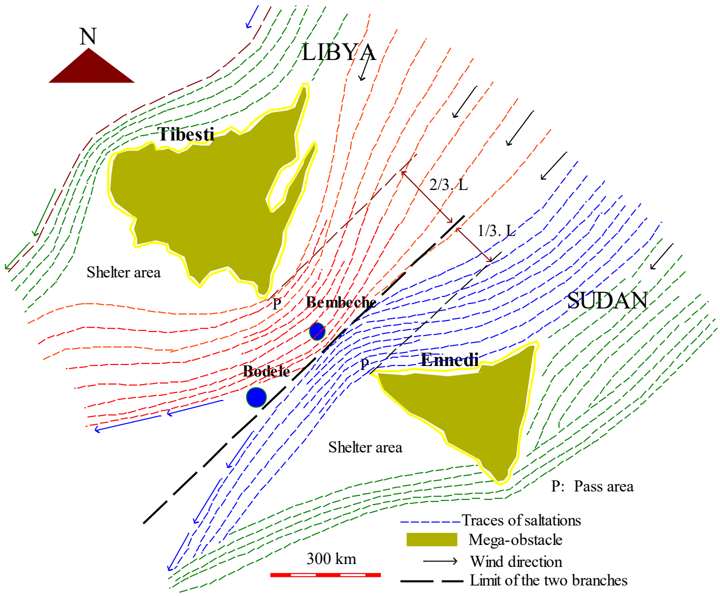
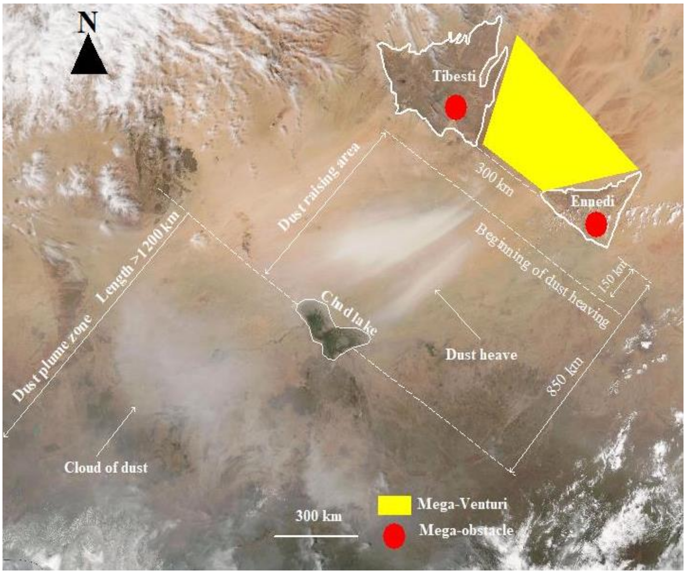


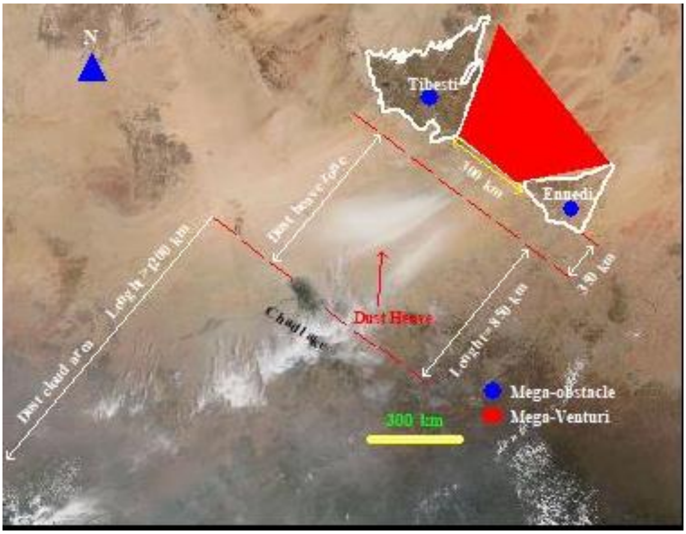
Figure 20: The size of the two branches bypassing the Tibesti and Ennedi obstacles in the Bourkou tunnel (Schéma Remini, 2022)

- The second phase concerns the rising of the dust. It begins just at the exit of the Venturi (Borkou Tunnel) in the region of Bembéché. At the level of the section (P-P), the speed of the wind flow is equal to 7/3 of the wind speed at the entrance of the Borkou convergent. It is the Venturi effect that has caused the tightening of the air streams at the level of the collar (P-P section), thus creating a depression, and consequently, the wind is blowing very hard (fig. 20). This leads to the lifting of dust approximately 150 km beyond the pass at the level of the D-D limit in the Largeau region. Why does dust rise at this threshold? Quite simply, this limit corresponds to the point of detachment of the air streams from the wall of the mega-obstacle, which is always accompanied by the appearance of vortices that raise the dust in the air. In another way, this dust start threshold corresponds to the contraction section (Sc). At the exit of an orifice of section S0, the liquid threads of the flow tighten to reach the contracted section Sc, and then the threads loosen. The same phenomenon occurs in the Largeau region, except that the fluid is air. In this case, section Sc corresponds to section (D-D). Before reaching Lake Chad over a distance of approximately 750 km from Bembéché, the two branches of the wind flow loaded with fine particles move further away. Lake Chad plays the same role as a topographic mega-obstacle. In addition, the right branch (depending on the direction of the wind) is much more important and very accentuated than the left branch. The more intense right branch is rather curved compared to that of the left branch, which is rather thin and elongated. This can be explained by the wind circulation around the mega-barriers Tibesti and Ennedi. The geometric shape of the topographic massif plays an important role in the formation of pass, reattachment and shelter areas. The latter is rather compressed in the case of the Tibesti massif. This explains well the rapprochement of the air streams toward the Tibesti massif on the south side. Unlike the Ennedi massif, the shelter area is rather elongated, which explains the distance of the air streams from the mega-obstacle on the southwest side. The branch around the Tibesti massif represents 2/3 of the width of the Borkou pass. The width of the branch around the Ennedi Plateau is equal to 1/3 of the width of the pass (fig. 20). This phase takes place over an area of 300,000 km^2 with a length of 700 km from the D-D limit, which corresponds to the lifting of dust that can reach Lake Chad. In this step, we defined effective uplift as uplift capable of sending fine particles beyond Lake Chad (Remini, 2022).

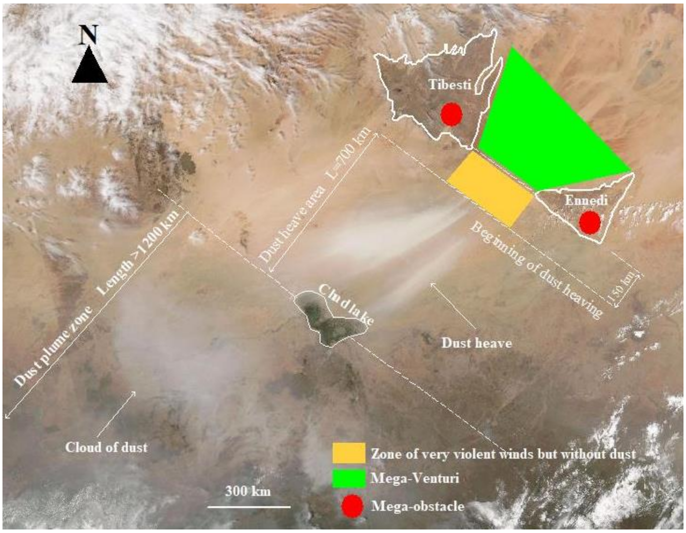
- The third phase begins from Lake Chad to the western border of the Sahara over a length that exceeds 1200 km. With regard to the problem of raised dust, two wind situations emerge: before and after Lake Chad. For the one before, the dust plume is at a low altitude and is very concentrated in fine particles with well-elongated air streams; the speed of the dust plume is very important. Regarding the situation downstream of Lake Chad (and which corresponds to the third phase), the dust plume is rather low in fine particle concentration, but occupies a much larger surface, it looks like clouds. Once separated by Lake Chad (which plays the role of a rocky relief), the two dust-carrying wind flows disappear, giving way to dust plumes that can cross an area of more than 3 million km^2 to reach the Atlantic shore. Forming clouds, the fine particles in suspension gain altitude and reach the highest heights of the atmosphere. This plume of fine particles behaves like clouds of fine particles that will be picked up by wind currents to transport them to the Atlantic, a journey of more than 1200 km. In a decreasing way, the particles fall according to their size, and only the lightest particles will continue their way to the Amazonian forest and can even reach the south of the United States, more than 8000 km (Remini, 2020). All the space of the path occupied by the dust plume will be sprinkled with millions of tons of dust. Of the 503 dust storms that occurred in the Bodélé depression, we have cited four examples, as shown in Figure 21 (a, b, c and d).



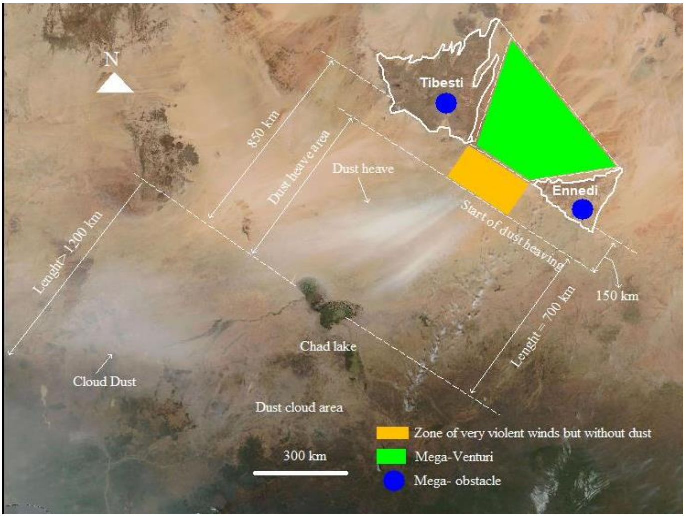
a) **Dust storm March 17, 2021 (@NASA Erath worldview)**



b) **Dust storm February 19, 2020 (@NASA Erath worldview)**



c) Dust storm February 17, 2018 (@NASA Erath worldview)



d) Dust storm December 20, 2015 (@NASA Erath worldview)

Figure 21: Mechanism of the formation of a dust plume in the Bodélé depression (Remini, 2022)

The raising of dust; the most complex stage of the transatlantic journey of fine particles

On the basis of NASA satellite images taken over the Sahara during the period 2001-2021, we have identified approximately 875 dust lifts in the Sahara, thus totaling a total of 4640 days of lifts of fine particles in the air distributed over the 3 foci: Bodélé (Chad), Tanezrouft (Algeria) and Aïr (Niger) (Remini, 2022). It turns out that 503 dust lifts (58%) occurred during 1627 days in the Bodélé depression (Chad) during the last 20 years (2001-2021). This does not explain why the dust storms caused by the 503 sand heavings, the equivalent of 4 and a half years (1627 days) of dust in the sky of Bodélé, will reach the other side of the Atlantic. Therefore, the duration of a dust lift is a determining parameter of an effective storm. a storm that can fly over the Atlantic Ocean. Efficient dust lifting means lifting capable of sending a large quantity of fine particles into the atmosphere. To initiate a dust plume, it is necessary to have an effective uplift that is directly related to the concentration of particles and the duration of uplift. Three types of dust risings emerge (Remini, 2022):

- Low uplift is uplift with a duration of no more than 3 days (duration <3 days). This causes a plume of dust that dissipates over a few kilometers.
- Medium uplift is dust uplift with a duration of between 3 and 6 days (3 days ≤ duration <7 days). It can cause a plume of dust that vanishes before reaching the west coast of the African continent.
- Heavy lifting is a lifting of dust whose duration exceeds 7 days (duration ≥ 7 days). It can give rise to a plume of dust that can fly over the Atlantic Ocean to reach the Caribbean and the continents of the Americas.

Figure 22 shows the evolution of the cumulative dust uplifts that occurred during the period 2001-2021 at the level of the Bodélé depression. The number of dust rising episodes increases linearly with time. An average of 25 dust risings occur each year in the Bodélé area. However, 35 dust events occurred during 2013 and 2017 (fig. 23). The year 2015 recorded the number of 117 days of dust, i.e., 1/3 of the year (fig. 23). This does not explain why all the amount of dust raised in the air flies over the Atlantic and reaches the other side of the ocean. It is in this order of idea that we have represented in Figure 24 the evolution over time of the three types of dust lifting: weak, medium and strong. At least 2 strong-type dust lifts have occurred every year. The dust plume travels more than 4000 km and sprinkles the Amazon forest. This type of dust lifting has manifested itself in the Bodélé depression. More than 40 strong-type uprisings have been recorded in the past 20 years. For medium dust lifts, approximately 205 dust lifts have been recorded during the last 20 years at a rate of 10 dust lifts per year. These fine particles are unlikely to fly over the Atlantic, and only dust storms will not cross the western border of the Sahara. Weak uprisings that do not exceed 3 days are the most widespread events, since more than 250 dust uplifts took place in the Bodélé area during the period 2001-2021 at a rate of 12 dust uplifts per year but without triggering dust clouds. These quantities of dust will not leave the Bodélé region and its margins.

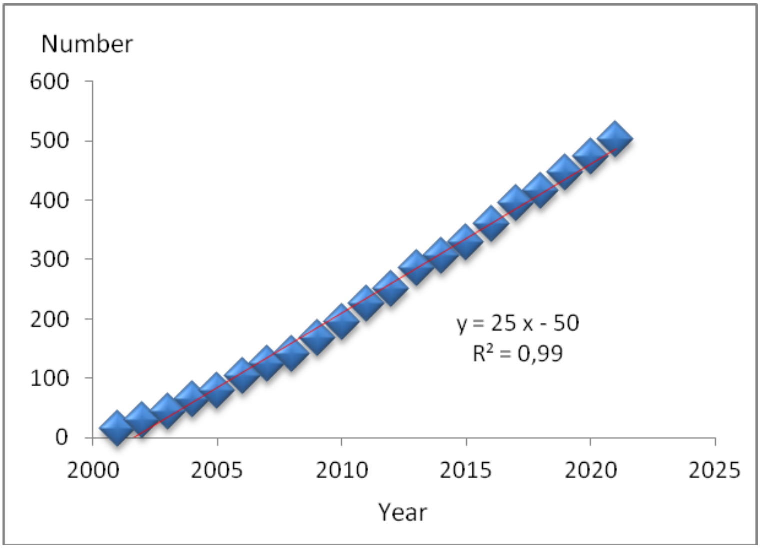


Figure 22: Evolution of the cumulative number of dust lifts in the Bodélé depression during the period 2001-2021 (Remini, 2022)

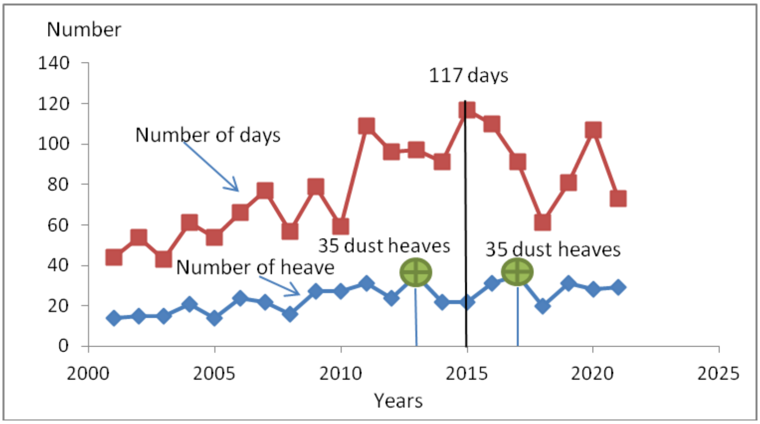


Figure 23: Evolution of uplifts and the number of dust days in the Bodélé depression during the period 2001-2021 (Remini, 2022)

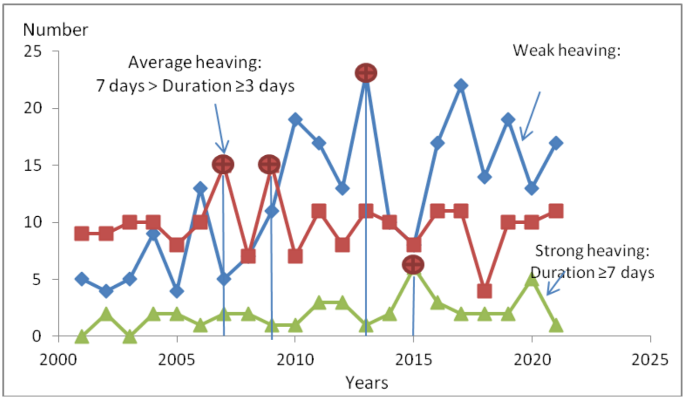
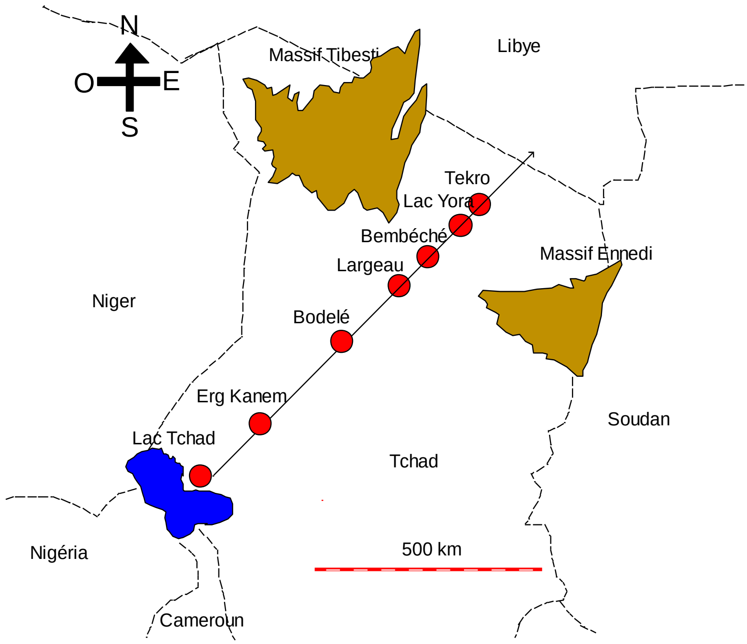
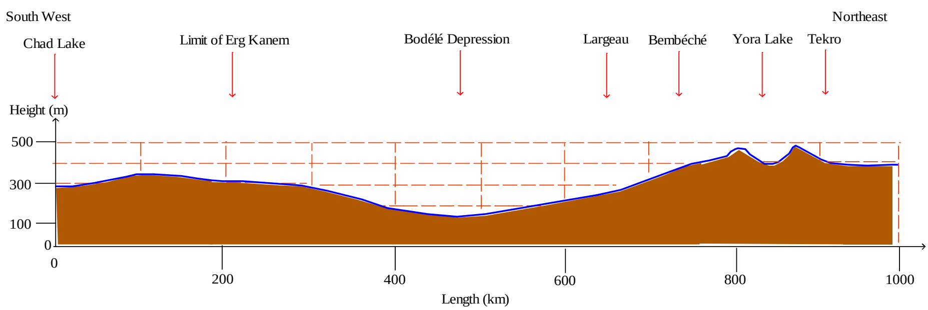


Figure 24: Evolution of the 3 types of dust lifts in the Bodélé depression during the period 2001-2021 (Remini, 2022)

The wind escapes from the pass in the region of Bembéché with a speed equal to 7/3 of the entry speed. At the level of the Largeau region (located approximately 150 km from Bembéché), this region represents the area of separation of the air streams from the mega obstacles Tibesti and Ennedi, which are accompanied by the formation of large eddies. These whirlpools raise dust into the atmosphere. According to the ConsoGlobe website, the Sahara is the site of powerful whirlwinds that send 2 billion tons of dust into the atmosphere each year. This supports our approach. These erosive winds, which occur along the Bembéché-Largeau-Bodélé axis up to the limit of Erg Kanem, produced approximately 503 uplifts of different types (strong, medium and weak), the equivalent of 1627 dusty days. Over the past 20 years (2001-2021). According to the ConsoGlobe site, approximately 2 billion tons of dust is released each year from the Bodélé basin to sprinkle the Amazonian forest. This large amount of dust is the result of the formation of 503 dust lifts in the Bodélé depression. Approximately 43 effective uplifts with an episode duration exceeding 7 days of uninterrupted dust uplift. According to the ConsoGlobe website, the largest dust storms (which we have called efficient uplifts) can bring ½ million tons of dust at once. This has a direct impact on the erosion of the bottom of the Bodélé zone of an area of 0.2% of the surface of the Sahara. The Bodélé depression is widely considered to be the greatest source of minerals on the planet (Washington et al, 2006): an annual transfer of 22,000 tons of phosphorus to the Amazon rainforest. Moreover, we found that 58% of dust lifts occur in the Bodélé depression. Sahara dust is a natural fertilizer, and more particularly that of the Bodélé depression, it is a fertilizer highly loaded with phosphorus, potassium, calcium and magnesium (Chavetnoir, 2015). With a rate of 25 dust lifts per year, the equivalent of more than 81 days of dust per year, the bottom of the Bodélé basin is eroding, thus causing over time a deep digging of more than 150 m in the center of the Bodélé area. According to Bristow et al. (2009), evidence of erosion indicates that up to 4 m of sediment was locally removed by deflation. According to the same author, optically stimulated luminescence dating shows that this occurred in less than 2400 years, which gives a deflation rate of approximately 1.6 mm/year. Figure 25 (a and b), which illustrates the axis of the Tibesti-Ennedi corridor to Lake Chad, clearly shows the effects of wind erosion on the soil.



a) Aerial view (Remini, 2018)



b) Topographic section (Mainguet and Chemin, 1990)

Figure 25: Érosion du fond de la cuvette de Bodélé suite aux multiples soulèvements de poussière (Remini, 2018)

CONCLUSION

As we mentioned at the beginning of this paper, the phenomenon of dust diffusion from the Sahara is a complex subject. Despite its small size, the Bodélé Depression is the dustiest region on the planet. More than 58% of the dust risings that occurred in the Sahara Desert during the period 2001-2021 originate from the Bodélé depression. The Amazonian forest is fed continuously by sending fine particles from this focus. We can say that the Bodélé depression has a rather planetary role, that of sprinkling the continents, the oceans, the seas and the Amazon basin with Saharan dust, an excellent natural fertilizer. A special and surprising relationship exists between the Bodélé depression and the great Amazonian forest, which owes its life to natural fertilizer from Bodélé (Chad) and Tamanrasset (Algeria). To answer the question "why the Bodélé depression is the dustiest focus on the planet", it must be understood that for the dust to fly more than 8000 km, it must first be lifted into the upper atmosphere. So you need very strong winds that last several days. This condition was dictated by the geography and geomorphology of the Bodélé region. It is found that upstream of this small region with an area of 0.25% of that of the Sahara, the arrangement of the two topographic reliefs Tibesti and Ennedi form the largest Venturi on the planet. It is this exceptional site that sends very violent winds (under the effect of Venturi and the passes of Tibesti and Ennedi) toward the region of Largeau (located 150 km from Bembéché); take-off area. In this case, the streams of air break off from the Tibesti and Ennedi massifs, which are accompanied by the formation of gigantic whirlpools that raise dust into the upper atmosphere. Thus, 503 dust lifts have taken place in the Bodélé depression during the past 20 years. Approximately 43 major storms, which we have called effective uprisings, have occurred during the period 2001-2021.

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