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Department of Geophysics and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv, Israel

Synoptic patterns associated with dusty and non-dusty seasons in the Sahara

J. Barkan, P. Alpert

With 4 Figures

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Summary

The difference in the synoptic situation between years with a large amount of dust and years with a relatively small amount, in the Sahara, have been examined for the period 1979–1992. A comparison has been made separately for each season. For every month the dustiest and least dustiest years, determined by the deviation from the mean, were chosen and the average of the three months of each classical season for these years was examined. The examination was made for wind flow, geopotential height and temperature at the 700 hPa level, and appropriate maps of these variables have been prepared. The data used were the daily aerosol index (AI) from the TOMS satellite-borne instrument and daily NCEP/NCAR reanalysis data for the years 1979–1992.

It was found that there is significant difference in the atmospheric variables between dusty and non-dusty years in the Sahara and the area to the north and to the west. In the spring, summer and autumn seasons there is a significant increase in cyclonic flow during dusty years relative to non-dusty years in western Europe and western North Africa. Accordingly, there is strong cooling and a decrease in geopotential height in this area. In the central and eastern Sahara and the central Mediterranean anticyclonic flow predominates, there is significant relative warming and an increase in the geopotential height.

In the winter season, the distribution of cyclonic and anticyclonic activity, instead of east to west, becomes orientated north to south. Mean cyclonic activity, together with cooling and decreased height, is found in south-eastern Europe, and anticyclonic activity is found in the Sahara.

1. Introduction

Dust in the atmosphere has recently become a frontline of research for the scientific community dealing with climate and climate change. The main source of dust is the Sahara desert. Huge amounts of dust are transported every year from the Sahara toward the American and European continents (Chiapello et al. 1997; Collaud Coen et al. 2003; Kaufman et al. 2005). The dust is originates from well-defined source areas which are active mainly in the summer months, with the exception of the Bodele depression source which is active throughout the year (Prospero 1996; Ginoux et al. 2001; Prospero et al. 2002; Washington et al. 2003; Barkan et al. 2004). Basically, the quantity of dust in the atmosphere depends on the amount of sun insolation (Alpert et al. 2006).

There are however, significant interannual differences in the dust amount (Dulac et al. 1996; Moulin et al. 1997; Barkan et al. 2004). These differences are, presumably, due to variations in the mechanisms which cause the lifting of dust into the atmosphere and its transportation effi-

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Correspondence: J. Barkan, Department of Geophysics and Planetary Sciences, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, Tel-Aviv, Israel, e-mail: yossib@vortex.tau.ac.il

ciency. The main mechanism is the strong heating of the desert during the warm part of the year, which causes convective disturbances up to 5–7 km and elevates huge quantities of dust into the atmosphere (Alpert and Ganor 1993; Duce 1995; Prospero 1996; Alpert et al. 2004). An additional factor is wind velocity. If wind velocity is greater then the threshold velocity, which depends on the soil type, vegetation cover and grain size, dust particles are lifted and transported according to wind velocity and direction (Duce 1995; Ginoux et al. 2001). The quantity of rainfall in a given year may also affect the amount of airborne dust (Middleton 1985; Dulac et al. 1996; Prospero 1996).

It can be stated, with reasonable confidence, that all these variables depend on the changing synoptic situation variability from year to year. Moulin et al. (1997) attributed particular importance to the level of the NAO (North Atlantic Oscillation) index. Variations in the activity of low pressure disturbances in different years can affect the dust level of a given year. The strength and frequency of these disturbances depend on the depth of penetration of cold air from the high latitudes southward (Dayan et al. 1991; Conte et al. 1996; Moulin et al. 1997; Barkan et al. 2005). In certain years there are very severe disturbances that can add huge amounts of dust to the expected load for a particular year (Alpert and Ganor 1993; Tsidulko et al. 1998; Kutiel and Furman 2003).

In this article we attempt to highlight some of the major differences in the synoptic variables between dusty and non-dusty years for the four major seasons.

2. The data used

Two data sources were used: The Total Ozone Mapping Spectrometer (TOMS) and the NCEP/NCAR reanalysis. The TOMS is a satellite-borne instrument which was originally intended to measure ozone in the atmosphere but was also found useful gathering information on the total column aerosol content (Herman et al. 1997). The Aerosol Index (AI) is a special index which has been developed to interpret the TOMS data. The AI is defined by the spectral contrast between two wavelengths in the near UV (340 and 380 nanometers) (Herman et al. 1997; Torres et al. 2002). The TOMS AI data are achieved by NASA/GSFC.

For the synoptic data we used the NCEP/NCAR reanalysis as described by Kalnay et al. (1996). The years 1979–1992 were analysed. In this period the TOMS data were most stable, while later on, the quality of the data deteriorated following the introduction of a new satellite.

3. Methodology and data processing

Two separate domains were defined for the research. The AI data for the dust were generated from the Sahara proper which is the main supplier

Table 1. Average monthly normalized AI by years. AI calculated over the domain (15° N–30° N, 15° W–30° E)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1979	1.84*	0.56	0.43	−1.68#	−1.37#	−1.22#	−1.55#	−1.05#	−0.64	−0.14	1.38*	0.77
1980	0.48	−1.31#	−1.5#	−1.46#	−1.05#	−0.75	−1.01#	−1.87#	−1.78#	−0.58	0.81	2.23*
1981	−0.49	−0.62	−1.37#	−0.8	−0.63	−1.55#	−1.13#	−1.12#	−1.09#	−0.68	0.23	−0.06
1982	−0.63	−0.43	−0.41	−0.51	−1.87#	−1.46#	−1.08#	−0.32	−0.21	0	1.15*	1.28*
1983	0.59	0.37	−0.4	0.56	1.11*	0.03	0.36	0.94	0.31	0.02	0.76	0.61
1984	1.58*	0.6	0.2	0.45	1.24#	0.54	−0.57	0.33	2.04*	2.94*	1.33*	0.17
1985	−0.72	1.65#	1.64*	−0.16	0.55	0.98	−0.17	0.79	0.32	0.46	−1.36#	−0.93
1986	−1.06#	−1.06#	−0.51	1.19*	−0.65	0.18	−0.08	0.37	−0.47	−1.48#	−0.72	−1.26#
1987	−1.02#	−0.56	0.03	−0.61	0.83	−0.53	1.3*	1.94*	−0.13	0.46	0.16	0
1988	0.76	−0.07	0.74	1.86*	0.41	1.87*	1.69*	−0.24	0.77	−0.84	−0.65	0.03
1989	−0.45	0.27	0	0.48	−0.8	0.41	0.52	0.5	1.6*	0.07	−1.65#	−1.2#
1990	0.19	−1.45#	−1.28#	0.45	−0.11	−0.01	0.01	0.75	0.49	−0.41	−0.87	−0.5
1991	−1.49#	0.19	0.95	0.9	1.79*	0.62	0.39	−0.36	−0.46	0.11	0.07	−0.05
1992	0.42	1.87	1.49*	0.29	−0.18	0.88	1.29*	−0.56	−0.12	0.08	−0.64	−1.1#

* Above one standard deviation

Below one standard deviation

of the dust (15° N–30° N, 15° W–30° E). To describe the synoptic situation we used a much larger area (10° N–50° N, 20° W–50° E).

We decided to focus on the whole of the Sahara in order to rule out local influences such as topography, agricultural activity and limited atmospheric phenomena, and to ensure the general trend remained intact. In addition, the same calculations were made for two halves of the study area, namely the western part (15° N–30° N and 15° W–10° E) and the eastern part (15° N–30° N and 10° E–30° E). No significant differences were found between the results of the whole area and for these two halves (the partial results are not shown).

Daily AI data were used for the entire period with 5059 data points altogether. Fifty-five days with missing AI data were not included. The mean, normalized AI for every month was calculated (Table 1). For every month, the years with above 1 and below -1, e.g., above or below one standard deviation of the AI value, were chosen and averaged (Table 2). These values were averaged for the three months of each classical season and the analysis continued on a seasonal basis (Table 3).

Table 2. Average AI by months of the years, above and below one standard deviation

Month	Average AI in months above one std.	Average AI in months below one std.	Difference above minus below one std.
January	1.05	0.72	0.33
February	1.11	0.85	0.26
March	1.53	0.99	0.54
April	1.94	1.22	0.72
May	2.39	1.49	0.90
June	2.78	1.66	1.12
July	2.37	1.55	0.82
August	2.05	1.28	0.77
September	1.73	1.05	0.68
October	1.32	0.85	0.47
November	0.89	0.64	0.25
December	0.89	0.65	0.24

Table 3. Average AI by seasons of the years, above and below one standard deviation

Season	Average AI in months above one std.	Average AI in months below one std.	Difference above minus below one std.
Spring (MAM)	1.95	1.23	0.72
Summer (JJA)	2.88	1.5	1.38
Autumn (SON)	1.31	0.85	0.46
Winter (DJF)	1.02	0.74	0.23

In order to ensure that the anlaysis were based on pure, uncontaminated, dust data several points were checked:

a. There was no significant biomass burning in the Sahara, excluding its most southern fringes (Arino and Melinotte 1994).
b. Although we were dealing with a large area it was decided not to perform cosine weighting for the meridians, which has real influence only in much higher latitudes (Huth 2006). However, some computations were made to ensure the degree of latitude would not affect the results: On latitude 15° the width of a one degree longitude band is 107 km; on latitude 30° it is 96 km, a difference of 11 km. For the whole 40° of the research area the difference is 440 km, less then 10%. On latitude 65° the width of a one degree longitude band is 46 km; on latitude 80° it is 19 km, a difference of 27 km.
c. A t-test was performed to determine the significance of the AI difference between the dusty and non-dusty years. The difference was found to be significant in all seasons at the 0.01 level.
d. We were aware of the problem of the changing of the vertical distribution mode from season to season, but because we are dealing with each season separately, it was decided not to take this aspect into account.

From the NCEP/NCAR reanalysis data the following variables for the research period were used: the u and v components of the wind, and temperature and geopotential height at 700 hPa. Averaged difference maps, one standard deviation above the monthly average minus one standard deviation below, were prepared for wind flow, geopotential height and temperature.

The 700 hPa level was chosen due to the fact that the main dust activity is chiefly around this level; although in the summer and spring months the activity is higher then during the rest of the year (Carlson and Prospero 1972; Prospero 1996; Swap et al. 1996; Chiapello et al. 1997; Alpert et al. 2003). Dust activity exists along the whole atmosphere column from the surface up, and can be different at different levels, hence variables were examined at 850 and 1000 hPa and at the surface. No significant difference between the 700 hPa and the lower levels were found, excluding the surface where topographic and other influences distorted the results.

The variances presented were chosen according to the main purpose of this paper, namely to show the synoptic difference between dusty and non-dusty years. The wind flow and temperature differences illustrate this well. These data are very useful for those interested in dust transportation such as forecasters, climatologists, air pollution experts, people connected to health problems etc. The geopotential height maps, although not providing much additional information, can present a clearer picture for those who are not accustomed to maps of by wind vectors. Hence, vectors and isohypses are placed on the same map.

4. Results and discussion

Before we examine the results, it should be noted, that all figures deal with the difference between the variables of the dustiest minus the least-dusty years. The results shown in the figures are not absolute values but are the relative values between the two years. Special attention is required when examining the wind flow figures which are the result of vector extraction, and which represent the real additional flow (Stidd 1956).

4.1 Difference – general

Examination of Table 1 shows a considerable difference in dust loading between the years. In the years 1979–1982 for instance, the average AI in almost all months is below the monthly average, while in years such as 1984 and 1988 the opposite is the case (Barkan et al. 2004).

In Tables 2 and 3, which deal with absolute average AI values in the extreme years, the quantity of dust and the difference between dusty and non-dusty years is greatest in summer and becomes gradually smaller toward the winter months (Barkan et al. 2004).

4.2 Spring

4.2.1 Wind flow and geopotential height (Fig. 1a)

The main features are a well-defined cyclone in the gulf of Biscaya and western Spain with a trough emanating southward toward the western Sahara and the Atlantic coast of Mauritania and the Canary Islands. In the centre of the cyclone there is a relative decrease in geopotential height of more than 40 m and around 20 m in Mauritania. A ridge emanates from the Black Sea toward the central Mediterranean and the central Sahara as far as Lake Chad.

There is an increase in geopotential height of 20 m in the central Mediterranean, growing smaller southward. In general, anticyclonic activity in the dusty years relative to the non-dusty ones, is weaker than cyclonic activity to the west.

4.2.2 Temperature (Fig. 1b)

There is relative cooling in the dusty years in Spain, western Mediterranean, and western Sahara and its Atlantic coast. In the vicinity of the cyclone, as previously mentioned, the strongest cooling is more then 2.5°. In the Balkans, the central Mediterranean and central Sahara there is warming of more then 2.5° in the north, which lessens southward.

The main feature in the spring is strong cyclonic activity in the west during dusty years and a weaker anticyclone to the east.

4.3 Summer

4.3.1 Wind flow and geopotential height (Fig. 2a)

The summer features of the wind flow and geopotential height differences are like those of the spring but the differences are less pronounced. The closed cyclone to the west exists, but is located somewhat to the south and is centre around the western coast of Morocco, while the decrease of height is only 20 m. The trough penetrates more to the south then in the spring.

There is a weak closed high covering the central Mediterranean, southern Italy and the Balkan Peninsula and penetrating into Libya with a very small increase of around 5 m in geopotential height.

4.3.2 Temperature (Fig. 2b)

The temperature difference between the dusty and the non-dusty cases shows a cooling of approximately 1° in Spain and along the Atlantic coast of Morocco, which lessens eastward and

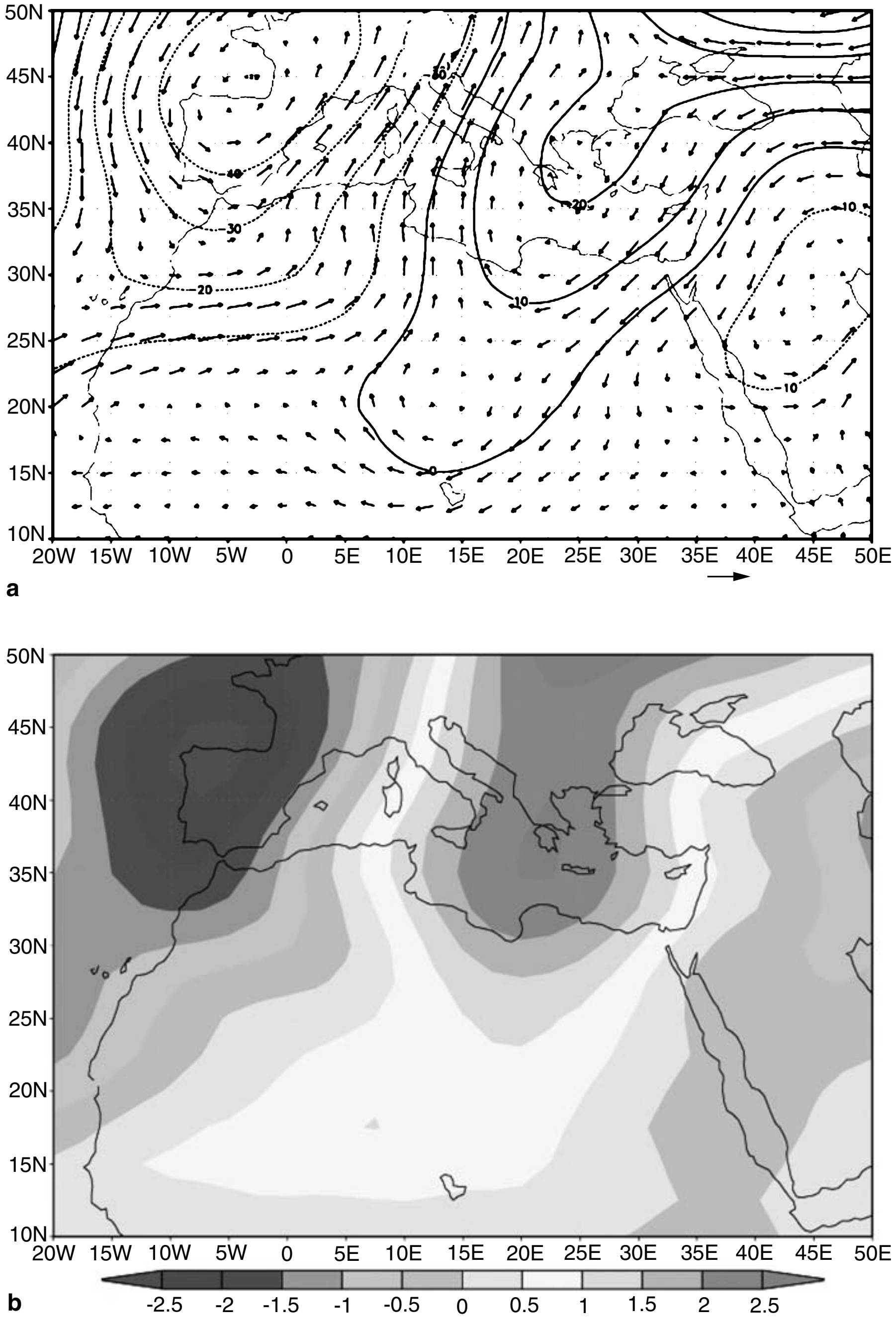

Fig. 1. (**a**) Average wind flow and geopotential height difference at 700 hPa in spring (MAM), between the months one standard deviation above and below the average AI, in the period 1979–1992. (**b**) Average temperature difference at 700 hPa in spring, between the months one standard deviation above and below the average AI, in the period 1979–1992

southward toward the western Mediterranean and western Sahara. There is warming of upto 1.5° in the Balkans, the central Mediterranean and central and eastern Sahara with various centres.

The man feature in the summer months, as in the spring, is cyclonic activity in the west during dusty years and anticyclonic activity in the central Mediterranean, although less marked then in the spring, presumably because of the generally weaker synoptic activity in this season due to the strong influence of the sub-tropic high.

4.4 Autumn

4.4.1 Wind flow and geopotential height (Fig. 3a)

The flow and height difference in this season is rather like that of spring and summer but with the systems shifted to the east. There is still a closed cyclone but it is centred on the Mediterranean

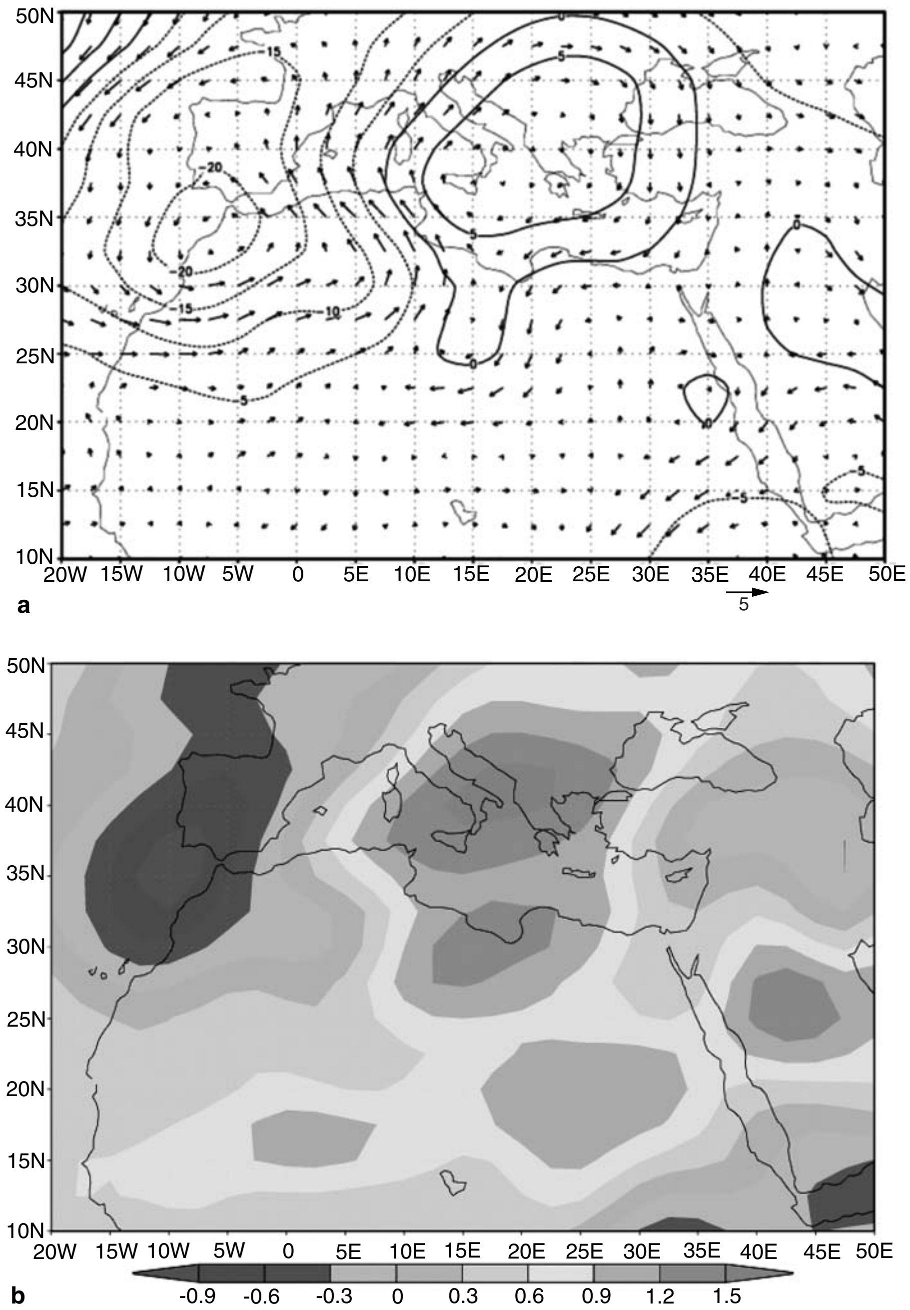

Fig. 2. (**a**) Same as Fig. 1 but for summer (JJA). (**b**) Same as Fig. 1 but for summer (JJA)

coast of Algeria with a relative height decrease of more then 20 m. From this low a trough penetrates southwestward, deeper into Mauritania, than in spring and summer.

To the east, considerable anticyclonic flow exists north of the Black Sea with a height increase of more then 15 m, but this weakens rapidly toward the south in the central Mediterranean and eastern Sahara.

In contrast, in Iraq, differences which were negligible in the previous seasons become prominent. There is a distinct cyclonic flow and a height decrease of 20 m or more.

4.4.2 Temperature

Similar to spring and summer, there is relative cooling in the western Mediterranean and to the north in south-western Europe. At its centre, in Provence, its value is more then 1.5° but the cooling, although lessening, extends southward through the western Mediterranean into Algeria.

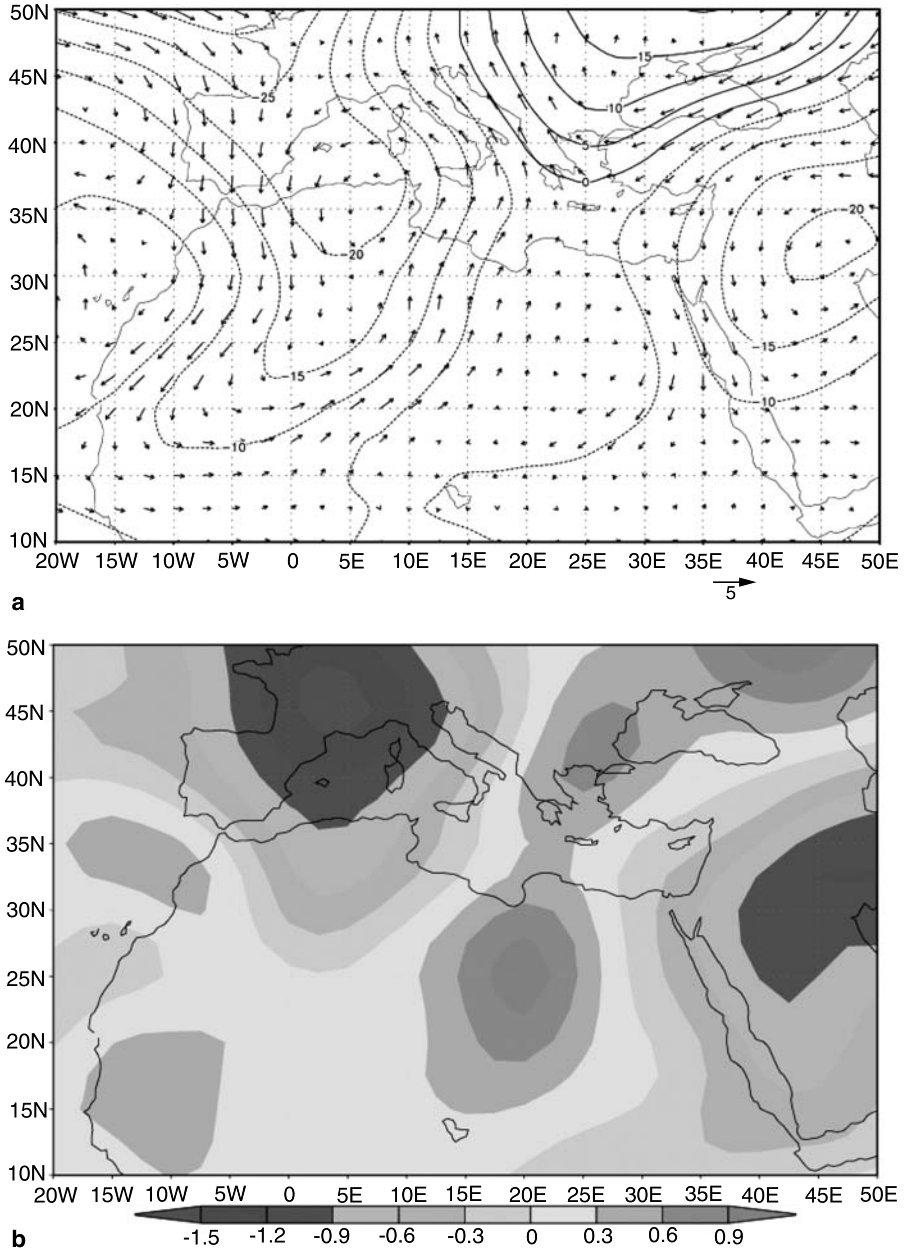

Fig. 3. (**a**) Same as Fig. 1 but for autumn (SON). (**b**) Same as Fig. 1 but for autumn (SON)

Relative warming of 1° or less extends from Russia through central Mediterranean and into eastern Sahara.

Another cooling centre exists in Iraq with a maximum value of approximately 1.5°.

The main feature in this season is cyclonic activity in the west, which exists in dusty years, although shifted more to the east. Another cyclonic centre develops in Iraq while the anticyclone between them weakens considerably, or in other words, the difference between the dusty and the non-dusty years in this region is small.

4.5 Winter

4.5.1 Wind flow and geopotential height (Fig. 4a)

The wind flow and height difference in this season is entirely different from the rest of the year. A strong cyclonic flow exists in most of Europe with a height decrease of more then 40 m. For the whole Sahara, the flow is weak anticyclonic with a 5 to 10 m height increase. Between these two systems a westerly flow exists along most of the Mediterranean.

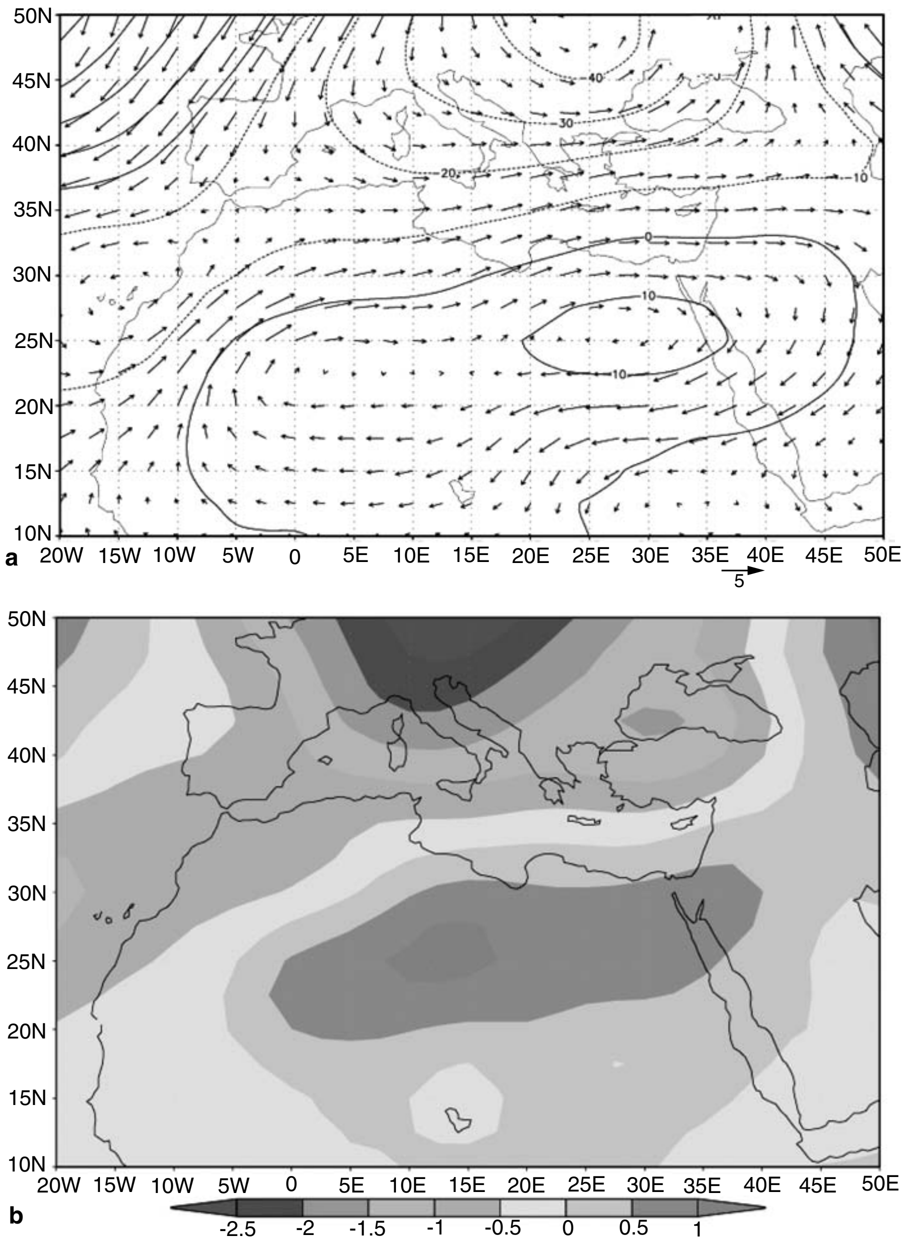

Fig. 4. (**a**) Same as Fig. 1 but for winter (DJF). (**b**) Same as Fig. 1 but for winter (DJF)

4.5.2 Temperature (Fig. 4b)

A strong relative cooling of more then 2.5° is present in central Europe lessening toward south Europe and the Black Sea region. In the Sahara there is warming of 0.5–1° with its centre located in the Libyan Desert. Between them, along the Mediterranean Sea, there is no significant difference between the dusty and the non-dusty years.

The main pattern in winter is significant cyclonic activity in Europe in the dusty years and weak anticyclonic activity in the Sahara, and a strong westerly flow along the Mediterranean.

5. Conclusions

The difference between the synoptic situations in the dustiest years versus the least-dusty years, for the four seasons, was examined, and a marked difference was found between them. The dusty years were characterized by enhanced cyclonic activity together with significant cooling, relative to the non-dusty years, in the western Mediterranean and western Sahara in the spring, summer and autumn seasons. In contrast, in the central Mediterranean and central and eastern Sahara, in dusty years the flow was more anticyclonic with relative warming and an increase in geopotential height. The differences were more marked in spring, less so in autumn and still less in summer where the differences were screened by the strong sub-tropical high.

In winter there was a marked difference between the dusty and the non-dusty years, but the cyclonic and anticyclonic regions were orientated north to south instead of east to west as in the other seasons. There was a strong cyclonic flow and a considerable deepening and cooling in south-eastern Europe relative to the non-dusty years, and a weak anticyclonic flow with slight warming and increase in geopotential height in the Sahara.

The intention of this work was to achieve a better understanding of the synoptic structures behind annual dust behaviour. This could assist in producing more accurate predictions of dust events, especially in densely populated areas such as Europe, with application to a wide range of topics including weather and air pollution forecasting, health problems, traffic safety and agriculture. In addition, the identification of the synoptic patterns associated with dusty and non-dusty years may become useful for the climatic distinction of future trends in dust generation.

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