Satellite climatology of African dust transport in the Mediterranean atmosphere — Source link

Cyril Moulin, Claude Lambert, Uri Dayan, V. Masson ...+8 more authors

Institutions: Hebrew University of Jerusalem, Icos

Published on: 20 Jun 1998 - Journal of Geophysical Research (John Wiley & Sons, Ltd)

Topics: Mediterranean sea, International Satellite Cloud Climatology Project and Mediterranean climate

Satellite climatology of African dust transport in the Mediterranean atmosphere

Cyril Moulin, C.E. Lambert, Uri Dayan, Valérie Masson-Delmotte, Michel Ramonet, Philippe Bousquet, Michel Legrand, Yves Balkanski, Walter Guelle, Beatrice Marticorena, et al.

Cyril Moulin, C.E. Lambert, Uri Dayan, Valérie Masson-Delmotte, Michel Ramonet, et al.. Satellite climatology of African dust transport in the Mediterranean atmosphere. Journal of Geophysical Research: Atmospheres, American Geophysical Union, 1998, 103 (D11), pp.13137-13144. 10.1029/98JD00171 . hal-02326603

HAL Id: hal-02326603
https://hal.archives-ouvertes.fr/hal-02326603

Submitted on 22 Oct 2019

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D11, PAGES 13,137–13,144, JUNE 20, 1998

Satellite climatology of African dust transport in the Mediterranean atmosphere

C. Moulin,[1] C. E. Lambert,[2] U. Dayan,[3,4] V. Masson,[1] M. Ramonet,[1] P. Bousquet,[1]
M. Legrand,[5] Y. J. Balkanski,[1] W. Guelle,[1] B. Marticorena,[6] G. Bergametti,[6] and
F. Dulac[2]

Abstract. A daily analysis of African dust concentrations in the Mediterranean atmosphere has been made between June 1983 and December 1994 using the International Satellite Cloud Climatology Project (ISCCP-B2) archive of Meteosat visible (VIS) channel images. The ISCCP-B2 archive of Meteosat infrared (IR) images has also been used to determine the frequencies of dust mobilization over the continent, north of 30°N. Despite a large daily variability, climatological results show a clear seasonal cycle with a maximum during the dry season: dust transport begins over the eastern basin in spring and spreads over the western basin in summer. These patterns are shown to be related to both cyclogenesis over North Africa and rainfall over the Mediterranean Sea. Indeed, the frequency of dust mobilization over the continent and of dust outbreaks over the sea are strongly related to the climatology of depressions affecting North Africa. Precipitations appear to be an important factor explaining both the seasonal east-west shift in transport location and the south-north gradients of dust concentrations over the Mediterranean.

1. Introduction

In the last 20 years, a large effort has been made toward the understanding of African dust transport over the Mediterranean Sea. Scientists are now convinced that dust transport, which was once considered as a series of spectacular and unpredictable events, plays an important role in our understanding of the biogeochemical cycling and sedimentation within the Mediterranean sea itself. The work on Mediterranean dust has developed in three directions: (1) evaluation of the impact of dust transport through continuous monitoring stations [*Bergametti et al.*, 1989a, b; *Molinaroli et al.*, 1993; *Kubilay and Saydam*, 1995; *Loÿe-Pilot and Martin*, 1996; *Guerzoni et al.*, 1996] or through the estimate of transport using trace elements in seawater [*Duce et al.*, 1991; *Measures*, 1996]; (2) tracing of the origin of dust storms from meteorological and isotopic studies [*Bergametti et al.*, 1989a; *Grousset et al.*, 1992]; (3) modeling dust transport in seawater [*Ruiz-Pino et al.*, 1990]. Recently, the European program *Mediterranean Dust Experiment* (*MEDUSE*) [1996] has been set to allow a prediction of dust large events through the use of source models [*Marticorena*, 1995; *Marticorena and Bergametti*, 1996], meteorological transport [*Nickovic and Dobricic*, 1996; *Schulz et al.*, 1996], and dust deposition [*Balkanski et al.*, 1996]. All these studies converge to show the chemical impact of African dust on the precipitations and surface waters in the Mediterranean basin. The radiative impact of dust has been demonstrated over the tropical Atlantic in the solar spectrum from satellite data [*Jankowiak and Tanré*, 1992] and in the infrared from model computations [*Tegen et al.*, 1996], but remains poorly known over the Mediterranean basin. This is mainly due to the complexity of the synoptic meteorology: surrounded by lands and located at the boundary of the subtropical and midlatitude atmospheric circulations, this region experiences very different meteorological conditions throughout the year [*Dayan et al.*, 1989; *La Fontaine et al.*, 1990].

Owing to their satisfactory spatio-temporal coverage, meteorological satellites enable long-term analysis over the western and eastern basins. A major interest of the satellite observation of desert aerosols is to enable the daily observation of large geographical zones. The retrieval of the aerosol optical depth in the visible spectrum is possible over marine areas with low and fairly constant albedo because the contribution from the atmosphere to the satellite signal is then dominant. Recently, 5 years (1984-1988) of Meteosat images [*Jankowiak and Tanré*, 1992] and 4 years (1989-1992) of Advanced Very High Resolution Radiometer (AVHRR) data [*Swap et al.*, 1996] were analyzed to quantify the African dust load over the tropical North Atlantic. *Moulin et al.* [1997a] used the results of an 11.5-year (June 1983 to December 1994) daily monitoring of dust transport retrieved from Meteosat International Satellite Cloud Climatology Project (ISCCP-B2) images over the Mediterranean and the Atlantic to evidence a large-scale climatic control on the interannual variability of the export of African dust.

In this work, we used the results of this Meteosat archive to present and explain the general pattern of the dust transport over

---

[1] Laboratoire de Modélisation du Climat et de l'Environnement, Commissariat à l'Energie Atomique, Direction des Sciences de la Matière, Gif-Sur-Yvette, France.

[2] Centre des Faibles Radioactivités, Centre National de la Recherche Scientifique - Commissariat à l'Energie Atomique, Gif-Sur-Yvette, France.

[3] Environment and Risk Assessment Section, Soreq Nuclear Research Centre, Yavne, Israel.

[4] Now at Department of Geography, Hebrew University of Jerusalem, Jerusalem, Israel.

[5] Laboratoire d'Optique Atmosphérique, Université des Sciences et Technologies de Lille - Centre National de la Recherche Scientifique, Villeneuve d'Ascq, France.

[6] Laboratoire Interuniversitaire des Sytèmes Atmosphériques, Université de Paris 7 et 12 - Centre National de la Recherche Scientifique, Créteil, France.

Paper number 98JD00171.
0148-0227/98/98JD-00171$09.00

the Mediterranean basin. We report here results of the first climatology of dust optical depth over this poorly documented region. The contrast between high daily variability of dust transport and "predictable" transport is highlighted by these analyses.

2. Method

2.1. Description

One daily Meteosat image of the visible (VIS) channel in the ISCCP-B2 format (apparent resolution of 35 km by 35 km over the Mediterranean), taken at 1145 UT, was analyzed from June 1983 to December 1994. These images were provided by the European Space Operations Centre (ESOC, Darmstadt, Germany). Since dust plumes over the Mediterranean generally last several days, it is expected that one daily image would be sufficiently representative for a long-term analysis, even in the case of 1-day events such as those reported by *Dayan et al.* [1991] coming from the Arabian peninsula over the eastern Mediterranean. During this period, four different sensors were used: Meteosat 2 through Meteosat 5. Whereas the spectral transmission of the VIS channel is centered around 0.7 µm for all sensors, its shape fairly differs from one to the next. In addition, the digitization increased from 6 significant bits for Meteosat 2 and 3 to 8 significant bits for Meteosat 4 and 5, yielding a greater sensitivity for the latter sensors.

The method used to perform a multiyear monitoring of daily African dust load over the Mediterranean has been described in detail by *Moulin et al.* [1997b]. First, pixels possibly contaminated by highly reflective surfaces such as clouds, lands and coastal waters were eliminated. For each clear-sky marine pixel, the satellite signal (numeric count) was converted into a radiance, taking into account a detailed calibration of the different radiometers [*Moulin et al.*, 1996]. The optical depth of desert dust at a wavelength of 0.55 µm was then retrieved using a radiative transfer model. The contributions of tropospheric and stratospheric sulfates were subtracted using climatological information [*Moulin et al.*, 1997a, b], and the mean optical properties of desert dust were validated by coincident sunphotometer measurements [*Moulin et al.*, 1997c]. The average uncertainty on the retrieved dust optical depth for clear sky pixels was estimated to be within ±25%.

The complete dust field was reconstructed for each day over the Mediterranean by interpolating the value of each cloudy pixel, using an inverse distance weighted mean. As discussed by *Moulin et al.* [1997b], this interpolation is certainly one of the major source of uncertainties, even if it has some physical basis and if too cloudy images are removed from the data set. However, this step remains important for the representativity of our climatological results since clouds are more frequent in some part of the Mediterranean and could thus bias the results. *Moulin et al.* [1997c] present a first assessment of the uncertainties related to the interpolation by comparison with sunphotometer measurements: interpolated optical depths are found to be retrieved within a factor of 2. However, the number of Sun photometer measurements available for this study is too small since it requires both cloudy conditions for Meteosat and clear-sky conditions for the sunphotometer (i.e., the sunphotometer has to view between two clouds). Only concentration measurements performed at the surface are thus suitable to complement our knowledge on the representativity of the interpolated results.

2.2. Representativity of the Results

We have tentatively assessed how much the cloud coverage could bias our results by comparing our data set with concurrent daily ground measurements performed by *Bergametti* [1987] at a station located in the northwestern Corsica at Capo Cavallo, during a period of 13 months between April 1985 and April 1986. This data collection consists in daily sampling of marine air and measurements of tracers of mineral dust (Al, Si). We have compared these data with a daily analysis of nine marine pixels close to the Corsican station (Figure 1). One does not expect a perfect correlation between these two data sets since dust transport may sometimes happen at high altitudes [*Reiff et al.*, 1986; *Martin et al.*, 1990], mainly in summer. In such cases, satellite data will show dust transport, but ground data will not detect any significant increase in dust concentrations. This occured five times during the coincident period (in mid-July 1985, early August 1985, beginning and end of November 1985, mid-February 1986). The reverse is of course not true: large dust

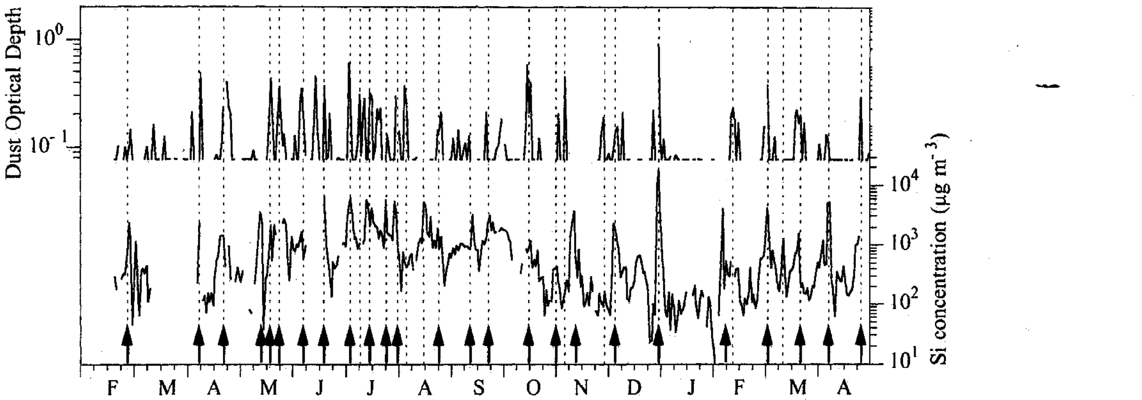

Figure 1. Comparison of the African dust loads recorded between February 1985 and April 1986 by Meteosat (optical depth; upper curve) and by surface measurements (silicium concentration; lower curve [from *Bergametti*, 1987] at Capo Cavallo, Corsica. For clarity, optical depths below 0.08 obtained from Meteosat are fixed to 0.08. Peaks observed in Meteosat data are indicated by vertical dashed lines. An arrow indicates that a dust event is registred using surface measurements.

Table 1. Summary Statistics for the 11-Year Period (1984-1994) of Daily Analysis of Meteosat Images

	Number of Days		Interpolated	Average Optical Depth Due to Dust			
Period	Analyzed	Retained	Pixels, %	Western Med.	Central Med.	Eastern Med.	Total Med.
Winter (DJF)	990	409	76	0.06 ± 0.02	0.08 ± 0.02	0.06 ± 0.03	0.06 ± 0.02
Spring (MAM)	1011	696	67	0.10 ± 0.04	0.15 ± 0.06	0.14 ± 0.05	0.13 ± 0.05
Summer (JJA)	1011	952	48	0.14 ± 0.04	0.18 ± 0.06	0.10 ± 0.04	0.14 ± 0.04
Fall (SON)	1001	656	66	0.07 ± 0.03	0.09 ± 0.04	0.07 ± 0.03	0.07 ± 0.03
Annual	4013	2713	61	0.10 ± 0.03	0.13 ± 0.04	0.10 ± 0.03	0.11 ± 0.04

The western, central, and eastern Mediterranean basins were arbitrarly defined by a first borderline between Tunis, Tunisia, and the tip of the Italian boot, and a second borderline between Athens, Greece, and Benghazi, Libya. Results were retained for a given day only if clear-sky pixels spread over at least 10% of each basin. The average percentage of interpolated pixels is computed only from retained images and includes turbid coastal water pixels and cloudy marine pixels. Surfaces of the western, central, and eastern Mediterranean basins are 1.035, 0.757, and 0.879 × 10^6 km^2, respectively.

concentrations at ground level are expected to be seen by Meteosat, except if too much cloudiness prevails. During the 13-month period of observation, 85 days were too cloudy to allow us to recover a useful Meteosat signal close to the station. Using all coincident days of measurements in Figure 1, we only missed three large dust events due to the cloud coverage (mid-May 1985, mid-November 1985, and beginning of February 1986) among the 22 peaks recorded at ground level by *Bergametti* [1987]. Two other ground events were missed by Meteosat, one in mid-August 1985 and one in mid-March 1986. For these two events, we analyzed the other images available during the day (at 0845 and 1445 UT). In both cases, one could observe a small dust plume which reached Corsica in the afternoon and had disappeared from the region by noon the next day: it is therefore not seen on our daily local records at 1145 UT. However, these two events have been observed and thus do not bias our estimates at the basin scale. This qualitative comparison shows that despite the elimination of numerous cloudy days (mainly in winter), our Meteosat analysis seem to remain sufficiently representative to observe the large majority of dust events.

Meteosat VIS window over the Mediterranean is of about 2000 pixels, and more than 4000 of these windows were analyzed for the 11.5-year period. Table 1 shows that the seasonal optical depth due to desert dust ranges from 0.06 to 0.18 and the standard deviation ranges from 0.02 to 0.06. Because of an important cloud coverage, about half of the images were rejected from the database in winter, and about one tenth were rejected in summer. The average optical depth and its standard deviation are especially low in autumn and winter. By contrast, in spring and summer, both average optical depth and standard deviation increase, especially over the central basin (Table 1).

3. Climatology of Dust Transport

3.1. Monthly Climatology

This annual cycle is evidenced in Figure 2 where the variations of both the daily dust optical depth over the three basins are shown for 1994, a year that was shown to be a mean year in terms of annual African dust export [*Moulin et al.*, 1997a]. The variations in optical depth are fairly different over each basin: most of the dust transport occurs between May and November for the western basin and between January and July for the eastern basin. The large-scale average optical depth during dust events is not significantly different between the three basins. Figure 2 shows that the cycle of dust transport varies significantly from one basin to the next and that it is characterized by both a change in peak frequency and in background level. *Bergametti et al.* [1989a] considered that dust peaks control the quantity of mineral particles in the atmosphere, whereas the baseline depends mainly on the residence time of the mineral particles in the atmosphere. Thus the seasonal cycles observed with Meteosat might result from these two combined phenomena, that is, both changes in the amount of dust injected in the marine atmosphere and of the atmospheric residence time of dust particles.

Our long-term analysis evidences well defined spatio-temporal structures of the African dust transport over the Mediterranean, as shown by the monthly climatological maps of the dust optical depth in Plate 1. The marked spatial structures clearly show that the transport follows a sufficiently regular pattern despite a large daily variability. The maximal northward transport shifts from the eastern to the western basin during March to August. During autumn and winter, there is very little dust transport. This general pattern of the monthly transport was verified for individual years. Indeed, despite large variabilities of the intensity of the dust export both from year to year for the last decade [*Moulin et al.*, 1997a] and from season to season for a given year, the dust transport always follows the same temporal development as the one shown in Plate 1. We will now discuss the processes that explain these patterns of the monthly climatological dust transport.

3.2. Transport Processes

Contrary to the African dust transport over the tropical Atlantic [*Prospero*, 1990, 1996], the average atmospheric circulation over the Mediterranean does not explain the northward transport of dust particles because winds mostly come from the west or northwest [*La Fontaine et al.*, 1990]. Thus African dust can only be transported over the Mediterranean with the northward winds generated by depressions. Numerous case studies have shown that the frontal region of these depressions can generate intense dust mobilization over North Africa and are able to transport dust over long distances toward Italy, France, and northern Europe [*Prodi and Fea*, 1979; *Reiff et al.*, 1986; *Franzén et al.*, 1994]. The climatology of the Mediterranean cyclones proposed by *Alpert et al.* [1990] using the meteorological analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) enables characterization of the most likely synoptic situations allowing dust transport over

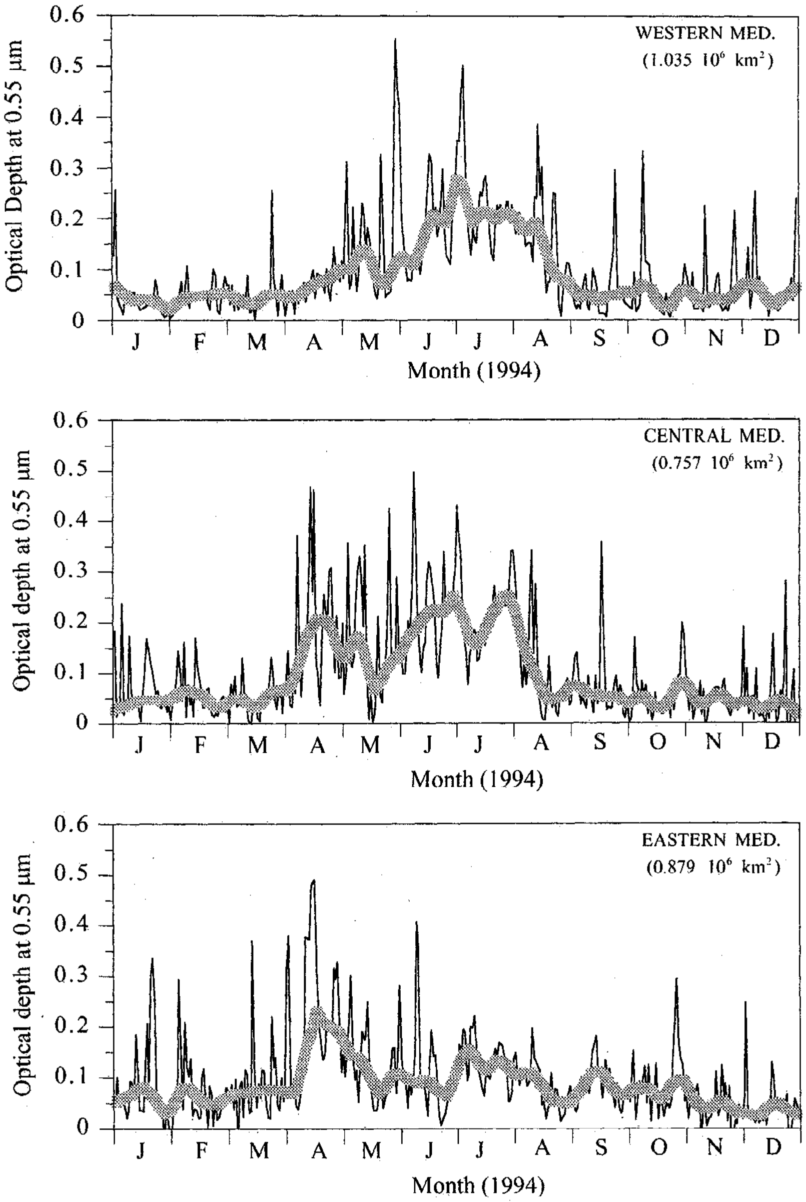

Figure 2. Daily variation of the optical depth due to desert dust over the three Mediterranean basins in 1994 (fine black line). We computed a background value of the optical depth (wide grey line) as a running mean over 5 days after elimination of peaks characterized as days with a dust load larger than the monthly average and larger than the two preceeding and two following days.

the sea in spring and summer; it is indeed easier to reduce the great variability of synoptic situations implying depressions over the Mediterranean basin if one takes only into account the main zones of cyclogenesis leading to dust mobilization [*Alpert et al.*, 1990].

Using this information, we have found three different major cyclogenesis situations which can explain northward dust transport respectively in April, June, and August, as shown in Plate 2. (1) Spring and early summer are the most favorable periods for the development of Saharan thermal lows (also called Sharav cyclones) south of Atlas, under the influence of the strong thermic contrast between the temperature of the cold marine waters and of the warm continental surfaces. Such cyclones move eastward along this thermal gradient just south of the North African coast and finally cross the Mediterranean between Libya and Egypt where they transport large concentrations of desert dust [*Alpert and Ziv*, 1989]. The trajectories of theses cyclones generally agree with the important spring transport of dust (Plate 1) over the eastern and central Mediterranean basins. (2) Dust transport in summer is different because it is linked to two synoptic situations described earlier by *Bergametti et al.* [1989a]. Saharan lows still develop, but the presence of a high over Libya prevents them from following a northeastern direction. This meteorological situation induces violent south or southwestern winds between the two systems and is characterized by a strong dust transport from Tunisia and western Libya. Such a configuration is in good agreement with the summer maps of the average dust optical depth deduced from Meteosat data which show a maximal transport north of Algeria and in the Gabes Gulf (Plate 1). (3) Toward the end of summer, Balearic Islands become an active depression center where Atlantic lows are reinforced before they go across the Mediterranean in the direction of

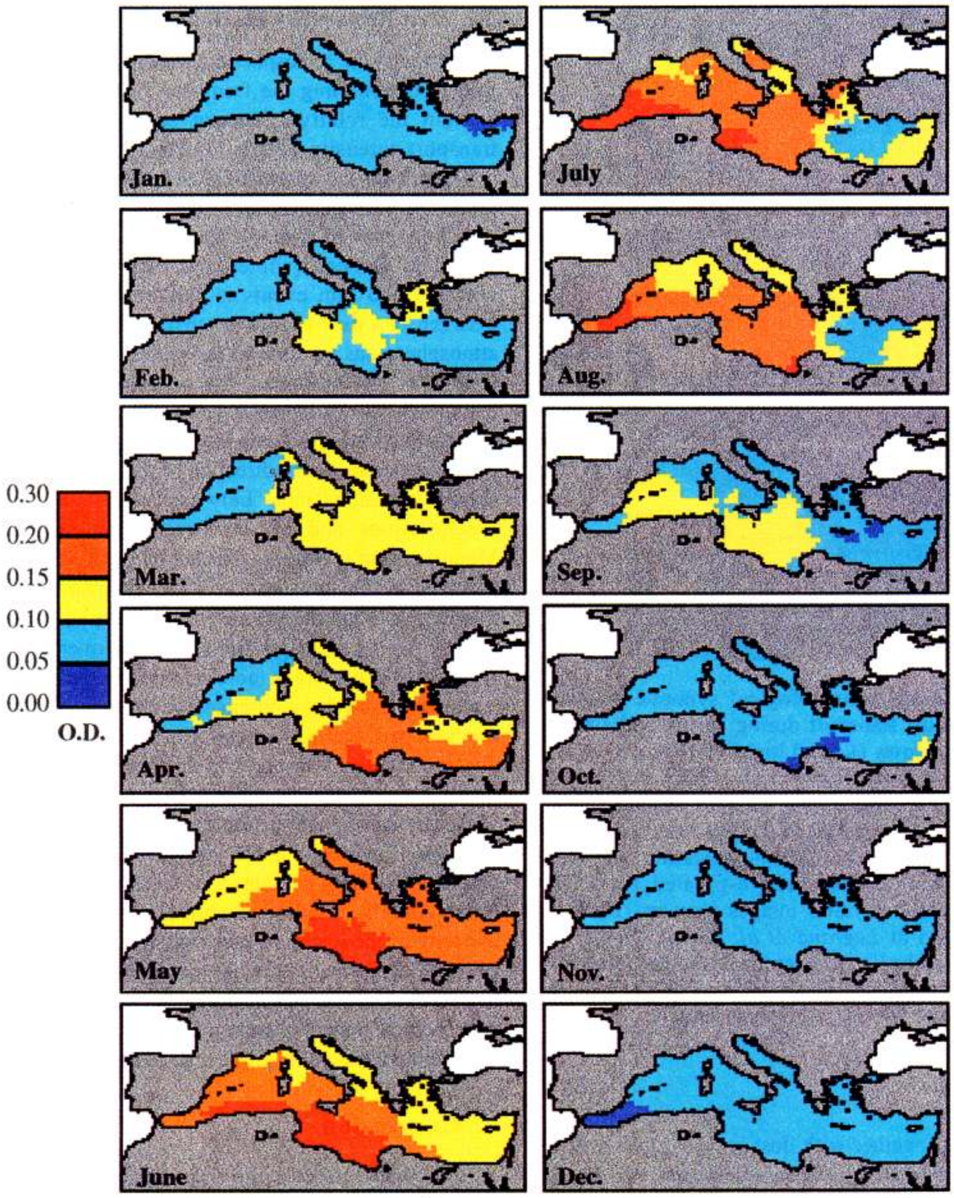

Plate 1. Monthly 11-year average of dust optical depths (O.D.). Data from available Meteosat images between 1984 and 1994 (see Table 1).

Corsica and Italy. This meteorological situation explains the high dust optical depths over the Alboran Sea in July and August (Plate 1). It is noteworthy that during summer, a semipermanent low, centered over Cyprus, takes place over the eastern basin and prevents dust transport by imposing southward winds.

Previous case studies based on air mass trajectory analysis for both western [e.g., *Bergametti et al.*, 1989a; *Dulac et al.*, 1992; *Prodi and Fea*, 1979; *Reiff et al.*, 1986] and eastern [e.g., *Dayan*, 1986; *Dayan et al.*, 1989; *Kubilay and Saydam*, 1995] basins follow these general features of the meteorological situations which generate the most frequent dust transport over the Mediterranean.

3.3. Location of Sources

Contrary to the principle schemes shown in Plate 2, case studies as cited above enable more or less determination of the location of source regions of dust particles. However, they do not provide a sufficient spatio-temporal coverage to assess climatological dust sources. We thus relied on infrared (IR) Meteosat images to observe the major dust sources over the African continent using the method of *Legrand et al.* [1994]. This method is based on the observation of a significant decrease of the brightness temperature and thus of the IR numeric counts during daytime over arid region when dust concentration increases in the atmosphere, provided that there is no cloud. This apparent cooling of the surface is due to the attenuation of the infrared radiance, emitted by the hot arid soil, by the colder atmospheric dust layer. This dust effect on infrared imagery is enhanced when one compares daily images to a composite image containing the warmest pixels of the week. For each Meteosat IR image during the 11.5-year period, we computed this qualitative infrared difference dust index (IDDI) for every clear-sky pixel over North Africa.

The monthly analysis of the frequency of dust mobilization over the North African continent using IR Meteosat data set is

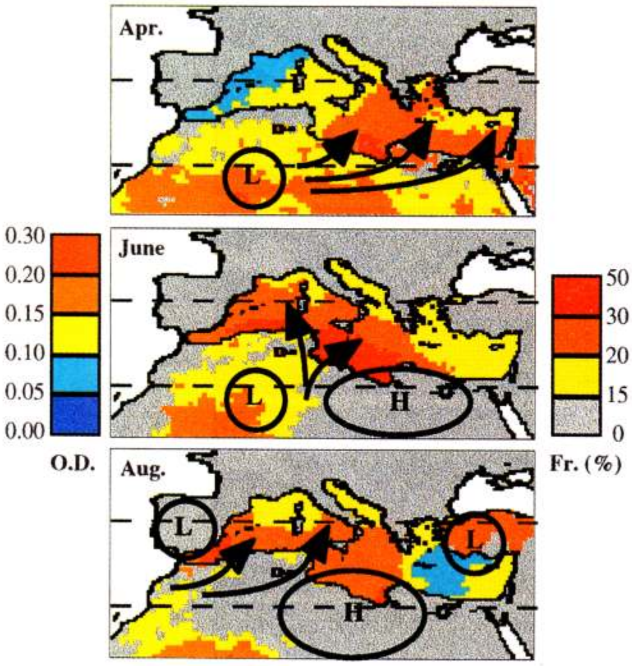

Plate 2. How the main meteorological synoptic situations generate a recurrent dust transport during spring and summer. Locations of the major lows (L) and highs (H) are shown. The cyclogenesis is adapted from *Alpert et al.* [1990]. It shows the Sharav cyclones in April; the coupling between Saharan low and Libyan high in June; and the effect of the Balearic cyclogenesis in August. The frequency (Fr.) of dust mobilization over North Africa during these months has been estimated from IDDI computed from Meteosat infrared images between 1984 and 1994, using the method of *Legrand et al.* [1994]. Finally, our monthly dust optical depths (O.D.) over the sea surface are shown as in Plate 1. The lower and upper horizontal dashed lines correspond to latitudes of 30° and 40°N, respectively.

also shown in Plate 2, together with dust optical depth over the sea and main meteorological situations for dust transport. April is shown to be a period of intense dust uplift over North Africa, in relation to the frequent moving cyclone tracks. Plate 2 shows that during this month, the major source regions for the Mediterranean are south Tunisia around 30°N for the western central basin [*Bergametti et al.*, 1989a]; Libyan desert just below 30°N for the eastern central and eastern basin [*Dayan et al.*, 1991; *Kubilay and Saydam*, 1995]; Egyptian desert for the far eastern Mediterranean [*Dayan*, 1986]. In June, the extent of North African sources decreases, while the dust export shifts westward. During this period, dust originates mainly from the northern Sahara below 30°N, from south Tunisia around 30°N, and from northern Algeria. Concerning this last source region, the meteorological situation presented for June does not seems to fit well, and the source might thus be activated by the occurence of summer situations of the "August" type. An important result for the June transport is that the dust transport over the central basin is mainly related to northwestern African sources. In August, source regions for the western Mediterranean dust transport are well defined and have a surprisingly small extent. They are located in Morocco and northern Algeria, as suggested by the work of *Bergametti et al.* [1989a] based on back-trajectories.

3.4. Dust Removal by Precipitations

Although the atmospheric circulation obviously plays a major role in determining the frequency of dust plumes, it does not explain the relatively strong south-north gradients of dust transport intensity (Plate 1). Precipitations are an important constraint on the extent of dust transport because washout by raindrops traps particles and deposits them to the surface [*Gatz*, 1977]. *Bergametti et al.* [1989a] have shown that during the wet period in Corsica (winter and autumn) the average interval between two rain events is shorter than the average interval between two dust events, so that, as a first approximation, the atmosphere has no time to be loaded again with dust particles. Over the Mediterranean, the probability for a dust plume to encounter rain increases toward the north, explaining the relatively strong gradients in dust optical depth observed in the principal (south-north) direction of the transport (Plate 1). Plate 3 shows a comparison between seasonal climatologies of precipitations and of our desert dust optical depths. The Mediterranean is heavily affected by precipitations in winter and autumn, which, together with the abundance of rain over the Maghreb, explain the absence of dust transport during this period. During spring, precipitations are low over the eastern basin, where dust transport is more intense, whereas the western basin remains affected by intense precipitations, especially in its northern part. During summer, the whole Mediterranean becomes dry, and the dust transport can then develop efficiently. Low dust concentrations over the eastern basin are then due to the presence of the semipermanent depression over Cyprus. This good spatio-temporal correspondance between dust optical depth and precipitation fields explains well the strong control exerted by the North Atlantic Oscillation on the interannual variability of the intensity of the dust transport over the Mediterranean [*Moulin et al.*, 1997a]. Indeed, it is obvious from Plate 3 that the shift in latitude of the precipitations induced by this large-scale meteorological phenomenon might have a strong influence on the geographical extension of the dust transport.

4. Conclusion

This work presents the first comprehensive analysis of the African dust transport in the Mediterranean atmosphere. The monthly climatology of African dust optical depths obtained from 11 years of daily Meteosat ISCCP-B2 VIS images shows a marked annual cycle of the dust transport. It begins in spring over the eastern basin, is maximum in summer over the western and central basins, and strongly decreases during autumn and winter. The desert dust transport results from combined actions of the atmospheric synoptic circulation which controls the frequency of mobilization and transport, and of the washout by precipitation which influences the residence time of particles in the atmosphere. Comparison of the results with existing climatologies of cyclogenesis and precipitation over the Mediterranean shows that over the Mediterranean, only perturbations of the atmospheric synoptic circulation generate dust transport and that the washout is specially important because it limits both the westward extension of dust transport during the spring and its northward transport during most of the year. The use of coincident Meteosat IR images enables the obtainment of a coincident climatology of dust source regions. Comparison between these two satellite climatologies indicates that Lybian desert constitutes one major source of dust over the eastern

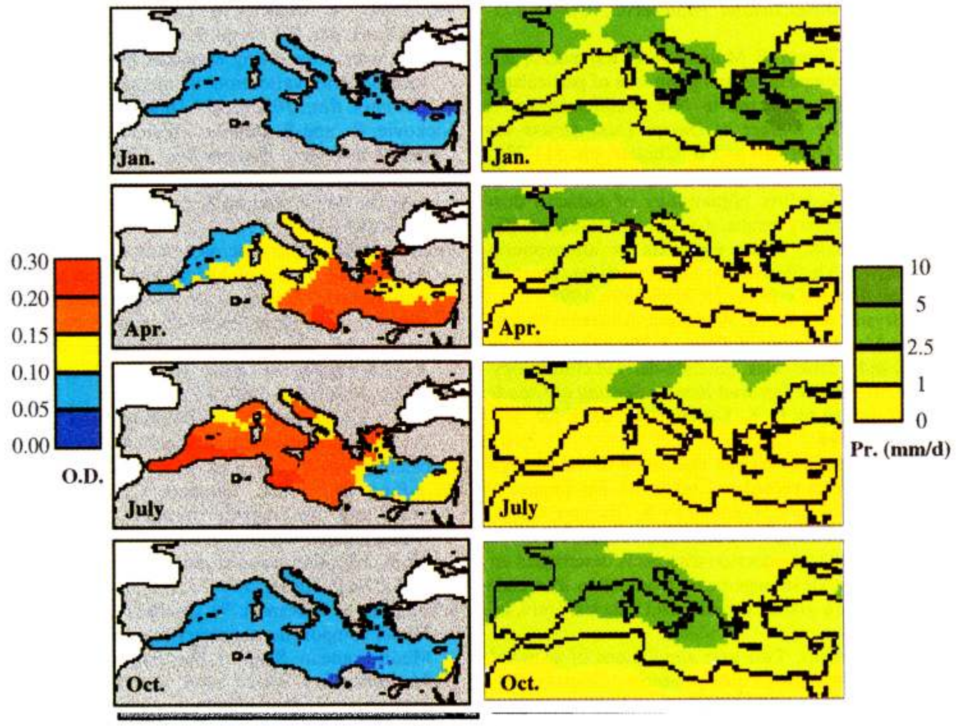

Plate 3. (left) Climatological maps of monthly dust optical depths (O.D.) between 1984 and 1994 (see Plate 1) and (right) precipitations between 1979 and 1988 (data from Atmospheric Model Intercomparison Project (AMIP) program [*Schemm*, 1992]).

Mediterranean and that some very local sources of the northwestern Africa strongly contribute to the dust transport over the western basin. Finally, this satellite climatology constitutes an unequaled data set for three-dimensional dust transport model validation which will enable accurate estimates of the deposition fluxes and of the radiative impact of African dust over the Mediterranean region.

Acknowledgments. We acknowledge the kind help of X. Schneider who participated in our computer testing experiments. This work is part of a close collaboration between the LMCE and the CFR and was supported by the French Commissariat à l'Energie Atomique (CEA) and Centre National de la Recherche Scientifique (CNRS). Additional support was provided by the CEC in the frame of the "Mediterranean Dust Experiment" program and by INSU/CNRS and the French Ministère de l'Environnement through the research project "Erosion Eolienne en Régions Arides et Semi-Arides." C. E. Lambert and F. Dulac would like to express their gratitude to the CEA for the computing facilities and the generous hospitality provided by the LMCE. This is contribution 418 from the LMCE and 2016 from the CFR.

References

Alpert, P., and B. Ziv, The Sharav cyclone: Observations and some theoretical considerations, *J. Geophys. Res.*, *94*, 18,495-18,514, 1989.

Alpert, P., B.U. Neeman, and Y. Shay-el, Climatological analysis of Mediterranean cyclones using ECMWF data, *Tellus*, *Ser. A*, *42*, 65-77, 1990.

Balkanski, Y., M. Schulz, B. Marticorena, G. Bergametti, W. Guelle, F. Dulac, C. Moulin, and C.E. Lambert, Importance of the source term and of the size distribution to model the mineral dust cycle, in *The Impact of Desert Dust Across the Mediterranean*, edited by S. Guerzoni and R. Chester, pp. 69-76, Kluwer Acad., Norwell, Mass., 1996.

Bergametti, G., Apports de matière par voie atmosphérique à la Méditerranée occidentale: Aspects géochimiques et météorologiques, Ph.D. thesis, Univ. of Paris 7, Paris, France, 1987.

Bergametti, G., A.-L. Dutot, P. Buat-Ménard, R. Losno, and E. Remoudaki, Seasonal variability of the elemental composition of atmospheric aerosol particles over the northwestern Mediterranean, *Tellus*, *Ser. B*, *41*, 353-361, 1989a.

Bergametti, G., L. Gomes, E. Remoudaki, M. Desbois, D. Martin, and P. Buat-Ménard, Present transport and deposition patterns of African dusts to the northwestern Mediterranean, in *Paleoclimatology and Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport*, edited by M. Leinen and M. Sarnthein, pp. 227-251, Kluwer Acad., Norwell, Mass., 1989b.

Dayan, U., Climatology of back-trajectories from Israel based on synoptic analysis, *J. Clim. Appl. Meteorol.*, *25*, 591-603, 1986.

Dayan, U., J.L. Heffter, and J.M. Miller, *Meteorological and Climatological Data From Surface and Upper Air Measurements for the Assessment of Atmospheric Transport and Deposition of Pollutants in the Mediterranean Basin*, *MAP Tech. Rep. Ser.*, vol. 30, U. N. Environ. Programme, Athens, 1989.

Dayan, U., J.L. Heffter, J.M. Miller, and G. Gutman, Dust-intrusion events into the Mediterranean basin, *J. Appl. Meteorol.*, *30*, 1185-1199, 1991.

Duce, R.A., et al., The atmospheric input of trace species to the world ocean, *Global Biogeochem. Cycles*, *5*(3), 139-259, 1991.

Dulac, F., D. Tanré, G. Bergametti, P. Buat-Ménard, M. Desbois, and D. Sutton, Assessment of the African airborne dust mass over the Mediterranean Sea using Meteosat data, *J. Geophys. Res.*, *97*, 2489-2506, 1992.

Franzén, L.G., M. Hjlemroos, P. Kallberg, E. Brosröm-Lunden, S. Juntto, and A.-L. Savolainen, The yellow snow episode of northern Fennoscandia, March 1991: A case study of long distance transport of soil, pollent and stable organic compounds, *Atmos. Environ.*, *28*, 3587-3604, 1994.

Gatz, D.F., A review of chemical tracer experiments on precipitation systems, *Atmos. Environ.*, *11*, 945-973, 1977.

Grousset, F.E., P. Rognon, G. Coudegaussen, and P. Pedemay, Origins of peri-Saharan dust deposits traced by their Nd and Sr isotopic composition, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *93*(3-4), 203-212, 1992.

Guerzoni, S., G. Quarantotto, G. Cesari, E. Molinaroli, G. Rampazzo, and O. Le Bolloch, Trace metal composition and grain-size of particulates in aerosols and precipitation collected in NW Mediterranean: A multivariate analysis, in *The Impact of Desert Dust Across the Mediterranean*, edited by S. Guerzoni and R. Chester, pp. 333-338, Kluwer Acad., Norwell, Mass., 1996.

Jankowiak, I., and D. Tanré, Satellite climatology of Saharan dust outbreaks: Method and preliminary results, *J. Clim.*, *5*, 646-656, 1992.

Kubilay, N., and A.C. Saydam, Trace elements in atmospheric particulates over the eastern Mediterranean: Concentrations, sources, and temporal variability, *Atmos. Environ.*, *29*, 2289-2300, 1995.

La Fontaine, C.V., R.A. Bryson, and W. M. Wendland, Airstream regions of North Africa and the Mediterranean, *J. Clim.*, *3*, 366-372, 1990.

Legrand, M., C. N'doumé, and I. Jankowiak, Satellite-derived climatology of the Saharan aerosol, in *Passive Infrared Remote Sensing of Clouds and the Atmosphere II*, edited by D. K. Lynch, *Proc. SPIE Int. Soc. Opt. Eng.*, *2309*, 127-135, 1994.

Loÿe-Pilot, M. D., and J. M. Martin, Saharan dust input to the western Mediterranean: An eleven years record in Corsica, in *The Impact of Desert Dust Across the Mediterranean*, edited by S. Guerzoni and R. Chester, pp. 191-200, Kluwer Acad., Norwell, Mass., 1996.

Marticorena, B., Modélisation de la production d'aérosols désertiques en régions arides et semi-arides: Développement et validation d'un code de calcul adapté au transport à grande échelle, Ph.D. thesis, Univ. of Paris 7, Paris, France, 1995.

Marticorena, B., and G. Bergametti, Two-year simulations of seasonal and interannual changes of the Saharan dust emissions, *Geophys. Res. Lett.*, *23*(15), 1921-1924, 1996.

Martin, D., G. Bergametti, and B. Strauss, On the use of the synoptic vertical velocity in trajectory model: Validation by geochemical tracers, *Atmos. Environ.*, *Part A*, *24*, 2059-2069, 1990.

Measures, C., Estimating dust input to the Atlantic Ocean using surface water aluminium concentrations, in *The Impact of Desert Dust Across the Mediterranean*, edited by S. Guerzoni and R. Chester, pp. 301-311, Kluwer Acad., Norwell, Mass., 1996.

MEDUSE, Mediterranean Dust Experiment, Program Environ. and Clim., Com. of the Eur. Communities, Bruxelles, Belgium, 1996.

Molinaroli, E., S. Guerzoni, and G. Rampazzo, Contribution of Saharan dust to the central Mediterranean basin, *Geol. Soc. Am.*, *284*, 303-312, 1993.

Moulin, C., C.E. Lambert, J. Poitou, and F. Dulac, Long-term (1983-1994) calibration of the Meteosat solar (VIS) channel using desert and ocean targets, *Int. J. Remote Sens.*, *17*(6), 1183-1200, 1996.

Moulin, C., C.E. Lambert, F. Dulac, and U. Dayan, Control of atmospheric export of dust from North Africa by the North Atlantic Oscillation, *Nature*, *387*, 691-694, 1997a.

Moulin, C., F. Guillard, F. Dulac, and C.E. Lambert, Long-term daily monitoring of Saharan dust load over ocean using Meteosat ISCCP-B2 data, 1, Methodology and preliminary results for 1983-1994 in the Mediterranean, *J. Geophys. Res.*, *102*, 16,947-16,958, 1997b.

Moulin, C., F. Dulac, C.E. Lambert, P. Chazette, I. Jankowiak , B. Chatenet, and F. Lavenu, Long-term daily monitoring of Saharan dust load over ocean using Meteosat ISCCP-B2 data, 2, Accuracy of the method and validation using sunphotometer measurements., *J. Geophys. Res.*, *102*, 16,959-16,969, 1997c.

Nickovic, S., and S. Dobricic, A model for the long range transport of desert dust, *Mon. Weather Rev.*, *124*(11), 2537-2544, 1996.

Prodi, F., and G. Fea, A case of transport and deposition of Saharan dust over the Italian peninsula and southern Europe, *J. Geophys. Res.*, *84*, 6951-6960, 1979.

Prospero, J.M., Mineral-aerosol transport to the North Atlantic and North Pacific: The impact of African and Asian sources, in *The Long-Range Atmospheric Transport of Natural and Contaminant Substances*, edited by A.H. Knap, pp. 59-86, Kluwer Acad., Norwell, Mass., 1990.

Prospero, J.M., The atmospheric transport of particles to the ocean, in *Particle Flux in the Ocean*, edited by P. Schäfer et al., pp. 19-52, John Wiley, New York, 1996.

Reiff, J., G.S. Forbes, F.T.M. Spieksma, and J.J. Reynders, African dust reaching northwestern Europe: A case study to verify trajectory calculations, *J. Clim. Appl. Meteorol.*, *25*, 1543-1567, 1986.

Ruiz-Pino, D.P., C.E. Lambert, C. Jeandel, and P. Buat-Ménard, Modelling the biogenic transport of atmospheric particles in the Mediterranean sea, *Global Planet. Change*, *89*, 47-64, 1990.

Schemm, J.K., Estimates of monthly mean soil moisture for 1979-1989, *NASA Tech. Memo.*, *104571*, 260 pp., 1992.

Schulz, M., Y. Balkanski, W. Guelle, F. Dulac, C. Moulin, C.E. Lambert, Model components necessary to capture a dust plume pattern over the Mediterranean Sea, in *The Impact of Desert Dust Across the Mediterranean*, edited by S. Guerzoni and R. Chester, pp. 51-58, Kluwer Acad., Norwell, Mass., 1996.

Swap, R., S. Ulanski, M. Cobbett, and M. Garstang, Temporal and spatial characteristics of Saharan dust outbreaks, *J. Geophys. Res.*, *101*, 4205-4220, 1996.

Tegen, I., A. A. Lacis, and I. Fung, The influence on climate forcing of mineral aerosols from disturbed soils, *Nature*, *380*, 419-422, 1996.

Y.J. Balkanski, P. Bousquet, W. Guelle, V. Masson, C. Moulin (corresponding author), and M. Ramonet, Laboratoire de Modélisation du Climat et de l'Environnement, CEA, CE Saclay, l'Orme des Merisiers, 91191 Gif-Sur-Yvette, France. (e-mail: cyril.moulin@cea.fr)

G. Bergametti and B. Marticorena, Laboratoire Interuniversitaire des Sytèmes Atmosphériques, Universite of Paris 7 and 12 - CNRS, F-94010 Crétiel, France.

U. Dayan, Department of Geography, Hebrew University of Jerusalem, Mount Scopus Campus, Jerusalem 91905, Israel.

F. Dulac and C.E. Lambert, Centre des Faibles Radioactivités, CNRS-CEA, 91198 Gif-Sur-Yvette, France.

M. Legrand, Laboratoire d'Optique Atmosphérique, USTL - CNRS, F-59655 Villeneuve d'Ascq, France.

**(Received June 25, 1997; revised November 24, 1997;
accepted January 13, 1998.)**