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A JET STREAM ASSOCIATED HEAVY DUST STORM IN THE WESTERN MEDITERRANEAN

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Abstract. Examination of the dynamical structure of a heavy dust storm event over the western Mediterranean revealed an almost exact coincidence of the western boundary of the dust plume with a cold front and a significant jet stream. A confrontation was found between the dry desert air mass associated with a notable downward flowing jet stream and the moister Mediterranean air mass. Vertical cross sections across and along the dust plume indicated that the high mountain Ahaggar region over the Sahara was probably the source of dust, which was transported northward more than 2400 km and washed out by heavy rainfall.

Introduction

The Saharan desert is considered the main source of mineral dust in the northern hemisphere. *Bucher and Lucas* [1984] and *Loye-Pilot et al.*, [1989] reported that the entire 20x10^6 tons/yr injected annually into the atmosphere toward France comes from the Sahara. *Chester et al.*, [1984] and *Prodi and Fea* [1979] showed that Saharan dust is transported to the Tyrrhenian Sea and over Italy. Many investigators have dealt with the dust effects in southern Europe and in Israel, including *D'Almeida* [1986], *Schuetz* [1989], *Westphal et al.*, [1987], *Joseph et al.*, [1973], *Yaalon and Ganor* [1973] and *Ganor* [1991].

The mobilization of the dust particles and its relation to atmospheric dynamics, especially as observed in empirical case studies, remains unclear mainly because of lack of appropriate data. The relationship of dust storms to wind intensity is quite straightforward, as discussed by *Bagnold* [1965] and *Gillette* [1979], while *Ganor* [1975] and *Alpert and Ziv* [1989] demonstrated a strong relationship between the jet stream and the dust plumes intrusion in the Mediterranean. But, atmospheric circulations near the dust plumes are difficult to analyze directly due to the relatively short duration of most dust episodes, and the existence of only a few meteorological stations, especially upper-level ones in the desert and above the Mediterranean Sea where these storms are common. Investigating dust plumes via satellite pictures is complicated by their frequent association with widespread cloudiness that obscures the geometry of the plumes even above sea when they are observable. These various constraints are absent only a few times a year. On December 30, 1985, 1235 UTC, a clear satellite picture of a relatively large plume stretching from Lybia through the Mediterranean Sea to Italy was observed virtually cloudless (Figure 1). The occurrence so close to 1200 UTC, the synoptic primary observation time, was especially fortuitous.

This case study focused on the three-dimensional atmospheric circulations associated with the dust plume in that unique event, with special attention to the relationship of the Saharan plume to the jet stream and cyclone structure.

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General Synoptic Situation

Figures 2 and 3 present the surface and 300-hPa maps for December 30, 1985, 1200 UTC, respectively. Figure 2a illustrates the areal distribution of the plume (from Figure 1), drawn to show its geographic position relative to the synoptic situation. Figure 2b shows the corresponding 1000 hPa map over a larger domain for the same time, based on the ECMWF (European Centre for Medium Range Weather Forecasts), initialized analysis. A deep surface low is centered west of Corsica, with a noticeable (winds of 10-15 m s^{-1}) cold front extending to southwestern Spain and a warm front to northern Yugoslavia (former) via northern Italy. The dust is found at the southwestern part of the surface cyclone, extending from Lybia to southern Italy. Although *Yaalon and Ganor*, [1973] showed that dust plumes are associated with fronts, the data in Figure 2a is insufficient to confirm the existence of a secondary frontal wave. However, the cloud coverage seen on the satellite picture (Figure 1) seem to indicate a secondary cyclone over south Italy, slightly west to the northern edge of the plume. Using this and other available synoptic data, the secondary frontal structure was also drawn in Figure 2a. Visibilities were reduced to 2-3 km below the plume both over land and over Malta (36°N, 14.5°E), with a few meteorological stations at the northern section of the plume reporting visibilities even less than 1000 m associated with fog and low stratus. Messina (~38°N, ~15.5°E) issued such a report, and the weight of suspended particulate matter measured by a high-volume sample collector was 164 μg m^{-3} for 24 hours (F. Fantauzzo, personal communication, 1990) a value about 4 times higher than a few days earlier. Prior to 1200 UTC, only few millimeters (or drops) were observed over south Italy and Yugoslavia (former), although large amounts of rainfall (30-40 mm) were reported in the ensuing 6 hours.

Figure 3 is a plot of the isohypes and

Fig. 1. A Meteosat satellite infrared image over the Mediterranean region for December 30, 1985, 1235 UTC, showing clearly a plume from Libya across the Mediterranean Sea towards south Italy.

isotherms at 300 hPa along with the observed wind vectors. The low is centered over north Finland, with a secondary minimum over Spain and a southwesterly jet over our area of interest, south Italy, which reached speeds of 50-60 m s^{-1}.

Atmospheric Cross Section Through the Dust Plume

Method

The atmospheric circulation in the vicinity of the plume was evaluated by the ECMWF initialized data sets. These data sets have a horizontal resolution of 2.5° x 2.5°, and seven mandatory pressure levels: at 1000, 850, 750, 500, 300, 200, 100 hPa. As noted by *Bengtsson*, [1988], the new observing systems like satellites provide a good coverage of data over previously data-sparse regions. The Mediterranean region, particularly above the sea and to its south, has relatively few stations, and as *Alpert et al.*, [1990] demonstrated, the ECMWF data sets are very useful for studying cyclonic structures even on the subsynoptic scale.

This unique data set was used in the present work to study the association between the dust plume and the jet stream above it. The method described previously by *Neeman and Alpert* [1990] employs a specially developed four-dimensional computer analysis program, 4DCAP, that allows one to choose any two-dimensional cross-section of any atmospheric variables, such as wind vectors, humidity and potential temperature. Humidity is stressed here since the origin of

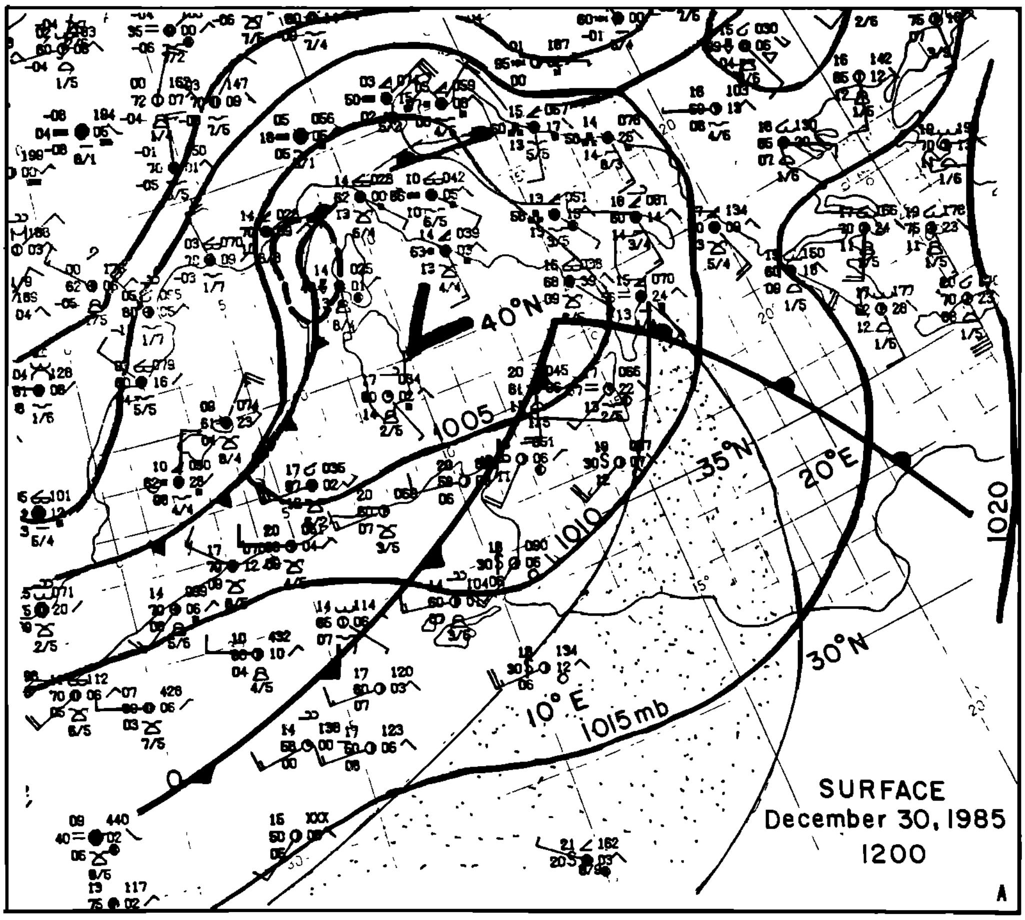


Fig. 2. Synoptic maps for December 30, 1985, 1200 UTC. (a) Western Mediterranean surface showing a main cyclone along with frontal systems. The dust plume is drawn above the map. (b) The larger domain 1000-hPa chart based on ECMWF initialized analysis showing the isohypses with a 4-dm interval. Wind arrows represent 9-hour displacements.

the dust plumes is usually very dry, and the evolution of the dry air mass moving northward across the Mediterranean Sea is traceable by humidity. In addition, the dry desert aerosols are strongly influenced by humidity, for example, particle swelling due to water absorption may cause fog or mist and even turn to ice nuclei [*Levin et al.*, 1990].

Atmospheric Cross Sections

The evolution of the plume and its surrounding atmosphere was followed drawing several cross sections parallel to the west Mediterranean Libyan coast (Figure 4). The areal distribution of the plume corresponding to Figure 1 is also shown for reference. The sharp border of the plume above sea was extended over land consistent with surface observations (Figure 2a), and the following cross section analyses.

Figure 5a shows the wind vectors and isolines of the relative humidity (RH) through the plume's head in cross section A. A prominent feature is the coincidence of the dust plume with the confrontation between a highly humid air mass to the west and a very dry air mass to the east, up to an altitude of about 600 hPa and associated with a substantial upward motion. Above 600 hPa the opposite confrontation exists: the humid air mass is located to the east of the plume and the RH is up to 90%. This zone of high RH corresponds well with the altocumulus cloud cover in Figure 1 between the plume and Greece (23°E). Beneath this cloud layer, whose base is about 5 km, there is a zone of maximum upward motion ($W \simeq 0.3$ Pa s^{-1} ~3 cm s^{-1}) at the front of the plume (Figure 5a). This is probably related to the aforementioned warm front.

Figure 5b presents the more southern cross section designated as B (Figure 4) parallel to and in close proximity to the Libyan coast. The dry air mass of the plume already appears modified by the sea to an altitude of about 700 m above sea level ($\Delta p \simeq 70$ hPa); this will be discussed in cross-section D. This modification occurred at a relatively short distance of about 100 km, reaching a maximum depth at about 28°E where the coastal distanc is somewhat greater. The confrontation of the air masses in both the lower and upper tropospheres are very similar to those mentioned earlier in cross section A.

Cross section C in Figure 5c is further inland at about 500 km from the Libyan coast. Again, the plume is located between an extremely dry air mass (~20% RH at surface) and the intrusion of moist air from above (at ~10°E). At the

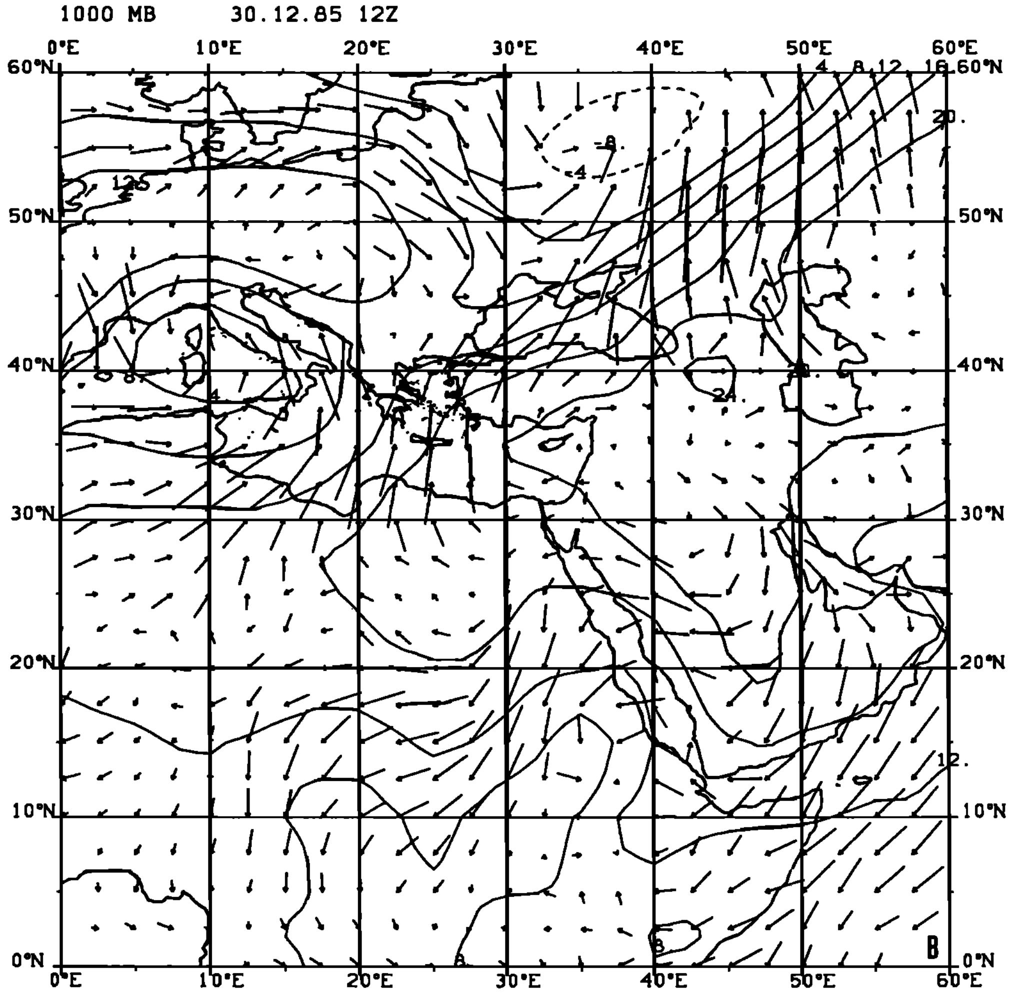


Fig. 2. (continued)

upper levels (300-400 hPa), a maximum RH of 90% directly above the plume is almost completely surrounded by very dry air. The sharp RH gradients are particularly noticable at 700 hPa, where a gradient of 30%/150 km is reached.

The variations along the plume are illustrated in Figure 5d cross section D, which cuts through the plume perpendicular to the North African coast (see Figure 4). The surface RH gradually increases from less than 20% at the plume's tail to about 90% at its head over southern Italy. At around 1500 m (850 hPa altitude) a dry air mass tongue intrudes from the Sahara above the Mediterranean into southern Italy, evidenced by the sharper curvature of the RH contours at the 850 hPa level between 30^0 and 40^{0}N. This dry air mass presumably corresponds to the altitude and the vertical dimensions of the plume. Hence we conclude that the plume's center is about 1500 m above mean sea level and has a vertical depth of about 1 km. It seems quite surprising that the ECMWF data with horizontal resolution of only 2.5^0 was capable of analyzing the dimensional features of the dry air mass associated with the plume. As discussed earlier, the air mass modification at the sea is clearly illustrated; that is, the RH increases from 60% on the coast to ~90% at ~200 km away. The latter value corresponds well with the theoretical estimation of the thermal internal boundary layer (TIBL) height. Following *Venkatram* [1977], the TIBL height, h, can be best estimated by

$$h = \left[\frac{2Q_o x}{(1-2F)U_m} \right]^{1/2} \qquad (1)$$

where Q_o is the kinematic heat flux, x the distance from shoreline, $\gamma \equiv \partial\theta/\partial z$ the potential temperature lapse rate, U_m the average surface wind speed, and F is a constant. Substituting the corresponding values for the Libyan coast on December 30, 1985, 1235 UTC, (γ = 5 K km^{-1}, $U_m \simeq$ 10 $m\ s^{-1}$, surface air temperature T_a = 17^{0}C and sea surface temperature T_w = 23^{0}C) and the [*Krishnamurti et al.*, 1987] formula for the heat flux

$$Q_o = \frac{Q}{C_p} = C_T \mid U_m \mid (T_w - T_a) \qquad (2)$$

we obtain the h value of 966 m for x = 200 km. The values ,C_p and C_T correspond to air density, specific heat at a constant pressure (C_p = 1004 $J\ kg^{-1}\ K^{-1}$) and a constant C_T = 1.4 x 10^{-3}. This calculated TIBL height is in agreement with the slope of the RH isoline of 60% in Figure 5d near the Libyan coast.

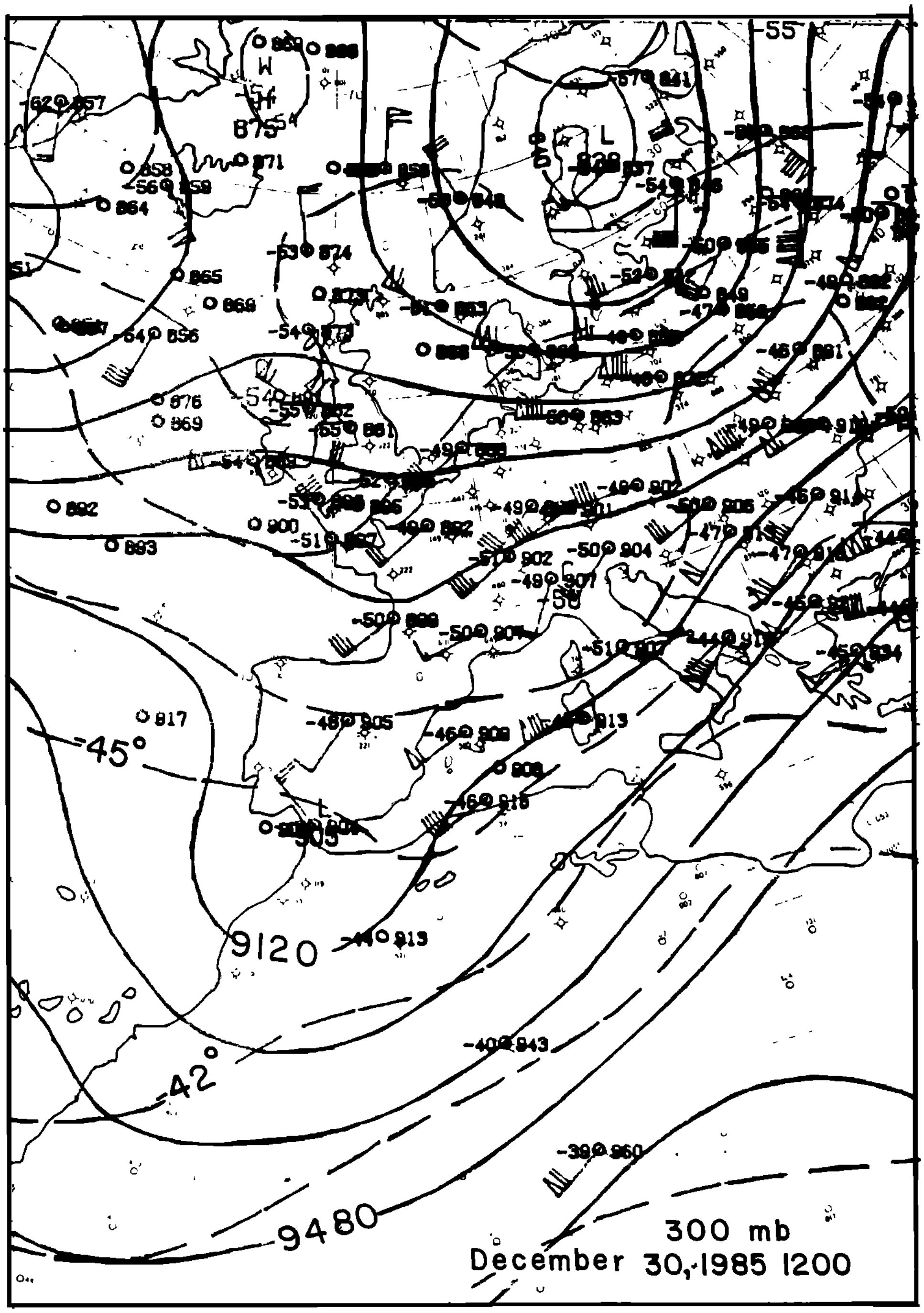


Fig. 3. The 300-hPa synoptic map for December 30, 1985, 1200 UTC, showing the jet winds over Sicily to south Italy.

Time Development of the Dust Storm

The time evolution of the dust storm was analyzed by drawing the same cross section 12 and 24 hours earlier. Figure 6 presents cross section A as in Figure 5 but 24 hours earlier on December 29, 1985, 1200 UTC. Major changes took place during the intervening 24 hours. Above Crete east of the plume region, a drier air mass replaced the original wetter air mass. The RH isolines indicate a discrete maximum of over 20% at the 880 hPa elevation (~1200 m ASL, Figure 7). Another important variation was the sharp intrusion of dry stratospheric air (~30% at 500 hPa) above Sicily next to the plume.

This dramatic development becomes even more pronounced when cross sections along the plume are composed at 24-hour intervals (cross section D, Figure 8). The 24-hour differences above the Sahara are relatively small and may be related to the sparseness of data in that region. But, north of the plume's head (~40°N), a deep convection zone extending up to ~100 mbar is noted, related to the heavy rainfall over this region (Figure 2a).

Discussion and Conclusions

This study of the dynamical structure of a heavy dust storm event on December 30, 1985 in

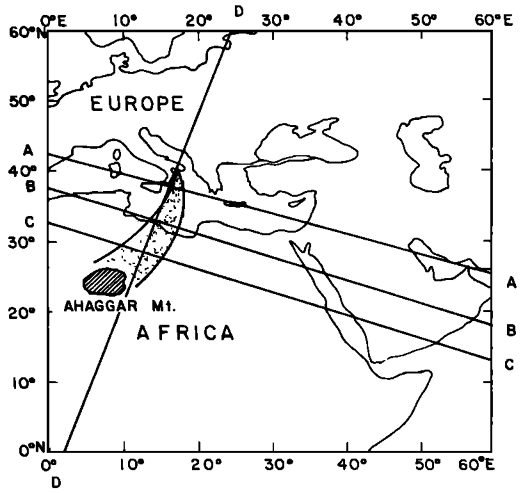


Fig. 4. A schematic map of cross- sections A, B, C and D referred to in the text. The plume's position (dot shading) and the Ahaggar Mt. area (line shading) above 1500 m are indicated.

the western Mediterranean revealed a number of findings. A relatively strong horizontal wind was found prior to the plume's development above the high mountainous Ahaggar region over the Sahara where the dust originated. The dust plume was found precisely at the confrontation between a lower troposphere moist airmass and a very dry airmass to the east. A similar confrontation was found above the boundary layer (700 hPa) but the position of the air masses was reversed. Finally, the ECMWF synoptic data seemed to capture the moisture characteristics of the dust plume.

One of the most interesting results is the three-way association found between the jet stream, the cold front and the dust plume. The interrelatedness between any two of these three phenomena was expressed in the following correlations. The cold front was found parallel to the plume's border (front and plume). The strong winds associated with the jet stream are believed to be responsible in most cases for the plume's generation (jet and plume). The established relationship between the cold

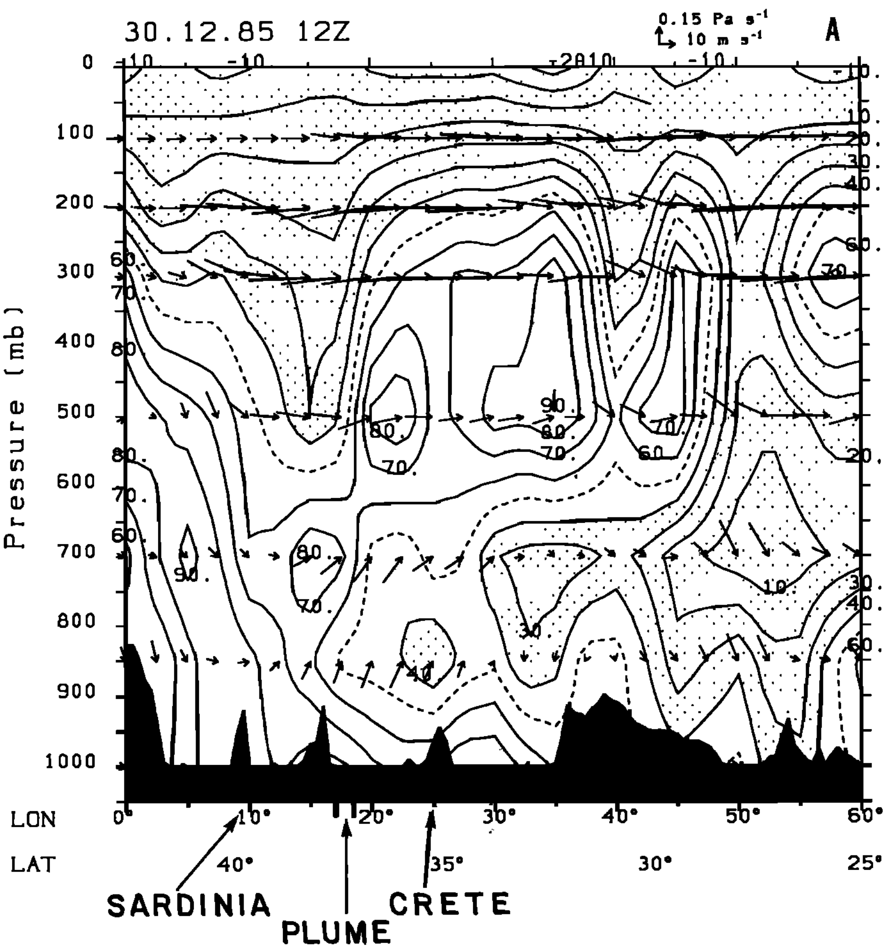


Fig. 5. Vertical cross-section through the plume along lines A(a), B(b), C(c) and D(d) from Figure 4, showing isolines of relative humidity with intervals of 10%. Wind arrows represent 4-hour displacement. Topography is shown in black at the bottom of the cross section. The location of the plume and the islands of Crete and Sardinia are indicated at the bottom of the figures for reference. The dry zones (RH $\leq$ 40%) are shaded. Plume location is indicated at the bottom.

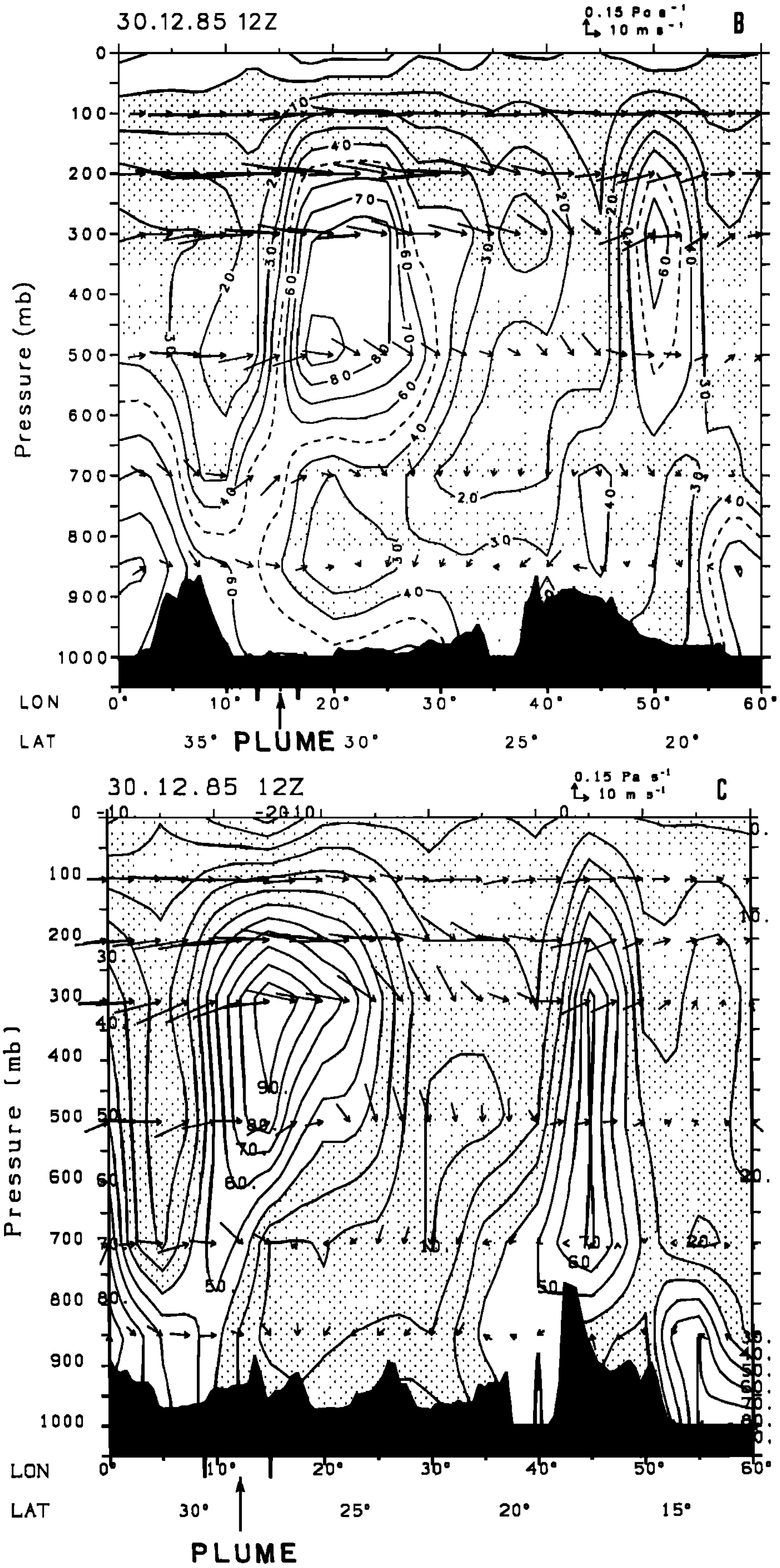
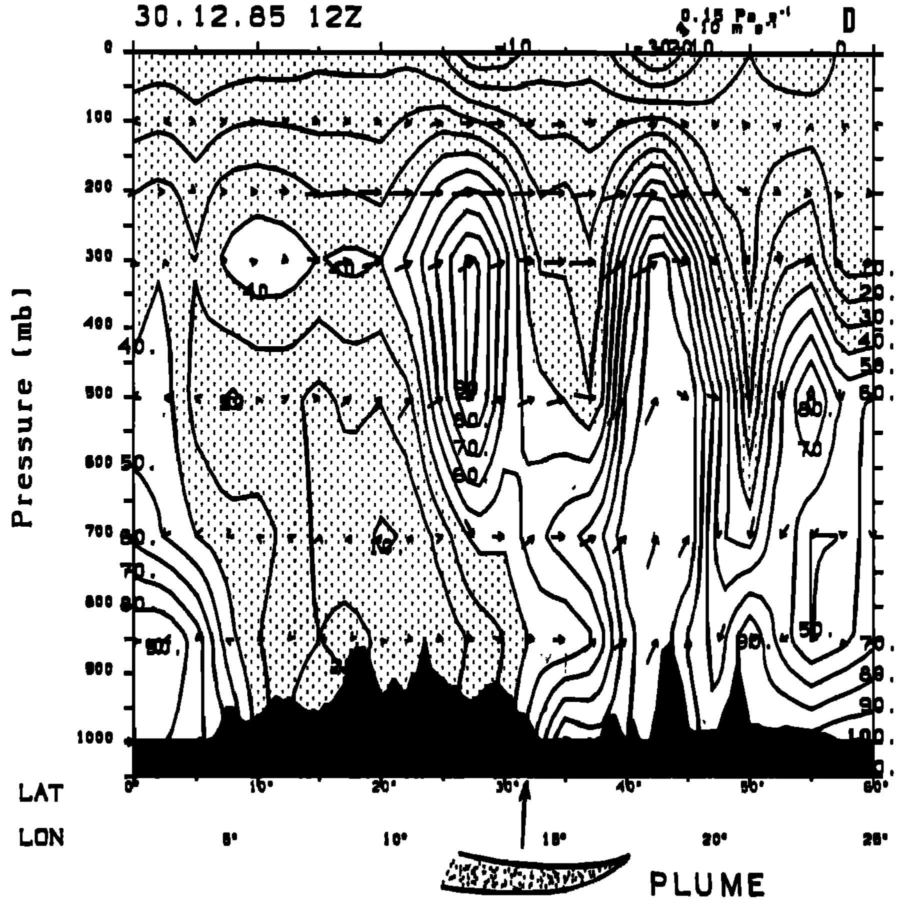


Fig. 5. (continued)



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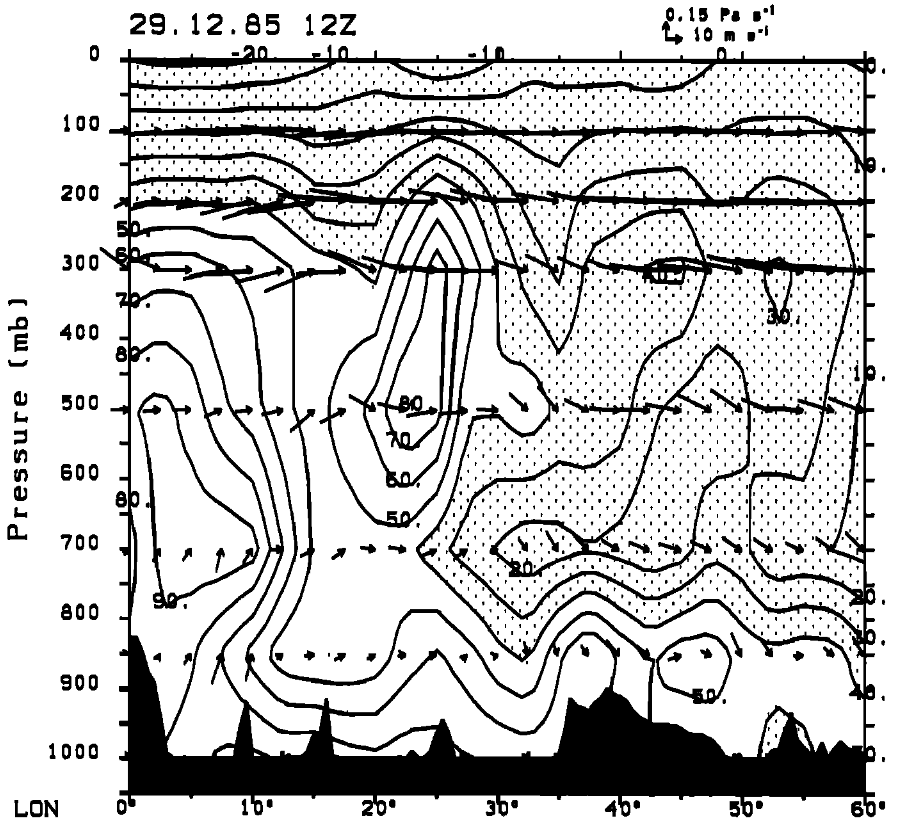

Fig. 6. Vertical cross section A as in Figure 5a, 24 hours earlier on December 29, 1985, at 1200 UTC.

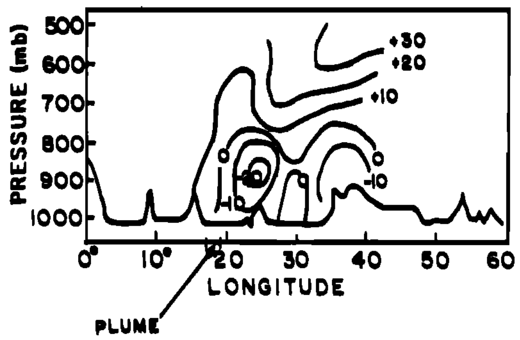

Fig. 7. The relative humidity (percent) isolines representing the 24 hour differences between December 29 and 30, 1985, 1200 UTC.

front and the jet stream is a direct result of the thermal wind equation, [e.g. Holton, 1979, front and jet].

The strong connection between the jet stream, the front and the dust plume is illustrated in cross section C showing the wind magnitude and potential temperature across the plume of Figure 9. The jet stream, shaded over 20 m s^{-1}, extends downward towards the region of the sharp temperature slopes associated with the front, and towards the western flank of the plume. While, according to Figure 9 the surface wind intensity is only about 10-15 m s^{-1}, this value represents the synoptic scale of the data; actual wind on the smaller scale (mesoscale) is probably significantly higher. The surface location of the jet stream is only a few hundred kilometers north of the Ahaggar foothills, the probable generation region for the dust storm in this case, as discussed earlier (Figure 4).

The relationship between the jet stream and severe dust storms was also reported by *Danielsen* [1974], who found the tropopause folding phenomena related to stratospheric potential vorticity (PV) intrusions. These PV intrusions to the troposphere and their association with dust plumes dictate further investigation of PV cross sections [see *Neeman and Alpert*, 1990].

Another noteworthy finding is the close association between the region of copious precipitation north of the plume's edge the high RH from the Mediterranean Sea, and the plume's edge where desert aerosol particles are advected into the cloud area and washed out by the rain. We speculate that these desert particles might become ice nuclei.

The use of synoptic cross section data indicates a plume height of about 1.5 km. This finding corresponds well with other research, including that of *Kalu* [1979] and *Westphal et al.* [1987], who reported the West African dust plume height.

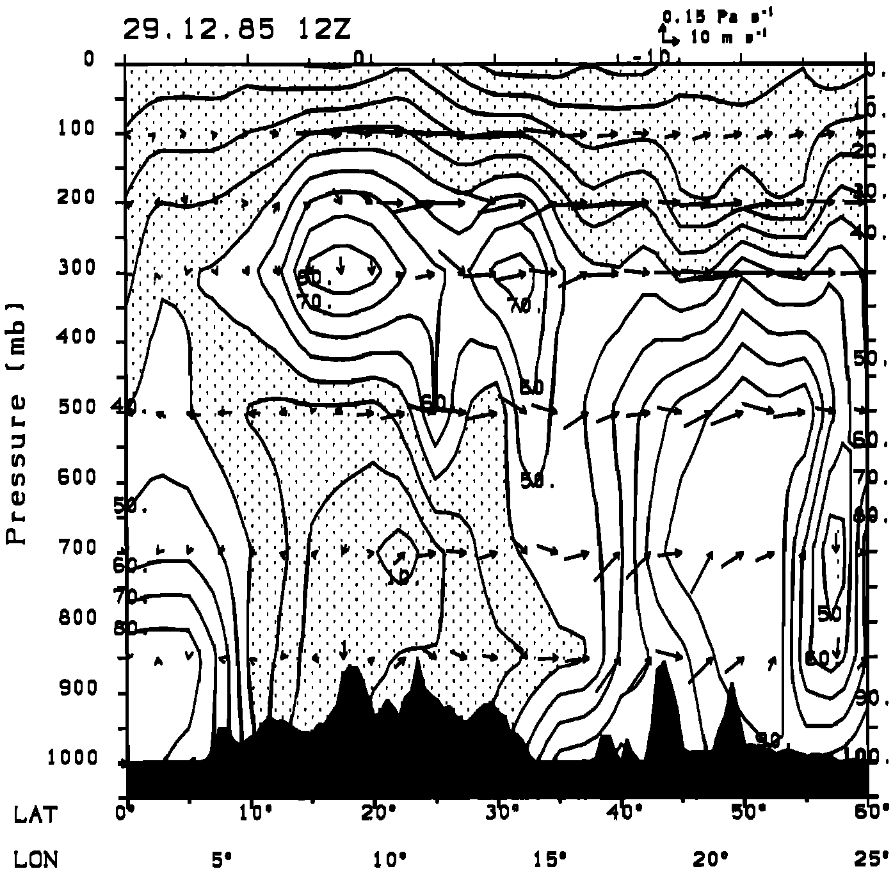

Fig. 8. Vertical cross section D as in Fig. 5d, 24 h earlier on December 29, 1985 at 1200 UTC.

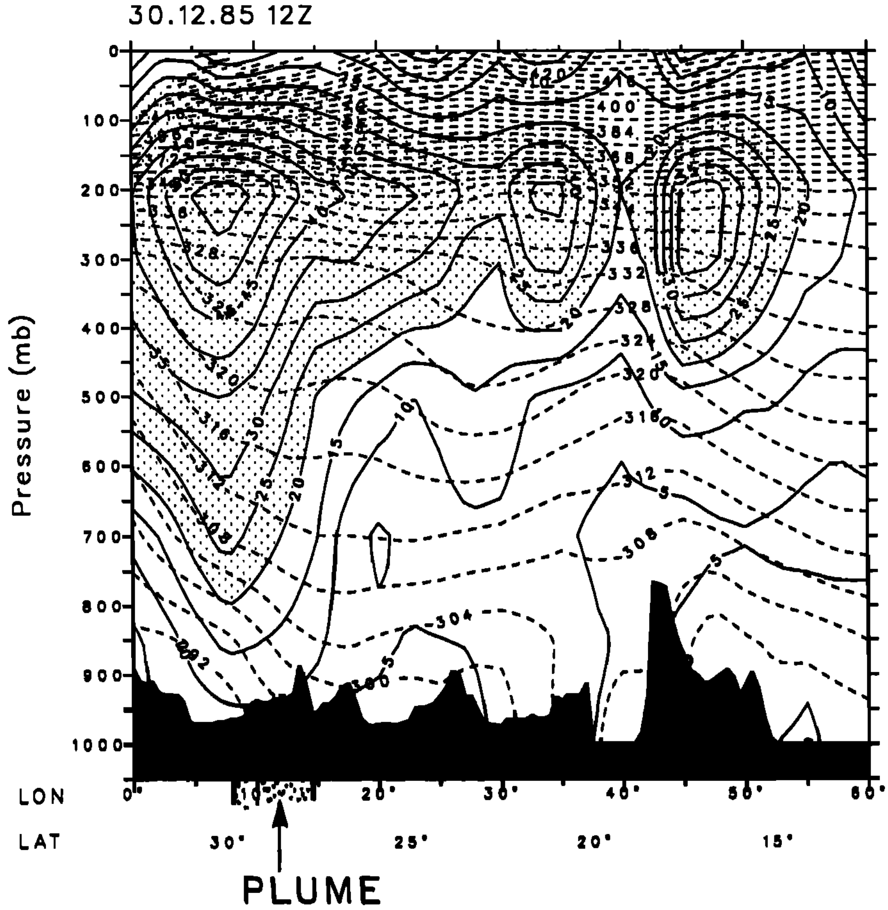

Fig. 9. Vertical cross section C for wind magnitude (5 m s^{-1} interval) and potential temperature (dashed; 4 K interval). Region with winds exceeding 20 m s^{-1} is shaded. Plume location is indicated at the bottom.

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