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African Dust Observed over Canary Islands : Source-Regions Identification and Transport Pattern for some Summer Situations

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Bulk filtration samples of dust were collected on Fuerteventura (Canary Islands) in July 1985 in order to investigate African dust transport over this region during summer. Air mass trajectories and elemental and mineralogical analyses allowed us to distinguish between oceanic and continental influences: three African dust transport cases occurred during this period. Geochemical and mineralogical tracers, combined with air mass trajectories, indicate that two different source regions of dust (Sahelian and Moroccan ones) are involved. Each of these exhibits specific Si/Al and Fe/Al ratios that can be considered as tracers of dust origin. A meteorological study, based on satellite imagery, meteorological maps, and air mass trajectories, confirms the previous identification of the source region. It is also possible to describe the meteorological situation controlling the atmospheric pathway of the dusts from the source regions up to the Canary Islands. This study suggests that some source regions (especially the Sahelian one) of dust affecting the Canary Islands during summer are rather different from the Moroccan ones observed in a spring situation by Coudé-Gaussen *et al.* (1987).

INTRODUCTION

During the last few years many authors have emphasized the major role that desert dusts play in various aspects of atmospheric physics and chemistry. For instance, it has been shown that the desert dusts significantly affect the optical properties of the atmosphere and consequently the general radiation budget of the Earth [Bach, 1976]. Moreover, these particles have been recently invoked in cloud formation, although studies of the impact on precipitation processes have not been done. The incorporation of the desert dusts, which contain basic compounds such as calcite, in rainwater leads to an alkalination of rains, especially in European countries [Löye-Pilot *et al.*, 1986; Schütz and Kramer, 1987] where acid rains are a critical problem.

Another important feature concerning the desert dusts is the ability of the soil-derived particles less than 10 μm in radius to undergo long-range transport [Tsoar and Pye, 1987]. The dust transport from northwestern Africa to the north tropical Atlantic and Caribbean Sea has been extensively investigated in the last two decades [Delany *et al.*, 1967; Prospero and Carlson, 1972; Carlson and Prospero, 1972; Savoie and Prospero, 1977; Buat-Ménard and Chesselet, 1979]. The African fingerprint of these dusts was detected even as far as 5000 km from their source [Prospero, 1981; Chester, 1986]. The ability of dusts to be transported long distances,

along with the large quantity of matter injected into the atmosphere from desert areas (260 Mt yr^{-1} for the African source [Schütz, 1980]) means that the aeolian source is responsible for a large part of the deep-sea sedimentation in various oceanic regions of the Earth [Chester *et al.*, 1979; Sarnthein *et al.*, 1982; Uematsu *et al.*, 1985; Rea and Jaenicke, 1982; Rea *et al.*, 1985].

The Canary Islands are a particularly interesting environment in which to study the northern source regions of African dusts reaching both the North Atlantic and north western Europe. Very few studies have been conducted in the subtropical Atlantic regions, while the tropical Atlantic and the Mediterranean area [Chester *et al.*, 1984; Prodi and Fea, 1979; Bergametti, 1987] are now well documented. An earlier study was performed in spring 1984 in order to characterize chemical and mineralogical properties of the desert dusts observed over Fuerteventura Island in relation to air mass trajectories and their source regions [Coudé-Gaussen *et al.*, 1987].

The present study tries to investigate trajectories and source regions of dust observed over the subtropical eastern Atlantic during summer, when the regional atmospheric circulation is rather different. Geochemical and mineralogical indicators are used to investigate the origin of the dusts. We will then describe at a synoptic scale some summertime meteorological situations which control the changes in dust source regions.

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SAMPLING AND ANALYSIS

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The sampling site was at Corralejo (29°12'N, 13°30'W) on the northern coast of Fuerteventura, one of the seven islands of the

Canary archipelago. Fuerteventura is the island nearest to the northwestern Sahara and is located 100 km west of the African coast. The local mineral assemblage coming from its volcanic substratum (basalts and gabbros) is very different from that expected from the potential Saharan sources (mainly clay minerals, calcite, and quartz) and allows a good distinction between the local and remote contribution. Moreover, local pollution sources are very scarce on this island.

The samples were collected between July 18 and July 31, 1985, at the top of a 15-m-high building, by bulk filtration on 0.4- μ m-pore-size Nuclepore filters. The sampling duration ranged between 12 and 36 hours. A flow rate of about 1 m³ h⁻¹ was used during the sampling period.

The samples were successively analyzed by X ray fluorescence (XRF), X ray diffraction (XRD), and by scanning electron microscopic analysis (SEM), coupled with an energy dispersive X ray analyzer (EDS).

Elemental analyses (Al, Si, P, S, Cl, K, Ca, Mn, Fe, and Zn) have been performed by wavelength dispersive X ray fluorescence spectrometry (CGR $\alpha 10$), according to the method described by *Losno et al.*, [1987], using an X ray tube with Cr or W targets. Analytical precision is better than 7% for every analyzed element except Zn (10%). Elemental concentrations are reported in Table 1.

Mineral components were identified directly on the filter by X ray diffraction (Philips Diffractometer PW 1130), using Fe filtered Co K α . The X ray record of an unexposed filter shows a strong line between 4.50 and 5.70 Å and reaches a maximum at 5.10 Å, this area was consequently unusable.

The gold-plated samples were examined by a Jeol JSM 2 SEM with energy dispersive system (EEDS Ortec). More detail about these analytical techniques is available in the work by *Coudé-Gaussen et al.* [1987].

METEOROLOGICAL SITUATION AND TRAJECTORY ANALYSIS

The Canary Islands are located in an area particularly affected by the seasonal meridional shifts of the subtropical anticyclone [*Huetz de Lempis*, 1969]. Moreover, these islands are also on the path of cold polar air masses. For these reasons, the climatology during the intermediate seasons (spring and fall) is extremely variable, and previous work [*Coudé-Gaussen et al.*, 1987] illustrates the complexity of the meteorological situations favorable to dust transport to the Canary Islands during spring. On the other hand, during summer the subtropical high moves northward: generally, the Canary Islands are dominated by its influence, and dry weather prevails. Hence the meteorological situation is very stable. It is also interesting to emphasize that the northern trade winds originate in this area.

Many studies have shown that air mass trajectories are a useful tool to describe dust transport at a synoptic scale [*Reiff et al.*, 1986]. These trajectories, combined with geochemical or mineralogical tracers, have been used to determine the source regions of natural or anthropogenic particulate matter in various environments [*Merrill*, 1986; *Bergametti*, 1987; *Colin et al.*, 1989].

Three-dimensional air mass trajectories have been computed by the Service des Etudes Spéciales de la Météorologie Nationale (France), using wind analysis processed 4 times a day by the European Centre for Medium-Range Weather Forecasting (ECMWF) in Reading, England. The software [*Imbard*, 1983] allows the computation of trajectories for any starting or ending point at any time. The vertical level is specified for the initial point and the trajectories are computed, taking into account the vertical velocity

TABLE 1. Sampling Dates and Elemental Concentrations

Sample and Trajectory Number	Date: Time, UT		Atmospheric Concentration, ng m ⁻³									
	Sampling Period		Al	Si	P	S	Cl	K	Ca	Mn	Fe	Zn
	Start	End										
1	18:2000	19:0800	555	1846	31	2380	6895	3120	1135	9	929	<12
2	19:0800	19:2000	1220	2406	29	850	6875	355	1370	13	1262	<15
4	20:0800	20:2000	811	2874	37	735	5395	335	1480	13	1411	<11
5	20:2000	21:0800	319	1120	13	565	3775	195	875	4	580	<13
6	21:0800	21:2000	2005	6754	89	855	5410	670	2665	34	3080	13.5
7	21:2000	22:0600	870	2905	38	1385	7345	330	1255	16	1533	<7.5
8	22:0600	23:0600	2048	7101	73	3605	4730	795	2405	36	3107	24
9	23:0600	24:0000	2594	7298	76	3780	6755	920	2315	28	2570	<21
10	24:0000	24:2000	4483	12115	173	3285	4685	1380	4130	67	5543	29
11	24:2000	25:0800	1584	5704	54	3240	10055	740	2205	26	2401	109
12	25:0800	25:2000	2517	8227	103	4865	7945	885	3260	42	3844	18
13	25:2000	26:0800	402	1324	19	2250	6470	320	1000	6	667	<17
14	26:0800	26:2000	1817	5989	76	905	8650	640	2515	29	2831	<15
15	26:2000	27:0800	505	1823	25	830	8865	320	1275	9	1070	26
16	27:0800	27:2000	1111	3626	52	725	6045	400	1490	21	1848	8.4
17	27:2000	28:2000	1888	6359	84	950	7365	630	2605	33	3133	<14
18	28:2000	29:2000	1613	5127	70	605	3135	475	1850	29	2442	<7.9
19	29:2000	30:2000	1443	5289	66	925	6705	555	2005	28	2409	<9
20	30:2000	31:0800	750	2604	37	860	10275	435	1590	16	1564	<15

Dates are days in July 1985.

values in the archive. *Martin et al.* [1987] have pointed out that the vertical velocity is a necessary parameter to integrate in computed trajectories in order to reproduce the actual displacement of the air masses.

In this study, two backward trajectories, ending at the 925- and 850-hPa barometric levels, have been computed for the median time of each sample. The duration of each trajectory is 96 hours.

As a first step, trajectory analysis enables the separation of six distinctive periods during the sampling experiment (Figure 1):

1. From July 18 (2000 UT) to July 19 (2000 UT), the Canary Islands are subjected to northern oceanic influence in the lower atmospheric layers (925 hPa) and are affected by African air masses at the upper barometric level (850 hPa), shown by trajectory 2 in figure 1.

2. From July 19 (2000 UT) to July 21 (0000 UT), we observe an oceanic influence for the two barometric levels investigated (trajectories 4, 5 in figure 1).

3. From July 21 (1200 UT) to July 25 (0000 UT), an oceanic circulation remains in the lower layer, while a new African influence is suggested by the trajectories ending at 850-hPa (trajectories 6 to 11 in figure 1).

4. From July 25 (1200 UT) to July 27 (1200 UT), the Canary Islands are again subjected to continuous oceanic conditions (trajectories 12 to 16 in figure 1).

5. From July 28 (0600 UT) to July 29 (0600 UT), the oceanic influence is always present in the lower layer, but a new African contribution is obvious in view of the 850-hPa trajectories (trajectories 17, 18 in figure 1).

6. From July 30 (0600 UT) to July 31 (0000 UT), only oceanic influences are indicated by air-mass trajectories (trajectories 19, 20).

In summary, it is worthwhile to note that the trajectories ending at 925-hPa indicate only oceanic influences during the whole sampling period. The advection of air masses from Africa is observed only in the 850-hPa trajectories.

The pure oceanic influences are easily characterized by an atmospheric circulation controlled by the Azores High. The July 21 (0000 UT) situation is given as an example of such conditions (Figure 2).

The advection of African air masses over the Canary Islands appears more complex and at least two different source regions can be deduced from trajectories: a northern source from Morocco and another one from more southern desert areas (Figure 1). It is obvious that these two different origins for the observed dust result from different circulation patterns controlled by the several active centers.

A first indication of the meteorological processes involved in the transport of African air masses to the Canary Islands is provided by

Fig. 1. Air-mass trajectories terminating over Fuerteventura for two barometric levels: 925 hPa (dotted-line curve), an 850 hPa (smooth line curve) during the whole sampling period (the numbers refer to dates reported in Table 1).

Fig. 2. Meteorological situation for oceanic influence over Canary Islands during the sampling period (July 21, 1985; 0000 UT; surface chart).

studying the vertical motion of the relevant trajectories at the synoptic scale. Figure 3 shows these vertical movements for the trajectories, indicating transport cases from Africa at 850-hPa. We observe that a systematic downward movement is associated with these trajectories. The mean barometric level of the air masses when they moved over the potential source regions lies between 700- and 850-hPa, depending on the case. So we focus our attention on the meteorological maps for these levels.

On these maps we have compared the situations corresponding to

the cases of dust transport from either Morocco or southern source regions (Figure 4). From these maps we note that the airflows are in the two cases controlled by a high-pressure cell located over Western Europe or Northern Africa, respectively. It is probable that the differences in dust source area can be attributed to fluctuations in the position of the high-pressure center. For example, from July 21 to July 24, 1985, the air mass coming from Africa, remains at 850-hPa. At this level, the subtropical anticyclone extends between the Azores and Western Europe, which is its average position for the summer season.

Consequently, such a situation generates a northeastern flow at 850-hPa over northwestern Africa and Fuerteventura, and hence it is likely that the dust observed on July 24, 1985 over the Canary Islands originated from the Atlas chain.

From July 24, 1985, the extended subtropical anticyclone moved southward, while the air masses, originating from Africa, were transported at 700-hPa. This anticyclonic motion results from the incursion of a polar air mass over the eastern Atlantic. Hence the African air mass transport is controlled by an eastern flow coming from more southern regions of North Africa. Moreover, on July 26, 1985, the polar air mass low cuts the anticyclonic wedge, which generates a closed high-pressure center over North Africa. Consequently, from this date the wind flow is diverted northward, which is well visible on the trajectory ending at 850-hPa on July, 28, 1985, at Fuerteventura (trajectory 17 in figure 1).

In this brief meteorological study of airflow patterns over the Canary Islands during this summer period, it has been pointed out that the high-pressure cells control the atmospheric circulation in this region. The respective positions of both the principal Azores center and its secondary branches (over southern Europe or North Africa) impose either global north to northwestern atmospheric circulation (at 925- and 850-hPa levels) or a split circulation

Fig. 3. Vertical movements during 4 days at a synoptic scale of an air mass originating from African regions and sampling over Fuerteventura (the sample numbers are reported on each vertical motion; the interval between two symbols corresponds to 6 hours).

Fig. 4. Silicon and sulfur average concentrations, geometric standard deviations and mineral compounds observed during oceanic (area A) and continental (area B) cases of transport.

(oceanic and continental) at each barometric level. Moreover, the meridional fluctuations of the continental high-pressure cells generate airflows from northern or more southern African origins.

CHEMICAL AND MINERALOGICAL COMPOSITION OF THE PARTICULATE MATTER

In order to investigate changes in particulate atmospheric matter in relation to air mass trajectories, different sectors of origin have been drawn. These sectors have been defined from 850-hPa trajectories which exhibit successively continental or oceanic influences. However, three samples have been eliminated: sample 1, for which the air mass trajectory at 850-hPa is not available; sample 2, for which the wind speed is particularly low and consequently the confidence in the air mass trajectory is limited; sample 3, which was not collected; and sample 12, which was also rejected because the relevant trajectory corresponds to an intermediate situation with a mixed origin of dust: in this case, one can consider that this sample is not purely representative of a typical kind of source region.

First, we will try to distinguish between continental and oceanic origins. From our samples we can define the two sectors reported on Figure 4: one corresponding to Atlantic air masses and the other one including the cases of transport from African regions. Transport from the south-west and from Europe does not occur during this field experiment.

Silicon, which can be considered as a tracer of the terrigenous contribution, and sulfur, which mainly results from anthropogenic activities, were selected to characterize the composition of these air masses in each sector. We can observe that both Si and S concentrations are significantly lower for samples associated with oceanic air mass trajectories than in the case of transport from the African continent. This agrees with the absence of important sources, either terrestrial or industrial, during Atlantic transport. Indeed, sulfur concentrations are rather comparable with those observed at these latitudes over marine regions [Bonsang, 1980; Delmas and Servant, 1982] and are also in accordance with those observed (unpublished results) during the previous study on Fuerteventura [Coudé-Gaussen *et al.*, 1987]. On the other hand, silicon concentrations are relatively high compared to those generally found over Atlantic Ocean without dust transport [Duce *et al.*, 1975; Buat-Ménard and Chesselet, 1979]. This is probably due to a significant local contribution, which is particularly evident considering SEM ex-

amination showing autochthonous particles such as pyroxene, olivine, and sphene. The occurrence of olivine is an interesting indicator of probable influence from Lanzarote Island (located about 20 km North of Corralejo), where this mineral is known to be abundant. This local contribution of soil particles is more important than that observed in April 1984 by Coudé-Gaussen *et al.* [1987]. This difference probably results both from more drier weather conditions and/or from an increase in local wind speed.

Obviously, Si concentrations are more than 2 times higher and both X ray diffraction and SEM examination show the presence of quartz and calcite when trajectories indicate transports from African regions. This should be related to a more intensive emission of soil-derived particles from the arid and semiarid regions of Africa.

In the same way, SEM and EDS examinations have been performed on the samples. According to their micromorphological features and mineralogical identification, the particles examined have been classified in terms of origins. Thus it is possible to distinguish particles very probably resulting from (1) anthropogenic emissions (Al or Ba microballs, Au or talc particles, flying-ashes); (2) marine source (mainly chlorides, etc.); (3) local terrestrial sources according to the volcanic substratum of the Canary Islands (pyroxenes/amphiboles, olivines, magnetites, volcanic glasses, etc.); (4) allogeneous terrestrial sources, showing the typical micromorphology and mineralogy of Saharan dust particles (quartz, rounded Ca carbonate or dolomite, wind-shaped palygorskite grains, rounded feldspars and kaolinite particles, etc.). On the other hand, many particles are less easily classified but often have some micromorphological or mineralogical characters that show a possible marine (gypsum, KCl, etc.) or allogeneous origin (clayed mixings, phyllites, etc.). In the samples examined by SEM, the percentages of each kind of particle have been counted, and they generally confirm the low contribution of the local material, as is well shown by these two cases (Table 2).

Sulfur concentrations also increase for samples associated with continental air masses, but we must emphasize that a significant dispersion of the values occurs for this element, as shown by its larger standard deviation (Figure 4).

Consequently, it is necessary to investigate more precisely the possible source regions of both dust and anthropogenic particles during cases of transport from the African regions. However, since Si and S come from different types of sources (crustal and mainly

TABLE 2. Origins of Mineral Compounds Observed on Samples 1 and 10.

Origin	Sample	
	1	10
Anthropogenic contribution	15%	4%
Marine source	18%	...
Possible marine source	15%	24%
Local source	8%	22%
Allochthonous source	16%	26%
Possible allochthonous source	27%	24%

anthropogenic, respectively), we have to define different sectors for each element.

As shown in Figure 5, sulfur concentrations change significantly when we consider transport from northern Morocco (3470 ng m^{-3}) or from more southern African countries (908 ng m^{-3}). This pattern is in agreement with the location of industrial activities in this region: the anthropogenic emission strength is significantly higher in northern Morocco, where the major cities and plants are located. In contrast, southern Morocco and the Sahelian countries are scarcely industrialized and are sparsely settled. According to these data, it is probable that the highest pollution levels observed over Fuerteventura originate from northern Morocco, at least during summer.

SOURCE REGIONS OF AFRICAN DUSTS

Meteorological Approach

Information on possible source regions of dust observed over Fuerteventura can be obtained by various other methods:

1. On the European Meteorological Bulletin (EMB), dust storms are reported when they are observed at a meteorological station. Moreover, strong atmospheric dust contents are also indicated.

2. Nephelanalysis (NA), performed from the Meteosat satellite (Centre de Météorologie Spatiale, Lannion, France) enables the determination of the dust cloud extent over the African continent.

3. Satellite imagery (from Meteosat or NOAA 9) from the visible channel (over the sea) or infrared channel (over the continent) is useful in reconstructing dust pathways from their emission up to the extinction of the signal; this occurs at different distances from the sources as a function of the intensity and dispersion or scavenging of dust.

Fig. 5. Average concentrations of particulate sulfur and geometric standard deviations for the two continental source regions.

Obviously, air mass trajectories also contribute to the global interpretation of the information deduced from the previous techniques. Using these tools, three different periods can be distinguished for the dust transport cases from African regions to Canary Islands during our sampling campaign:

1. On July 16, EMB indicates a duststorm originating on the loop of Niger (Gao meteorological station, Mali). In this region the surface circulation is controlled by a small trough (located over Taoudeni Basin), which generates a south-southwestern flow. The dust cloud is clearly visible on the Meteosat image (July 16, 1985, 1200 UT), which shows that the dust extended up to 25°N (Figure 6a).

Fig. 6. Atmospheric pathway of the dust cloud from its rising area (Gao region, Republic of Mali) on July 16, 1985, to Fuerteventura Island on July 21, 1985. Circled number indicate the date when the phenomenon is observed; the letter S indicates dust rise high dust content in the atmosphere; the letter S with a vertical line indicates dust rise; dots with a dashed margin indicate the boundaries of the dust cloud as observed from satellites images; arrows indicate movement of the dust; dotted margin around the letter L indicates low pressure at ground level; solid lines around the letter H indicate high pressure at 850 hPa; solid curves with crosses indicate three-dimensional air mass trajectory ending on Fuerteventura at 850 hPa.

Fig. 7. Vertical movements of African air masses reaching the Canary Islands on July 21 and 22, 1985 (curves with open circles indicate July 21; curves with solid circles indicate July 22).

On July 17, at 1200 UT, Meteosat and NOAA images showed that the dust cloud had moved westward from 5° to 10°W (Figure 6a).

On July 18 the dust cloud moves northward (Meteosat image). At this point, air mass trajectories arriving on Fuerteventura on July 21 and 22 are compatible with the transport of this dust cloud from the African continent to the Canary Islands (Figure 6b). These trajectories are typical of an anticyclonic circulation, which is generated by the high-pressure cell located over Maghreb. It is worthwhile to note that these trajectories indicate that the transport of this dust over the African continent occurs at the 600-hPa barometric level until it reaches the Atlantic shoreline when an abrupt downward movement is observed (Figure 7).

2. On July 24, at 1228 UT, the NOAA 9 satellite shows a dust cloud, which extended over the Canary Islands. An air mass trajectory arriving over Fuerteventura on July 24 (0000 UT) indicates a transport of the order of 2 or 3 days from northeastern Moroccan regions. Between these Moroccan regions and the Canary Islands, a northeastern flow is established and controlled by a high-pressure cell located on Spain and the western Mediterranean sea. EMB mentions an anomalous high dust concentration over the Tafilelt on July 21. Hence it is probable that the dusts observed over Fuerteventura on July 24, at 0000 and 1200 UT originated from northeastern Morocco (Figure 8).

3. The dust observed over Fuerteventura on July 28 and 29 results from an atmospheric pathway and source region similar to those described for July 16-18 (Figure 9).

On July 24, EMB indicates a duststorm originating in the Gao region. This dust was loaded in a south-southwestern flow, resulting from a trough located over the Tanezruft Plain (Figure 9a).

On July 25, EMB indicates a high dust content in the atmosphere over the western Hoggar. The same day, NOAA 9 shows an extension of this dust cloud northward (Figure 9a). Air mass trajectories arriving over Fuerteventura on July 28 (0600 UT) and 29 (0600 UT) show that the western part of this dust cloud was transported to the Canary Islands by an anticyclonic southwestern

Fig. 8. Atmospheric pathway of the dust cloud from its rising area (Tafilelt, Morocco) on July, 21, 1985 to Fuerteventura Island on July 24, 1985 (symbols are the same as for Figure 6).

flow resulting from the high-pressure cell located over the Sahara (Figure 9c).

We can conclude that dust transports from African regions to the Canary Islands seem to be possible only when the Azores High is separated in two distinctive cells, one located over the Atlantic Ocean and the other over Africa. This division results mainly from the incursion of a polar air mass over the eastern Atlantic. The African cell allows the dust to move northward along the discontinuity (Figure 10).

Fig. 9. Atmospheric pathway of the dust cloud from its rising area (Gao region, Republic of Mali) on July 24, 1985, to Fuerteventura Island on July 28, 1985 (symbols are the same as for Figure 6).

Geochemical and Mineralogical Approach

This meteorological analysis of source regions and transport processes of African dust over Fuerteventura enables the distinction of two different origins: a Sahelian origin for dust arriving on July 21-22 and 28-29 and a Moroccan Atlas origin for the dusts arriving on July 24.

Now we will compare chemical abundance and mineral composition of desert dusts for each source region. Figure 11 reports the Si/Al and Fe/Al ratios of dusts for each case. Note that both Si/Al and Fe/Al ratios increase strongly for dusts associated with a Sahelian source compared to a Moroccan one. These results can be compared with those obtained on Corsica Island by Bergametti *et al.* [1989]. These authors investigated six cases of dust transport from northern Morocco and they noticed a Si/Al ratio equal to 2.67, which is very close to our values of 2.70 and 2.87, whereas a slight difference exists between our Fe/Al ratio (1.1) and theirs (0.67). In the same way, these authors documented a case originating from a Sahelian source similar to ours and they found Si/Al ratios (3.35-3.61) and Fe/Al ratios (1.53-1.69) very close to those that we observe for the dust originating from these regions (Si/Al: 3.18-3.60; Fe/Al: 1.51-1.76).

The difference in composition of dust from these two source regions must be interpreted in relation to the nature of the respective soils. The increase of Si/Al ratios for dust of southern regions probably reflects the more sandy character of the Sahelian regions compared to the Atlas mountains. The increase of Fe/Al ratios probably results from changes in clay minerals. The Sahelian regions are known to present abundant ferrallitic soils [Millot, 1964; Sys, 1967]. SEM and EDS examinations confirm these assumptions: dust originating from Sahelian regions shows numerous clay minerals in which iron is a dominant element, while iron only appears as a minor component in clay minerals present in dust originating from northern Morocco.

CONCLUSIONS

This study suggests that two different African source regions are involved in the transport of desert dust to the Canary Islands and the Northern Atlantic in summer. Transport from the Sahelian regions is observed when a wedge resulting from a southern incursion of the polar depression cuts the Azores High into two anticyclonic cells, an oceanic and a continental one, the continental anticyclonic cell being located on the Maghreb.

On the other hand, northeastern Morocco is the main source region of dust affecting the Canary Islands when the Azores High is in its average summer position, that is, when it extends from the western Atlantic up to Western Europe. In contrast to the previous work by Coudé-Gaussen *et al.* [1987] who documented dust transport over the Canary Islands during an intermediate season (spring 1984), the source region of dust in summer is rather different. Coudé-Gaussen *et al.* have shown that only northern and southern Moroccan areas emitted dust that is transported to the Canary Islands. Allowing for the limited duration of each campaign and their low representativeness from a climatological point of view, it seems that the Sahelian regions mainly contribute to the dust content in this area during summer, while our data suggest that the Canary Islands can be submitted to dust transport from Moroccan sources whatever the season.

Another important feature is that the summer cases of dust transport are always characterized by anticyclonic trajectories, allowing a direct transfer from source regions to Canary Islands. On the other hand, during spring, Coudé-Gaussen *et al.* [1987] have

Fig. 10. Typical meteorological situation for dust transport over the Canary Islands in an anticyclonic flow (July 28, 1985; 0000 UT; 500 hPa). The arrow indicates the direction of the dust transport.

Fig. 11. Si/Al and Fe/Al ratios for dust associated with air masses coming from northern and southern African source regions.

largely documented a dust outbreak from Morocco transported in a cyclonic flow, which has lead to an indirect transport of dust: a 6 day voyage over the North Atlantic is observed before the dust reaches the Canary Islands.

It is obvious that long time series of measurements are necessary to clearly point out the major dust transport patterns in this marine region. However, the work performed by Oliva *et al.* [1983] provides a useful statistical basis to approach the dust transport over this area. These authors, by using satellite imagery over a 1-year period (1979), have shown that the frequency of dust export beyond the Moroccan shorelines is maximal during the warm period (May-August). So it can be proposed that the Sahelian sources of dust, even though they are a relatively large distance from the Canary Islands, could be a significant contributor to acolian transport in this region.

Another conclusion in this study is the confirmation of the usefulness of elemental ratios such as Si/Al and Fe/Al in connection with air mass trajectories in distinguishing various source regions of dust. The signatures observed for Sahelian or Moroccan sources are both in good agreement with the previous observations performed in the western Mediterranean when African dust incursions occurred. Although further investigations are needed, it seems that the variations of these ratios can be related to changes in clay mineral composition and/or in quartz content.

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