

Weak Pressure Gradient over the Iberian Peninsula and African Dust Outbreaks

A New Dust Long-Transport Scenario

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African dust outbreaks over the Iberian Peninsula have been related to four synoptic patterns responsible for the advection of dust:

- 1) *A North African high located at surface level.* African dust penetrates Iberia via an Atlantic arch due to an anticyclone located over southern Iberia, North Africa, the western Mediterranean, or off the Atlantic coast. The reference system of the northern Atlantic high at these latitudes, the Azores high, does not appear or it is displaced to show the same strength over Iberia as in its typical position, so convex plumes reach Iberia after covering the Atlantic coasts of the peninsula. The transport of desert dust happens at lower atmospheric levels (< 1,000 m). Figures 1a and 1b present an example of this synoptic pattern on 31 December 2006.
- 2) *An Atlantic depression centered over northwestern Africa, western Iberia, or the southwest of the Portuguese coast with an associated high or ridge over the Mediterranean Sea.* African dust reaches Iberia due to a northward flow from Africa that

transports the dust in lower and upper levels. Figures 1c and 1d present an example of this synoptic pattern on 1 November 2006.

- 3) *A North African depression.* A system of three centers of pressure controls the flows affecting southern Europe and the Mediterranean basin: a trough placed over northern Africa, the western Mediterranean, or even the Iberian Peninsula; the Azores high located to the west of the trough; and a frequent high or ridge over eastern Europe or the eastern Mediterranean basin. This scenario could be considered a rotation of the former pattern, with the depression in an eastern position. In this case, the transport of African dust toward Iberia is across the Mediterranean and is limited to the lower levels. Figures 1e and 1f present an example of this synoptic pattern on 16 June 2006.
- 4) *A North African high located at upper levels.* This scenario is associated with thermal lows over northern Africa, or even the Iberian Peninsula, due to the intense heating in summer. Once the convective system has injected the dust in the midtroposphere (up to 5,000 m), a massive transport of dust covers the western Mediterranean basin and Iberia, forming a wide plume toward the north. Figures 1g and 1h present an example of this synoptic pattern on 17 May 2006.

Consequently, particulate matter (PM) levels in Iberia are expected to rise when any of these atmospheric synoptic scenarios prevail. Nevertheless, PM levels might not increase due to wet deposition, as Spain receives the most African-derived dust rain events of any European country. A temporal revision of these African dust outbreaks confirmed the linkage between these meteorological conditions (cause) and the worsening in air quality (consequence).

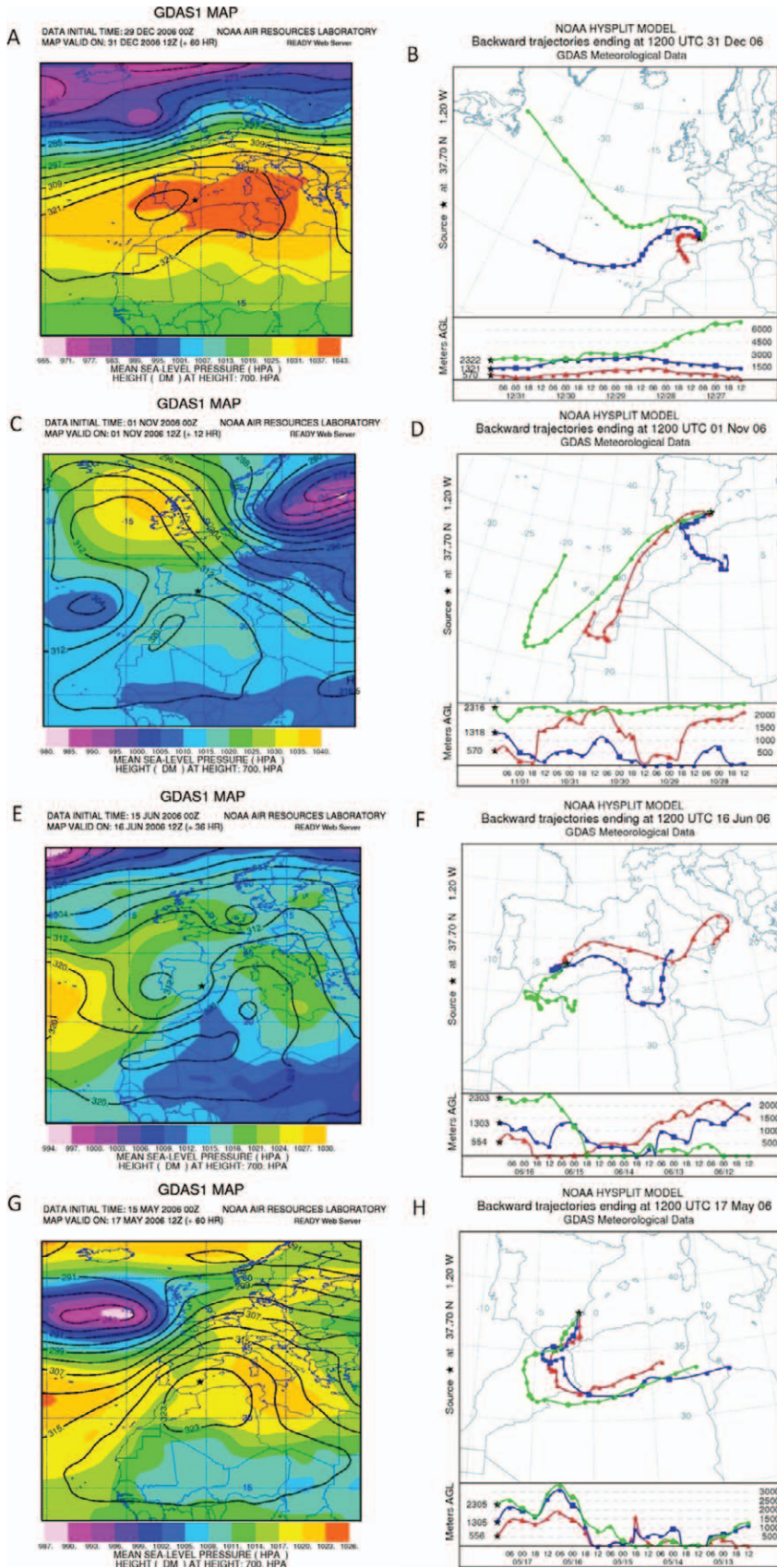
In this study, a meteorological scenario different than the above situations is evaluated. An in-

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crease in African dust in the southeast Iberian Peninsula is caused by a scenario not previously defined. African dust was detected at surface levels in southeastern Iberia during 562 of 1,613 days between January 2004 and May 2008. During this period, 117 of these African dust days were associated with the new synoptic pattern presented here. This newly identified pattern exemplifies how transition and/or stagnation conditions between strong synoptic systems can also result in augmentation of PM levels with a north African origin. This is appealing, as current European legislation allows air pollution managers to account for natural contributions when assessing legal accomplishments anytime there is solid proof of such natural contributions. As a consequence, a solid knowledge of the circumstances causing these events is necessary. Pursuing this further, an example of this newly identified scenario

FIG. 1. Examples of four synoptic patterns conducive to African dust outbreaks over the Iberian Peninsula. Mean sea level pressure is colored, and 700-hPa heights are solid black lines (left pictures); five-day air mass isentropic back trajectories arriving in the southeastern Iberian plateau are indicated at 750 (red), 1,500 (blue) and 2,500 (green) m above sea level for a point in the Iberian southeast (right pictures). (a) and (b): 31 Dec 2006; (c) and (d): 1 Nov 2006; (e) and (f): 16 Jun 2006; (g) and (h): 17 May 2006.

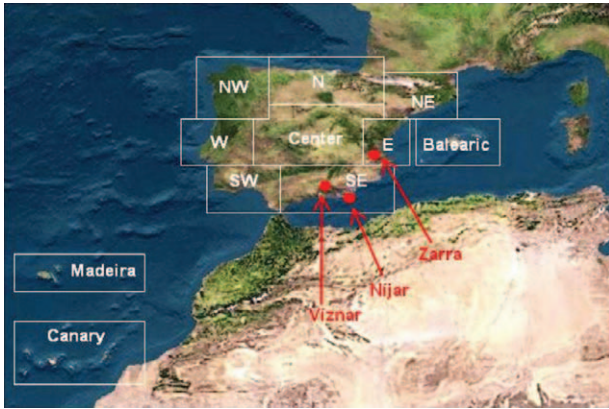


FIG. 2. Geographical distribution of sectors of the network of regional background stations of Portugal and Spain with the three regional background stations considered in this study: Níjar, Víznar, and Zarra. Figure modified from Querol et al. (2010), background image courtesy of Google Earth.

that occurred during October 2006 will be discussed in the subsequent paragraphs.

Two regional background stations in southeastern Iberia (Níjar and Víznar) registered the occurrence of African dust on 8–11 October 2006. Another regional background station in the eastern sector of Iberia (Zarra) observed the African dust on 9–11 October 2006. This geographical distribution of sectors (Fig. 2) is based on the network of regional background stations that the Portuguese authorities and the Spanish Ministry of Environment and Rural and Marine Affairs use for monitoring background air pollution. Although Zarra is considered to be in the eastern sector of Iberia, it is also utilized to study the synoptic patterns during the elevated PM level events in the southeast. The proximity of Zarra to the southeast sector and the additional data the location provides help illustrate the evolution of an African dust outbreak.

An African dust outbreak is identified at a station when the level of PM₁₀ (particulate matter $\leq 10 \mu\text{m}$) in a day exceeds the monthly (30 days) moving 40th-percentile value, excluding outbreak days. This 40th-percentile value is assumed to be the theoretical concentration of PM at the regional background station during a day without a dust outbreak. The benefit of taking the values of percentiles between 5th and 50th has been discussed in literature, with results indicating that using the 30th and 40th percentiles are the most advisable in Spain. As a result, Spanish legislation currently establishes the 40th percentile as the value to consider. The subtraction of this 40th-percentile value from the daily PM₁₀ will yield the net African dust. To illustrate this, Table 1 depicts the registered PM₁₀ and the net African dust at Níjar, Víznar, and Zarra during the 8–11 October 2006 dust outbreak, as well as one day before and one day after the outbreak.

Synoptic patterns at mean sea level pressure and at 700 hPa are presented in Fig. 3. Five-day air mass isentropic back trajectories arriving in the south-

TABLE 1. Concentration of PM₁₀ and estimated net African dust in $\mu\text{gPM}_{10}\text{m}^{-3}$ at Níjar, Víznar, and Zarra during the African dust outbreak on 8–11 Oct 2006 and one day before and after.

Day	$\mu\text{gPM}_{10}\text{m}^{-3}$	Níjar	Víznar	Zarra
7	Concentration	16	22	18
	Estimated net African dust	No dust outbreak	No dust outbreak	No dust outbreak
8	Concentration	19	26	18
	Estimated net African dust	3	14	No dust outbreak
9	Concentration	19	95	10
	Estimated net African dust	3	83	3
10	Concentration	16	63	18
	Estimated net African dust	<1	51	10
11	Concentration	28	19	18
	Estimated net African dust	12	7	10
12	Concentration	23	18	7
	Estimated net African dust	No dust outbreak	No dust outbreak	No dust outbreak

eastern Iberian plateau at 750, 1,500, and 2,500 m above sea level on 7–12 October 2006 are displayed

in Fig. 4. These back trajectories were computed with the Hybrid Single-Particle Lagrangian Integrated

Trajectory (HYSPLIT) model via the Real-time Environmental Applications and Display System (READY), a world network of data managed by the Air Resources Laboratory at NOAA. Aerosol maps of the Navy Aerosol Analysis and Prediction System (NAAPS) for those days are presented in Fig. 5.

On 7 October 2006, the Iberian plateau was affected by a high over the Bay of Biscay at mean sea level pressure (Fig. 3a). The Azores High remained with weak influence over Spain and Portugal at 700 hPa. The origin of the southeastern Iberia back trajectories was the northwestern Atlantic (Fig. 4a). These humid air masses were discharging the moisture as wet deposition over the northern Spanish territories until they reached the Iberian southeast based on the database of the State Meteorological Agency of Spain (AEMET, not shown). No wet deposition was recorded over the southeastern territories during the period of the dust outbreak. The NAAPS map presents minimum optical depth for dust over the Spanish plateau at this time (Fig. 5a).

On 8 October 2006, high pressure became more accentuated over central Europe at mean sea level (Fig. 3b). Conversely, southwestern territories of Europe, the western Mediterranean, and northern Africa remained under barometric stagnation at 700 hPa. The back trajectories of the upper levels penetrate the peninsula through the western Atlantic respect to Iberia; they even originate from the occidental coasts of Africa (Fig. 4b). Moreover, a slowdown of the back trajectories

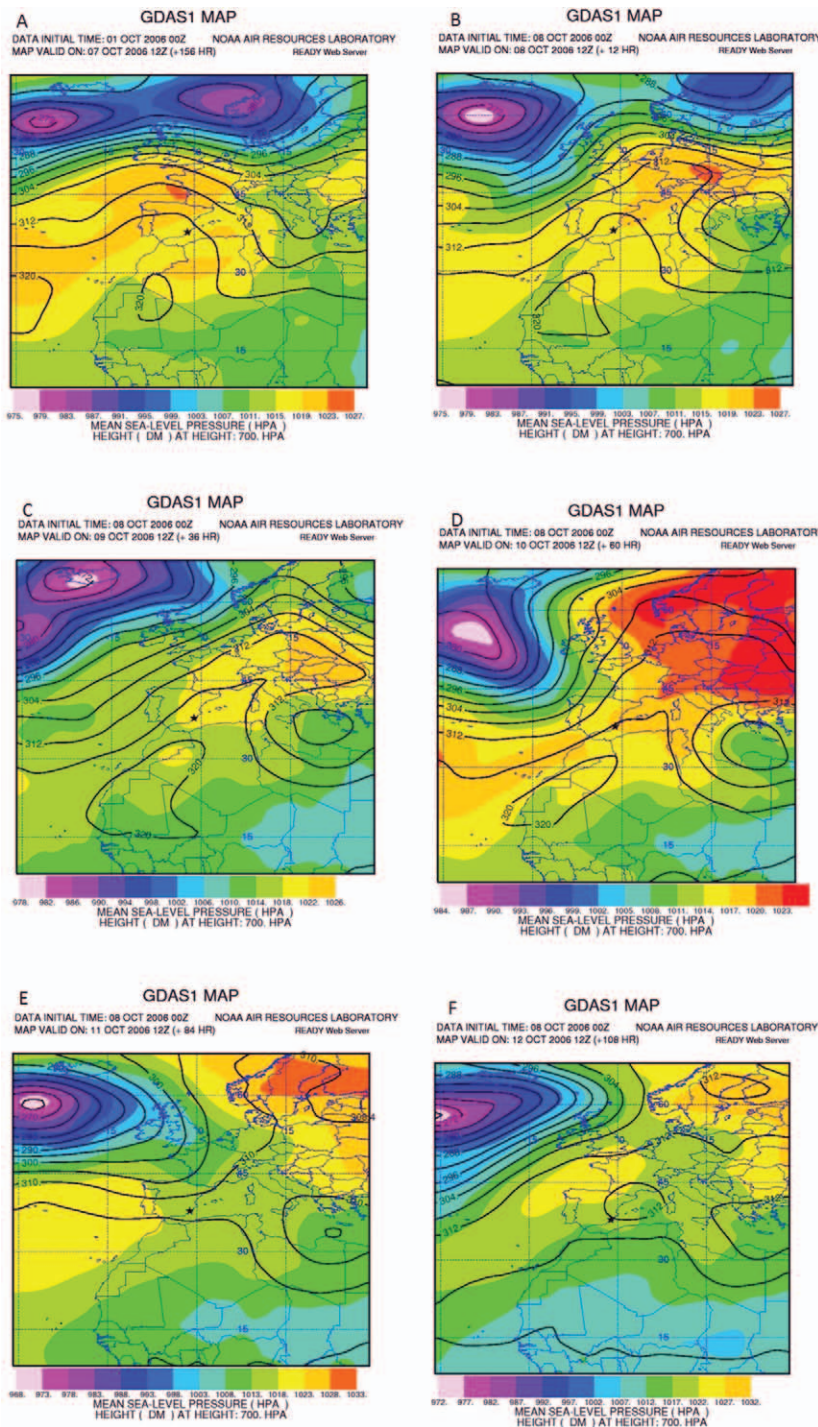


FIG. 3. Forecast charts for the African dust outbreak over the Iberian southeast on 8–11 Oct 2006. One day before and after the event are also provided. Mean sea level pressure is colored and 700-hPa heights are solid black lines. (a) 7 Oct; (b) 8 Oct; (c) 9 Oct; (d) 10 Oct; (e) 11 Oct; and (f) 12 Oct.

is observed on their way to southeastern Iberia. This slowdown is depicted as a circular trajectory during the latter portions of the trajectory period. This feature may be related to the presence of African dust over the Iberian southeast, as this zone is only about 200 km from Africa. The vicinity of the Iberian southeast to Africa implies that once the air masses have left the African continent, they are able to reach Spain with only a simple recirculation over the area. The NAAPS analyses (Fig. 5b) indicate a ridge that extends over Iberia from Africa with optical depths for dust between 0.4 and 0.8 and concentrations of dust up to $80\text{--}160\ \mu\text{gPM}_{10}\text{m}^{-3}$.

On 9 October 2006, the system of high pressure at mean sea level continues over Central Europe, with scarce influence over Spain (Fig. 3c). The western Mediterranean basin remains as the day before at 700 hPa, far away from relevant systems of pressure. The circular back trajectories (Fig. 4c) convert into loops when they reach their destiny over southeastern Iberia. These loops, especially in the case of the highest back trajectory, penetrate the north of Morocco about 100 km. The NAAPS maps present optical depths for dust between 0.8 and 1.6 over the southeast of the Iberian Peninsula and the stain of dust covers the Iberian plateau with peaks up to $80\text{--}160\ \mu\text{gPM}_{10}\text{m}^{-3}$ (Fig. 5c). The notably high levels of PM₁₀ (Table 1) observed at Víznar [1,071 m above sea level (asl)] in comparison to Níjar (353 m asl) and Zarra (523 m asl) are explained by the differences in altitude.

On 10 October 2006, the high pressure extended from central Europe to Scandinavia at mean sea level, so the influence

over Spain is further diminished (Fig. 3d). The plateau is constrained under stagnant conditions. At the same time, a system of high pressure is located over Morocco and Sahara at 700 hPa. This description of a

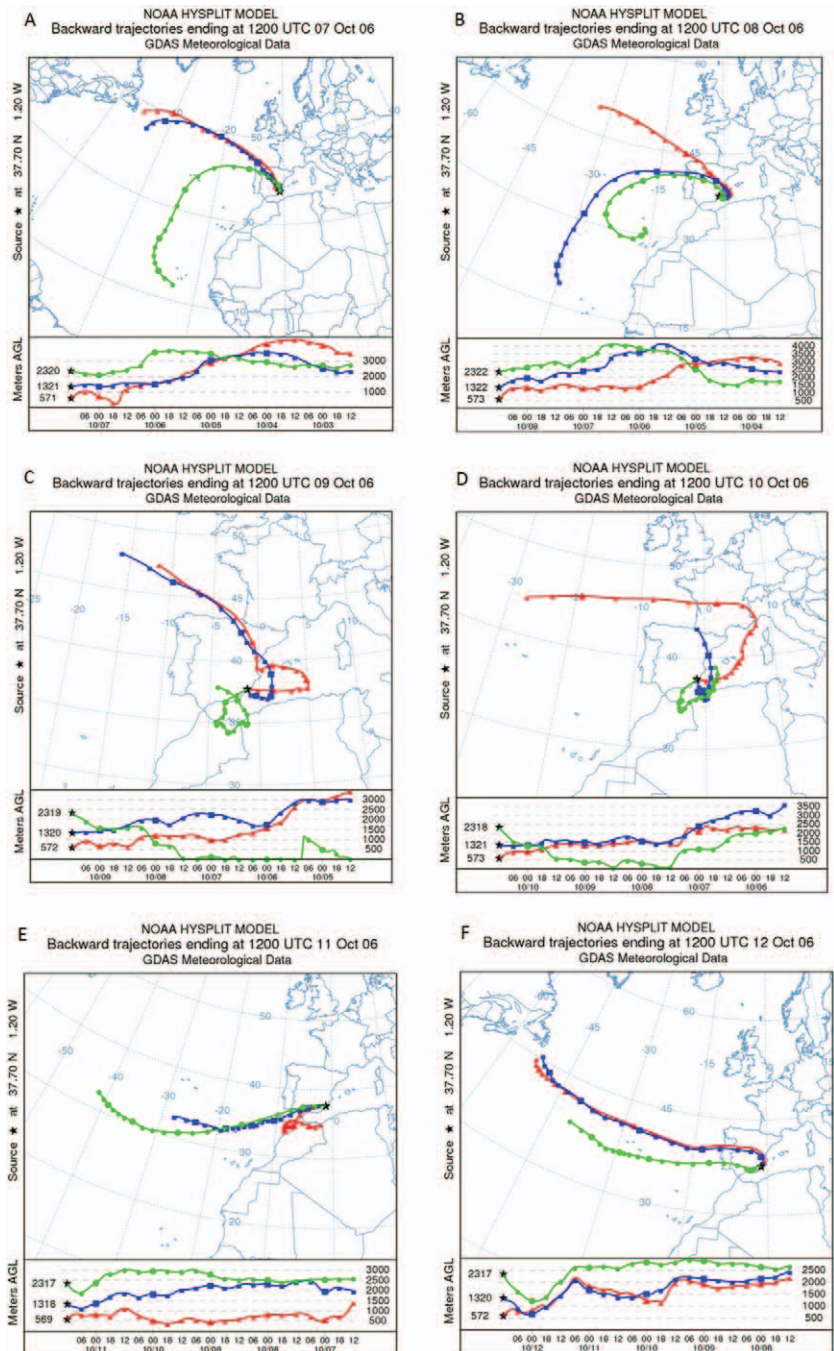


FIG. 4. Five-day air mass isentropic back trajectories arriving in the southeastern Iberian plateau at 750 (red), 1,500 (blue) and 2,500 (green) m above sea level for a point in the Iberian southeast during the African dust outbreak from 8 until 11 Oct 2006. One day before and after the event are also provided. (a) 7 Oct; (b) 8 Oct; (c) 9 Oct; (d) 10 Oct; (e) 11 Oct; (f) 12 Oct.

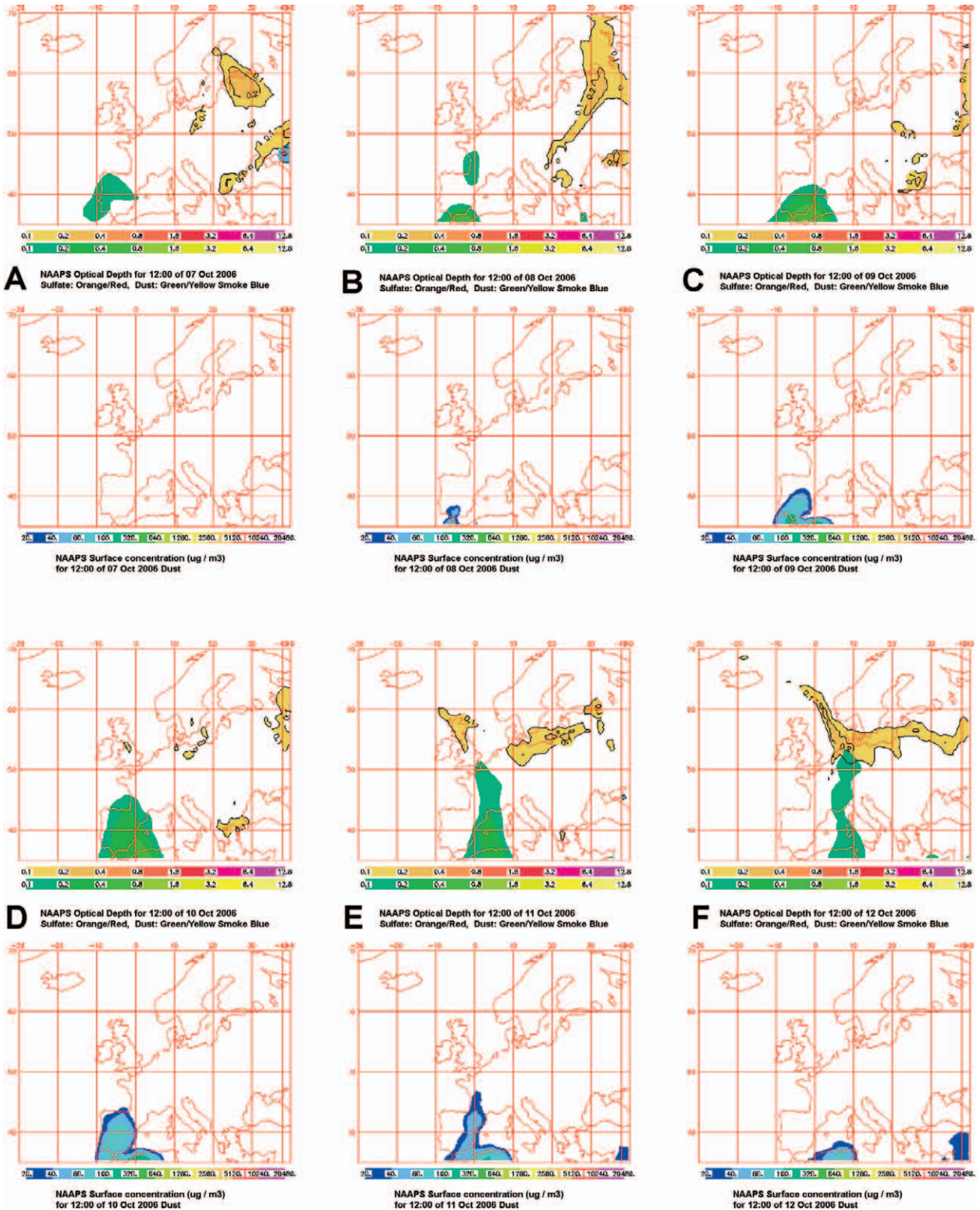


FIG. 5. NAAPS analysis of the (top) optical depth and (bottom) surface concentration of aerosol during the African dust outbreak over the Iberian southeast on 8–11 Oct 2006. One day before and after the event are also provided. (a) 7 Oct; (b) 8 Oct; (c) 9 Oct; (d) 10 Oct; (e) 11 Oct; and (f) 12 Oct.

high centered over the north of Africa at upper levels of the atmosphere accompanied by lows at mean sea level corresponds to one of the scenarios described previously in literature (Escudero et al. 2005). The loops of the back trajectories (Fig. 4d) are notable. The highest air-parcel trajectories originate in air masses relatively close to their endpoints over southeastern Iberia. The lowest air parcels slow down considerably over the western Mediterranean during the latter stages of their trajectories. To summarize, the highest air masses remain within a radius of around 800 km during the five days, when substantial levels of African dust are detected. The signal for the optical depth for dust from the NAAPS analysis (Fig. 5d) covers Iberia and the western Mediterranean basin, whereas the stain of dust extends over most of Iberia, peaking with 80–160 $\mu\text{gPM}_{10}\text{m}^{-3}$.

The African dust outbreak over southeastern Iberia ends during 11 October 2006. The high pressure at mean sea level continues to move away through Scandinavia, and the Azores High is not strong enough to cause important advections over the Spanish southeast (Fig. 3e). The western Mediterranean basin remains under a very light flow at 700 hPa. The back trajectory of the lowest air masses runs through the Gibraltar Strait with loops (Fig. 4e). Simultaneously, the highest air masses start to change their origin. Although they still penetrate through the Iberian southwest, sweeping along the dust in front of the African coasts, they originate thousands of kilometers west over the Atlantic Ocean. As a consequence of the barometric valley over the western Mediterranean basin, the NAAPS analysis of optical depth for dust (Fig. 5e) presents a narrowing and a lengthening of the covered area, including the whole Spanish east coast up to the English Channel. The values of optical depth for dust account for 0.1–0.2 in most of the area. This geographical distribution is similar to that shown by the NAAPS map for dust, with levels peaking up to 40–80 $\mu\text{gPM}_{10}\text{m}^{-3}$.

By 12 October 2006, the dust event has ended (Table 1). The Iberian plateau is again affected by a high over the Bay of Biscay and residual systems of pressure over the Mediterranean basin at mean sea level (Fig. 3f). The back trajectories originate in the Atlantic, thousands of kilometers away from western Iberia [i.e., in the case of the lowest back trajectories close to the Canadian coasts (Fig. 4f)].

As this case illustrates, by examining the levels of PM every day and the models of the origin and trajectory of the air masses, it can be concluded that

synoptic patterns without strong systems can be responsible for peaks in atmospheric pollution across parts of Iberia. These peaks are due to a natural source hundreds of kilometers from the affected area. The authors believe this scenario could be extended to other places with increases in pollution and no dispersive conditions. Similarly, Yu and Pielke (1986) observed how slow-moving high pressure conditions were associated with stagnant conditions causing a worsening of atmospheric pollution in the Lake Powell Area (southern Utah/northern Arizona), and Kallos et al. (1993) noticed some of the worst pollution episodes in Athens, Greece, caused by weak pressure gradients associated with transport of warm air masses from northern Africa. Although only three regional background stations have been assessed in this document, the interaction between natural and anthropogenic pollutants might be expected to increase the levels of secondary pollutants where the human factor is more prominent.

Finally, the scenario presented here is different than the associations established by Escudero et al. (2005) between synoptic patterns and the occurrence of African dust over the Iberian plateau. As with the four synoptic scenarios described by Escudero et al. (2005), the pattern described here does not necessarily indicate the detection of African dust in the Iberian southeast. In other words, the measure of African dust can be related to stagnation conditions, but it does not imply that every time stagnation conditions appear there is an advection of African dust toward the Iberian southeast. During the 53 studied months, this stagnant regime appeared 60 times accounting for 117 days in total. The duration of the events under this regime was 1 day (33 times), 2 days (19 times), 3 days (once), 4 days (3 times), 6 days (twice), 7 days (once), and 12 days (once). Nevertheless, on just four occasions (7 days in total) this regime appeared separated in time by more than 24 hours from any of the synoptic patterns responsible for the transport of dust over the Iberian Peninsula, as described by Escudero et al. (2005). This regime, along with the other types of synoptic patterns, suggests that the presence of dust in the Iberian southeast under the new scenario has mainly either a residual, transitional, or incipient character of any other dust-transporting synoptic patterns. Back trajectories showing many loops can be considered as a signal for the new scenario. The four times when the new scenario did not appear in the vicinity of the others would correspond to the beginning of any

other scenario that did not develop. In summary, this stagnant system would be joined to the presence of African dust over the Iberian southeast if any of the other synoptic patterns is somehow (either in time or generation) associated with it.

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