CHAPTER 1

Review of the North African Climate with Particular Emphasis on the Production of Eolian Dust in the Sahel Zone and in the Sahara

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ABSTRACT

The aridity of the Sahara, the high temperatures reached by its soil and the strong diurnal thermic turbulence resulting from these, are all factors which favour the production of dust and its suspension in the atmosphere. The directions of the prevailing winds account for the transport of this dust towards the Sudan and towards the Atlantic off Mauretania and Senegal, but do not explain its movements towards the continent of Europe. In order to understand the latter movements one must take into account the effects of depressions crossing the Sahara and the distribution of the air currents in its medium and upper atmosphere, which from autumn to spring is in the sphere of influence of the polar front of the medium latitudes.

The extent of the areas affected by the Saharan dust, at the present time, is large in the southern and western Sahara as well as in the Middle East and is not negligible, though infrequent, over the European continent. It is likely that this dust has played an important role during the last ice ages, particularly in the melting of the glaciers.

The Sahara, with its axis along the Tropic of Cancer, is a hot desert, perhaps a typical example of a hot desert. It is therefore above all a region where rain is extremely rare. One day of rain in a hundred, and then only for a few hours, as at In Salah in the centre of this 'attenuated desert' which forms the western half of the Sahara, two days in a thousand in the other half, the 'absolute desert' (cf. Gautier, 1928). Drought is therefore a normal phenomenon. Its average duration in the middle of the Sahara is five or six months in the west and two years in the east. There is, however, a difference between the northern and southern edges. In the northern Sahara the drought occurs mainly during the summer and is broken up into short periods, while in the south and the Sudanese Sahel a long desert period alternates each year with a short rainy period. The first is centred on the cold season and extends well beyond it. The second is limited to the middle of the summer and decreases rapidly with increasing latitude. Of course, these periods without precipitation become less pronounced with increasing a'titude in mountainous areas.

To this lack of rain is added the great evaporating power of the Saharan atmosphere. If this is not a necessary factor in the creation of deserts – which can be proved by the existence of coastal deserts – it nevertheless remains a factor which enhances this. It depends mainly on the great saturation deficit of the Saharan air, i.e. the great difference between the actual water content of the air, which during the winter season is of the same magnitude as in France, and the theoretical water content at saturation at the actual temperature. This results in an extremely low relative humidity favouring the development of a field of static electricity around all isolated bodies like dust particles. The relative humidity is about 10% in the central Sahara and can sink to 2% in extreme cases. This saturation deficit depends partly on the high air temperature in the Sahara, characteristic for the latitude, partly on its continentality and partly, as will be shown below, on the fact that the air masses crossing the desert normally move from north to south – from the Mediterranean towards the Sudan – i.e. towards increasingly warmer areas, and this without being able to absorb any water vapour. To this might be added the capture by giant ions and dust particles of the water vapour in the atmosphere.

The lack of rain and the strong potential evaporation result in a thinning out and, later, disappearance of the vegetation cover, which in its turn facilitates an eolian soil drift.

Owing to the small angle of inclination of the sun's rays, the length of the day, not varying much during the year, the apparent annual migration of the sun in this area giving short winters and long summers, and the pronounced dryness of the atmosphere, the ground receives great quantities of heat from the sun. Notwithstanding the always great albedo of the Saharan soil and its own radiation, the surface layer of the ground always reaches high temperatures in the middle of the day: at least 30°C in wintertime in the northern part of the area, between 60°C and 65°C during the summer all over the flat parts of the Sahara and sometimes exceeding 70°C. This means that the air in contact with the ground is rapidly heated from sunrise on, which explains the high shade temperatures observed, particularly in the desert or semi-desert regions in the south, where, moreover, the thermic equator is situated. This heating of the gound leads during the day to a strong thermic turbulence, which reaches quite high altitudes: usually more than 2,000 m and sometimes over 4,000 m during the hot season. Even though this turbulence disappears at the end of the day, giving way at night to a great stability of the lower layers of the atmosphere caused by a strong temperature inversion close to the ground surface, due to the great cooling of this surface, the fine dust particles in suspension in the air do not reach the ground during the night, but stay in the atmosphere for weeks or even months. These particles give rise to the so-called 'dry haze'. This haze is particularly dense and frequent in the southern Sahara and the Sudanese Sahel at all seasons and in the western Sahara in summer. It forms an almost inexhaustible reservoir of air-borne dust particles. When these move at low altitude with the prevailing winds they will only disappear after a rain or after the intrusion of a cold and stable air mass, provided they are not transported out of the desert area. Later we will see how they are renewed.

The normal pattern of the winds in the Sahara is dependent upon the yearly oscillation of a zone of low pressure, called the 'Intertropical Convergency Zone', which follows the apparent movement of the sun with a time lag of six weeks to two months. This is not peculiar to the Sahara, but is a part of a global phenomenon since this low pressure zone girdles the whole globe. Actually this zone consists of a string of low pressure centres, the position, extension and depth of which vary geographically and with the season. As far as we are concerned the zone is situated during the winter along the latitutde of the Gulf of Guinea in the west and at somewhat lower latitudes in the east. During the summer it comes in contact with the whole Saharan desert. In actual fact this convergency zone is restricted in Africa to a front towards which the winds converge and which is called the Intertropical Front (ITF). This front demarcates to the south a maritime equatorial air mass (the Sudanese monsoon, or more exactly the 'Sudanese summer monsoon') which is warm and moist with a high dew point (21°C to 22°C), from an air mass north of the front arriving from the northeast or east, which in wintertime is cool in the Sahara but warm in the southern Sudan, and during the summer always burningly hot. The most characteristic properties of this air mass are its dryness, a strong thermic turbulence and its great content of air-borne dust particles. In winter it comes from the belt of high pressure extending from the Azores to southern Asia via the northern Sahara and Arabia. The relevant wind is weak northerly at its source but turns gradually towards the east and increases with decreasing latitude.

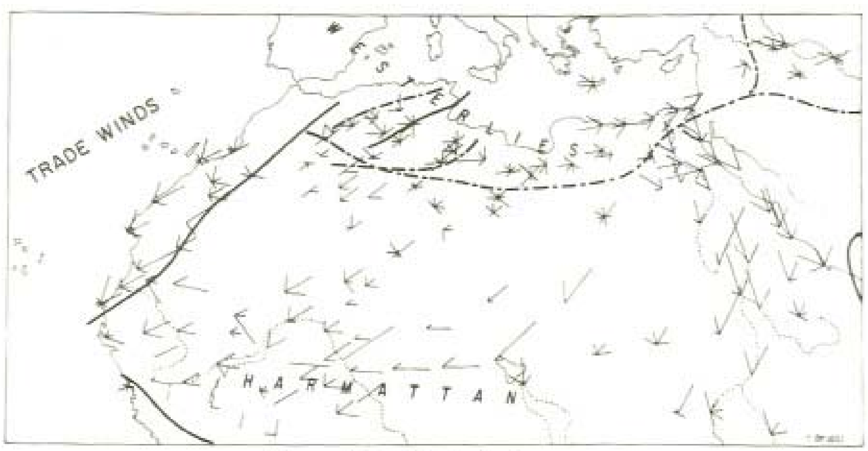

Figure 1.1 Winds in January

In the Sudan it is called the 'harmattan' (Figure 1.1). During the first months of the year the earlier barrier of high pressure breaks up and moves towards higher latitudes while the ITF moves northwards. During the summer it is only the Azorean high pressure which survives. This expands over part of the European continent and gives rise to northerly winds on its southeastern flank. These winds penetrate to the Sahara and the Middle East after having blown over the eastern Mediterranean. They were called 'the Etesian winds' during Classical times. They reach Africa and the Middle East having the character of a maritime trade wind, are rapidly heated over the continents, are dried out, turn towards northeast, later east and finally show the same characteristics as the harmattan (Figure 1.2). The ITF is then situated close to or just south of the Tropic of Cancer. It is these winds which cause the summer drought in northeastern Africa and the Middle East. One should add that from autumn to spring the harmattan may be more or less mixed with, if not replaced by, polar air, after the passage of a 'family of polar front depressions' crossing southern Europe and the Mediterranean. We will see that these circumstances are of some importance in relation to the present problem. Further west, over the Mauretanian areas and over the eastern Atlantic the true trade winds prevail. We are speaking of maritime tropical air originating from the Azorean high pressure. These cool and moist trade winds blow from a northerly direction the whole year round. They can be surmounted by the harmattan to the south, sometimes even to the north. Like the latter they may be more or less mixed with polar air. The harmattan and the trade winds increase rapidly in vertical extent when approaching the Sudanese area. They surmount the northward-moving monsoon and reach higher altitudes as the latitude decreases. Finally they join at high altitude the equatorial easterlies. Note that as there is a very small angle between the Sudanese monsoon and the horizontal plane its vertical extent is never great: 2,500 to 3,000 m in the southern parts at a maximum; nevertheless it can rise above

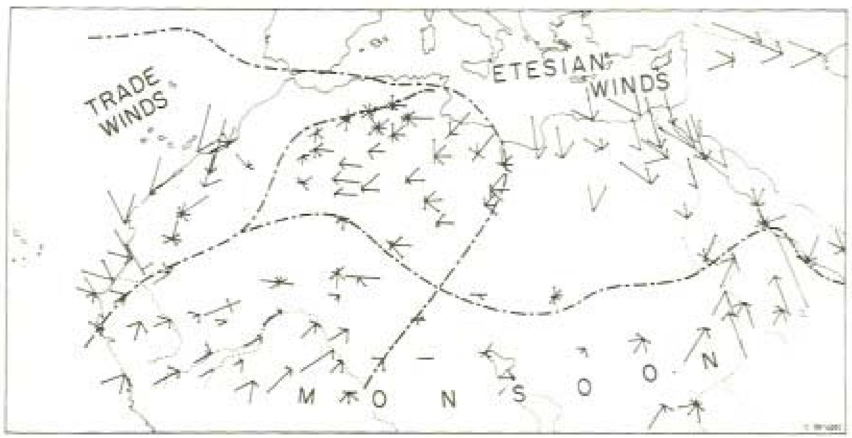

Figure 1.2 Winds in August

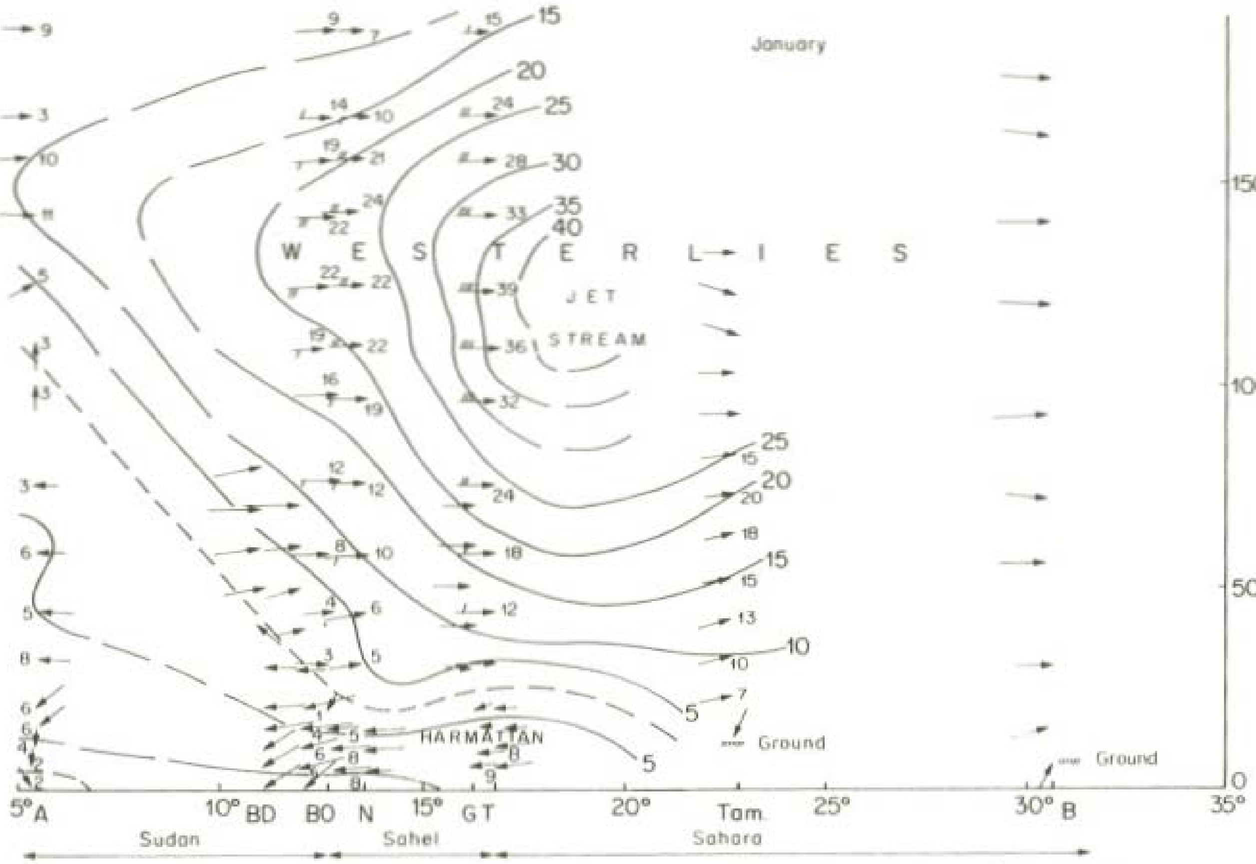

Figure 1.3 Predominant wind directions and mean wind speeds in upper levels at 0° longitude in January

A = Abidjan	B = Bamako	T = Tombouctou
BD = Bobo Dioulasso	N = Niamey	Tam = Tamanrasset
O = Ouagadougou	G = Goa	B = Béchar

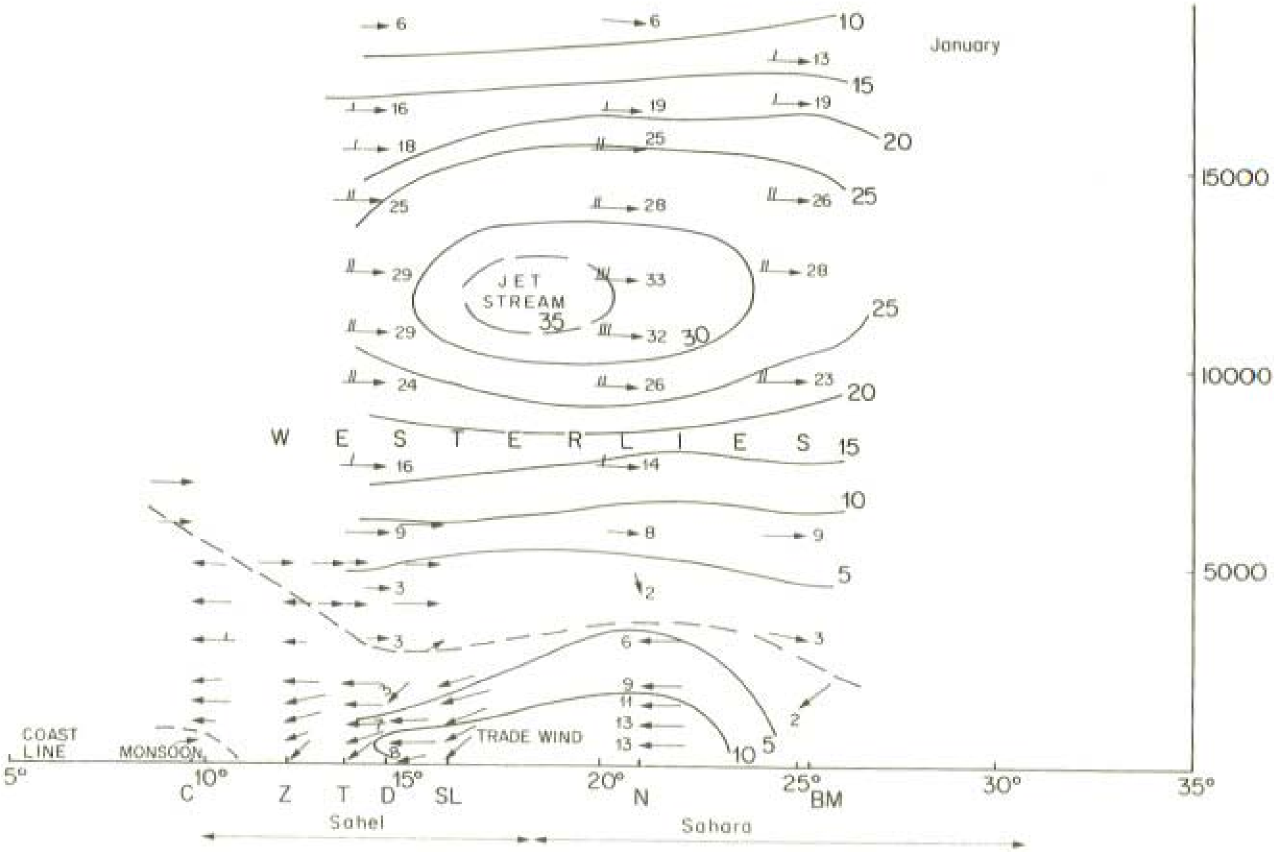

Figure 1.4 Predominant wind directions and mean wind speeds at upper levels at the African Atlantic coast in January

C = Conakry
Z = Ziguinchor
T = Tabacounda
D = Dakar
SL = Saint Louis
N = Nouadhibou
BM = Bir Moghreim

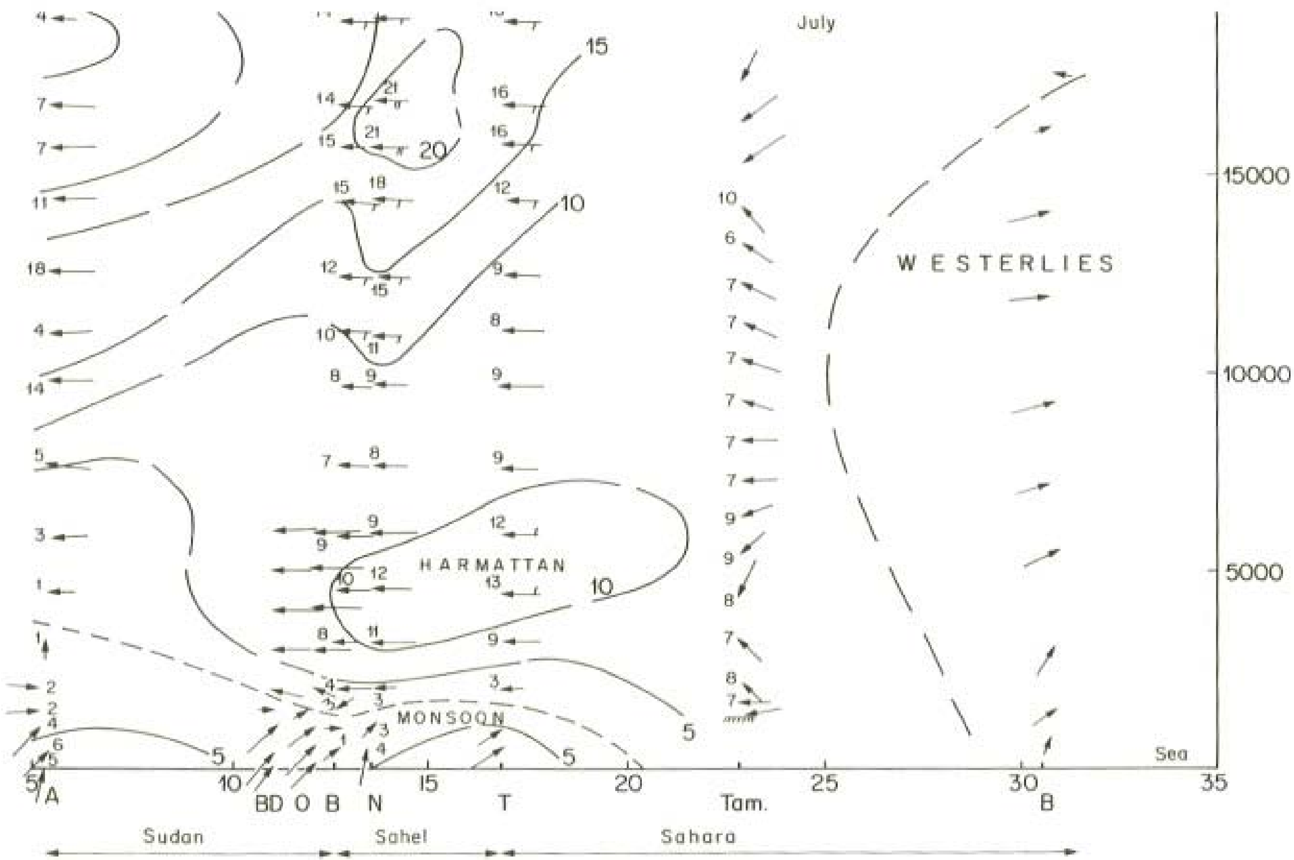

Figure 1.5 Predominant wind directions and mean wind speeds in upper levels at 0° longitude in July

A = Abidjan, BD = Bobo Dioulasso, O = Ouagadougou, B = Bamako, N = Niamey, T = Tombouctou, Tam = Tamanrasset, B = Béchar

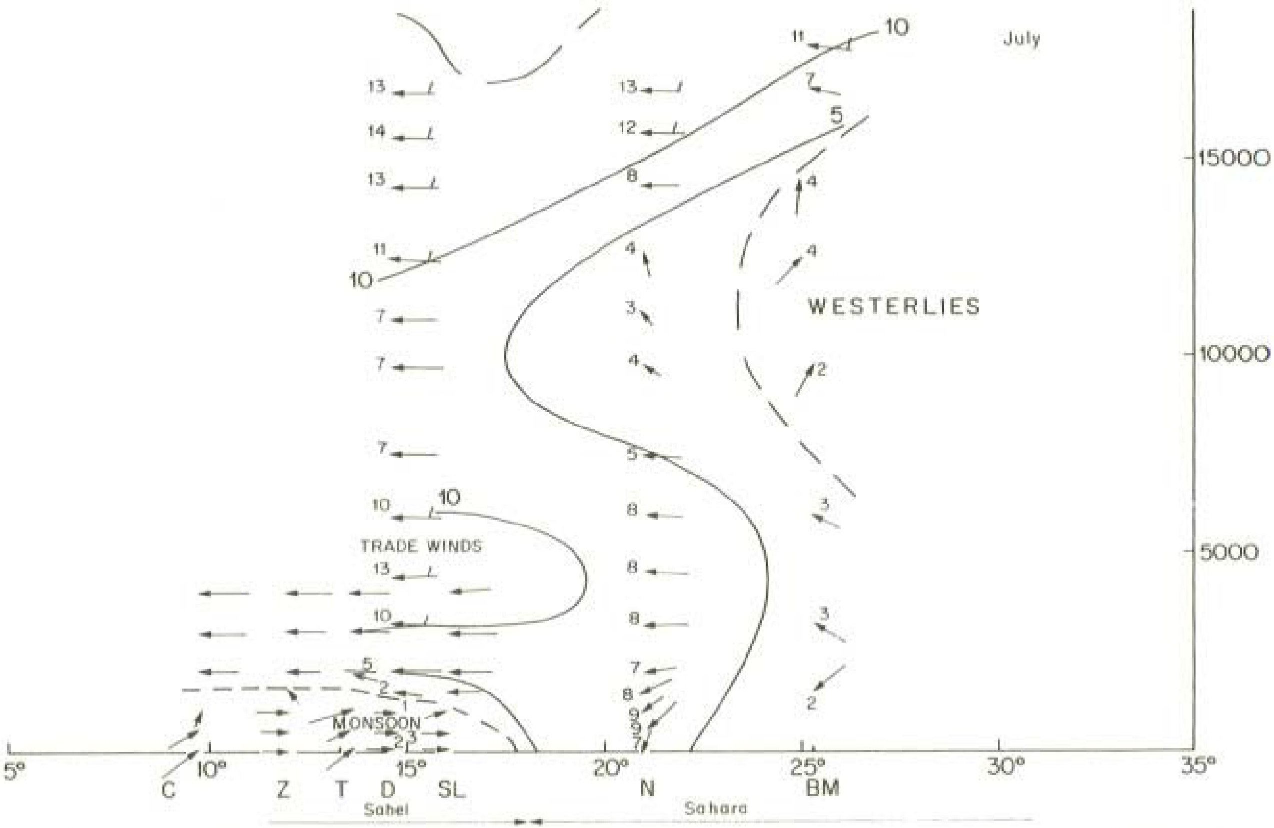

Figure 1.6 Predominant wind directions and mean wind speeds in upper levels at the African Atlantic coast in July

C = Konakry
Z = Ziguinchor
T = Tabacounda
D = Dakar
SL = Saint-Louis
N = Nouadhibou
BM = Bir Moghreim

4,000 m in more mountainous areas as is the case in summer at Mount Cameroun, which it literally deluges. Of course the dust particles in the harmattan air are transported above this monsoon towards very low latitudes until they are brought down to the ground by thunder showers.

The harmattan and the maritime trade winds are bounded on the north and surmounted largely on the south by the westerlies, which – and this is very important – are coupled to the low pressures of the medium latitudes. If this were not so the transport of dust towards Europe would not be possible. As the latitude decreases the westerlies are found at higher and higher altitudes, while their speeds increase. In winter a very strong westerly air current may be found at 8,000 to 10,000 m above the area from southern Mauretania to the loop of the Niger: the 'jet-stream' (Figures 1.3 and 1.4). Further east its course is from southwest to northeast as far as the north of Arabia, then frequently being marked by very characteristic high clouds. In summer the jet stream moves back towards North Africa and its speed decreases. To the south of this great air current the west winds gradually disappear and give way to the equatorial easterlies (Figures 1.5 and 1.6).

The above pattern is well illustrated by a graph of the winds at Tamanrasset, situated in the middle of the Sahara 100 km south of the tropic and 1,300 m above sea level. In winter the westerly winds prevail from about a thousand metres above the ground up to the highest altitudes. They have very high speeds, particularly at around 10,000 metres (Figure 1.7). This system is maintained until the end of May, but with diminishing wind strengths. In June it changes completely in the lower layers where easterly winds set in, from ground level up to 7,000 metres, above which altitude the westerly winds persist. In July and August the easterlies prevail everywhere, wind speeds are low. From September on, westerly winds reappear at high altitude. They draw successively closer to the ground until the end of October, at which time the winter situation is resumed. To sum up, from autumn to spring practically the whole of the high Saharan and north Sudanese troposphere forms part of the great stream of westerly winds governed by the low pressure systems of the medium latitudes. These winds draw progressively nearer the ground with increasing latitude. In summer, on the other hand, the whole of the troposphere of the southern Sahara, and with greater reason of the Sudan, above the monsoon, is in the sphere of influence of the easterly winds – harmattan or trades – surmounted by the equatorial easterlies, that is to say of the equatorial system. This distribution of the winds in altitude enables one to understand the long-distance transport of Saharan dust.

It has been established that in winter and at ground level all the Sudanese regions are under the influence of the Saharan desert climate. Swept by the harmattan, drought sets in everywhere, ponds disappear and their alluvial surfaces become the prey of wind erosion. Thermic turbulence, due to high near-ground temperatures, is considerable in the daytime and keeps in suspension the dust torn away from the soil of the southern Sahara and the Sudanese Sahel during dust storms. This constitutes what has been aptly named the 'harmattan haze' or 'dry haze' or again 'dust haze'. It is particularly dense in the neighbourhood of the ITF, where there is also a maximum amount of freezing nuclei, strongly concentrated in clay and especially in kaolinite (Bertrand, 1974). This haze is a striking phenomenon for aeroplane passengers as it entirely conceals the countryside, in the same way as low clouds (See Figure 1.8). Accompanying the ITF in its movements, it is to be found

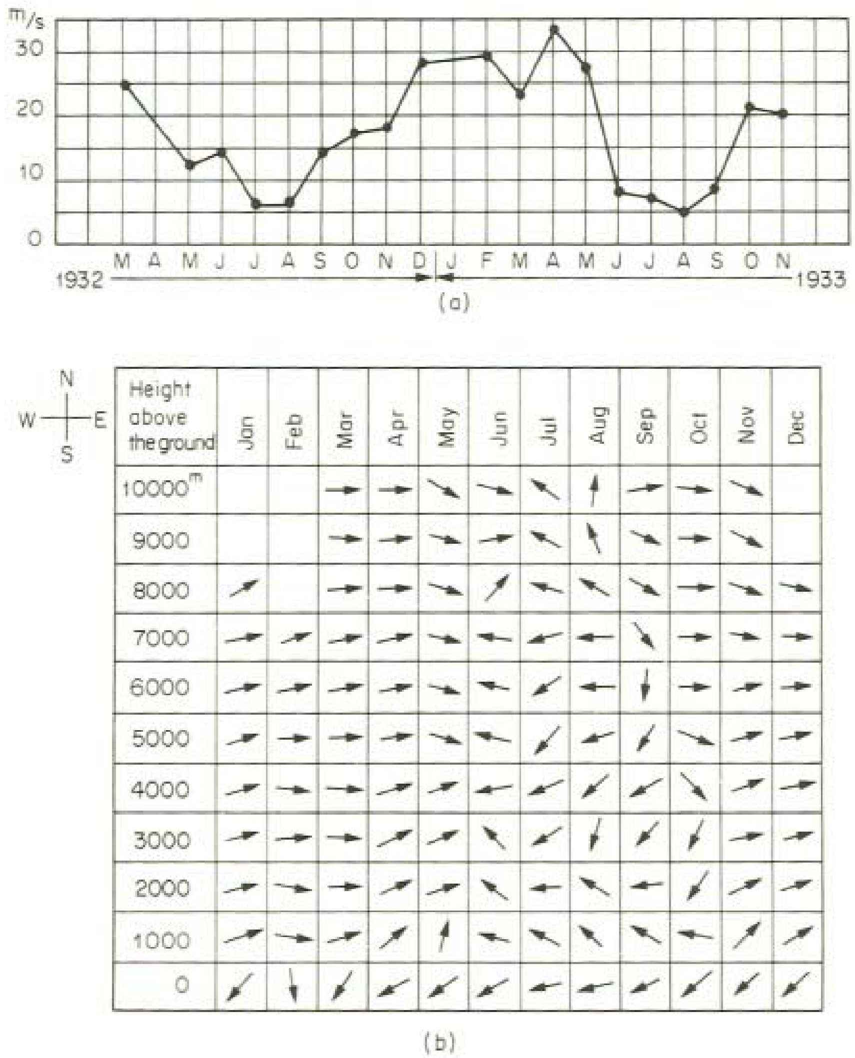

Figure 1.7 (a) Mean wind speed at an altitude of 10,000 m (above the ground) at the station Tamanrasset.

(b) Mean wind direction at the station Tamanrasset (the mean for the period 1932–1933; wind measurements made between 07^h and 08^h)

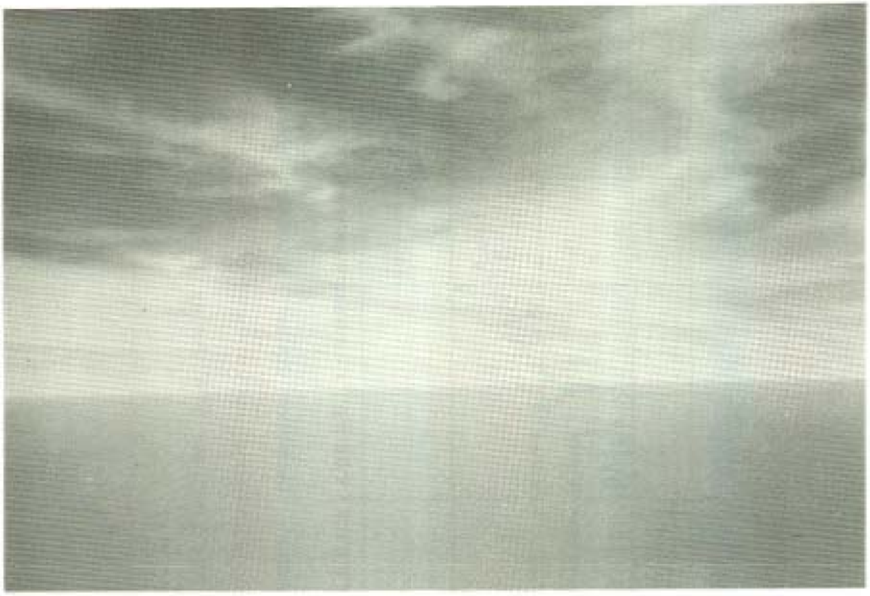

Figure 1.8 Cirrus clouds above a layer of dense dry haze as seen from a Caravelle flying at a height of 8000 m between Douala in Cameroon and Ndjamena (former Fort Lamy) in Tchad. The photo was taken 26 January 1969

in spring, more or less mingled with fine ash from bush fires, from south of the Tropic to the regions where it is precipitated to earth in rainstorms, namely between 200 and 500 km south of the ITF. That is to say in regions where the layer of the monsoon is sufficient to maintain the cumulus through the dry layer of the harmattan. This pattern is, however, rather oversimplified. Indeed, it is difficult to distinguish between haze due to dust in suspension and that caused by humidity in the air, when the two are not combined. Their effect upon the soil is, however, not the same. A. Cerf (1974) has shown, for instance, that in the tropical humid zone the aerosols manifested themselves by an increase in ground temperature for the whole 24 hours during the period of the harmattan, while in the dry zone where the humidity is low the warming up and greenhouse effect is limited to the daytime. The greenhouse effect is cancelled at night by the increased radiative cooling of the dust due to the absence of water in the atmosphere. In summer and particularly in August, the ITF is in its most northerly position. It may quite often be observed in the Hoggar and the Tibesti areas and it sometimes reaches the plateau of Tademaït, in the western Sahara. In autumn, following the southwards withdrawal of the monsoon, the Saharan desert climate quickly replaces the equatorial climate in the Sudan.

The above describes average movements of the ITF, which are not literally true: in fact the latter oscillates widely on both sides of these theoretical average positions. Neither does it show the straightness of outline of the average position, in

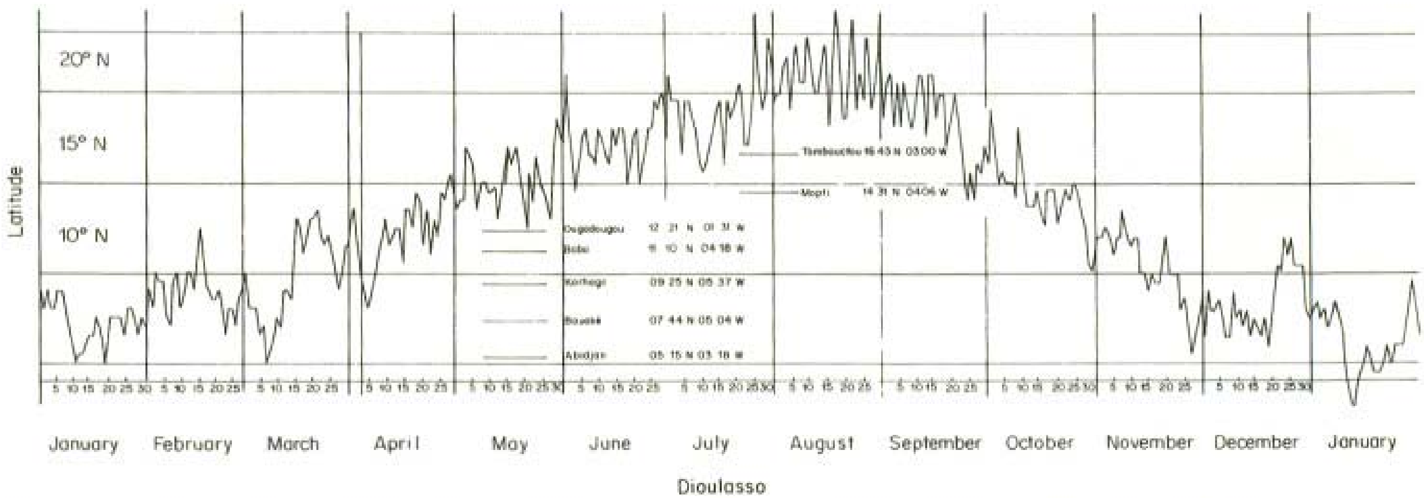

Figure 1.9 Position of the Intertropical Front (ITF) at surface at the longitude 5°W during 1973, in accordance with the meteorological charts prepared at Abidjan

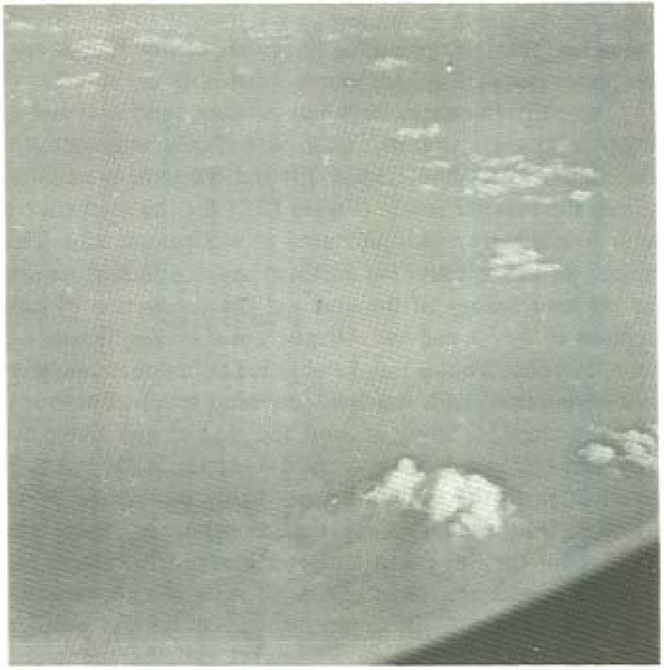

Figure 1.10 The tops of cumuliform clouds emerging from a layer of dense dry haze. It is possible to distinguish within this layer much more voluminous cloud masses which are partly invisible from an observer in an aircraft. The photo was taken from a DC 9, north of Lagos, Nigeria on 14 January, 1969, just before landing

fact it curves back and forth across this, that is why these advances and withdrawals from the front of the monsoon may be compared to the waves of the sea, rolling different distances up the beach, while still ebbing or flowing with the tide (Figure 1.9).

This distribution of prevailing winds during the year appears to be confirmed by the traces of eolian erosion which may be observed in photographs of the Sahara taken from satellites. However, a careful study of aerial photographs taken from a plane leads to much less conclusive proofs, at least in the northern part of the desert, and, in order to understand the orientation of some dune formations in relation to the above distribution, one has to resort to some rather rash hypotheses as in Mainguet and Canon (1976) (Figure 1.10). The study of sand and dust winds in this Saharan region shows, finally and above all, that their most frequent directions are totally different from those of the prevailing winds. As proof of this observations may be taken in the sirocco in the Maghreb, the ghibli in Libya and the khamsin in Egypt. The above conclusion has led us to study the frequencies of winds from the various points of the compass in relation to their strength (Dubief, 1952). We soon see that the prevailing directions at low speeds are very often different from those observed at high speeds, when they are not directly opposite (Figure 1.11). Thus, the frequency of winds between southwest and northwest is seen to increase with their strength, until they finally represent almost all the violent winds, that is to say those which lift and transport most of the dust and sand. Apart from the summer season (Figure 1.12) and the southern regions of the Sahara, easterly to northerly winds do indeed prevail but are light. This is why, in the northern part of the country, the northern and continental air masses cannot contribute to the morphology of the ergs and the production of dust, with the possible exception of Egypt and the Atlantic coast of the Sahara, but there the problem is more complex. To this may be objected at first that sand and dust winds are sometimes encountered with relatively low wind speeds. But in this case their origin has another cause. A lifting of sand and dust occurs when the dunes are approached by 'contrary' winds, if I may use the expression. That is to say winds in the opposite direction to the equilibrium previously established by winds in the contrary direction. One could also say that moderate or strong winds are too infrequent to account for the eolian transport phenomena. This is to forget that these are accidental phenomena, just like rain, and thus it is not surprising that they should be produced by exceptional causes such as high velocity winds: exceptional causes produce exceptional phenomena. Remember, too, that the force of the wind is not alone in causing these phenomena. To it should be added its turbulence,

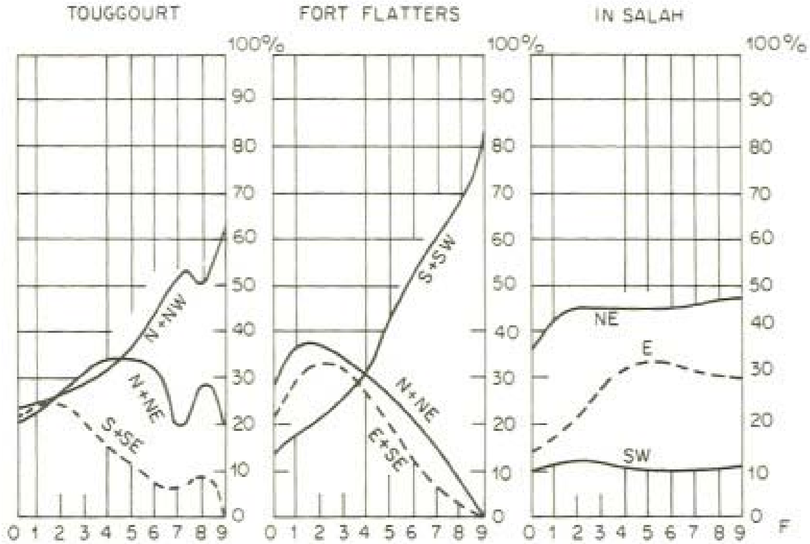

Figure 1.11 Windforce frequency at different wind directions (F: Windforce according to the Beaufort scale)

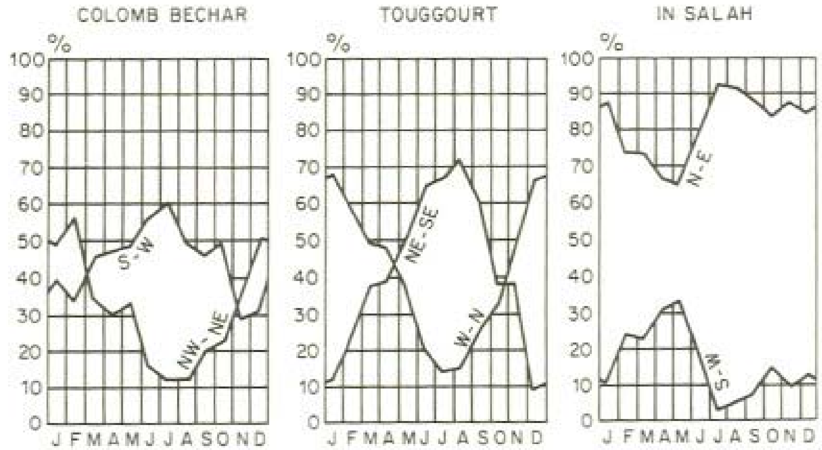

Figure 1.12 Yearly variations of predominant wind sectors (only wind forces above 3 Beaufort are considered)

thermic, orographic or otherwise, in order to explain eolian liftings and transports. A strong, steady, laminary wind lifts little sand and dust and, if it does so, to no great height (one or two metres only). This is why dust winds are often associated with sharp rises in temperature and are frequently encountered in the warm sectors of depressions. I would like to emphasize that often, not always, as sand winds are sometimes to be met with in the cold sector of a depression and also, especially in the southern Sahara, on the intrusion of cold winds, but here their turbulence is of orographic origin: this is the case, for instance in the southeast of the Tibesti.

These moderate to strong southwesterly winds and the accompanying movements of sand can usually be related to depressions involving the Sahara. The most important of these are the ones which arise locally in the warm sector of these perturbations. They may be seen at first as small rivulets of sand, very wavy, separate from each other and close to the ground. By degrees, as the speed and turbulence of the wind increase, these rivulets of sand run together, the air quickly darkens, while the depth of the air-borne dust increases, normally reaching around 2,000 metres. These hot winds full of sand mixed with dust increase slowly in intensity during the morning, reaching a maximum during the afternoon. Their turbulence is therefore mainly of thermic origin. When the depressions are on a large scale and allied to European perturbations, these winds of sand and dust may extend to the whole of the Sahara and the dust transported by the upper winds, from between southeast and southwest, may reach the Mediterranean basin and Europe. This is what Navlikine (1969) called 'intercontinental dust-storms'.

These depression have various origins. They may be:

(1) Mediterranean depressions skirting the Mediterranean coast of Africa. Their

action is reinforced when they halt for some days at certain spots on the coast or in the eastern Mediterranean.

(2) Atlantic depressions, connected, like the above, to polar front depressions when these approach the Sahara by the south of Morocco. This usually only occurs in winter.

(3) Secondary south-Moroccan depressions originating in the southern part of Morocco when the trajectory of the Atlantic depressions reaches a turning point at the level of the Iberian Peninsula and then moves towards the northeast. Paul Queney (1936) drew attention to these and formerly designated them as 'Saharan depressions'. Moving eastward through the north of the Sahara and the Maghreb, they reach Libya and the eastern Mediterranean basin. If they are linked to strong European polar front perturbations they enable the dust, raised south of the Atlas chain, to reach higher latitudes and the continent of Europe. It is probably these last two types of depression which have inspired the Meteorological Office in London to think that the majority of 'khamsin depressions' in Egypt originate from the Atlas Chain wind (Bejjani, 1975).

(4) Depressions arising along the ITF, thus in the Sudan area. With Paul Queney (Dubief and Queney, 1935) we at first called them Saharo–Sudanese depressions, then, with Robert Capot-Rey (1953), Sudano–Saharan depressions. They are in fact, and more simply, tropical depressions. They develop when the polar or pseudo-polar air mass, in conjunction with modifications of the upper atmosphere, meets a vast wave of the polar front. Jalu and his collaborators have recently studied them with greater resources than we formerly used (Jalu, 1965; Jalu *et al.*, 1965).* At first their trajectories stretch across the Sudan from east to west, like all the Sudanese perturbations, then, often after encountering a turning point, they move towards the north or northeast. Then, swept along by the westerly upper winds, they cross the Sahara and reach the Mediterranean coast, where they continue on their way, more or less linked to the polar front depressions (Figure 1.13). Their most frequent trajectories go from Senegal to Morocco in autumn, from the loop of the Niger to the Gulf of Sirte in spring and, to a lesser degree, in May–June, from the north of Nigeria to Lower Egypt. In the latter country they are known as 'khamsin depressions'. It is they which usually give rise to the Libyan 'ghibli' (Sutton, 1946). It should be noted that these 'khamsin depressions', after having caused strong sand and dust winds in Egypt, sometimes as far as Assouan, reach the Lebanon and Syria, bringing with them considerable clouds of dust (Bejjani, 1975). Contrary to our opinion, El Tantawy (1964) believes that they might be caused, either by a divergency in the upper atmosphere in the neighbourhood of the sub-tropical jet stream, or by a special development of this divergency zone.

*The terminology used by Jalu to designate the air masses is different from ours and may lead to confusion. To him the monsoon is a humid tropical air mass and the harmattan a northerly trade wind; whereas to us, as has been seen, the former is an equatorial maritime air mass and the latter a tropical continental one.

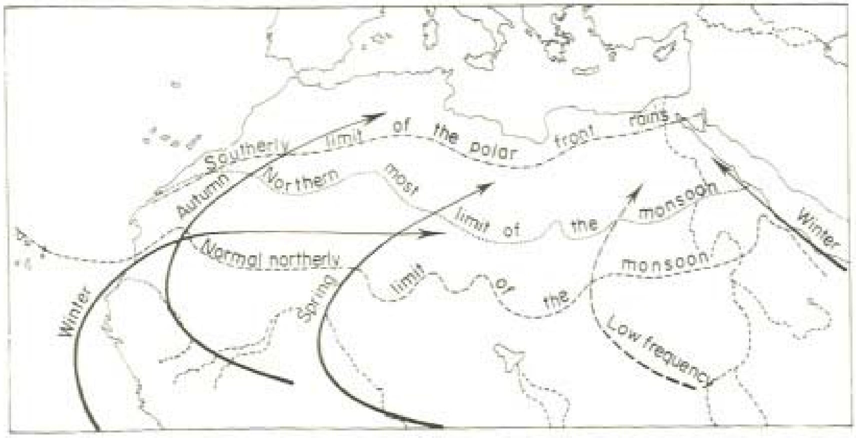

Figure 1.13 Trajectories of Sudano–Saharian depressions and limits of the polar front and monsoon rains

In order that the dust torn away from the Saharan soil may reach Europe, it is necessary, as we have said, for it to be linked to European polar front depressions and the 700 to 500 mb contour charts show a very marked trough (a "thalweg"), with a north-south axis and touching North Africa. This is shown on the charts given by Bücher and Lucas (1975) and by Champollion (1963). In this case the dust may attain altitudes of 5,000 metres and more and reach areas as far away as the north of the Federal Republic of Germany. Because the upper air currents take slightly different directions at different levels, dust from the same Saharan region may be spread across a vast area by the end of its journey, as shown on Champollion's map of April 1962 (Champollion, 1963). The duration of this transport, one or two days at most to reach France, and the distance travelled are determined by the meteorological circumstances: speed of the upper winds, zones of precipitation, calms, etc. In exceptional instances the Saharan dust can reach remote parts of Europe, as happened in March 1903, when falls were observed over the Atlantic, from the Canaries to the Azores, in Great Britain and Central Europe, while Spain, curiously enough, was spared (Hermann, 1903). Zamorsky has studied the movements of dust clouds on the 20 and 24 March 1964 which reached the Caucasus and then the northern part of the Caspian Sea and the Penza area, near the Volga, at latitude 53°N (Nalivkine, 1969).

It should be noted that these Saharan dust clouds may be augmented by other forms of dust, algae, pollen – from hazel for instance (Bücher and Lucas, 1972 and 1975), even alfa fibres (Champollion, 1963, page 80) lifted from the soil of the countries on the way and adjoining the desert. This is the case when the rising current persists for a long enough distance at the beginning of its course. They may also remain in the upper air and be unnoticed from the ground, as happened in Spain in 1903, where all that was observed was a darkening of the atmosphere. This was also the case in the Bagnères area (Central Pyrenees) on the same date (Bücher and Lucas, 1972). Usually this dust is precipitated by rain (rains of mud or 'blood') (Combier *et al.*) or snowfall (Clement *et al.*). Nevertheless, it may gradually fall earthwards simply by means of gravity, owing to an exceptional calm in the atmosphere and perhaps, too, aided by a subsiding movement of the air. This is what occurred at Bagnères de Bigorre in February 1903 and, recently, in February 1972 (Bücher and Lucas, 1972).

In the rear of these Saharan depressions, the arrival of the cold front is sometimes accompanied by a raising of sand which gives the impression of a 'wall of sand and dust'. Two to three thousand metres high, it is spectacular in the extreme. This is what is depicted in paintings and photographs when wishing to illustrate sandstorms engulfing caravans (*sic*). Several hundred kilometres long and some tens of kilometres wide, they are of fairly short duration (from ½ to 2 hours) for they travel at rather high speed. While they are passing a particular spot the visibility is suddenly and very greatly reduced. Unlike the previously-mentioned liftings, the wall of sand is essentially migratory and may be easily followed on weather charts. Due to its origin, it is accompanied by a drop in temperature and a change of wind direction to the north.

When, in late spring and early summer, the whole atmosphere of the southern Sahara is occupied by easterly winds and a zone of relatively high pressure is found at 500 or 200 mb, the above-mentioned Sudano-Saharan depressions move only from east to west. If they are very active they give rise to strong sand and dust winds which involve the whole of the southern Sahara and the Sahel. This was the case between the 5 and 9 June 1967 (Figure 1.14). There were, in fact, two depressions rapidly following each other from the loop of the Niger to the sea area off Senegal. Their northern sectors comprised dry, burning, violent east to north-east winds. At Saint-Louis, for instance, maximum temperatures went from 28°4 on the 5th to 40°3 on the 7th and 42°8 on the 8th, dropping to 29° on the 9th, while an east-northeast wind blew, reaching a strength of 18 m sec^{-1} at midday on the 7th. It was evidently accompanied by a particularly intense dust haze which reached Dakar and remained there from the 7th to the 9th. Injected into the medium layers of the atmosphere, this haze pursued its course over the eastern Atlantic, the famous 'sea of shadows'. We have not been able to study the origins of the dust cloud which crossed the Atlantic from 29 June to 4 July 1969 and which was photographed by a satellite (Courrier de l'UNESCO August to September 1973).

Sand and dust winds may have quite a different origin to the above. It is then a question of so-called 'accelerating winds of sand and dust' (Berenger, 1963). These are relatively cold. Although they affect the desert on a large scale, they are less extensive and the reduction of visibility is less than in the above. Also the dust is raised to a lesser height. They are less turbulent and the turbulence is mainly from orographic causes and their speed is higher than in the preceding cases. They blow

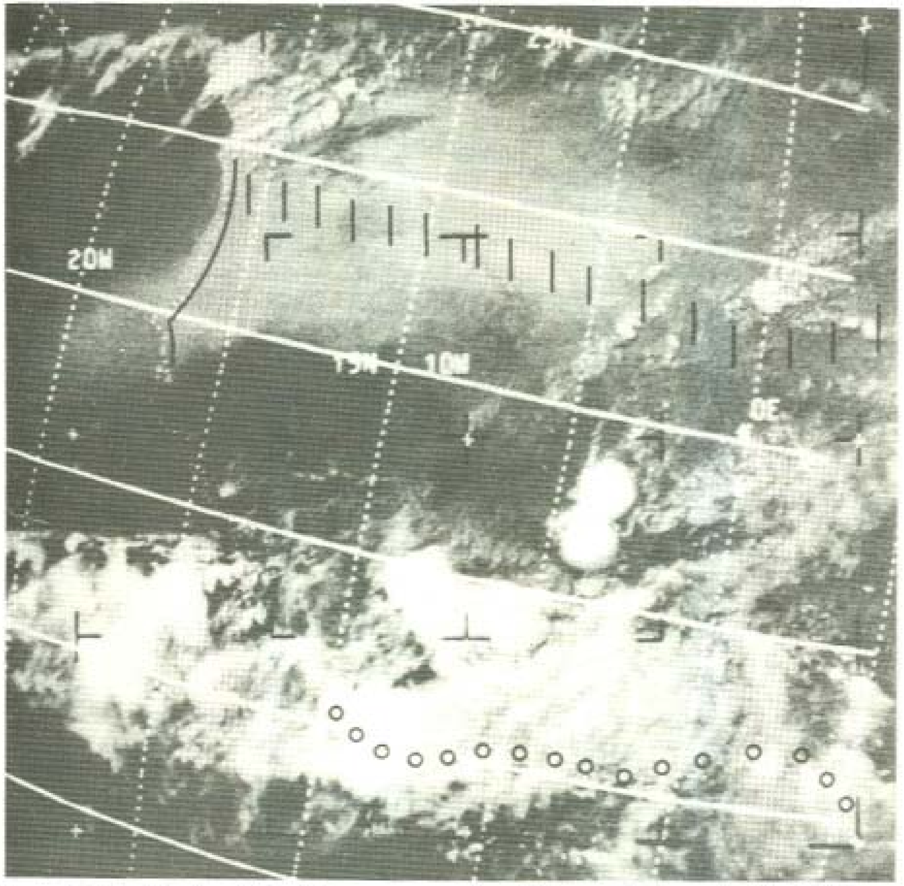

Figure 1.14 Sand- and dust-storm over western Sahara, photographed by ESSA on 5 June 1967. Driven by very warm and dry violent winds between north and east the dust cloud extends off the coasts of southern Mauritania and Senegal. The warm sector is situated north of the depression, the cause of the dust storm. The position of the depression was 14°N and 17°W on 5 June at 12^h GMT

mainly in the morning and not in the afternoon like the ones we have studied. They may be met with south of the Tidikelt plateau and southeast of the Tibesti, for instance, as well as in the Ténérés and the Tanezrouft of the southern Sahara. In the Tchad basin, these dust winds which follow the sand winds travel in a day or two and at a low altitude from Faya (Borkou) to Fort Lamy (Ndjamena), 800 km further south. They subsequently turn towards Nigeria and Upper Volta and in winter reach the coast of the Gulf of Guinea. Figure 1.15 shows an example of the progress of this kind of dust haze. They obviously feed the harmattan dry haze. Their precipitation over the Sudan area is considered beneficial by the Africans because of the fertilizing mineral elements they bring.

To these principal causes of dust clouds may be added secondary causes, giving

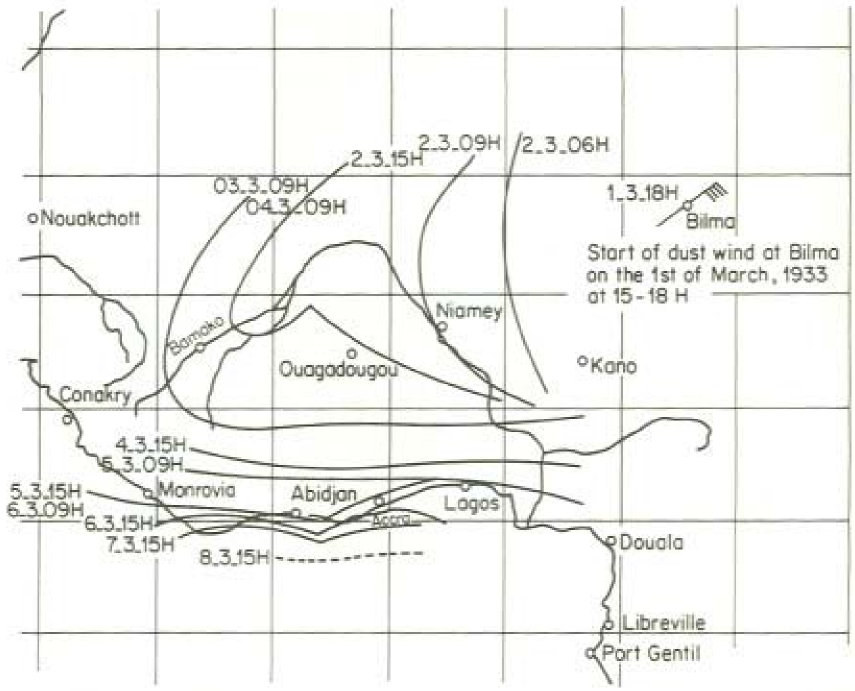

Figure 1.15 Migration of the front of dust haze above West Africa from the 2nd to the 8th March 1973 (after J. Bertrand, 1974)

rise to less spectacular phenomena. This is the case when particles of sand and dust are lifted in conjunction with thunderstorms. We meet this in the Sudanese region, mainly in the northern part and particularly in the Sudan itself. These are the 'haboobs' of the Khartoum area. They are walls of sand reaching up to the base of the Cumulo-nimbus and sometimes beyond these. They may be several kilometres long but of no great thickness. They are of variable, but usually short, duration, the average being half an hour. Similar but lesser phenomena may be seen at the onset of Saharan thunderstorms, especially in the summer, at night, in the northern part of the desert.

In addition, there are the small dynamic, thermic whirlwinds with vertical axes, the 'dust devils' which may be seen on the plain on calm and hot days. Some tens of metres in diameter at ground level, they may widen to several hundred metres at the top, thanks to their intense whirling movement and the violent rising current in the centre. As in the above, the amounts of dust which they can put in suspension in the air are minimal compared with the phenomena discussed earlier.

Dry haze may also become noticeable on the arrival of a humid air mass, by the absorbtion of water vapour by large ions in suspension in the air. We have observed this on various occasions at Tamanrasset, under the virgas of a rain cloud or on the arrival of a 'splash' of monsoon.

Lastly, dry haze linked to the harmattan may intrude very suddenly into the southern regions of the Sahara and particularly the central Saharan massif, following an exceptional northward movement of the ITF. It is then very dangerous as it drowns all the landmarks in dust and makes the most experienced guides lose their way. It causes even more mortal accidents than do the sand winds. When it appears in spring in the Hoggar, the Tuaregs believe it to mean rain in the Sudan.

To conclude, the Sahara, owing to its climate, appears to be the chosen territory of eolian erosion, this being particularly active on its northern and southern edges, where alluvia are still able to settle and where a dynamic balance in relation to the wind has not yet been reached. It is also a conspicuous centre for the dispersion of dust drawn up from the ground, and has been for thousands of years. If the normal course of this dispersion, in view of the prevailing winds, appears to be towards Black Africa and the Atlantic, it seems on the other hand to take a contrary course to these when moving towards the Mediterranean basin and Europe. This is only conceivable if one considers the effects of the various depressions involving the Sahara, in conjunction with those of the big air currents of the lower and middle atmosphere. For a large part of the year these currents are influenced by the low pressure systems of the medium latitudes. Strong injections of this dust into the upper altitudes permit it to reach the European continent, and, in exceptional cases enable it to arrive at some of the shores of America.

The big intrusions of cold air masses, more or less connected with the polar front, which from time to time overrun the Sahara from the north, reinforce the permanent action of the harmattan in winter and the 'Etesian winds' in feeding and displacing the mass of dust in suspension which remains in the neighbourhood of the intertropical convergency front and in the southern regions at all seasons, in summer in the centre of the western Sahara. These combined effects serve to compensate the losses to the mass of dust in suspension through tropical precipitation. The continuous action of the prevailing winds sweeps it towards the south and west of the Sahara. This dust haze gives to the Sudanese regions a climatic character very noticeable to travellers crossing or flying over them.

These dispersions of Saharan dust over Europe, while episodic at present are not without effect upon the climate there. Some years they certainly contribute to the melting of Alpine glaciers and it is very probable that their effects have been most important for thousands of years past.

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