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WHEN THE SAND OF THE SAHARA LEAVES ITS TERRITORY – MECHANISM OF DUST RISING

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ABSTRACT

This paper deals with the mechanism of the uplift of dust from the Sahara in the atmosphere. The first study carried out in 2001 showed that it is at the level of the mega-obstacles of the Sahara that the wind dynamics are very active. So, if there is dust rising, it will be at the level of these rock masses. To answer these hypotheses, we used satellite images taken over the Sahara during the period: 2001-2021. The results obtained showed that the Sahara recorded about 875 dust lifts during the period: 2001-2021. It is these uplifts that can send dust flying over the Atlantic. The years 2017 and 2020 recorded the highest number of dust lifts exceeding 600 days. Three types of dust lifting were highlighted: weak (Duration < 3 days), medium (7 days > duration ≥ 3 days) and strong (Duration ≥ 7 days). We have defined effective uplift as uplift capable of propelling a significant amount of dust into the atmosphere. A map of dust lifting areas in the Sahara has been established. Three foci of dust risings in the Sahara have been located. These are the areas induced by the mega-obstacles: Hoggar-Tassili N'Ajjer (Algeria), Aïr (Niger) as well as Tibesti and Ennedi (Chad).

Keywords: Sahara, Wind dynamics, Atlantic Ocean, Mega-obstacle, Dust rising.

INTRODUCTION

Dust in the air; a meteorological phenomenon that occurs frequently during the spring season in the Sahara. These fine particles even go up to the northern Wilayas in the form of storms. It is a phenomenon that originates in arid regions under certain meteorological conditions that allow strong winds to lift significant amounts of dust from Ergs and dunes into the atmosphere. Commonly, such a phenomenon is referred to as sandstorm or dust storm, despite the difference in particle size. Dubief, in 1952, already insisted on the problems of definitions of sandstorms and dust storms. In this regard, he notes the role of observation, which varies from one individual to another (in Nouaceur, 2004). The effects of erosion and wind dynamics in hot deserts are not limited only to their own territories, but they are propagated outside and can even reach other continents. Planet Earth holds 10 hot deserts that emit dust into the air. The mass of dust released into the air can reach 3 billion tons. However, the desert which diffuses more particles in the atmosphere is the Sahara which largely exceeds that of the Arabian Peninsula and the desert of China. The deserts of Australia, the Americas and South Africa are the least active deserts. Every year two billion tons of dust leave the Sahara to reach the continents of Europe and the Americas (ConsoGlobe, 2022), i.e. 75% of the total dust traveling in the atmosphere. Thus, during the period February 5 and 6, 2021, a dust storm flew over the Mediterranean Sea to reach the northern shore of the old continent. Millions of tons of fine particles traveled by air currents a distance of about 2000 km from the north of the Hoggar-Tassili N'Ajjer rock mass to reach France and Spain. Even, these particle-laden winds sprinkled the mountains of the Pyrenees (France) thus giving these snow-covered massifs an orange color (Cheron, 2021). Each year clouds of dust weighing several million tons from the Sahara fly over the Atlantic Ocean to reach the Caribbean and the Americas. Thus, during the period from June 4 to 26, 2020, a dust storm left the Algerian Sahara (Tamanrasset) to reach the countries of the Caribbean, northern South America, Central America and southern United States (Remini, 2020). Called Godzilla; an impressive dust storm not recorded for more than 50 years took 22 days to travel more than 10,000 km. The "Godzilla" dust cloud is gigantic and has a high concentration of fine particles; its tail is in Tamanrasset, while its head is flush with the coasts of the American continent (Remini, 2020). Sahara dust is a good natural fertilizer that dusts the soil of the Americas and the Caribbean annually. The Amazonian forest benefits from this dust from the Sahara and more particularly the phosphorus element which is essential for the development of plants. Indeed, each year about 182 million tons of dust leaves the Sahara to fly over the Atlantic and reach the other shore, of which 27.7 million tons of dust land on the entire surface of the Amazonian forest (Aline, 2016; Grey, 2015). Of this amount of dust, 22,000 tons of phosphorus falls on the Amazon River basin (Remini, 2017; Aline, 2016; Grey, 2015; Barthélémy, 2015).

If today, the overflight of the sand of the Sahara towards the Atlantic Ocean is known by the scientific community, however the mechanism of the uprising of these particles in the air is not yet mastered. A first approach to this problem was published in 2017 and 2018 (Remini, 2017; Remini, 2018). Three areas of sand uplift have been identified and located in the Sahara. These are Algeria, Chad and Niger. The present work gives more details on the mechanism of the uplift of sand particles in the atmosphere.

STUDY AREA AND WORK METHODOLOGY

Study region

On planet earth, ten hot deserts are spread over the five continents with the exception of Europe. Covering an area of 9.2 million km^2 (Gourdjian, 2021), the Sahara, the largest desert in the world, is located in the north of the African continent. It covers 11 countries: Algeria, Mali, Mauritania, Niger, Tunisia, Morocco, Sudan, Chad, Libya, Egypt and Western Sahara (fig. 1). The Sahara is a territory whose boundaries are not fixed, since it gains square kilometers each year due to climate change. This is how its extent increased by 10% during the period: 1920-2013 (Le point Sciences, 2018). This increase does not only concern the borders of the Sahara, but all the other deserts on the planet will see their territories expand in the years to come. The most beautiful desert in the world is occupied by dunes, Ergs, plateaus, Regs, Hamadas, Oueds, rocky massifs, Sebkhas, Chotts, Gueltas and oases. The sandy or dune space formed by the Ergs represents only 20% of the total surface of the Sahara.

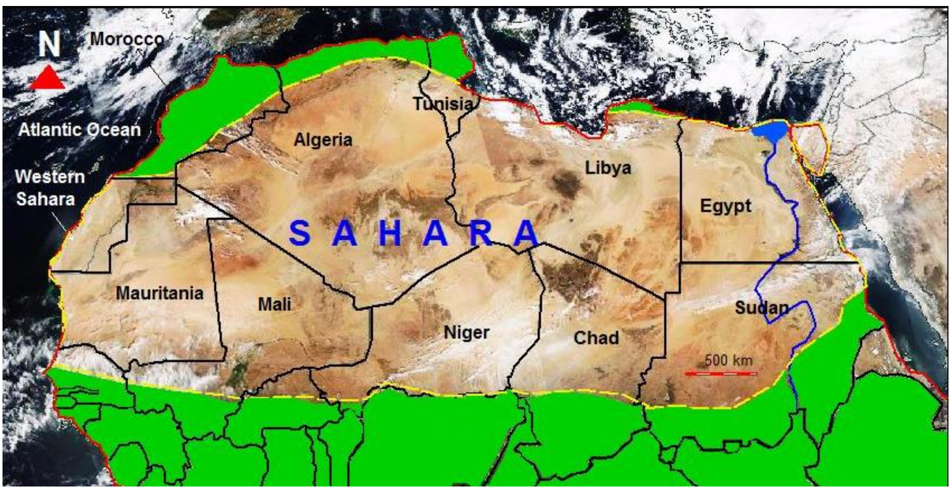


Figure 1: Geographical location of the Sahara (Remini, 2022)

Methodology of work

At the end of the 1990s, I had the chance to work in the laboratory of Professor Monique Mainguet at the University of Champagne Ardenne – Reims on the phenomenon of silting. In 2001, I defended my doctorate on the impact of mega obstacles on wind dynamics and the shaping of Erg. Our study has shown that it is the large rocky massifs of the Sahara (Tibesti, Hoggar-Tassili N'Ajjer, Ennedi, Eglab, Adrar Ifoghas, Eder

Doutchi, Air and Lake Chad) that have an effect on the sand-carrying winds. This is how we located the areas: deposits, erosion, pass and shelter. We have highlighted the role of these massifs on the wind dynamics and the shaping of the Ergs. But at the time, even though we know that the sand leaves the territory of the Sahara, we never imagined that the sand of the Sahara can reach the Amazon forest. But it was not until 2014 when the NASA satellite showed impressive images of the flyover from the dust of the Sahara towards the Amazon forest over a distance of more than 4000 km. This encouraged us to work on the lifting of dust towards the atmosphere. To answer these hypotheses, we used in this study satellite images taken by NASA on the Sahara during the period 2001-2021.

RESULTS AND DISCUSSIONS

How is sand lifted into the atmosphere?

During each year and more particularly during the spring season, clouds of dust coming from the south to the north of Algeria thus cause irritating air pollution for the eyes and the respiratory tract. This regular and frequent meteorological phenomenon pushed dust from the Sahara to even fly over the Atlantic Ocean to reach the Caribbean and the southern United States (Remini, 2020). If today, we know well the benefits and the impact of Saharan dust on the soil and aquatic life, questions about the lifting of dust to reach the atmosphere remain an unanswered problem. Starting from the idea that to raise the dust in the air you need to have a very violent wind; the wind speed should be maximum. Such a phenomenon can only be obtained when the wind encounters rock masses. The circulation of the wind around an obstacle generates saddle areas which create depressions and increase the speed of the wind. These are the ideal foci for raising dust. The effect of the Venturi is much more powerful than the effect of an obstacle; the narrowing of the section between two obstacles increases the wind speed and decreases the pressure; this is the best place to lift the sand.

The effect of an obstacle on the flow

In a fluid mechanics laboratory, an isolated obstacle placed in a fluid current opposes a resistance to the flow and causes a subdivision of the current lines into two branches. Once the obstacle has been crossed, the two branches converge and meet downstream in a reattachment area and the flow returns to its initial state. Between the obstacle and the reattachment area, a zone is formed where there is a flow disorder called the wake area or shelter area. This wake results from the separation of the fluid threads, it has an effect on the different areas that form in the vicinity of the obstacle. Five areas have been differentiated by the dynamic behavior of the fluid (fig. 2):

- Area upstream of obstacle (O); the pressure is maximum and the speed is low or zero at the stopping point O. This sector is the seat of an obstacle deposit. For transportable winds of sand, the ideal place is to deposit these solid particles.

- Neck area (C): the threads of the fluid tighten creating a depression and consequently the speed of the fluid increases. For the wind, transport or wind corrosion is very active, it is the beginning of uplift of fine particles.
- Detachment area (D); In the case of a wind, the air streams deviate and detach from the obstacle, the uplift is accentuated. The sand particles begin to gain altitude. The boundary layer detaches from the wall from the detachment point D, forming a vortex wake area where total disorder reigns. This is the ideal time for the “birth” of dust storms. In this area (S) also called shelter area is practically empty of sand. On the other hand, the sandy deposit is found at the outer limit of this wake area. The two branches of the air streams bypass the wake area to meet downstream of the obstacle at the point of convergence (R); this is the reattachment area (R). It is an area of deposits of sandy particles. The sand-carrying winds after being deflected by the obstacle return to their initial directions.

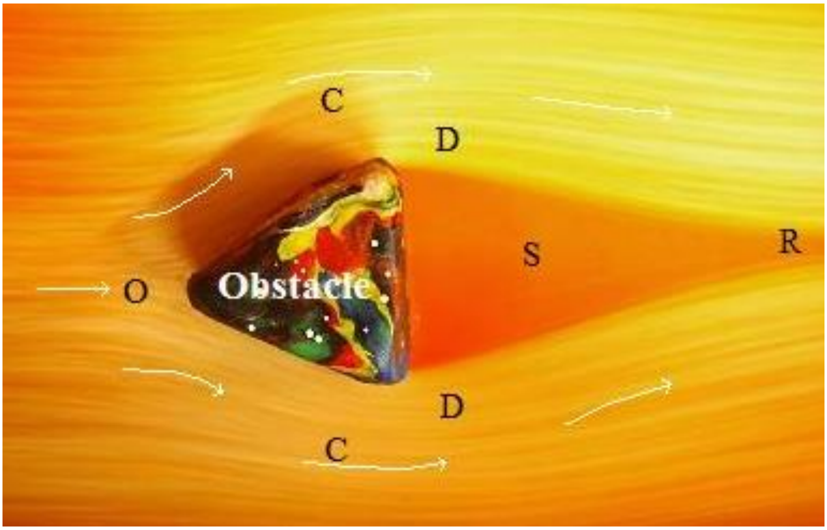


Figure 2: Dynamic behavior of a fluid flow in the presence of an obstacle (Photo Remini, 2020)

Another phenomenon that accelerates the wind is the Venturi effect caused by a narrowing of the wind current. It is based on Bernoulli's principle which expresses the conservation of energy and applies to both gases and liquids. Neglecting the effect of gravity, areas of high velocity are areas of low pressure and areas of low velocity are areas of high pressure. So the Venturi effect is the depression created by a constriction between two obstacles which causes the tightening of the lines of currents (fig. 3). As a result, the airflow velocity becomes important according to the principle of flow conservation.

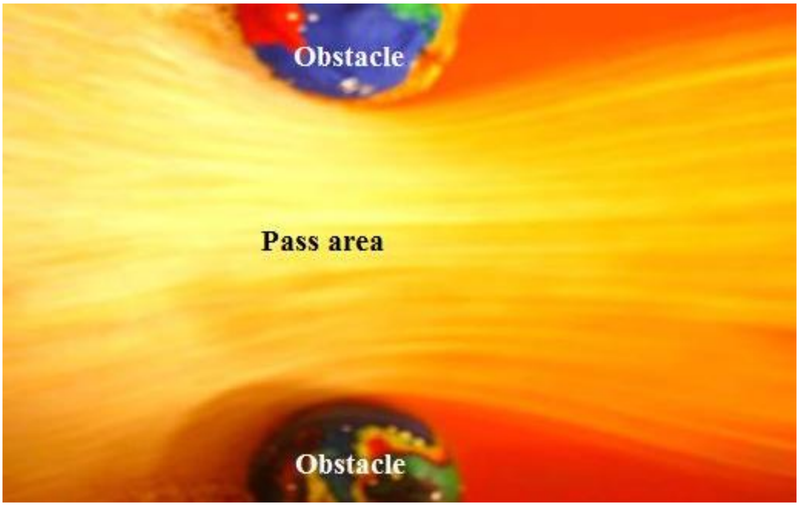


Figure 3: The effect of the Venturi on the speed of a fluid (Photo Remini, 2022)

The effect of the Mega obstacles of the Sahara on the wind dynamics

In parallel with what has been described previously, the effect of a rock mass on the wind transporting sand at the synoptic scale will have the same results; appearance of five areas each with its dynamic behavior (fig. 4); the area upstream of the obstacle, and an area of sand deposits with a positive sedimentary balance. Generally the Ergs formed upstream of the mega obstacles are large Ergs. Two privileged areas can be places of uplift at the synoptic scale. These are indeed the two pass areas, the Ergs formed are Ergs of erosion, with a negative sedimentary balance; these Ergs are emptied in time. In the col area, the pressure decreases and the winds increase. On the other hand in the Shelter area (wake area); it is disorder, we are witnessing whirlwinds and turbulence. By analogy, we deduced that topographic reliefs in the Sahara have the same effect (Remini et al, 2011; Mainguet and Remini, 2004; Remini and Mainguet, 2004). In the pass areas, the wind nets that circumvent the rocky massif tighten, creating a depression and the wind becomes very violent. Such a situation favors wind erosion, thus giving rise to longitudinal cords; the sedimentary budget is negative (Remini, 2001). Downwind of the mega obstacle, a recirculation area devoid of sand is formed (shelter area). In times of wind, because of the disorder, the dust rises in the atmosphere. Downstream of it, an area of consolidation where the winds, after having been deflected vertically and horizontally, return to the initial direction of the wind currents. The Erg formed has a positive sedimentary budget; Sif-shaped dunes predominate (Remini et al, 2011, Remini, 2001).

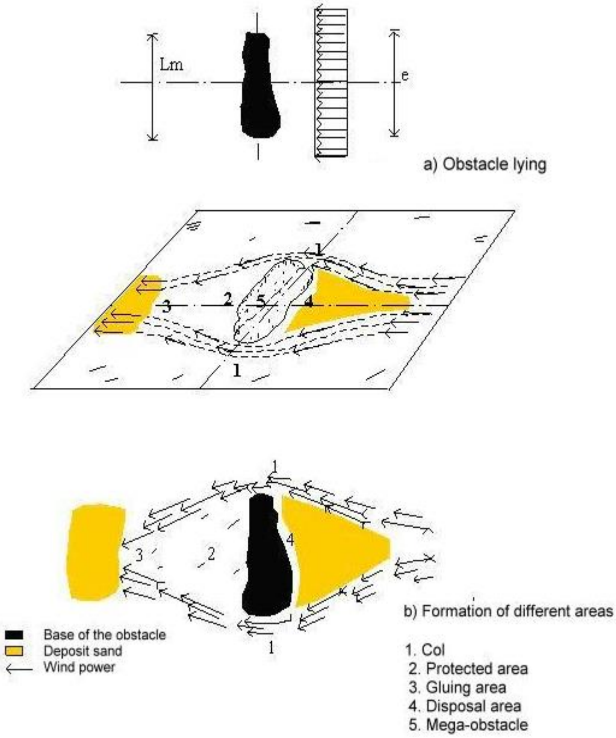


Figure 4: Diagram of the areas obtained under the effect of a mega-obstacle on wind circulation (Remini et al, 2011)

Dust storms occur in arid regions. The raising of large amounts of dust in the atmosphere is ensured by strong winds. These sandy particles can fly over thousands of kilometers and can thus reach the most distant destinations possible such as the Caribbean and the southern United States. Every year, this meteorological phenomenon manifests itself in the hot deserts of the planet. Considered the largest desert on the planet, the Sahara is driven by a very active wind dynamic. Moreover, the Sahara is the desert that exports more fine sand and dust to the oceans and continents than the other deserts on the planet (Remini, 2020). More than half of the dust deposited in the oceans comes from the Sahara desert. In second place comes the Arabian desert, followed by that of Central Asia and finally the Chinese desert. On the other hand, the deserts of America and South Africa are the least active.

The most beautiful desert in the world, the Sahara is a vast arid territory of 9.2 million km^2. Only Ergs and sand dunes occupy 20% of the total area, or 1.7 million km^2. Dust emissions from the Sahara Desert are the largest compared to other deserts on the planet. In the Sahara, the wind is the main sand transport agent. Obstacles, whatever their size, shape and nature (trees, slopes, reliefs, massifs) introduce a roughness which causes an increase in pressure drop and a reduction in wind speed, thus favoring the deposit of sand and the formation of dunes. The mega-obstacles, by their geometric configurations, and the topographic depressions (lakes, chotts and sebkhas) form and shape the ergs. The distribution of the massifs in the Sahara creates corridors, and Venturi, obeying Bernoulli's theorem. Moreover, the largest Venturi on the planet is in the Sahara desert and more precisely in the Chad desert (Remini, 2018).

This wind dynamic is not the work only of its immensity but rather of the existence of 11 rocky massifs and plateaus: Hoggar-Tassili N'Ajjer (fig. 5 and 6), Eglab, Adrar, Tibesti, Ennedi, Air, Adrar des Ifoghas, Adrar Doutchi, Massak, Haruj El Aswed and Akakus. These obstacles occupy an area of 820 km^2, or 10% of the total area of the Sahara and half of the area occupied by the dunes (fig. 7). In addition to the existence of wind and sand, the ideal layout of the mega-obstacles creates exceptional wind dynamics, thus allowing the formation and shaping of Ergs as well as the lifting of dust obeying the laws of Fluid Mechanics.

Figure 5: A view of a rocky mountain from the Hoggar Mega obstacle of the Algerian Sahara (Photo. Remini, 2006)

Figure 6: A view of a rocky mountain from the Tassili N'Ajjer Mega obstacle of the Algerian Sahara (Photo. Remini, 2021)

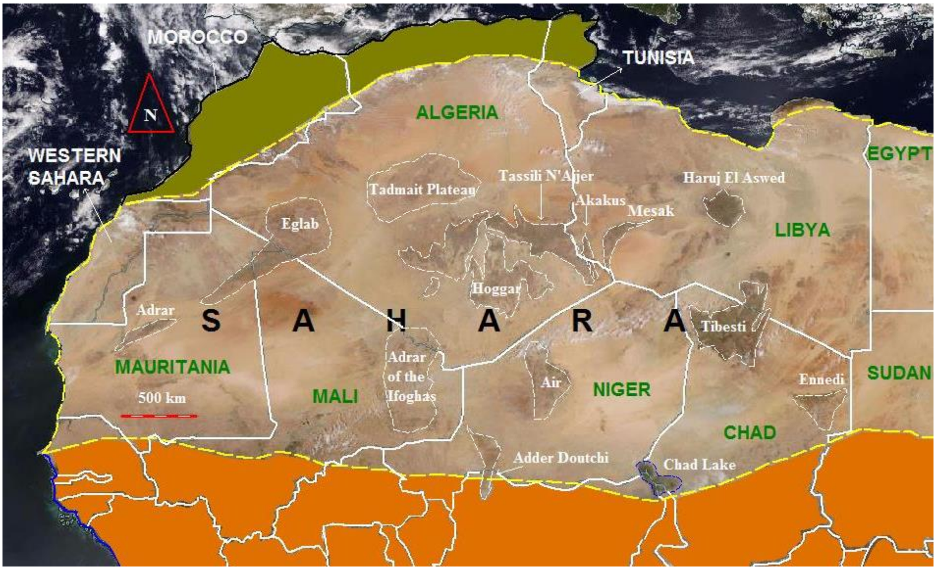


Figure 7: Arrangement of mega-obstacle in the Sahara Desert (Remini, 2020)

The existence of 13 large Ergs in the Sahara is the result of a very active wind dynamic generated by the distribution of these 12 mega-obstacles. These Ergs are as follows: Grand Erg Occidental (fig. 8), Grand Erg Oriental (fig. 9), Erg Erraoui, Erg Echech, Erg Iguidi, Grand Erg de Bilma, Grand Erg de Rebiana, Grande mer de sable, Erg El Djouf, Erg Aoukar, Erg Issouane, Idehan Ubari, Idehan Murzuk. Ergs of significant dimensions are formed in the four corners of the Sahara thanks to wind dynamics created by the circulation of the winds around the mountains and the Djebel (fig. 10).

Figure 8: A view of the Grand Erg Occidental (Photo Remini, 2014)

Figure 9: A view of the Grand Erg Oriental (Photo Remini, 2014)

Figure 10: A view of Erg Tin Merzouga (Djanet Tassili N'Ajjer) (Picture Remini, 2021)

Favorable places of dust rising in the Sahara

The over flight of several tons of dust from the Sahara towards the American continents is known by the scientific community. On the other hand, the places and mechanisms of the lifting of dust in the atmosphere remain an unsolved problem. As we mentioned before, the wind must blow very hard with an extremely high speed capable of lifting the dust as far as possible in the atmosphere. Once these fine particles in suspension gain altitude, they will be picked up by atmospheric currents to transport them out of the Sahara towards the Caribbean and the continents of the Americas. The Sahara has all the conditions to locate the privileged places of the rising of dust. The most active sources of dust rising in the Sahara are located downstream of the pass areas that appeared on either side of the mega obstacles (fig. 11):

- The areas of the passes generated by the Hoggar-Tassili N'Ajjer massifs (Tanezrouft desert-Algeria)
- The downstream zone of the M mega-Venturi formed by the massifs: Tibesti and Ennedi (Bodélé, Chad Desert)
- The areas of the passes generated by the Aïr massif (Niger Desert).
- Other areas of passes generated by the massifs: Ader Doutchi (Niger Desert), Adrar Ifoghas (Mali Desert), and Ennedi (Chad Desert)

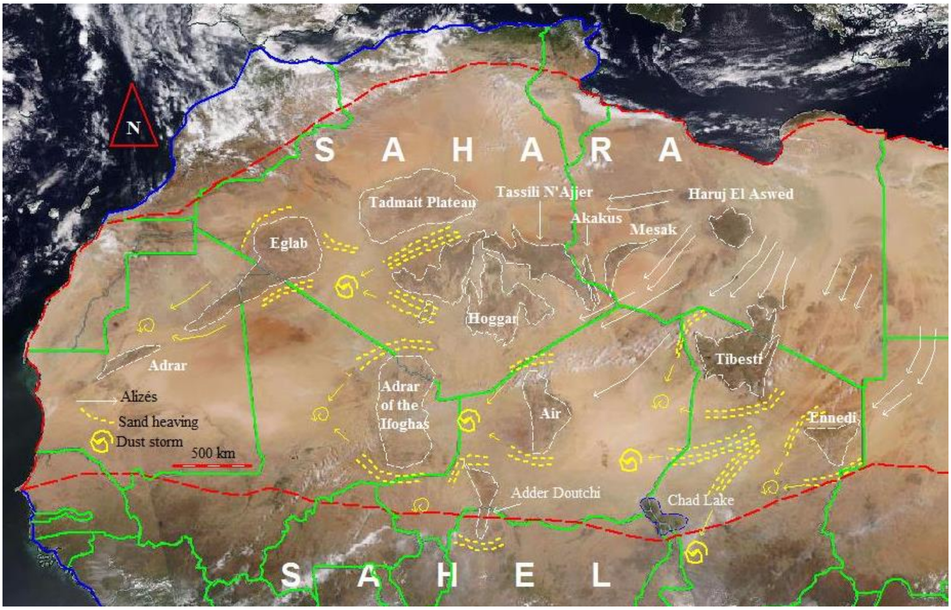


Figure 11: Map of dust rising areas in the Sahara (Remini, 2022, @ NASA Earth worldview)

Areas of dust rising generated by the Hoggar-Tassili N'Ajjer mega-obstacle

The first focus of the Sahara dust uplift is caused by the effect of the massifs: Hoggar-Tassili Najjer (grouped into a single unit) placed in the line of wind currents carrying sand from Libya. The subdivision of the wind flow into two branches; one passes through the north of the massif. The other passes through the south of the massif to meet downstream of the latter to form the reattachment area. The pass areas deduced from the wind circulation around this set of massifs which are also areas of tunnels formed by the Hoggar mountain and the Tademaït plateau in the north. In this area, wind erosion is very active and therefore the lifting of dust is very frequent. In the south, the nets of the wind currents rush and tighten in the corridor formed by the massifs of Hoggar and Aïr. At the exit, the winds accelerated under the effect of the pass, bypass the mega-obstacle of Hoggar-Tassili N'Ajjer and describe an arc under the effect of the Adrar des Ifoghas massif to then reach the topographic relief of the Eglab. The dust storm is supported by the winds which circumvent the shape of the Eglab massif well (fig. 12). The wind flow which blows from the NE-SW direction following the tunnel generated by the Tademaït reliefs and the Hoggar-Tassili ensemble abuts against the Eglab massif (elongated over a length of 700 km on the NE-SW line on the harmattan) and divides into two branches. One crosses Erg Echech and the other passes through Erg Iguidi whose nets of areas tighten and the speed increases in order to reach the Adrar plateau. In this case, the sand-carrying wind current is divided into two branches which accelerate under the effect of the saddle areas to reach the Atlantic Ocean. At this stage the dust storms are picked up and transported by ocean currents to the Amazon rainforest. In total, the dust storm travels a distance of 2000 km.

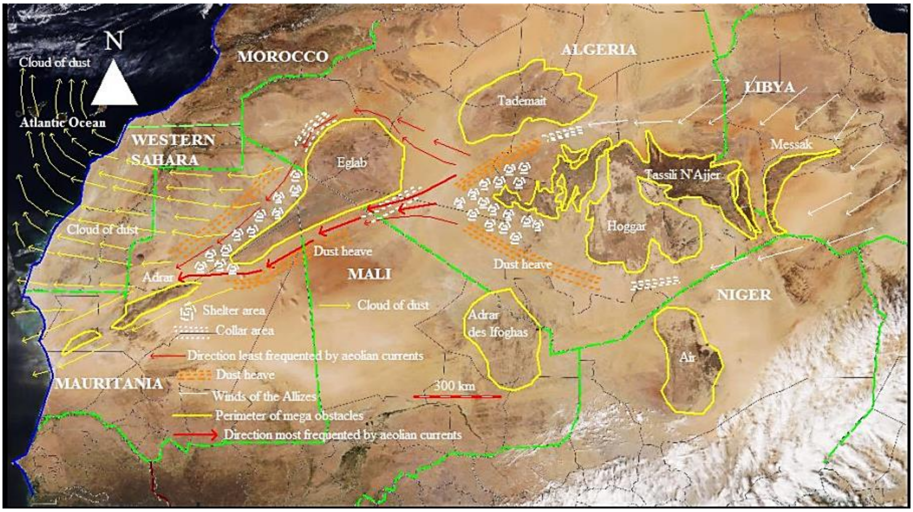


Figure 12: Dust rising areas induced by the Hoggar-Tassili N'Ajjer mega-obstacle (Remini, 2022, @ NASA Earth worldview)

Dust lifting area (Bodélé) generated under the effect of the Venturi: Tibesti-Ennedi

The second source of dust rising is the Bodélé area. The sand heaves are carried out under the effect of the mega-Venturi of Borkou (Chad). The air streams tighten in the Tibesti-Ennedi tunnel, thus causing a depression and an acceleration of the winds. At the exit of the tunnel, the wind blows very hard and raises the dust upwards. Lake Chad which is located 700 km downstream of the Bodélé depression, playing the role of a topographic relief, divides the wind flow into two branches. The speed of the two wind currents obtained is much greater than before reaching the lake. These winds still propel the dust particles higher in the atmosphere in order to reach the coast of the Atlantic Ocean an average distance exceeding 2000 km from the Bodélé area. From there, the sandy particles (depending on the grain size) are transported by sea currents to the other side of the Atlantic over an average distance of 6000 km.

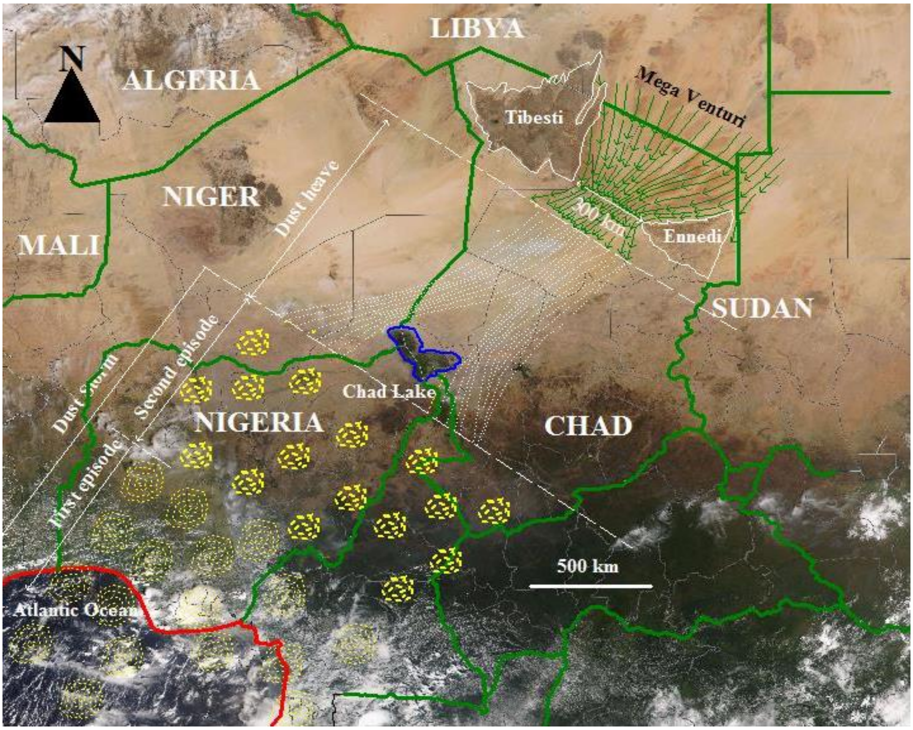


Figure 13: Dust rising area induced by the mega-Venturi Tibesti –Ennedi (Remini, 2022, @NASA Earth worldview)

Areas of dust rising induced by the Aïr massif

We have located the third source of dust rising in the Niger desert and more precisely at the level of the Aïr mega-obstacle pass areas. Under the effect of the importance of the speed of the two branches of wind currents which bypass the Aïr massif, dust uplifts occur to the north and south of the massif in the areas of the passes. The dust-carrying winds before reaching the Aïr massif are divided into two branches by the Tibesti massif. The latter is located 750 km upstream of the Aïr massif. These two wind flows from the Tibesti massif are accelerating under the effect of the passes induced by the Tibesti massif. Passing in a second time by the pass areas generated by the Aïr massif, create a depression and increase the speed. Another trajectory coming from Erg Mourzouk is deviated towards the north of the Air and thus takes a significant speed under the effect of the pass of the Aïr massif. The Adrar Ifoghas massif, which is 500 km downstream from the Air massif, further accelerates the winds to raise the dust higher to easily reach the Atlantic Ocean (fig. 14). Dust clouds driven by high energy easily reach the Atlantic Ocean.

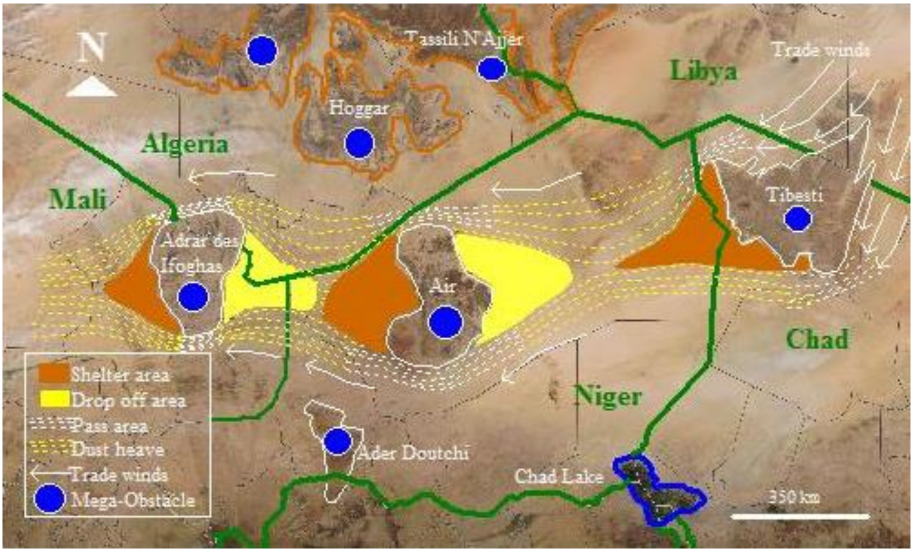


Figure 14: Areas of dust lift induced by the Aïr Mega-Obstacle (Remini, 2022; @NASA Earth worldview)

DISCUSSION

As we mentioned at the beginning of this article, the planet's 11 hot deserts scatter dust outside their borders. The Sahara is the first desert in the world that exports more of its fine material outside its territory. These fine particles can reach countries in Europe, the Caribbean and the southern United States. In second place comes the Arabian Desert called Rub El Khali which sends less sand outwards. Its surface area equal to more than 650,000 km^2 is significantly smaller than that of the Sahara with an area of more than 9 million km2. Unlike the Sahara, Rub Al Khali has few rock masses capable of generating areas of erosion and dust lifting like that of the Sahara. These two hypotheses justify the classification of the two deserts.

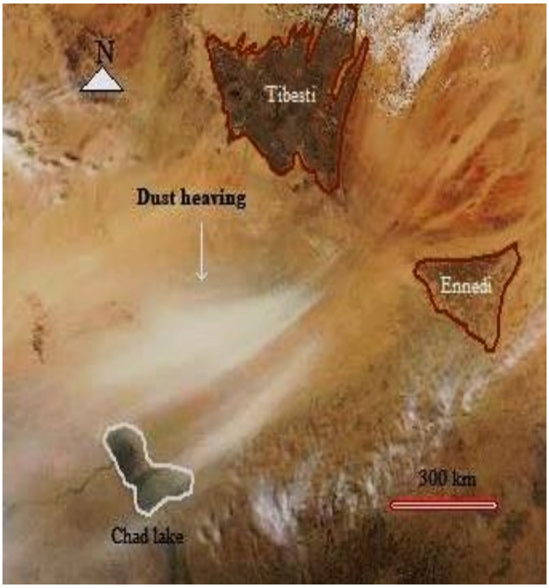
The Sahara annually diffuses more than 180 million tons of sand outside the territory (Borunda, 2021). Based on the satellite images taken over the Sahara, sandstorms ranging in duration from one day to 3 weeks continuously without interruption occur on the ground of the Sahara. The largest desert in the world diffuses sand particles across these 4 borders. From the eastern limit, the dust flies over the Red Sea. On the western side, the dust crosses the Atlantic. From the northern border, the sand winds from the Sahara cross the Mediterranean Sea. From the southern border, dust storms from the Sahara dust the Sahel region. Every day there is a departure of dust towards the outside of the desert of which the majority of the export of dust outside the Sahara is carried out by simple winds of sand. However the long journey of transatlantic sand to the Caribbean and the continents of the Americas, the mechanism of diffusion of particles are much more complex. In a first approach, dust diffusion takes place in two phases. The first comes down to the uplift of sandy particles from the ground towards the atmosphere. In the second phase, the particles that have reached the atmosphere will be picked up by wind currents to transport them as far as possible. The raising of the dust does not take place at any point in the expanse of the Sahara, but in very precise places which verify the unique condition: "The winds must blow very strongly" to propel the dust the most possible high in the air.

Based on satellite images taken over the Sahara during the period 2001-2021, we have identified about 875 dust risings in the Sahara spread over the 3 foci defined above. Table 1 summarizes the percentage of heaving according to the 3 hearths.

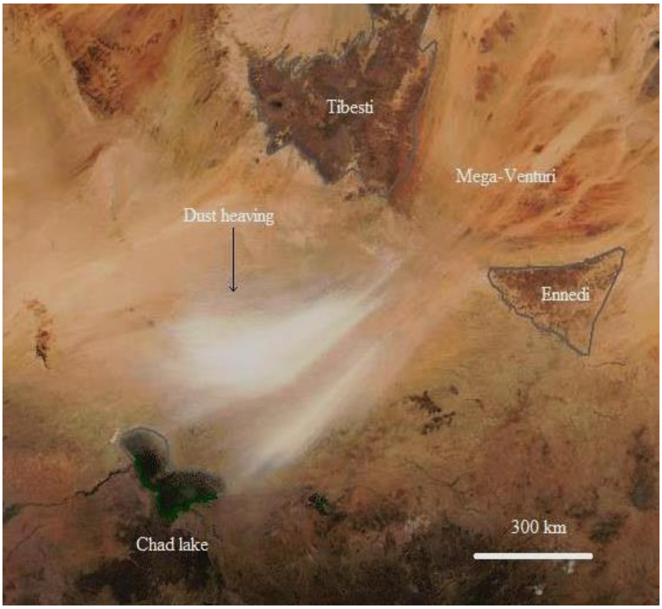
Table 1: Number of dust rising in the Sahara

Sources of dust heaving	Percentage (%)
Bodélé (Chad)	58
Tanezrouft (Algeria)	36
Aïr (Niger)	4
Adrar des Ifoghas (Mali), Idder Doutchi (Niger), Ennedi (Chad), Tibesti (Chad)	2

We find that 58% of the dust lifts took place in the Chad desert and more particularly in the Bodélé area. This is due to the ideal arrangement of the triangular massifs of Tibesti and Ennedi which forms the largest Venturi on the planet and which is located in the north of Chad. Trade winds from Libya rush into the Venturi convergent with a width of 750 km. The air streams tighten at the level of the pass over an average length of 300 km, thus creating a depression and an increase in wind speed at the exit of the 250 km long tunnel. At this location, the speed of the trade winds is 7/3 higher than before the entry of the Venturi (Remini, 2018). After traveling over 650 km from the point of uplift, the dust-carrying wind encountering Lake Chad splits into two branches; one to the north and the other to the south of the lake. The satellite images taken in the Bodélé region clearly show that Lake Chad divides the wind flow from Bodélé into two branches (North-East West and North-East South-West). This division of the wind flow caused by the condensation and evaporation of the lake (which plays the same role as a rocky relief) increases the wind speed of the two branches more. This second blast after the one caused by the Venturi effect pushes the dust towards the atmosphere (fig. 15 a and b). The plume of dust is carried by wind currents towards the Atlantic. The Bodélé area is the windiest and dustiest region on the planet and it is thanks to the mega-Venturi which is located upstream of the Bodélé region. With 58% of the total number of dust risings that occurred in the Chad desert, the Bodélé area is the first focus of the Sahara exporting dust to the Atlantic.



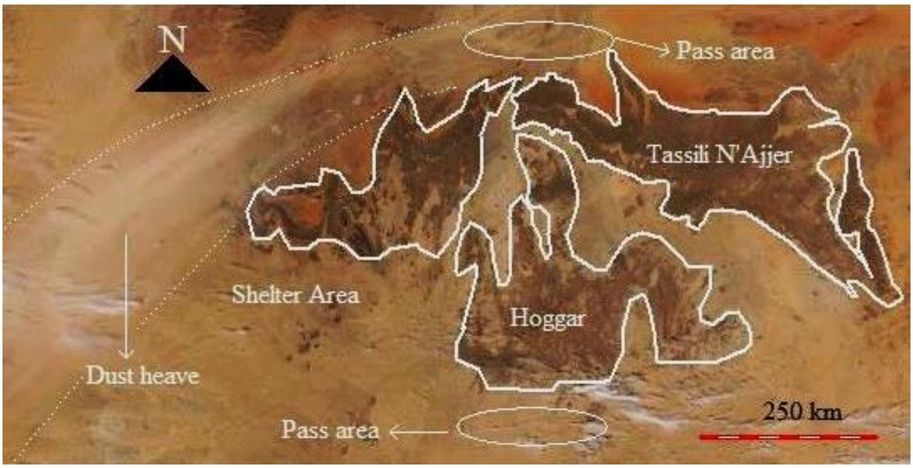
a) January 10, 2015 dust uprising @NASA Earth worldview



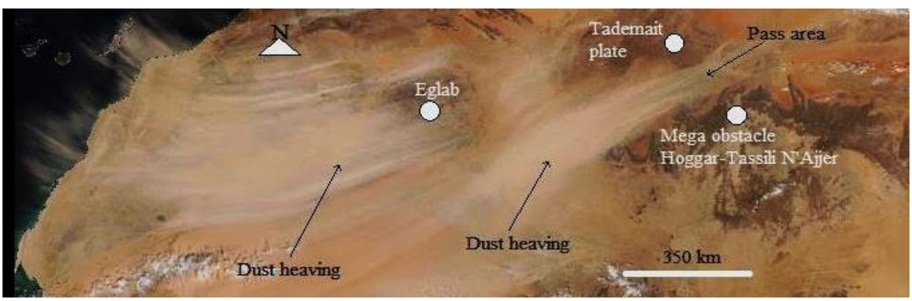
b) December 17, 2018 dust uprising @NASA Earth worldview

Figure 15: Dust rising in the Bodélé region caused by very violent winds under the effect of the mega-Venturi Tibesti-Ennedi

In second position, the Algerian Sahara and more particularly the Tanezrouft area with a percentage of 36% of the total number of dust risings which occurred during the period 2001-2021. These dust lifts were caused by the mega obstacle Hoggar-Tassili N'Ajjer which accelerated the trade winds from Libya. Once, passing through the neck areas, the air streams from the two branches narrow, thus creating a depression and an increase in the speed of the two wind flows. The branch of the wind coming from the tunnel formed by the Hoggar and the Tademaït is further divided under the effect of the mega obstacle of the Eglab into two wind currents. With extremely high speed, these winds propel dust into the atmosphere. The sandy plume formed leaves the Sahara towards the Atlantic (fig. 16 a and b).



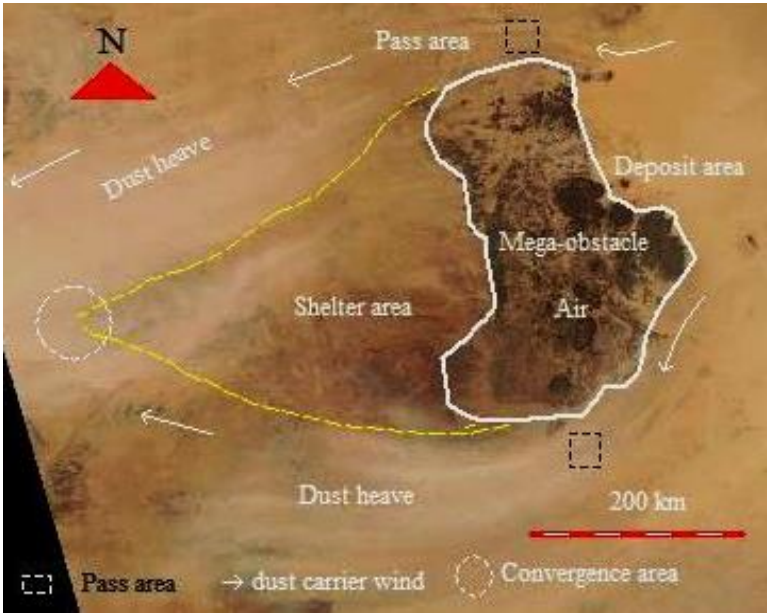
a) Dust rising of March 7, 2015 @NASA Erath worldview



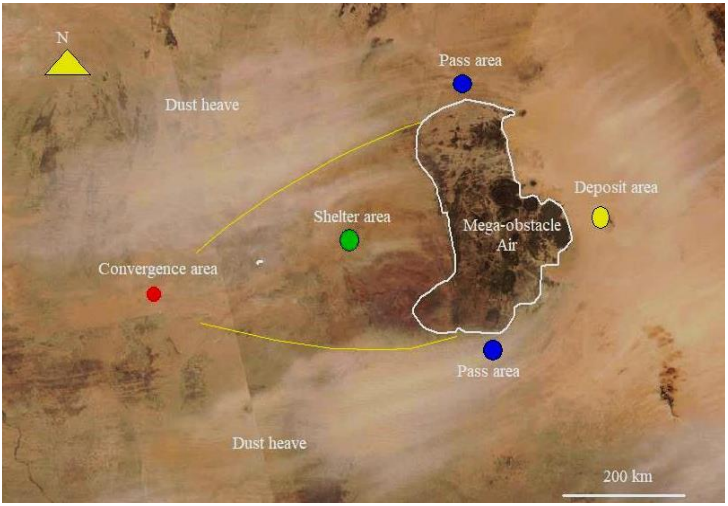
b) Dust rising on February 15, 2021@NASA Erath worldview

Figure 16: Dust rising in the Tanezrouft region caused by very violent winds under the effect of the Hoggar-Tassili N’Ajjer mega-obstacle

In third position, the Nigerien Sahara and more particularly the Aïr zone with a percentage of 4% of the total number of dust risings which occurred in the Sahara during the period 2001-2021. The dust heaves were caused by the effect of the Aïr mega-barrier, which increased the speed of the winds from Libya passing through the pass areas (fig. 17(a, b and c)). The Aïr massif is a very good example of fluid mechanics which clearly shows the wind circulation around a synoptic scale mega-barrier. This very active wind dynamic has given rise to the appearance of pass, deposition, shelter and convergence areas. On a reduced scale, we observe the same wind dynamics which generates the same areas obtained by a flow around an obstacle (fig. 18). As we can see on the satellite images of Figures 17 (a, b and c), the dust rising occurs just after the two neck areas of the mega-obstacle. In the Sahara of Niger, more than 20 dust events took place during the period 2001-2021.



a) Dust rising of January 17, 2017@NASA Erath worldview



b) Dust rising of December 31, 2017@NASA Erath worldview

c) Dust rising of November 30, 2015@NASA Earth worldview

Figure 17: Dust rising in the Niger Sahara caused by very violent winds under the effect of the mega-obstacle Aïr

Figure 18: Flow around a complex-shaped obstacle (Photo. Remini, 2011)

Over the period 2001-2021, the Sahara recorded about 875 dust lifts in the air, thus totaling a number of 4640 days of fine particle lifts in the air. This does not explain that the dust clouds caused by the 875 sand heaves all flew over the Atlantic Ocean. So the duration of a dust lift is a determining parameter of an effective storm, i.e. a storm that can move over the Atlantic Ocean. Efficient dust lifting means lifting capable of sending a large quantity of solid particles into the atmosphere. The cloud of dust thus formed can fly over several kilometers. During its journey, the sediment content decreases according to its displacement, only the fine particles will be able to reach the place as far as possible. In addition, the coarse particles dust the areas along the path of the dust plume.

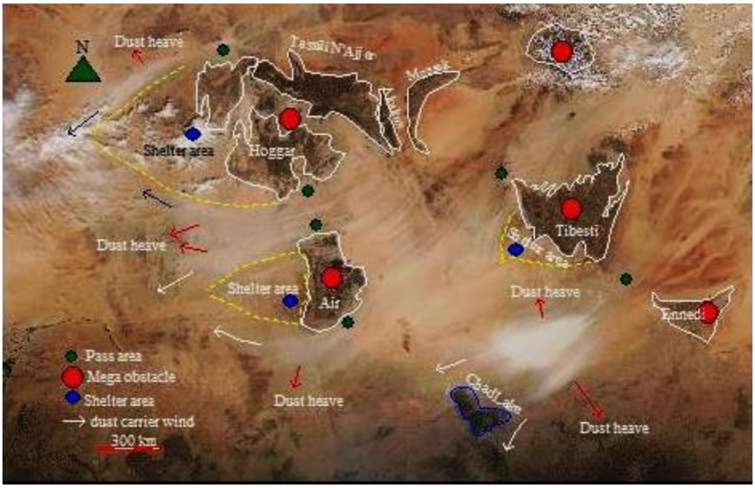
To initiate a dust plume, it is necessary to have an effective uplift which is directly related to the concentration of particles and the duration of uplift. Three situations can occur:

- A dust lift that does not exceed 3 days causes a dust plume that dissipates over a few kilometers.
- A dust lift of 3 to 6 days causes a plume of dust which vanishes before reaching the west coast of the African continent.
- A dust lift of more than 7 days gives rise to a dust plume that can fly over the Atlantic Ocean to reach the Caribbean and the continents of the Americas. At the limit, the cloud can release these particles on the ocean.

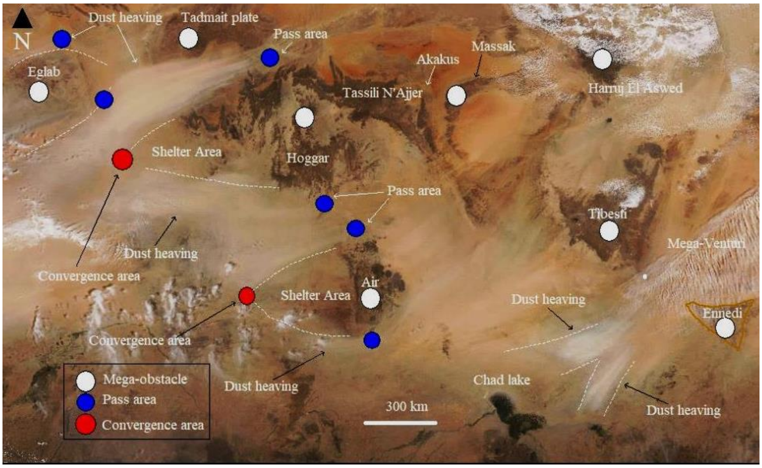
Dust uprisings lasting no more than one day represent more than 60% of the total number of uplifts that took place in the Sahara during the period 2001-2021. Dust lifts that exceed one week without interruption accounted for 20% of the total number of sand lifts during the period 2001-2021. It is this type of uplift that can generate dust clouds that can reach the Amazon. Dust uplifts lasting more than 100 days but with several episodes have been recorded in the Algerian Sahara. This massive departure of sand towards the atmosphere occurred during the months of June, July, August and September of each year during the period 2001-2021. This meteorological event which occurred exceptionally in the Tanezrouft desert of the wilaya of Tamanrasset for 20 years can only be the result of a very active wind dynamic. The trade winds coming from Libya meet in a first phase the largest rock massif of the Sahara, the Hoggar-Tassili N'Ajjer complex. Covering an area equal to 400,000 km2, this mega-obstacle divides the winds into two branches, thus creating two pass areas. The air streams tighten in the collar areas, thus creating a depression and an increase in the speed of the winds. Once, in the reattachment area, the wind flow carrying sand meets the mega-obstacle of the Eglab (which is about 300 km from the Hoggar-Tassili N'Ajjer massif) thus causing wind circulation around the Eglab. Two pass areas form on either side of the massif, the air streams tighten, creating depressions and accelerating winds. This double wind circulation around two mega-hurdles propels much more dust beyond the limits of the Sahara. For example, the departure of the largest amount of dust outside the Sahara that has never been recorded since 1977; date of the taking of the first real-time satellite image taken by the American satellite KH-11. Called Godzilla, this gigantic sandstorm manifested itself for 3 weeks from June 4 to 26, 2020 in the Algerian Sahara and more precisely in the Tanezrouft region (Remini, 2020). Unlike the long-lasting dust uplifts that occur in the Algerian Sahara and are marked by episodes, those that occur in the Sahara of Chad are rather dust uplifts with a maximum duration not exceeding 20 days, but they are continuous without interruption.

The dust lifts that occur in the Sahara of Niger are the results of the bypassing of the trade winds from Libya around the mega-barrier of Aïr with an area of 95,000 km^2. Except that the wind dynamics are quite low compared to other homes. In this case, only 4% of uprisings were recorded during the period 2001-2021. This is due to the wind flow that escapes from the northwestern part of the Tibesti mega-hurdle. After passing through the northwestern pass area of Tibesti, the air streams tightened, causing a depression and an increase in wind speed. It is the latter, which are even more violent, which circumvent the Aïr massif located about 700 km from Tibesti. These two branches after their reattachment 500 km from Tibesti find the initial wind current. But the Adrar Ifoghas massif, 500 km from the Aïr, divides the flow into two branches, thus increasing their speeds. These winds propel dust skyward. Only the dust does not rise much at the level of this focus (Aïr), for lack of the rarity of the winds coming from Libya which circumvent the mega-obstacle of Tibesti. The dust plumes generated by the dust risings at this focus (Niger Sahara) were always small and never reached the other side of the Atlantic. The duration of dust lifts varies from 1 to 3 days. With the exception of the sandstorm of June 20, 2002 which was produced by an uprising lasting 6 days. Unique in the Sahara, the dust cloud generated by this 6-day long uprising traveled a distance of 400 km to reach the west coast of Africa.

There remain the two foci: Tanezrouft (Algeria) and Bodélé (Chad) which diffuse a large part of the dust from the Sahara very rich in phosphorus towards the continents of Europe and the Americas. During the last twenty years (2001-2021), approximately 95% of the dust risings which have appeared in the Sahara are located in these two foci. In general, major dust risings are triggered when the two or three sources (Tanezrouft, Bodélé and Aïr) at the same time (fig. 19a and b). In this exceptional case, hundreds of tons of dust rise in the atmosphere and leave the territory of the Sahara towards the Atlantic. For these particular events which manifest themselves little, the dust of the Sahara will attract on the soil of the American continents. Due to climate change, this particular meteorological phenomenon may increase in the future.



a) Dust rising of November 30, 2015@NASA Erath worldview



b) Dust rising of February 16, 2021 @NASA Erath worldview

Figure 19: Raising of dust at the level of the 3 centers of the Sahara (Bodelé, Tanzerouft, Aïr)

It is interesting to note in figure 20 that the evolution of the number of dust risings in the Sahara has an increasing trend during the period 2001-2021. The years 2017 and 2020 recorded the highest number of dust lifts in the past 20 years. More than 300 days of particles rising in the sky in more than 80% of all the days of the year. It's impressive. These are the two dustiest years in the Sahara so far. On the other hand, the year 2001 is the least dusty since only 87 particle uplifts took place.

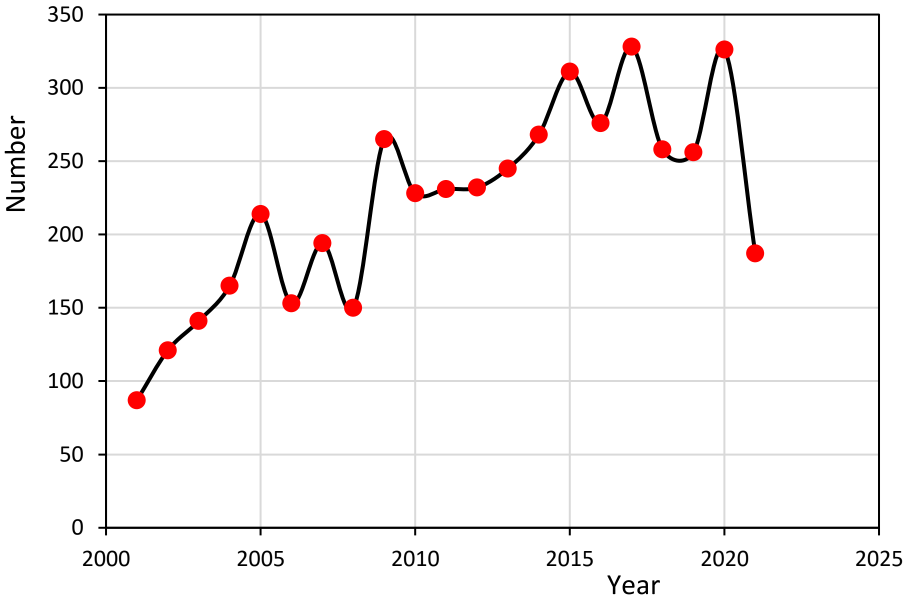


Figure 20: Evolution of the number of dust risings in the Sahara during the period: 2001-2021 (Remini, 2022)

CONCLUSION

After having underlined at the beginning of the paper the complexity of the phenomenon of the diffusion of dust from the Sahara towards the oceans and the continents, two distinct phases of the diffusion process have been highlighted. The first phase is marked by rising dust in the sky. In the second phase, the finest particles reach the atmosphere; they will be transported by wind currents as far as possible. Our study focused on the dust lifting mechanism. To start a departure of dust from the ground to the atmosphere, you have to have very violent winds. In the Sahara, three main foci that meet the conditions for uprisings have been located. These are Bodélé (Chad), Tanezrouft (Algeria) and Aïr (Niger). More than 58% of the uprisings took place in Chad, followed by Algeria with 36% and Niger with only 4%. The 2% of the dust lifts took place in the regions of Adrar

Ifoghas (Mali) and Eder Doutchi (Niger). During the period 2001-2021, the Sahara recorded about 875 dust lifts in the Sahara totaling a number of 4640 days of fine particle lifts. However, an uprising of dust does not automatically explain that there is an over flight of the Atlantic by fine particles. For this purpose, we have defined effective uplift as uplift capable of sending a large amount of fine particles into the atmosphere. The dust cloud thus formed can fly over hundreds of kilometers. Dust lifts that exceed one week without interruption accounted for about 20% of the total number of sand lifts in the air during the period 2001-2021. It is this type of uplift that can generate dust clouds that can reach the Amazon. During the period 2001-2021, the number of dust events in the Sahara has an upward trend. The highest number of dust lifts in the past 20 years were recorded during the years 2017 and 2020. With a number of more than 300 days of particulate lifts in the sky, more than 80% of all days of the year.

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