JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, D18S08, doi:10.1029/2004JD004731, 2005

Wet and dry African dust episodes over eastern Spain

M. Escudero,[1,2] S. Castillo,[1] X. Querol,[1] A. Avila,[2] M. Alarcón,[3] M. M. Viana,[1]
A. Alastuey,[1] E. Cuevas,[4] and S. Rodríguez[1]

Received 3 March 2004; revised 10 May 2004; accepted 23 June 2004; published 26 April 2005.

[1] The impact of the African dust on levels of atmospheric suspended particulate matter (SPM) and on wet deposition was evaluated in eastern Iberia for the period 1996–2002. An effort was made to compile both the SPM and wet episodes. To this end, the time series of levels of TSP and PM10 in Levantine air quality monitoring stations were evaluated and complemented with the computation of back trajectories, satellite images, and meteorological analysis. Wet deposition frequency was obtained from weekly collected precipitation data at a rural background station in which the African chemical signature was identified (mainly pH and Ca^{2+} concentrations). A number of African dust episodes (112) were identified (16 episodes per year). In 93 out of the 112 (13 episodes per year) the African dust influence caused high SPM levels. In 49 out of 112 (7 episodes per year), wet deposition was detected, and the chemistry was influenced by dust. There is a clear seasonal trend with higher frequency of dust outbreaks in May-August, with second modes in March and October. Wet events followed a different pattern, with a marked maximum in May. Except for one event, December was devoid of African air mass intrusions. On the basis of seasonal meteorological patterns affecting the Iberian Peninsula, an interpretation of the meteorological scenarios causing African dust transport over Iberia was carried out. Four scenarios were identified with a clear seasonal trend. The impact of the different dust outbreak scenarios on the levels of PM10 recorded at a rural site (Monagrega, Teruel, Spain) in the period 1996–2002 was also evaluated.

Citation: Escudero, M., S. Castillo, X. Querol, A. Avila, M. Alarcón, M. M. Viana, A. Alastuey, E. Cuevas, and S. Rodríguez (2005), Wet and dry African dust episodes over eastern Spain, *J. Geophys. Res.*, *110*, D18S08, doi:10.1029/2004JD004731.

1. Introduction

[2] Mineral dust may influence the atmospheric radiation balance through scattering and absorption processes [*Tegen et al.*, 1997; *Haywood and Boucher*, 2000; *Harrison et al.*, 2001; *Sokolik et al.*, 2001; *Arimoto*, 2001; *Intergovernmental Panel on Climate Change*, 2001]. Cloud nucleation may also be highly influenced by mineral dust [*Levin et al.*, 1996].

[3] In addition to its effects on climate, mineral dust may have an important incidence on levels of suspended particulate matter (SPM) recorded in air quality monitoring networks. This is especially relevant in southern Europe [*Querol et al.*, 1998, 2004; *Rodríguez et al.*, 2001] and in some Atlantic islands [*Prospero and Ness*, 1986; *Coudé-Gaussen et al.*, 1987; *Savoie et al.*, 1987; *Bergametti et al.*, 1989a; *Savoie et al.*, 1992; *Prospero et al.*, 1995; *Chiapello et al.*, 1995; *Arimoto et al.*, 1997; *Caquineau et al.*, 1998; *Viana et al.*, 2002]. Furthermore, the mineral dust deposition largely influences deposition fluxes of metal nutrients in southern Europe [*Ganor and Mamane*, 1982; *Sequeira*, 1982; *Löye-Pilot et al.*, 1986; *Samara et al.*, 1992; *Camarero and Catalán*, 1993; *Rodà et al.*, 1993; *Guerzoni et al.*, 1995; *Avila*, 1996; *Alastuey et al.*, 1999; *Avila and Alarcón*, 1999; *Avila and Rodà*, 2002] and ocean regions [*Falkowski et al.*, 1998; *Fung et al.*, 2000; *Arimoto*, 2001].

[4] North African dust is injected into the atmosphere through resuspension processes at the source areas, and it is then transported at different altitudes (from sea level up to 4–6 km). On the basis of a recent evaluation of mineral dust sources from northern Africa [*Prospero et al.*, 2002], it can be concluded that the maximum dust transport occurs in summer when large quantities of dust are carried across the Mediterranean basin to Europe and the Middle East [*Bergametti et al.*, 1989b; *Dayan et al.*, 1991; *Dulac et al.*, 1992; *Chester et al.*, 1993; *Molinaroli et al.*, 1993; *Guerzoni et al.*, 1997; *Moulin et al.*, 1997; *Avila et al.*, 1997, 1998; *Avila and Alarcón*, 1999; *Moulin et al.*, 1998; *Querol et al.*, 1998; *Rodríguez et al.*, 2001; *Ryall et al.*, 2002] and across the Atlantic ocean to the Caribbean [*Prospero and Nees*, 1986; *Coudé-Gaussen et al.*, 1987;

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[1] Institute of Earth Sciences "Jaume Almera," Consejo Superior de Investigaciones Científicas, Barcelona, Spain.

[2] Centre for Ecological Research and Forestry Applications, Autonomous University of Barcelona, Barcelona, Spain.

[3] Department of Physics and Nuclear Engineering, Polytechnic University of Catalonia, Barcelona, Spain.

[4] Izaña Atmospheric Observatory, Instituto Nacional de Meteorologia, Santa Cruz de Tenerife, Spain.

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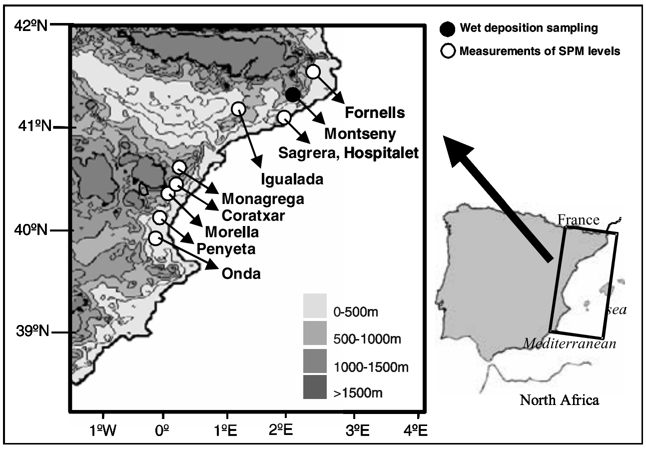

Figure 1. Location of the stations measuring levels of atmospheric suspended particles (SPM), and the Montseny (La Castanya and Santa María de Palautordera) for wet deposition sampling.

Bergametti et al., 1989a, 1989b; *Prospero et al.*, 1995], the southeastern United States [*Perry et al.*, 1997; *Prospero*, 1999], and the midlatitude western North Atlantic [*Arimoto et al.*, 1995]. In winter, there is also considerable transport when large quantities of dust are carried toward South America [*Prospero and Carlson*, 1981; *Swap et al.*, 1992] and sporadically to western Europe [*Querol et al.*, 2002].

[5] The low precipitation in the Mediterranean basin favors the long residence time of PM in the atmosphere with the consequent impact on air quality. Furthermore, at urban sites, from 25 to 60% exceedances of the PM10 daily limit value established by the 1999/30/CE European directive (50 μg PM10/m^3) in Spain have been attributed to dust outbreaks [*Querol et al.*, 2004]. Although many studies have dealt independently with African episodes influencing bulk deposition and levels of ambient SPM in Spain (see references above), to our knowledge, none of them have considered wet deposition and suspended particulate matter to investigate such dust outbreaks over Spain.

[6] Given that most African events accompanied by rain episodes lead to a decrease in the levels of SPM, studies on only SPM levels would not detect the occurrence of such "wet episodes." By contrast, in the case of weekly samplings of wet deposition, "dry events" may result in the deposition of African dust, which could be attributed to a subsequent or prior rain episode. On the basis of the information from time series of both chemistry of wet deposition and daily levels of SPM, an accurate study of the occurrence of these African events affecting eastern Iberia is carried out. This study seeks to carry out a statistical and a meteorological analysis of the occurrence and seasonal distribution of African dust outbreaks over the eastern Iberian Peninsula for the period 1996–2002.

2. Methodology

2.1. High SPM Events

[7] In order to study the impact of African dust outbreaks on ambient SPM levels, 1996–2002 time series of levels of TSP and PM10 (total suspended particles, and suspended particles <10 μm, respectively) from 18 air quality monitoring stations from the eastern Iberian Peninsula (from the Autonomous Governments of Catalonia and Valencia, and one station belonging to ENDESA) were selected. Selection criteria were based on data availability, geographical location, pollution level, and type of emission sources influencing the monitoring stations. TSP and PM10 time series were then intercorrelated, showing that nine of them exhibited parallel trends for the selected period. Consequently, nine stations (Monagrega, Morella, Coratxar, Hospitalet, Igualada, Sagrera, Fornells, Penyeta, and Onda, Figure 1) were finally chosen for this study. The Monagrega rural station was chosen to represent regional background levels because of its location (rural area in the Calanda desert in the semiarid Ebro basin), far from the direct influence of anthropogenic emissions.

[8] TSP measurements were carried out by the Beta attenuation method (FAG and Dasibi instruments) at all sites, with the exception of Monagrega where measurements of PM10 were performed with TEOM (oscillating microbalance method) instrumentation. PM10 real-time TEOM measurements were validated by means of a comparison with DIGITEL DH-80 gravimetric equipment for 143 measurement days. A relation of TEOM = 1.01 × DIGITEL with $R^2 = 0.85$ was found for spring, summer and autumn, whereas for winter the relation was TEOM = 0.68 × DIGITEL with $R^2 = 0.57$. This results in an underestimation of PM10 mass in winter of 32% due to the loss of species (such as NH_4NO_3 and specific semivolatile organic compounds) due to the difference of temperature between ambient conditions and the heated inlet (50°C to prevent water condensation). However, for African events this loss of material is not expected to be relevant because of the major mineral composition of PM10 in these events.

[9] After identifying a number of simultaneously recorded concentration peaks in the TSP and PM10 time series, the possible attribution to an African dust episode and the transport mechanisms which generate it were investigated by means of the evaluation of Total Ozone Mapping Spectrometer ((TOMS) NASA aerosol index maps [*Herman et al.*, 1997]; SKIRON and Navy Aerosol Analysis and Prediction System (NAAPs) aerosol maps provided by the University of Athens [*Kallos et al.*, 1997] and the Naval Research Laboratory (http://www.nrlmry.navy.mil/aerosol/), respectively; meteorological charts by National Centers for Environmental Prediction (NCEP) Climate Diagnostics Center (http://www.cdc.noaa.gov/Composites/Hour/) and the NOAA Air Resources Laboratory (http://www.arl.noaa.gov/ready/amet.html); and satellite imagery supplied by NASA Sea-viewing Wide Field-of-view Sensor (SeaWIFS) [*McClain et al.*, 1998]. Moreover, back trajectories were calculated daily with the HYSPLIT model [*Draxler and Rolph*, 2003] in order to interpret the different source regions of the air masses reaching the study area. To this end, 5-day isentropic back trajectories at three different altitudes (1500, 3000, and 4500 masl) were obtained for each day of the study period.

2.2. Wet Deposition Events

[10] Data on the chemical composition of bulk deposition were used to identify wet African episodes. To this end, sampling was carried out at La Castanya (Montseny,

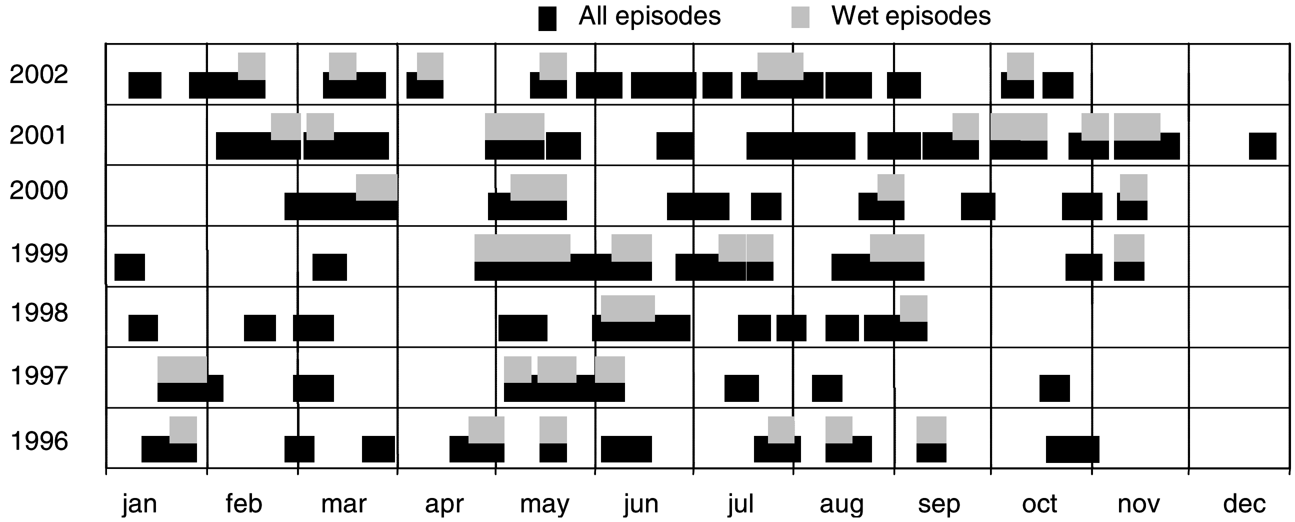

Figure 2. Occurrence of African dust outbreaks over eastern Iberian Peninsula for 1996–2002. Episodes occurring simultaneously with precipitation are highlighted.

Barcelona, 41°46′N, 02°21′E, 700 m above sea level (masl)) from January 1996 to the end of September 2000 and at a nearby station at the base of the Montseny Mountains (Santa Maria de Palautordera, 41°41′N, 02°27′E, 200 masl, 7 km from La Castanya in a southern direction) from October 2000 to December 2002. Precipitation for analysis was collected on a weekly basis in an open bulk deposition collector (placed 1.5 m above the ground) which consisted of a 19-cm diameter-polyethylene funnel connected by Tygon tubing to a 10-L polyethylene bottle. A clean nylon sieve was placed in the neck of the funnel to prevent sample contamination from insects or particle debris. The bottles were lined with a dark cover to avoid light-induced alterations of collected water. In each sampling, the collector was retrieved and replaced by one cleaned in the laboratory (washed with deionized distilled water). After sampling, the rainwater was taken to the laboratory where conductivity, pH, and alkalinity were measured in unfiltered samples. Then, samples were filtered through 0.45-mm pore size Millipore filters and deep frozen for further analyses of the major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-}, NO_3^- and Cl^-). The pH was measured with an Orion pH meter with pH electrodes for low ionic strength solutions. Alkalinity was measured by Gran titration. Concentrations of base cations in the filtered rainwater were determined by atomic absorption spectrometry (AAS). Soluble anions were determined by ion chromatography and ammonium by flow injection analysis and gas diffusion. The quality of data was verified by two methods: (1) a cation–anion balance and (2) the comparison of the measured electric conductivity with the conductivity calculated from the concentration of all ions and their specific conductivity.

[11] African wet episodes were defined as rainfall events that gave a reddish brownish color to the rainwater filters.

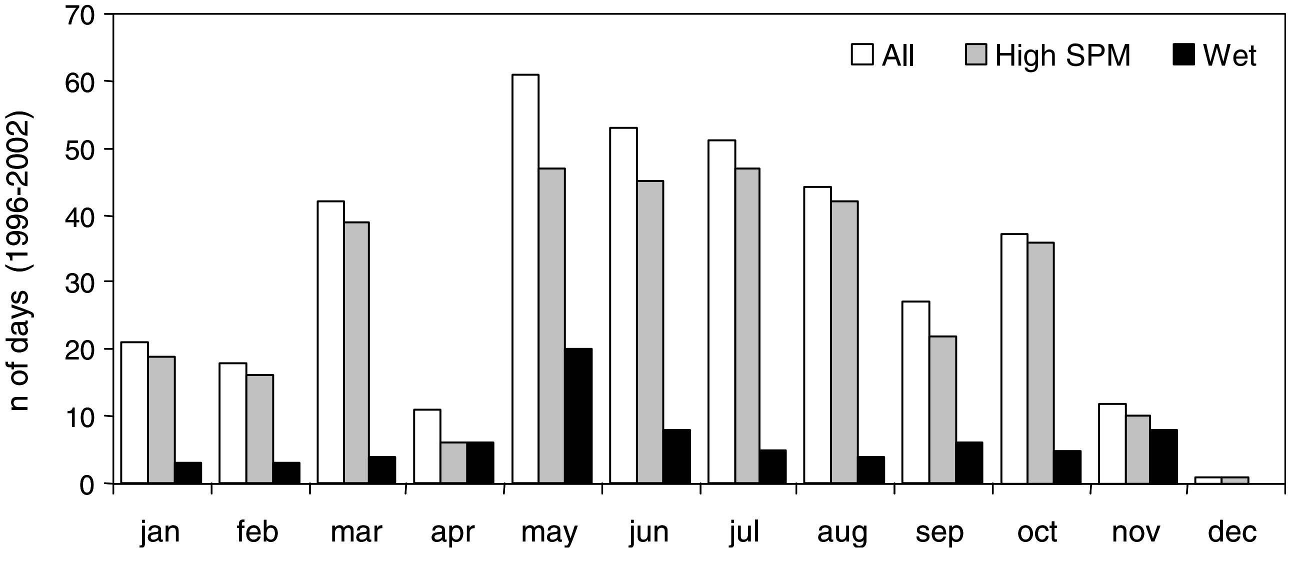

Figure 3. Number of days per month with African dust outbreaks over eastern Iberia for 1996–2002. High SPM and wet deposition events are distinguished.

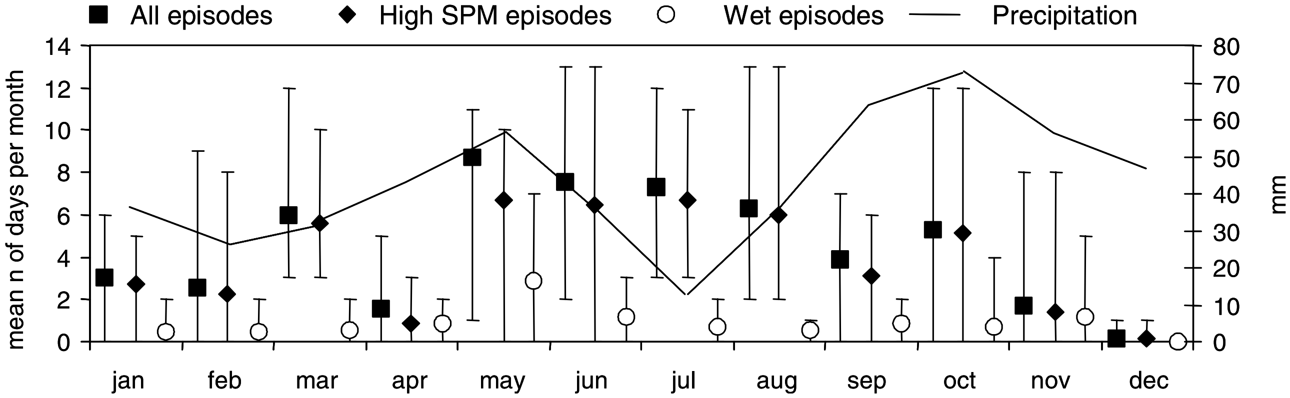

Figure 4. Mean monthly precipitation of Tortosa (40°49′N, 00°29′E, 48 masl) for 1971–2000 [*Instituto Nacional de Meteorologia*, 2001] and mean number of days with African event per month for 1996–2002.

These events are known as red rains for this reason. The chemistry of these episodes is characterized by very high pH and high concentration of Ca^{+2} [*Avila and Alarcón*, 2003]. The African episodes had pH > 6 and $[Ca^{+2}] > 80$ µeq/L. The identification of African events was confirmed by means of back trajectory analysis using the above procedure. Given that the sampling was carried out on a weekly basis, the identification of the exact dates of the African rain episode was obtained from the precipitation records of the La Castanya station and from the Santa María de Palautordera (the latter belonging to the meteorological service of Catalonia, Meteocat).

[12] Once the time series of wet deposition and high SPM events influenced by African episodes were obtained, these were combined to create a time series of dust outbreaks. The meteorological scenarios causing these episodes, the duration, the seasonal trends, and the levels of SPM recorded in regional background sites were then investigated.

[13] In addition to the above procedure, a determination of the meteorological scenarios causing the African dust outbreaks over Spain was carried out. To this end, each dust event was studied using three parameters: (1) geopotential height for 850, (2) geopotential height for 700 hPa, and (3) mean sea level pressure (MSLP). The data files were obtained from the NOAA Air Research Laboratory. The African dust outbreaks occurred under certain synoptic scenarios. Following the classification of events, geopotential height and MSLP data were averaged and plotted using the data of the first day of each dust episode. Thus an average map was obtained for each scenario.

3. Results and Discussion

[14] Results from back trajectory analysis showed that for the period 1996–2002 in eastern Iberia, around 53% of the days were influenced by Atlantic advective flows, relatively low percentages when compared with northwestern Iberia (86% of the days [*Querol et al.*, 2004]). However, in 15% of the days the African air masses reached the eastern regions and only 5% the northwestern regions. Another important difference is the high annual percentage of atmospheric regional recirculation episodes [*Millán et al.*, 1997] and European (including Mediterranean) transport episodes in the eastern regions (12 and 20%, respectively) when compared with the northwestern areas (<1 and 9% of the days, respectively).

3.1. Occurrence of African Episodes

[15] During the period 1996–2002, 112 African dust episodes were identified accounting for a total of 378 days, with a mean duration of 3.3 days per episode. This represents a mean of 16 episodes per year and that 15% of the days the African dust reached eastern Iberia. The mean monthly occurrence for the study period is 4.5 days per month.

[16] In 93 out of the 112 episodes (330 days, with a mean of 3.6 days per episode) an impact on levels of SPM in the air quality monitoring stations was detected. This represents a mean of 13.3 episodes per year and that in 13% of the days the African dust influenced the levels of SPM in eastern Iberia. The mean monthly occurrence for the study period is 3.9 days per month.

[17] In 49 out of 112 episodes (72 days, with a mean of 1.4 days per episode) wet deposition occurred simultaneously with African events. This represents a mean of 7 episodes per year (3% of the days). The mean monthly occurrence for the study period is 0.8 days per month. It should be pointed out that the total number of episodes differs from the addition of SPM and wet episodes since some of the episodes included days during which SPM levels were influenced by dust outbreaks and, simultaneously, wet dust deposition.

[18] The highest number of episodes was recorded in 2001 (26) and the lowest in 1997 and 1998 (12). The number of events with influence on SPM events reached its maximum in 2001 (26) and its minimum in 1999 (11). As regards the wet events, the maximum amount of episodes was recorded in 1999 (11) and the minimum in 1998 (3).

[19] The highest number of days with African episode was recorded in 2001 (77 days), the lowest number of days was recorded in 1997 (32). The number of high SPM events reached to its maximum in 2001 (75) and to its minimum in 1997 (26). The number of days with wet African event was maximum in 1999 (19) and minimum in 1998 (4). Furthermore, in the last two years of the record a higher number of episodes and days were recorded. This can be due to increasing dust emission in the source areas or to a more

Table 1. Monthly Mean Duration of Episodes and Mean Number of Days With African Dust Transport Over Northeastern Iberia During 1996–2002[a]

	Mean Duration of Episodes, days			Mean Number of Days With Episodes		
	All	SPM	Wet	All	SPM	Wet
January	2.5	2.3	1.0	3.0	2.7	0.4
February	2.2	2.0	1.5	2.6	2.3	0.4
March	3.4	3.3	1.3	6.0	5.6	0.6
April	2.8	3.0	2.0	1.6	0.9	0.9
May	4.0	5.3	1.5	8.7	6.7	2.9
June	5.8	6.9	2.2	7.6	6.4	1.1
July	3.6	4.1	1.0	7.3	6.7	0.7
August	4.1	4.4	1.0	6.3	6.0	0.6
September	3.7	3.6	1.5	3.9	3.1	0.9
October	4.4	4.3	0.8	5.3	5.1	0.7
November	2.2	2.3	1.8	1.7	1.4	1.1
December	1.0	1.0	0.0	0.2	0.2	0.0
Annual (1996–2002)	3.3	3.6	1.4	4.5	3.9	0.8

[a] All episodes, wet episodes and episodes influencing ambient levels of SPM.

frequent occurrence of transport situations. However, the number of tools that were available for the detection of dust episodes was superior in the last years than in the first years of the period 1996–2002, this allowed the detection of more dust events. This can be reflected in the number of episodes recorded for this study.

[20] The monthly distribution of African episodes is characterized by three modes with a clear prevalence of the period May to August (Figures 2–4). In particular, the period May-August has the highest mean number of days per month (from 6.3 to 8.7 days), followed by March and October (with 6.0 and 5.3 days per month, respectively), whereas the lowest monthly occurrences are recorded for December, November, and April (with 0.2, 1.7, and 1.6 days per month). It is noticeable that in March, May, June, July, and August, dust events are always present, while in December only one dust invasion day was recorded in the whole study period (1996–2002). The above seasonal pattern of the African episodes is clearly dominated by the SPM (nonwet) episodes given that the same trend described is shown. Wet events only showed relatively higher monthly frequency in May (with 2.9 days per month).

[21] Saharan dust outbreaks last longer in the period May–October than in the rest of the year with the exception of March when the duration of the episodes is similar to that of the summer events (Table 1 and Figure 5). The longest Saharan episodes take place in June with mean and maximum lengths of 5.8 and 13 days for all episodes and 6.9 and 13 days for the SPM (nonwet) events. Wet episodes show the higher mean duration in April-June and November (1.5 to 2 days), whereas the longest wet episodes were recorded in May, June, and November (3 days).

3.2. Phenomenology of Dust Outbreaks Over Eastern Iberian Peninsula

[22] On the basis of the results of the meteorological evaluation of the African episodes identified, the following scenarios giving rise to the transport of highly dust loaded air masses from northern Africa to the Iberian Peninsula may be distinguished.

3.2.1. Scenario 1: North Africa High Located at Surface Level

[23] This type of scenario accounts for the occurrence of African air mass intrusions over the Iberian Peninsula from

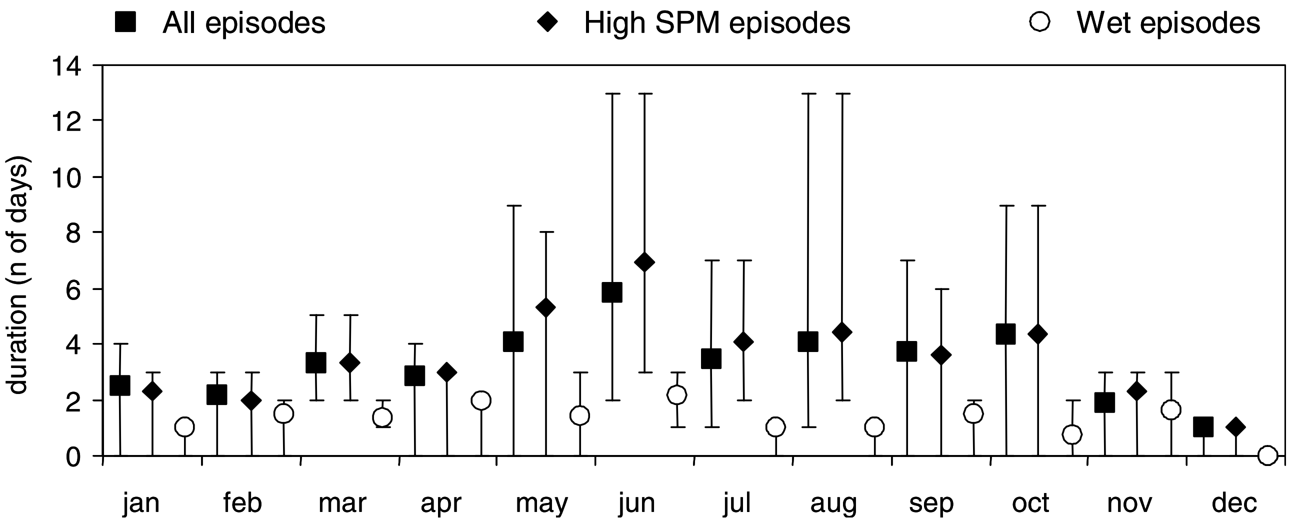

Figure 5. Mean duration of African episodes per month for 1996–2002.

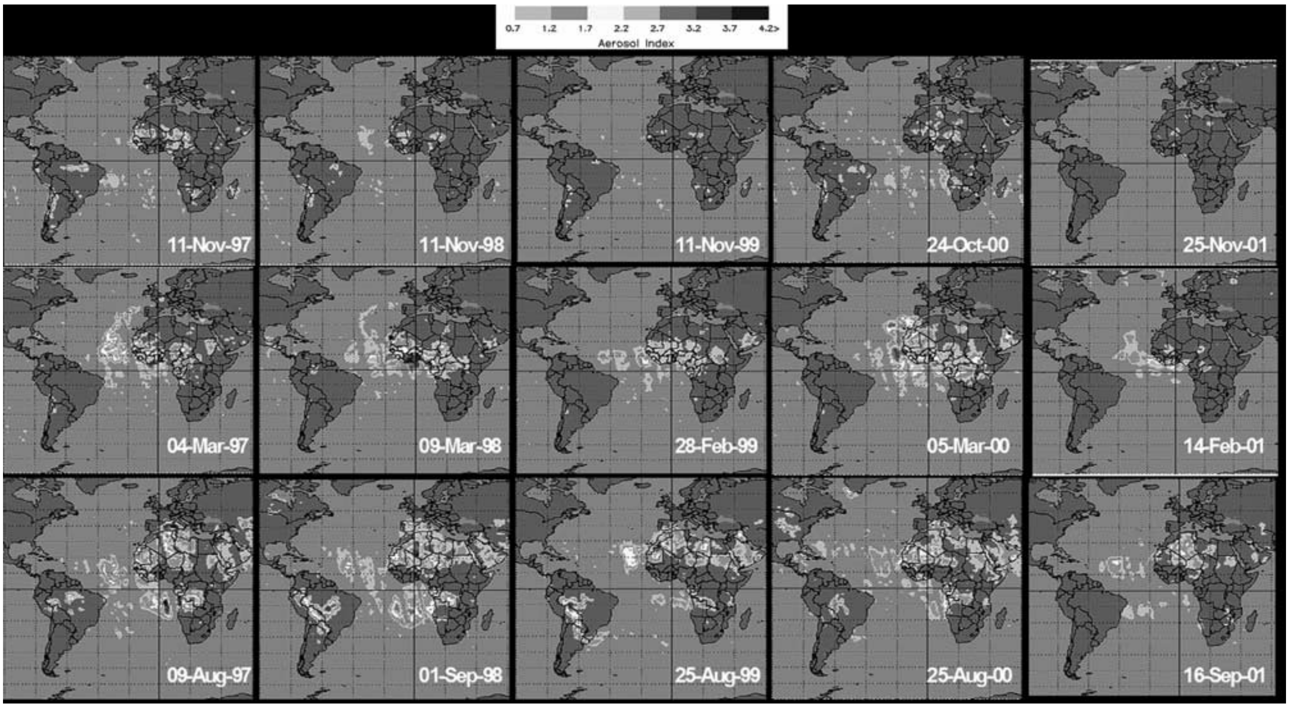

Figure 6. Aerosol index from TOMS-NASA for selected days in different periods of the year: autumn, late winter, and summer for 1997–2001. See color version of this figure at back of this issue.

the western Atlantic via an Atlantic arch [*Querol et al.*, 2002]. As shown by the TOMS aerosol index maps, this scenario is present in most of the study period during January to March (Figures 6 and 7). The most outstanding feature of this scenario is the no presence of the quasi-permanent Azores high. These convex and Atlantic long-range transport plumes are caused by an anticyclone located over southern Iberia, North Africa, the western Mediterranean or off the Atlantic coast [*Rodríguez et al.*, 2001] (see Figure 7). The transport is confined at low levels and it is well detected at ground level and 850 hPa as shown in Figure 7. Figure 7 also shows that the major sources of dust for this scenario are western Sahara and Sahel, although it has to be noted that dust transport constrained to the lower atmospheric levels (<1000 m) is not detected by TOMS measurements [*Torres et al.*, 1998, 2002]. Only 3 out of the 15 North Africa high located at surface level (NAH-S) episodes identified occurred with wet deposition (20%).

3.2.2. Scenario 2: Atlantic Depression

[24] A relatively deep low pressure (observed from sea level to 700 hPa centered southwest off the Portuguese coast with an associated high or ridge over the central Mediterranean sea) may also be the cause of dust transport toward eastern Iberia [*Rodríguez et al.*, 2001]. This transport scenario results in a synoptic flow coming from the south in all altitude levels (Figure 7). Source areas for mineral dust may vary widely but according to the transport scenario, western regions (Mauritania, Mali, Morocco) may be the main emission areas. Nine out of the 22 Atlantic Depression (AD) episodes identified occurred with wet deposition (41%).

3.2.3. Scenario 3: North African Depression

[25] The Azores high is lightly shifted to the east of its normal position, a ground level low is centered over Morocco, Algeria, Tunisia, or even the western Mediterranean, and a trough is observed over the Iberian Peninsula. This meteorological scenario favors the transport of African air masses toward Iberia across the Mediterranean (Figure 8). The air mass transport associated with this scenario is confined to the lower layers. Most of these episodes occur with rain events. North African Depression (NAD) situations may commonly arise by the entry of depressions from over the Atlantic to North Africa or the western Mediterranean. According to this scenario, the dust sources may be regions from Algeria, Tunisia, Libya and Chad. Twenty out of the 23 NAD episodes identified occurred with wet deposition (87%).

3.2.4. Scenario 4: North African High Located at Upper Levels

[26] The most frequent scenario causing dust outbreaks over Iberia is produced by the intense heating of the Sahara and the consequent development of the North African thermal low (Figure 8) and the considerable vertical growth of the boundary layer. This convective system pumps dust up to 5000 m asl. Once the dust is injected into the midtroposphere it may be transported toward Iberia by the eastern branch of the high present over North Africa (lifted to upper atmospheric levels, see Figure 8 and *Rodriguez et al.* [2001] for case studies). In these cases the air masses are

Figure 7. Mean geopotential height for 850 and 700 hPa and mean sea level pressure (MSLP) calculated from the NOAA meteorological daily data of the first day of each dust episode for scenario 1 (15 episodes) and scenario 2 (22 episodes).

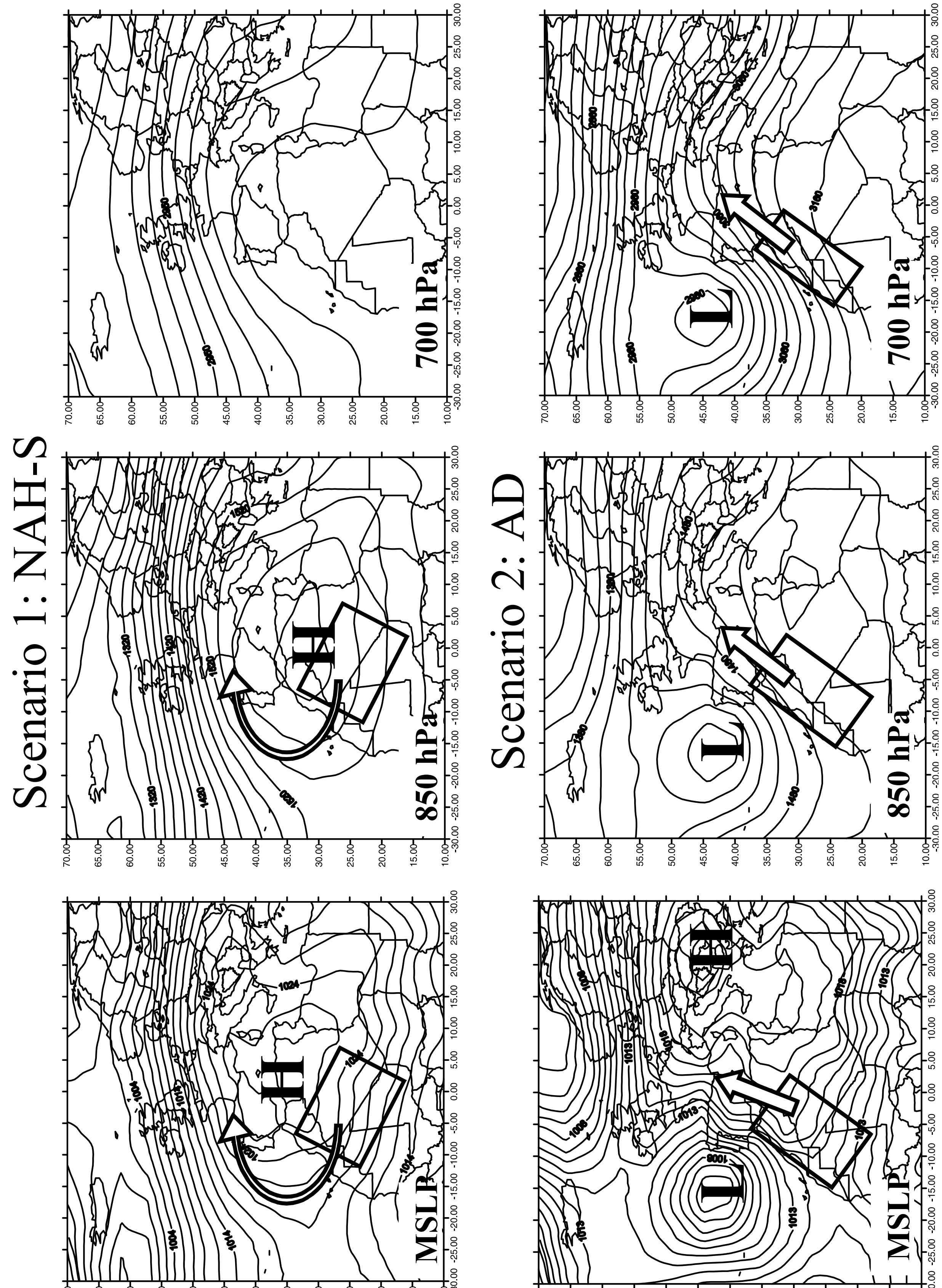
Scenario 1: NAH-S
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Figure 7

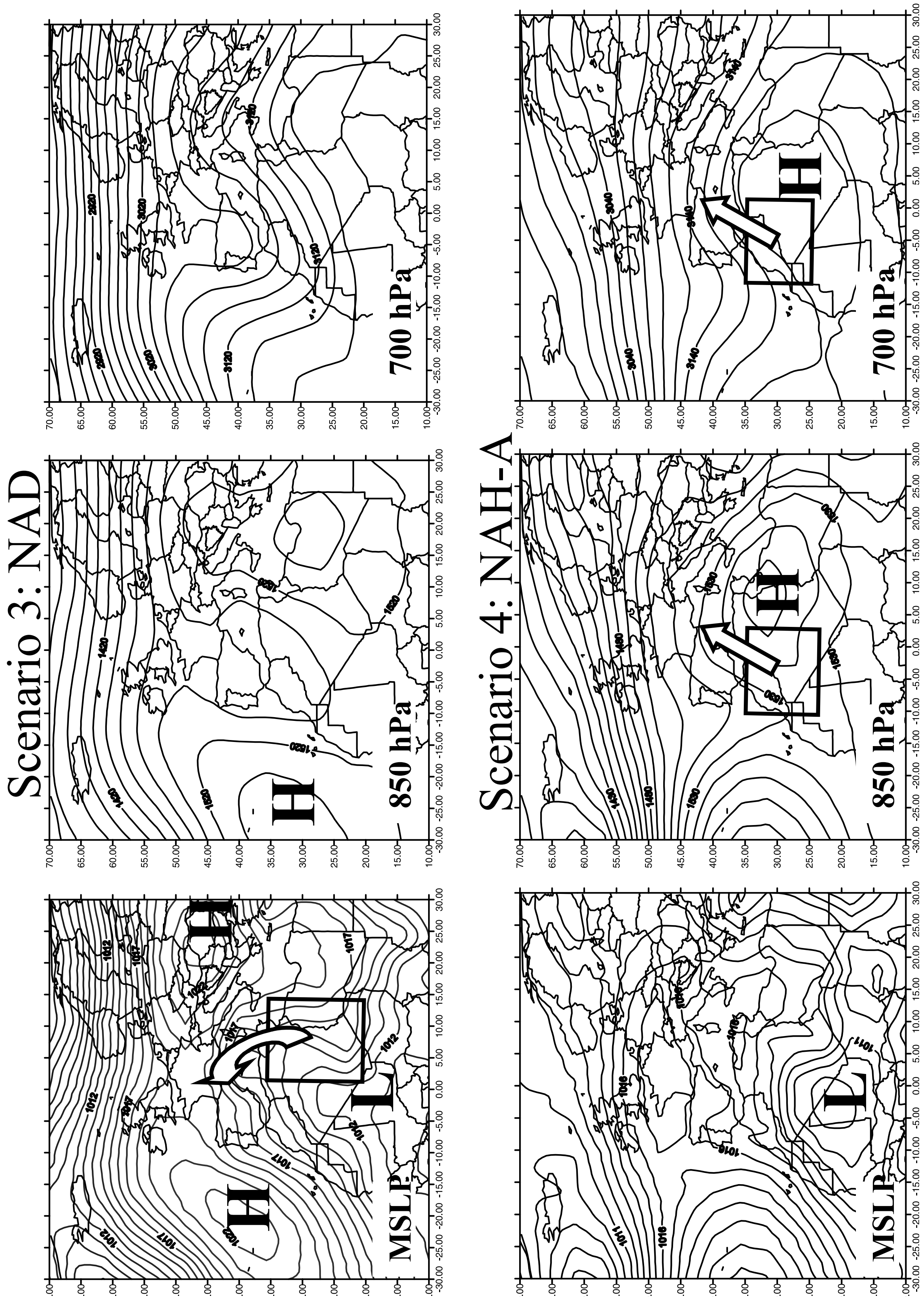
Scenario 3: NAD
Scenario 4: NAH-A
MSLP
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Figure 8

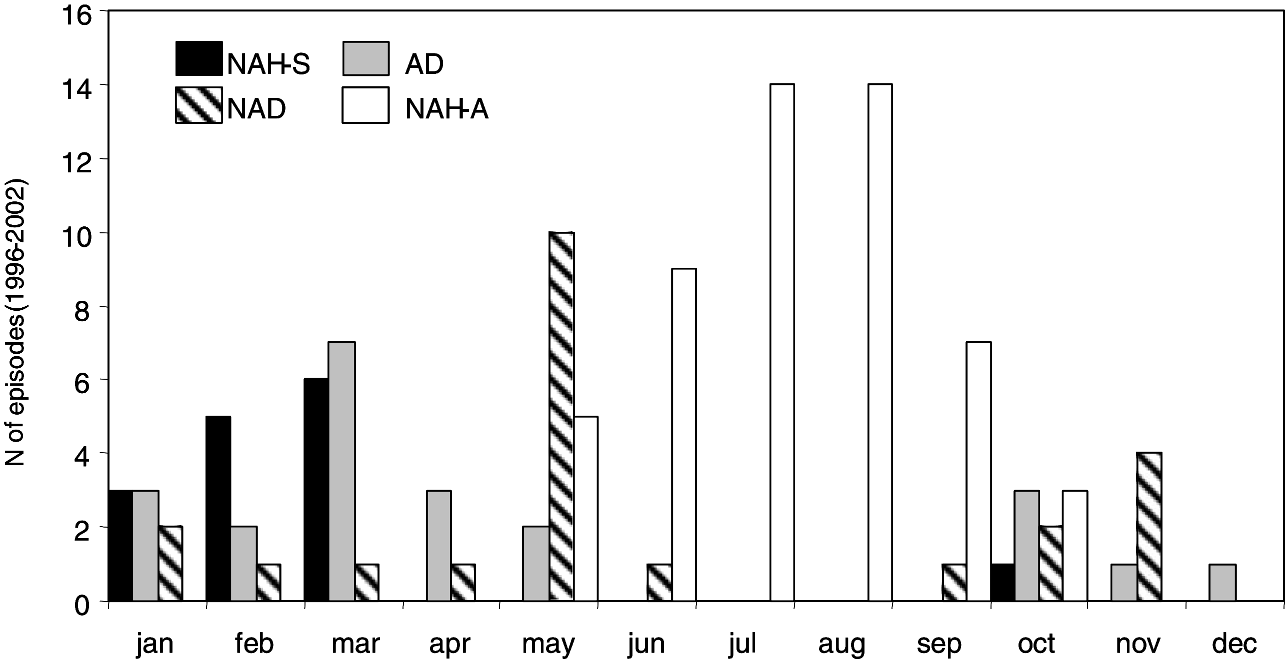

Figure 9. Number of dust outbreaks per month in 1996–2002 under the meteorological scenarios distinguished.

heavily loaded with dust and are transported toward the north covering most of the western Mediterranean basin and Iberia, forming a wide plume of dust. By contrast, narrow Atlantic arches are formed in NAH-S scenarios (Figure 6). Given that the transport of dust is carried out at a considerable altitude, a number of studies have documented episodes of dust transport over Europe reaching altitudes of up to 6 km without impact on the low atmospheric levels [*Ansmann et al.*, 2003]. These episodes exerted considerable influence on the levels of SPM over the eastern Iberia since only 17 out of 52 North African high located at upper levels (NAH-A) (33%) were accompanied by local convective rains.

[27] The scenario NAH-S accounted for the occurrence of 13% (15 episodes in the period 1996–2002) of the African episodes recorded in eastern Spain, whereas the scenario NAH-A accounted for 46% (52 episodes in the study period). Scenarios AD and NAD accounted for around 20% of the episodes in each case (22 and 23 episodes). As shown in Figure 9, the seasonal occurrence of the four African transport scenarios is well defined. Thus all NAH-S episodes detected in the study period occurred in the period January-March, with the exception of one case in October. AD events occurred in winter, autumn and spring, but conversely, NAH-A episodes were detected only from May to October. Finally, most of NAD episodes occurred in May and November, but none in July August.

3.3. Levels of Ambient SPM in Eastern Iberia During African Episodes

[28] The air quality monitoring station of Monagrega (Teruel), which forms part of the monitoring network of ENDESA (Empresa Nacional de Electricidad, SA) and is located in a rural area, was selected as a regional background site to evaluate the incidence of dust outbreaks in the ambient levels of PM10. Mean annual ambient PM10 levels measured at Monagrega in 1996–2002 ranged from 17 to 19 μg/m^3, with the exception of 2002 when a very rainy summer accounted for a marked decrease in PM10 levels (13 μg/m^3).

[29] The influence of African dust transport on the levels of PM10 measured at Monagrega is very evident given that of the 24 peak PM10 events exceeding daily levels of 50 μg/m^3, 20 were measured under the influence of the African transport (Figure 10). This resulted in 27 days exceeding 50 μg/m^3 in the whole period 1996–2002 owing to dust outbreaks. The maximum annual exceedances attributed to dust events occurred in 1998 (8), whereas in 1996 and 2002 only one day exceeding 50 μg/m^3 for African events was registered.

[30] Considering only the days influenced by African dust outbreaks over eastern Spain in 1996–2002 (378 out of 2557 days), a mean PM10 level of 22 μg/m^3 was obtained, similar to that obtained for the days characterized by regional recirculation processes (21 μg/m^3, 307 days) but much higher than for the other atmospheric scenarios (13 μg/m^3, 1361 days, with local PM contributions and an Atlantic advection prevalence, or 15 μg/m^3, 511 days, with European and Mediterranean transport). The highest mean annual PM10 levels for the African events were registered in 1998 (33 μg/m^3) and the lowest were measured in 2002 (21 μg/m^3).

[31] The regional recirculation episodes are typical from summer and were reflected in SPM time series by an

Figure 8. Mean geopotential height for 850 and 700 hPa and mean sea level pressure (MSLP) calculated from the NOAA meteorological daily data of the first day of each dust episode for scenario 3 (23 episodes) and scenario 4 (52 episodes).

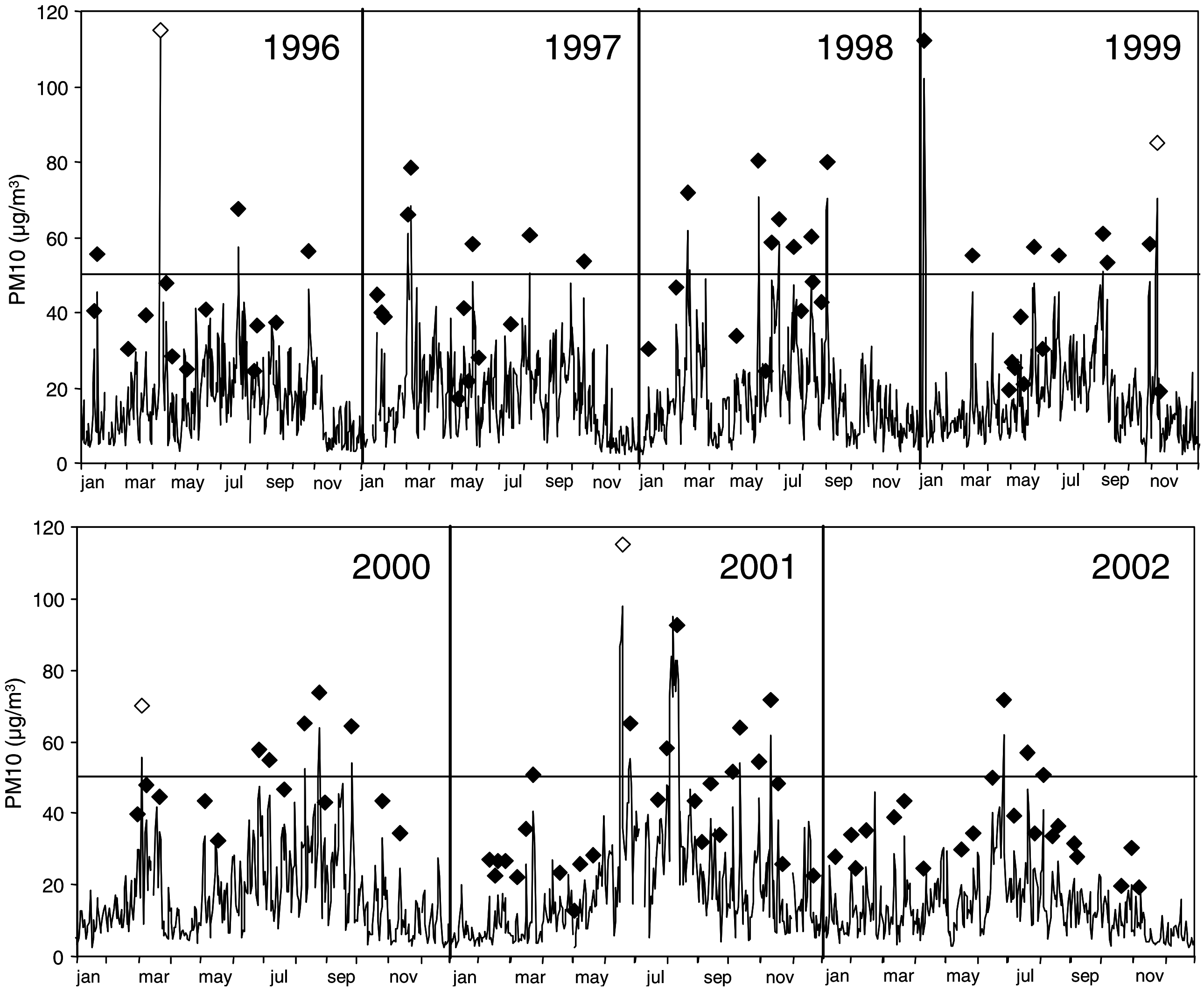

Figure 10. Daily PM10 levels in Monagrega for 1996–2002. The black dots mark African dust episodes and the white ones episodes exceeding 50 µg/m^3 with non-African origin.

increase of the background levels in all stations. These peaks had more temporal extent but were less pronounced than the peaks due to African events. Furthermore, the elevation in SPM levels was always accompanied by elevation in O_3 levels. These facts allowed the detection of these events and the differentiation of these two types of events. It has to be noticed that the occurrence or not of intense high SPM events in February and March may highly influence the interannual variation of TSP or PM10 mean annual values at a given station (Figure 10).

[32] Although there are wide variations in the levels of PM10 in the case of the different African transport scenarios (Table 2), the highest mean PM10 levels were measured for the NAH-S and NAH-A scenarios (31 and 30 µg/m^3, Table 2), whereas the lowest levels were measured for the NAD scenario (17 µg/m^3). However, if we combine the mean number of days and the mean levels of PM10 into an impact index (I is mean number of days per year influenced by each type of scenario multiplied by the mean PM10 levels for each scenario in the whole period 1996–2002), we can conclude that NAH-A has the highest impact on PM10 levels (I = 874, Table 2). The other three scenarios have a very similar impact on PM10 levels in the range of I = 186 – 228 (Table 2), approximately 4 times less than the NAH-A scenario. The lower levels recorded under low-pressure scenarios result mainly from the higher rainfall rates. Under anticyclonic settings, two situations may arise. During NAH-S episodes, larger amounts of dust are injected into the troposphere than during NAH-A events because of the intensive convective processes which take place at the source regions. However, under the NAH-S scenario the dust laden air masses are transported a longer way than under the NAH-A scenario (transport over the Atlantic ocean versus over the Mediterranean basin), and thus they are subject to higher dust segregation by transport. Consequently, the average PM levels recorded under both types of episodes are similar (31 and 30 µg/m^3). Although the dust transport occurs at high altitudes in the case of the NAH-A scenario, the considerable vertical development of the boundary layer over the continental areas of the Iberian Peninsula (up to 2500 m [*Crespi et al.*, 1995]) causes the dust to abate, resulting in a high impact on surface SPM levels.

[33] In the period January–March, the highest monthly PM10 means are found for the scenario NAH-S (19–

Table 2. Number of Days With Dust Outbreaks Occurred Under the Four Different Meteorological Scenarios Differentiated and Mean Daily Ambient Air Levels of PM10 Recorded at Monagrega Rural Site (Teruel, Spain) for Those Days[a]

	NAH-S	AD	NAD	NAH-A
2002				
PM10, μg/m^3	16	13		23
Days	14	8	0	48
2001				
PM10, μg/m^3	23	12	17	39
Days	4	12	30	30
2000				
PM10, μg/m^3	29	21	21	30
Days	3	11	7	25
1999				
PM10, μg/m^3	78	33	10	35
Days	2	3	10	41
1998				
PM10, μg/m^3	42	39	41	31
Days	7	2	4	31
1997				
PM10, μg/m^3	46	39	15	19
Days	6	6	16	7
1996				
PM10, μg/m^3	30	20		27
Days	9	20	0	22
Mean PM10, μg/m^3	31	21	17	30
Impact index, μg m^{-3} yr^{-1}	199	186	228	874

[a] The impact index of each type of scenario is defined as the mean number of days per year with that scenario multiplied by the mean PM10 levels recorded with that scenario.

40 μg/m^3), while in the other two scenarios occurring in this period (AD and NAD) PM10 monthly means range from 12 to 23 μg/m^3 (Table 3). In May a higher simultaneous occurrence of African and rain episodes results in low PM10 monthly means for the NAD and NAH-A scenarios (15 and 19 μg/m^3) and higher PM10 monthly means (34 μg/m^3) for the scenario AD, although this scenario is not common in May (0.7 days per month, Table 3). From June to September the monthly means of PM10 for the African episodes (NAD and NAH-A) are high (32–40 μg/m^3) with the exception of the NAD episode in September with a monthly mean of 18 μg/m^3 (Table 3). In October, similar PM10 monthly means are recorded for all scenarios (24 to 30 μg/m^3). Finally, in November and December, few episodes occurred, with relatively low PM10 monthly means for all the scenarios (12–19 μg/m^3, Table 3).

[34] Four examples of the different African dust episodes are given in Figure 11. The examples show how different types of stations (whether rural, suburban, urban background, or industrial background) record simultaneous peaks during the African episodes, whereas nonsimultaneous maxima result from local sources. The African dust contribution is added to the local SPM levels at each site, thus resulting in higher levels at the industrial background site of Onda than at the regional background one at Monagrega. Figures 11a and 11d (NAH-S and NAH-A) show how the highest SPM levels are reached under anticyclonic scenarios, as Monagrega registers increases from 11 to 46 μg PM10/m^3 (Figure 11a) and from 19 to 64 μg PM10/m^3 (Figure 11d). Conversely, under scenarios AD and NAD the SPM increases are not as marked (25–30 μg PM10/m^3 at Monagrega, Figure 11b; 15–20 μg PM10/m^3 at Monagrega, Figure 11c).

[35] The following periods can be distinguished in accordance with the seasonal distribution of the different transport scenarios and the analyses of the SPM time series:

[36] 1. In January-March, 30 episodes occurred during 1996–2002. Fourteen of these African air mass intrusions may be classified as NAH-S dust outbreaks, whereas 12 events belong to the AD type. The remaining 4 episodes belong to the NAD type. Given that the rain in the first quarter of the year is scant in eastern Iberia, there is a low frequency of wet African episodes (8 events in 7 years). Furthermore, most of these episodes take place in the lower levels of the atmosphere. Consequently, these episodes often exert considerable influence on levels of SPM (Figure 2).

[37] 2. In April, African episodes are infrequent over the Iberian Peninsula. Only 4 episodes were recorded (3 with wet deposition), 3 of them being of the AD type and the remaining one NAD.

[38] 3. In May the frequency of African dust outbreaks over the Iberian Peninsula is high, and 17 episodes occurred during the study period. Of these episodes, 10, 5, and 2 correspond to the NAD, NAH-A, and AD types, respectively. May is a very rainy month in the western Mediterranean, and as a consequence, 13 episodes were accompanied by wet deposition.

[39] 4. In June–August, as reported for May, the summer period has also a high frequency of African events (38 events in the study period). However, this period is characterized by a lower number of wet episodes than in May (13 episodes in May and 11 episodes between June and August during the study period) owing to the antyciclonic conditions of summertime.

[40] 5. In September–October, African events are less frequent than in the previous three months. However, 17

Table 3. Number of Days per Month With Dust Outbreaks Occurred Under the Four Different Meteorological Scenarios Differentiated and Mean Daily Ambient Air Levels of PM10 Recorded at Monagrega Rural Site (Teruel, Spain) for Those Days

	NAH-S	AD	NAD	NAH-A
January				
Days per month	1.0	1.1	0.6	0.0
PM10, μg/m^3	32	19	23	
February				
Days per month	1.4	0.6	0.4	0.0
PM10, μg/m^3	19	12	14	
March				
Days per month	2.4	3.3	0.3	0.0
PM10, μg/m^3	40	21	18	
April				
Days per month	0.0	1.6	0.3	0.0
PM10, μg/m^3		16	8	
May				
Days per month	0.0	0.7	3.4	4.6
PM10, μg/m^3		34	15	19
June				
Days per month	0.0	0.0	0.6	7.4
PM10, μg/m^3			40	32
July				
Days per month	0.0	0.0	0.0	6.6
PM10, μg/m^3				32
August				
Days per month	0.0	0.0	0.0	6.9
PM10, μg/m^3				36
September				
Days per month	0.0	0.0	0.6	3.4
PM10, μg/m^3			18	31
October				
Days per month	1.3	1.3	1.3	1.4
PM10, μg/m^3	30	27	25	24
November				
Days per month	0.0	0.3	1.4	0.0
PM10, μg/m^3		19	16	
December				
Days per month	0.0	0.1	0.0	0.0
PM10, μg/m^3		12		

episodes occurred in these months, 7 of them accompanied by wet deposition. The NAH-A was the dominant scenario in 10 out of the 17 episodes, followed by NAD and AD scenarios, whereas only one NAH-S episode occurred in this period.

[41] 6. In November, five episodes were found, 4 of them with wet events. The high rainfall rate of this month accounts for the high proportion of wet episodes (Figures 2 and 3). All these episodes are of the NAD and AD type.

[42] 7. In December, only 1 episode occurred in the 7-year period (AD type).

4. Conclusions

[43] This study focused on the occurrence and seasonal distribution of African dust outbreaks over the eastern Iberian Peninsula for the period 1996–2002, combining information from the time series of (1) chemistry of wet deposition and (2) daily levels of SPM.

[44] The results from back trajectory analysis showed that around 53% of the days were influenced by Atlantic advective flows, 15% by African air masses, 12% by regional recirculation episodes and 20% by European (including Mediterranean) transport episodes.

[45] During the 7-year period, 112 African dust episodes accounted for a total of 378 days, with a mean duration of 3.3 days per episode and a mean of 16 episodes per year.

[46] An impact on levels of SPM at the air quality monitoring stations was detected in 93 out of the 112 episodes, and wet deposition occurred simultaneously with African events in 49.

[47] The monthly distribution of African intrusions is characterized by three modes with a clear predominance of the period May to August, whereas the lowest monthly occurrences are recorded for December, November and April.

[48] On the basis of meteorological evaluation, four different scenarios causing transport of dust air masses from northern Africa were distinguished. These scenarios were characterized by the presence of (1) a North African high located at surface levels (NAH-S), (2) an Atlantic depression (AD) situated in front of Portugal, (3) a North African depression (NAD), and (4) a North African high located at upper levels (NAH-A). These meteorological patterns showed a clear seasonal trend.

[49] As regards source areas, the NAH-S and AD scenarios favor air mass transport at low levels from the western Sahara, Mauritania, and the Sahel. These situations occur mainly in winter. The NAD scenario may cause airflow from Algeria, Tunisia, Libya, and Chad and the NAH-A scenario favors transport from the western Sahara, Mauritania, and Algeria but at high altitudes (2500 m or above).

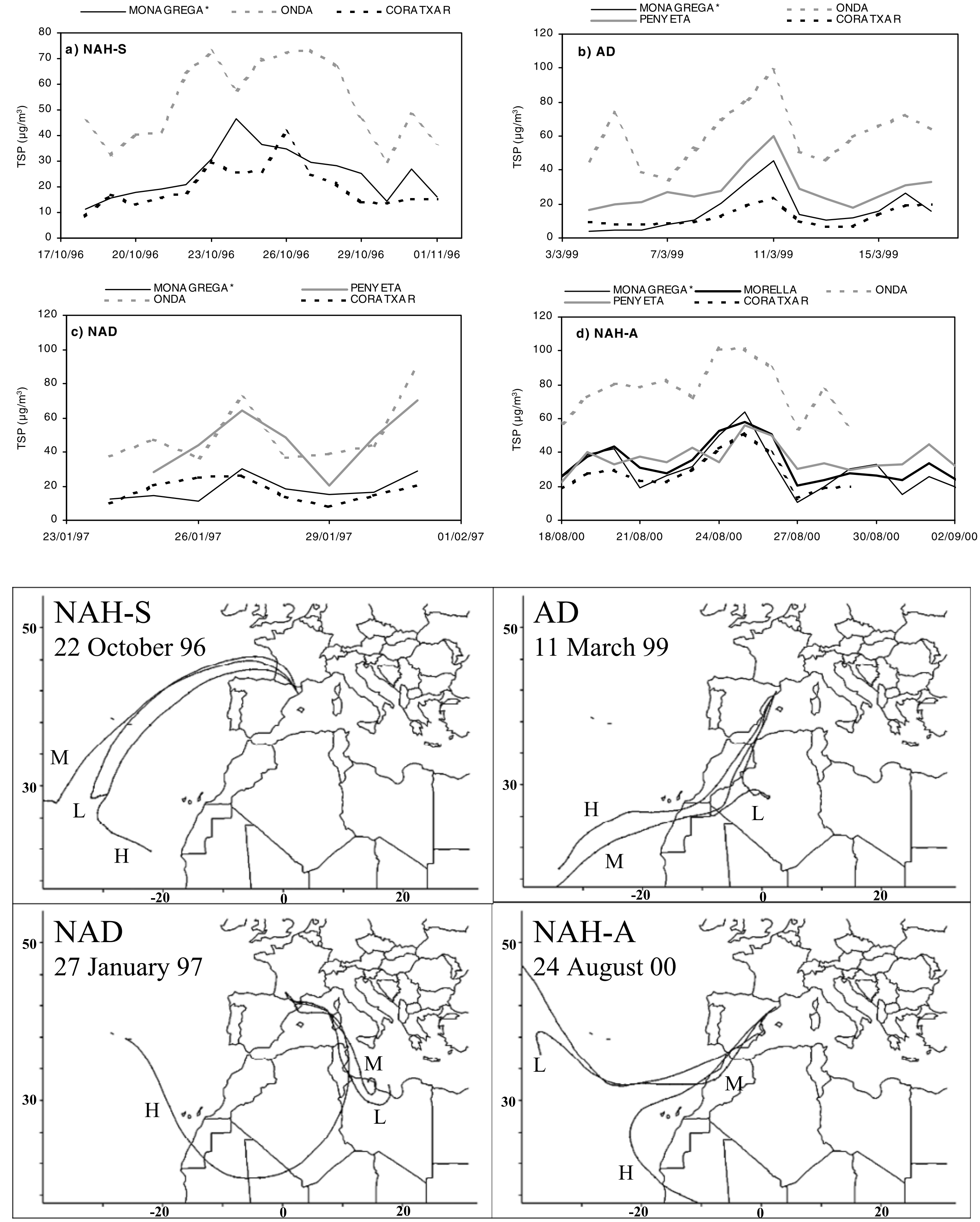

Figure 11. Examples of SPM episodes corresponding to the four meteorological scenarios defined: (a) NAH-S, (b) AD, (c) NAD, and (d) NAH-A. Back trajectory analysis for the given dates.

This scenario is produced exclusively in May and in the summer months. African dust outbreaks have an important impact on the regional background SPM levels in eastern Iberia. Mean daily levels of PM10 at the rural station in Monagrega show increases when a dust outbreak occurs. The mean daily levels in Monagrega for the days with African intrusion of the NAH-S and NAH-A type are 31 and 30 $\mu g/m^3$, whereas when the AD and NAD scenarios are produced, the daily means are lower (21 and 17 μg/m^3 respectively). Nevertheless, taking into account the number of days during which each scenario is produced, the impact on PM10 levels in Monagrega was studied. The impact of the NAH-A scenario (mainly occurring in summer) proved to be approximately 4 times greater than that of the other three scenarios.

[50] **Acknowledgments.** This study was financed by the Spanish Ministries of the Environment and Science of Technology, project REN2001-0659. The authors would like express their gratitude to the Atmospheric Modeling and Weather Forecasting Group in the University of Athens for the SKIRON model outputs; to the NASA Goddard Space Flight Center, NOAA Air Resources Laboratory (ARL), Naval Research Laboratory; and to SeaWIFS Project (NASA) for the provision of the TOMS-AI maps, the HYSPLIT transport and dispersion model, the NAAPs aerosol maps, and the satellite imagery, respectively. Meteorological charts were provided by the NOAA CIRES Climate Diagnostics Center, Boulder, Colorado, and the NCEP Climate Diagnostics Center. The authors also acknowledge ENDESA, the Autonomous Governments of Valencia and Catalunya for providing the data from the air quality networks and for supporting this study and Meteocat for supplying daily rainfall data from Santa María de Palautordera.

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M. Alarcón, Department of Physics and Nuclear Engineering, Polytechnic University of Catalonia, Av. V. Balaguer s/n, E-08800, Vilanova i La Geltrú (Barcelona), Spain.

A. Alastuey, S. Castillo, X. Querol, S. Rodríguez, and M. M. Viana, Institute of Earth Sciences "Jaume Almera," CSIC, C/Luis Solé i Sabarís s/n, E-08028, Barcelona, Spain.

A. Avila and M. Escudero, Centre for Ecological Research and Forestry Applications (CREAF), Building C, Autonomous University of Barcelona, E-08193, Bellaterra (Barcelona), Spain. (m.escudero@creaf.uab.es)

E. Cuevas, Izaña Atmospheric Observatory, INM, C/La Marina, 20, 6^{a} Planta, E-38001, Santa Cruz de Tenerife, Spain.

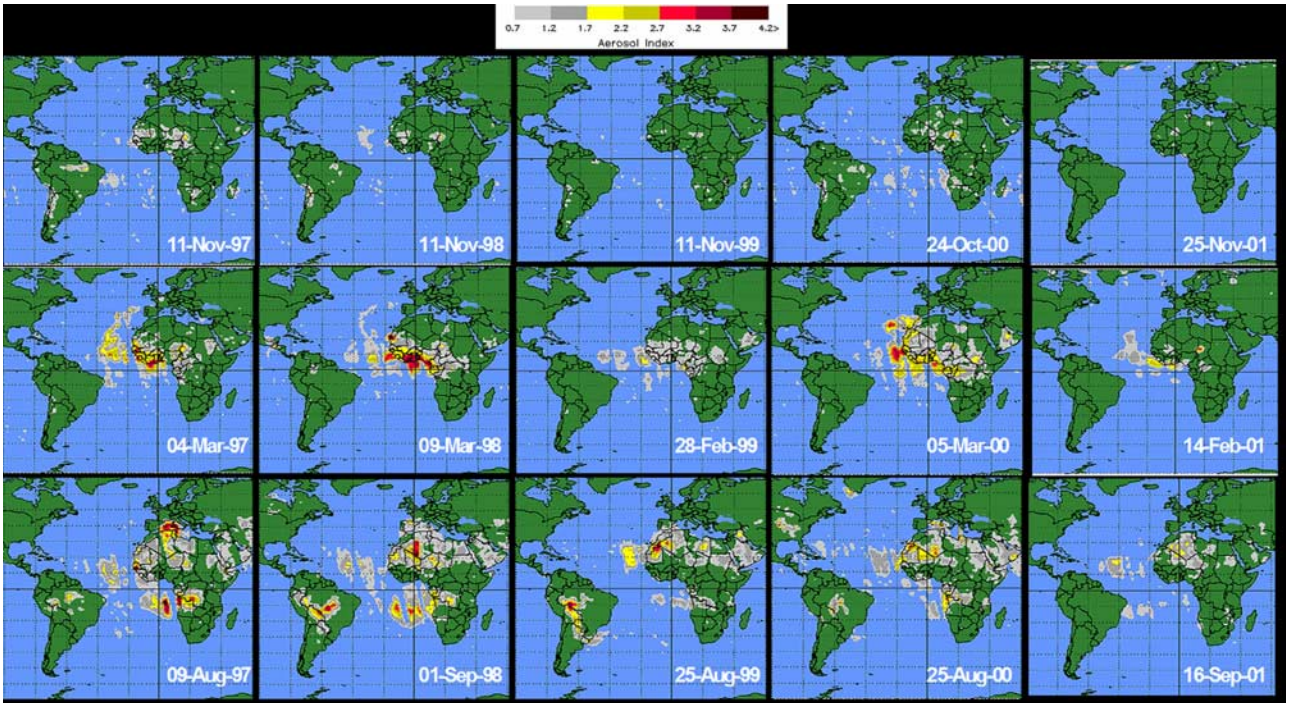

Figure 6. Aerosol index from TOMS-NASA for selected days in different periods of the year: autumn, late winter, and summer for 1997–2001.