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Synoptic classification of lower troposphere profiles for dust days

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[1] The goal of this research is to identify meteorological characteristics distinguishing dust storm days from no-dust days. During this pioneering research, the vertical profiles of temperature, wind components, and humidity for days with dust and with no dust were compared and analyzed in order to identify features accompanying dusty conditions. Three data sets, all for the 49 year period of 1958–2006, were used. The first was the daily dust observations at Tel Aviv, Israel. The second was the eastern Mediterranean daily surface synoptic classification. The third was the vertical data over the eastern Mediterranean grid point closest to Tel Aviv at 32.5°N, 35°E. The two latter data sets were based on the National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis. The meteorological parameters were averaged over the 49 year period by season, pressure level, synoptic-type, and dust and no-dust days. Prominent differences between dust and no-dust days were found for relative humidity and wind components during fall, winter, and spring at 700, 600, and 500 hPa levels. Relative humidity was found to be higher during dust episodes. This result, linking dust and humidity, looks promising for future research on connection between desert dust, ice nuclei, and precipitation. The governing eastern Mediterranean synoptic systems are low-pressure systems. For these systems, vertical velocity (*Omega*) values are negative. It was found that absolute *Omega* values were higher on dust days than on days with no dust. Southerly and westerly components of wind were found to have higher values during dust days. It was found that for most synoptic systems, temperature below the 700 hPa level was equal or higher during dust days. Thus, during dust days the lower troposphere is unstable.

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1. Introduction

[2] Dust storms (DS) are, for the purposes of this work, clouds of dust aerosols lifted into the atmosphere at sources in Algeria, Libya (Ahaggar Mountains), Chad (Bodélé depression), Sudan (Marrah Mountains), Saudi Arabia, and Syria, and passing over the eastern Mediterranean (EM), at heights of several kilometers. Some of the dust sinks to ground level and is deposited by gravity or precipitation [*Ganor*, 1994].

[3] Dust storms are among the major climatic events in the EM region, and of significant impact on public health [*Annesi-Maesano et al.*, 2007], transportation, meteorology [*Goudie and Middleton*, 2001; *Rosenfeld et al.*, 2001; *Kaufman et al.*, 2005; *Ansmann et al.*, 2005], and soil enrichment [*Rahn et al.*, 1979].

[4] Dust has low residence time in the atmosphere, of order of a few days to a week. However, it could affect clouds and rain. This is of special importance for the semiarid eastern Mediterranean zone, and may also have an impact on climate [*Andreae*, 1995; *Ramanathan et al.*, 2001; *Levin et al.*, 2005; *Levin and Cotton*, 2007].

[5] Mineral dust is identified at ground level by aerosol measurements and visually from visibility limits, sky color, and dry or wet deposition. In this work, the term dust day (DD) refers to days during which mineral dust from DS is observed near the surface.

[6] To our knowledge, all the published DS studies have been carried out for a period of a few years [*Derimian et al.*, 2006] except for two cases [*Ganor et al.*, 2010; *Dayan et al.*, 2008]. Since DS are a relatively rare event with high annual variability, it is not clear that results from short periods are representative. The 49 year classification presented here, which is based on the NCEP/NCAR reanalysis, made it possible to significantly deepen DS studies.

[7] The motivation for this work is to show the meteorological differences between days with dust and no-dust days. These meteorological differences could be used for a better understanding of the DS phenomenon, and its influence on the direct and indirect radiative effects [*Carmona et al.*, 2008; *Derimian et al.*, 2006; *Alpert et al.*, 2005; *Markowicz et al.*, 2002; *Stanhill and Cohen*, 2001]. This new understanding may lead to improved forecasting techniques, and better estimation of the effect of climatic change on the DS phenomena.

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Table 1. TAU Synoptic Classes Joined Into Synoptic Types for a Dust Study

Synoptic Types	Synoptic Classes and Typical Cases
A, Sharav Lows (SL)	A1, western SL; A2, central SL
B, southern Winter Lows (WL)	B1, deep WL_S; B2, shallow WL_S
C, Highs	C1, eastern High; C2, western High; C3, northern High; C4, central High
D, Red Sea Troughs (RST)	D1, RST with an eastern axis; D2, RST with a central axis; D3, RST with a western axis
E, Persian Troughs (PT)	E1, weak PT; E2, medium PT; E3, deep PT
F, shallow Winter Low to the east	F
G, Winter Lows apart from those in B and F	G1, cold WL to the west; G2, deep WL to the north; G3, shallow WL to the north; G4, deep WL to the east

[8] We expect differences between dust and no-dust conditions to appear in the vertical profiles of meteorological parameters, since the dust is transported over large distances from remote origins. We therefore investigate vertical profiles sorted by synoptic types and by separation of all days into dust days (DD) and no dust days (no-DD).

[9] It is important to emphasize that the analyzed synoptic types are the surface ones, excluding the Cyprus Low which evolves through all troposphere levels. An upper troposphere synoptic system over the E. Mediterranean can be a trough from the north reaching sometimes to Egypt, or a high from the south or from the north. However, the dust measured close to the surface arrives there due to instability at the lower levels. Therefore, the surface systems are eventually responsible for the dust suspension and deposition.

2. Data Sets

2.1. NCEP/NCAR Reanalysis Data

[10] The NCEP/NCAR reanalysis data sets [*Kalnay et al.*, 1996] have been used in this work for deriving daily vertical profiles at 1200 UTC for air temperature T, geopotential height *Hgt*, relative and specific humidity *RH* and *SH*, respectively, and vertical, zonal and meridional wind components *Omega* (ω), *U-wind* (U), and *V-wind* (V), respectively, at 1000, 925, 850, 700, 600, and 500 hPa pressure levels over 1958–2006. All profiles were taken over the grid point 32.5°N/35°E located 40 km north of the dust observations spot at Tel Aviv.

2.2. TAU Daily Synoptic Classification

[11] A method for semiobjective synoptic systems classification using NCEP/NCAR reanalysis data was developed at Tel Aviv University [*Alpert et al.*, 2004b; *Osetinsky*, 2006]. The Tel Aviv University (TAU) method, "a modified discriminant analysis," was applied to the NCEP/NCAR reanalysis daily data since 1948 [*Alpert et al.*, 2004c]. The method allows the automatic classification of regional synoptic systems at daily resolution and was found to be applicable to any region and over any long period. This synoptic classification for 1958–2006 at 1200 UTC was used in this research. The 19 original synoptic classes detailed by *Alpert et al.* [2004b] were joined into 7 synoptic types for the present work, specifically for dust conditions and dust transfer analysis [*Ganor*, 1975].

[12] The 7 synoptic types used here are as follows (Table 1): (1) Type A, Sharav Lows west to and over Israel; (2) Type B, Mediterranean Lows south to Cyprus; (3) Type C, Highs east to, west to, north to, and over Israel; (4) Type D, Red Sea Troughs; (5) Type E, Persian Troughs; (6) Type F, Shallow Lows east to Cyprus (Eastern Shallow Low); (7) Type G, Lows west and north to Cyprus, and deep Lows east to Cyprus.

[13] The seasons were defined according to the EM synoptic classification [*Alpert et al.*, 2004c]: winter from 7 December to 30 March, summer from 31 May to 22 September, and spring and fall in between.

2.3. Daily Dust Observations 1958–2006

[14] Dust was identified from the ground in Jerusalem 1958–1973 and in Tel Aviv 1974–2006. Measurements were made manually every day except for a week during Passover. Since the 1980s measurements were not taken for about 2 weeks a year, usually during summer which is not dust season in Israel. Since 1995 identification has been possible by automatic measurements of PM10 (particulate matter with aerodynamic diameter of less than 10 μm).

[15] Before 1995, and also after 1995 in conjunction with the PM10 measurements, dust was identified on dry days visually from visibility limits and sky color. A dust day had to have horizontal visibility below 5000 m, the WMO standard of low visibility [also see *Mahowald et al.*, 2007], and brown, yellow or orange sky color.

[16] Since 1968 a high-volume sampler was operated on days in which dust was identified in the morning, from 0800 to 2000 h, and the collected aerosols examined for color and under a microscope.

[17] For wet deposition, dust was identified in rain and drops by evaporating water from rain collectors and checking the residue. In Jerusalem, rarely, snow fell with dust, in which case the lower snow layer appeared brown.

[18] Cases were also identified by deposited dust. Every evening a one square meter clean glass at one meter above the ground was left outside. In the morning the glass was brushed with a clean brush into an envelope, and the collected aerosols examined under a microscope. For a severe dust storm the layer of dust appears as an obvious yellow layer on surfaces.

[19] The results of all these measurements were used to compile a list of days with dust for the years 1958 to 2006, a total of 966 dust days and 16931 days with no dust [*Ganor et al.*, 2010].

[20] The daily observations lead to a conclusion that the main gateway for dust transported into the EM region is between 850 hPa and 700 hPa. The lower levels play a role in transferring dust to the surface, either with rain or via subsidence. This conclusion is supported by the Tel Aviv University Dust Model [*Barkan et al.*, 2004; *Alpert et al.*, 2004a], and by airline pilot reports.

[21] The higher levels also serve as gateways for dust. For example, airline pilot reports indicate that dust from Chad and

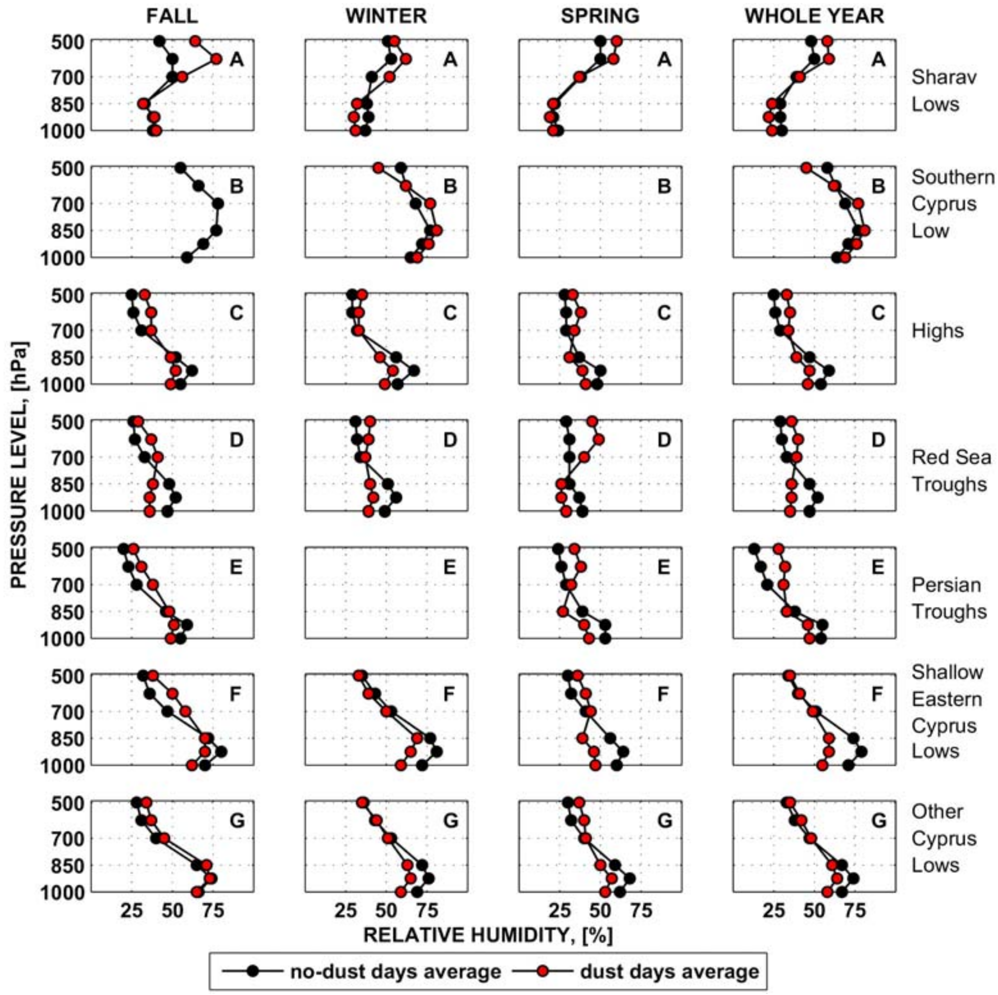

Figure 1. Profiles of relative humidity (*RH* in percent) averages for dust days and no-dust days, by synoptic types and seasons. Red circles are for days with dust, and black circles are for days without dust.

Mali is transported at heights of 5–6 km, from East Sahara at 4–6 km during the Red Sea Trough synoptic system, from Libya and Egypt at 3–4 km during Sharav Low, and at 2 km during Sharav Low which becomes a rain system, for Saudi Arabia at 4–5 km, for Sinai and Negev deserts at 1 km during Red Sea Troughs and Sharav Lows. In general, dust moves over the sea at a height of 1–3 km, while over the land at a height of 1–6 km.

3. Method

[22] For each day during 1958–2006, vertical profiles of air temperature, geopotential height, humidity and wind components at 1000–500 hPa levels, were downloaded from NCEP/NCAR reanalysis database, at the grid point of 32.5N/35E, the closest grid point to Tel Aviv where most dust observations were carried out. The days were divided into two groups: dust days (DD) and no-dust days (no-DD). Within every group, there were further subdivisions into seasons and into synoptic types.

[23] We checked if DD form a different population than no-DD for some of the parameters. For these tests a single parameter at a single pressure level and a specific synoptic type was chosen, and the DD population was compared with the population during no-DD. This was done using the daily values of the parameters, while Figures 1–4 show only the average of the daily values over the entire period.

[24] The standard deviation for DD and no-DD was found not to be a good measure of significance. For all cases the standard deviations are so large that the averages differ by less than one standard deviation. We therefore used the standard *t* test. However, formally *t* test is only valid for Gaussian distributions. Therefore, as a check on the robustness of the results, we used a bootstrapping method described below.

[25] There are many more no-DD than DD. For example, for G-type over the entire 49 years we have 1795 no-DD and 306 DD. For any specific set of synoptic type, pressure level, and meteorological parameter, for example G-type 850 hPa *RH*, we take random samples from the no-DD population. The number of samples is equal to the number of DD with the synoptic type. For the above example this is 306 samples out of the 1795 available. The samples are averaged, and the process is repeated until we have 1000 means each of, for this example, 306 values randomly picked out of 1795 no-DD. The distribution of these means should be a normal distribution even if the underlying set of data is not normally distributed. We calculate the average and the standard deviation of the 1000 means. We then calculate the average of the

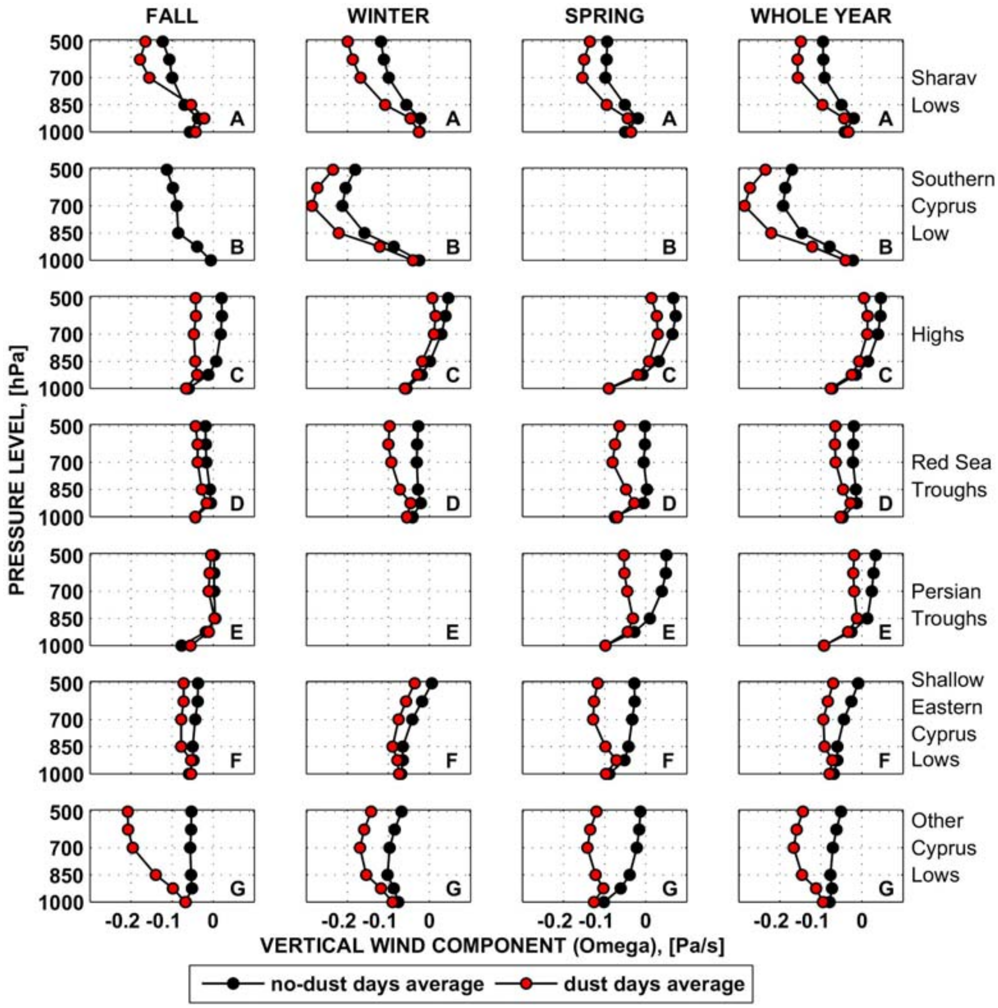

Figure 2. Profiles of vertical wind component (*Omega* in Pa/s) averages for dust days and no-dust days, by synoptic types and seasons. Red circles are for days with dust, and black circles are for days without dust.

chosen parameter at the specific pressure level for all the DD, and normalize the difference between the two averages by dividing it by the standard deviation of the distribution of the means. This distance is an indicator of how different the DD and no-DD populations are

4. Results

[26] Among all analyzed parameters, major differences between DD and no-DD were found for wind components and for relative humidity. The profile Figures 1–4 show meteorological parameters averaged over the 49 year period by season, pressure level, synoptic-type, and dust and no-dust days. For example, the value shown for RH during spring, at 850 hPa, for D synoptic-type, and no-DD, is the average of all RH values during spring days over the period 1958–2006, at 850 hPa, during D-type, during no-DD.

[27] Figures 1–3 show vertical profiles of relative humidity, *Omega*, and *V-wind*, respectively, for DD and no-DD. The profiles are depicted for standard pressure levels of 1000, 925, 850, 700, 600, and 500 hPa. The four columns present fall, winter, and spring seasons [*Alpert et al.*, 2004c], and the entire year. Each row presents one synoptic type, A through G. Each value is the average of the parameter over all days during the 49 year period having the above characteristics. The DD averaged parameters are shown in red, no-DD in black. Figure 4 summarizes the most significant differences for D-type in spring, E-type for a whole year, and G-type in winter. These three are the most common synoptic types in Israel.

[28] Table 2 shows calculations of statistical significance with *t* test for a number of parameters, and Table 3 shows these calculations with bootstrapping. The synoptic types chosen are G, D, C which are those with the most DD, and type E was added to complete the set used for Figure 4.

4.1. Relative Humidity

[29] Figure 1 shows that for most cases *RH* increases with height at DD at least until the 850 hPa level, while in most no-DD cases *RH* begins to decrease at 925 hPa. At 1000 hPa level, *RH* is higher in no-DD than in DD by 6–16% for the whole year and by 3–13% in spring. This holds for all synoptic types (except for a rare B-type). This tendency continues up to 850 hPa level (except B-type). Starting at 700 hPa level upward, *RH* during DD is higher compared to no-DD by 1–15% for the whole year (apart from a B-type at

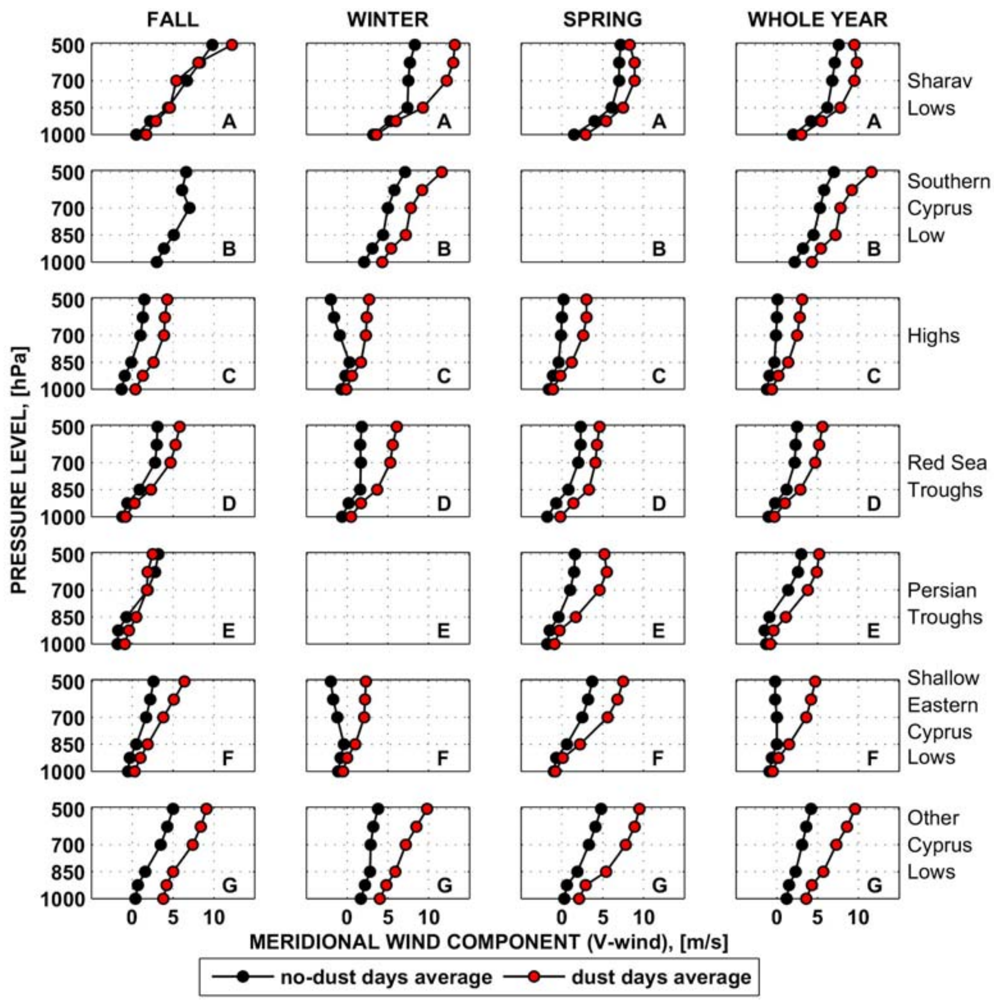

Figure 3. Profiles of meridional wind component (*V-wind* in m/s) averages for dust days and no-dust days, by synoptic types and seasons. Red circles are for days with dust, and black circles are for days without dust.

600 and 500 hPa levels). In spring, *RH* is higher in DD than in no-DD by 1–18% starting at 700 hPa (apart from an A-type at 700 hPa).

[30] The *RH* differences may be summarized in the following way:

[31] 1. For DD, *RH* is higher than for no-DD starting at 700 hPa upward: at 700 hPa level, *RH* is 41% on average for DD and 30% for no-DD. At 600 hPa level, *RH* is 41% on average for DD and 26% for no-DD. At 500 hPa level, *RH* is 36% on average for DD and 23% for no-DD.

[32] 2. At the dust gateway level of 700 hPa, *RH* is less than at 1000 hPa by only 5% (46% and 41%) for DD, while for no-DD this difference increases to 25% (55% at 1000 hPa, 30% at 700 hPa).

[33] The noticeable feature during the Red Sea Trough synoptic type in spring (Figure 1) is the large differences between the 600 hPa *RH* values for DD, 49%, and for no-DD, only 31%. One of the possible explanations may be that RST by that level is replaced by an upper trough from the north which brings moisture from the Mediterranean Sea.

4.2. Vertical Velocity

[34] Vertical velocity *Omega* (Figure 2) is negative at all levels for all synoptic types, apart from some cases of C-type (Highs) and E-type (Persian Trough replaced aloft by highs). *Omega* during DD is always more negative than in no-DD. For example, *Omega* reaches minus 0.2 Pa/s for G-type (Cyprus Lows) in DD in fall, while in no-DD *Omega* is almost constant with values at minus 0.05 Pa/s. The maximum negative value for *Omega* in DD is minus 0.3 Pa/s for a B-type (Southern Cyprus Low).

4.3. Horizontal Wind

[35] The meridional wind component *V-wind* (Figure 3) is distinguishably more positive and has higher values during DD than no-DD for almost all surface synoptic types at all levels. In the few cases where the *V-wind* has negative values (northerly wind), its absolute values are smaller for DD than for no-DD. For DD in all cases, southerly *V-wind* at 500 hPa is noticeably stronger than in no-DD.

[36] The zonal wind component *U-wind* (not shown) is mainly positive (westerly wind) and characterizes both DD and no-DD for almost all synoptic types at all levels. Exclusions are Sharav Lows and Red Sea Troughs (A-type and D-type) having a small negative component (easterly wind) at low levels. The westerlies at 500 hPa level are stronger for DD than no-DD for all synoptic types (except Red Sea Trough).

Table 2. Testing for Entire Year Data if the Parameter at Times During a Dust Storm Is From the Same Population as the Parameter During No-Dust Days[a]

Synoptic Type	Pressure Level	*RH*	*U-wind*	*V-wind*	*Abswind*
C	1000	1.0E-15	**0.470**	5.8E-06	1.5E-03
C	925	1.2E-16	**0.032**	1.4E-10	2.7E-07
C	850	9.2E-08	6.6E-08	1.3E-15	1.9E-18
C	700	7.0E-06	2.4E-10	7.8E-14	1.9E-13
C	600	1.6E-13	3.8E-10	9.9E-11	2.1E-11
C	500	3.5E-11	5.5E-10	6.8E-09	2.6E-10
D	1000	4.9E-29	6.2E-07	4.8E-08	6.4E-09
D	925	1.6E-30	7.6E-05	4.8E-13	1.2E-18
D	850	2.3E-14	**0.048**	1.6E-16	3.2E-28
D	700	5.0E-06	**0.196**	7.0E-14	1.6E-09
D	600	1.2E-13	**0.050**	1.1E-11	8.7E-04
D	500	1.2E-07	**0.026**	7.9E-10	**0.147**
G	1000	4.4E-16	2.9E-10	4.4E-32	5.5E-21
G	925	3.9E-17	9.3E-15	1.4E-33	3.0E-27
G	850	1.5E-06	3.0E-18	6.8E-40	2.6E-35
G	700	**0.178**	2.1E-19	9.7E-31	4.0E-36
G	600	9.7E-04	1.9E-17	3.2E-26	2.3E-29
G	500	**0.015**	1.8E-14	1.1E-21	1.1E-21
E	1000	8.0E-12	2.0E-04	2.6E-04	3.3E-07
E	925	8.0E-08	4.1E-08	7.0E-10	1.1E-13
E	850	2.2E-04	5.3E-23	2.1E-17	1.7E-38
E	700	5.3E-16	1.5E-22	2.8E-08	1.2E-35
E	600	2.1E-31	1.1E-20	5.8E-06	7.9E-29
E	500	3.5E-40	2.7E-18	4.4E-05	3.2E-25

[a]Bold numbers are for *t* test failing the 1% significance test. Table 2 shows that for most cases the distribution during DS is significantly different than the distribution during times without dust. Population sizes are C no-DD 5522, C DD 210, D no-DD 3372, D DD 210, G no-DD 1795, and G DD 306.

[37] The horizontal wind (not shown), calculated from its *U-wind* and *V-wind* components, was found to be stronger in DD than in no-DD for all synoptic types at all levels (except for F-type at 1000 and 925 hPa levels).

4.4. Main Differences

[38] Figure 4 summarizes most significant differences for D-type in spring, E-type for a whole year, and G-type in winter, the most common synoptic types in Israel. For the Red Sea Trough (D-type), it is shown that DD conditions are characterized by enhanced southerly winds (*V-wind*) through the lower troposphere, stronger by 2–3 m/s as compared to no-DD. At the same time there is an increase of wind magnitude at all levels up to 500 hPa in DD. The upward motion (strong negative values of vertical wind *Omega*) during DD demonstrates the lower tropospheric instability, in strong contrast to no vertical wind during no-DD. The instability is also noticeable in the warmer air (*T*) near the surface (up to 850 hPa). The strongest signal of the DD is found in the *RH* profile. Here it is seen that air near the surface (below 850 hPa) is drier and there is increased moisture aloft (700–500 hPa). This can be explained by moisture transport at upper layers and by the advection of relatively dry air from the south typical for this system.

[39] The Persian Trough (type E) is typical for summer, and is the most common type in Israel, along with RST. The wind profiles are quite similar to those for the RST. There is a clear distinction in the temperature profiles in which there is a noticeable tendency in DD for the higher levels to become unstable (700–500 hPa). This can be explained by the fact that in the Persian Trough (PT) with northwesterly winds (*V* and *U*) the dust can reach Israel only at the upper levels, at about 700 hPa and above. In the *RH* profile there is a strong decrease above 850 hPa because of the persistent marine inversion during a PT type. For DD, RH is higher at heights above 850 hPa and lower near the surface (below 850 hPa), as for the RST type.

[40] The E and D synoptic types cover together most of the year, about 200–250 days, and show mostly similar characteristics for DD.

[41] For the Cyprus Low (G), here also there are similarities with other types, such as that during DD horizontal winds are stronger, both meridional and zonal (*U*- and *V*-winds, respectively), the atmosphere is less stable (*T*), and the static instability is noticeable particularly in the lower levels. In this regard, G-type is similar to RST and different from PT, since the strong winds bring the dust at lower levels. A specific feature of the Cyprus Low is a strong upward motion (*Omega*) in both no-DD and in particular for DD conditions. This supports the notion that there are strong winds combined with large-scale convergence, which result in the strong upward motion. Relative humidity is quite different in the G-type: in the upper levels *RH* is similar for DD and no-DD. The reason is that the dust is primarily in the lower troposphere, up to 700 hPa. The G-type *RH* profiles show that this is the most humid type among the three synoptic types, because of the strong westerly winds (*U*) and moisture advection from the Mediterranean Sea.

4.5. Significance of DD and No-DD Differences

[42] We tested the significance of the differences between the DD and no-DD populations. We used the common *t* test

Table 3. Significance of Difference Between DD and No-DD Cases With Bootstrapping[a]

Synoptic Type	Pressure Level	*RH*	*U-wind*	*V-wind*	*Abswind*
C	1000	−7.86	**0.13**	4.61	3.09
C	925	−8.64	**1.94**	6.51	5.13
C	850	−5.39	5.59	8.35	9.31
C	700	4.33	6.60	7.70	7.68
C	600	7.68	6.19	6.66	6.73
C	500	6.90	6.35	6.03	6.26
D	1000	−11.40	−5.16	5.55	5.81
D	925	−12.26	−3.98	7.59	9.00
D	850	−7.37	**−1.81**	8.56	11.76
D	700	4.49	**−1.00**	7.74	6.57
D	600	7.53	**−1.64**	6.83	3.21
D	500	5.37	**−2.03**	6.34	**1.04**
G	1000	−8.78	7.10	12.80	10.54
G	925	−9.29	8.40	13.61	11.79
G	850	−4.98	9.40	14.89	14.34
G	700	**1.04**	9.88	12.55	13.68
G	600	3.29	9.02	11.32	12.44
G	500	**2.39**	8.30	10.34	10.51
E	1000	−7.01	3.57	3.54	5.23
E	925	−5.25	5.56	6.61	7.66
E	850	−3.54	10.13	8.57	14.00
E	700	8.28	9.76	5.62	12.95
E	600	11.99	9.65	4.47	12.01
E	500	13.47	9.31	3.87	10.95

[a]Bold numbers are for *t* test failing the 1% significance test. For each synoptic type, pressure level, and parameter, the distance in standard deviations of DD average from the average of the means distribution. The standard deviations are also derived from the means distribution. Population sizes are C no-DD 5522, C DD 210, D no-DD 3372, D DD 210, G no-DD 1795, G DD 306, E no-DD5336, and E DD 95.

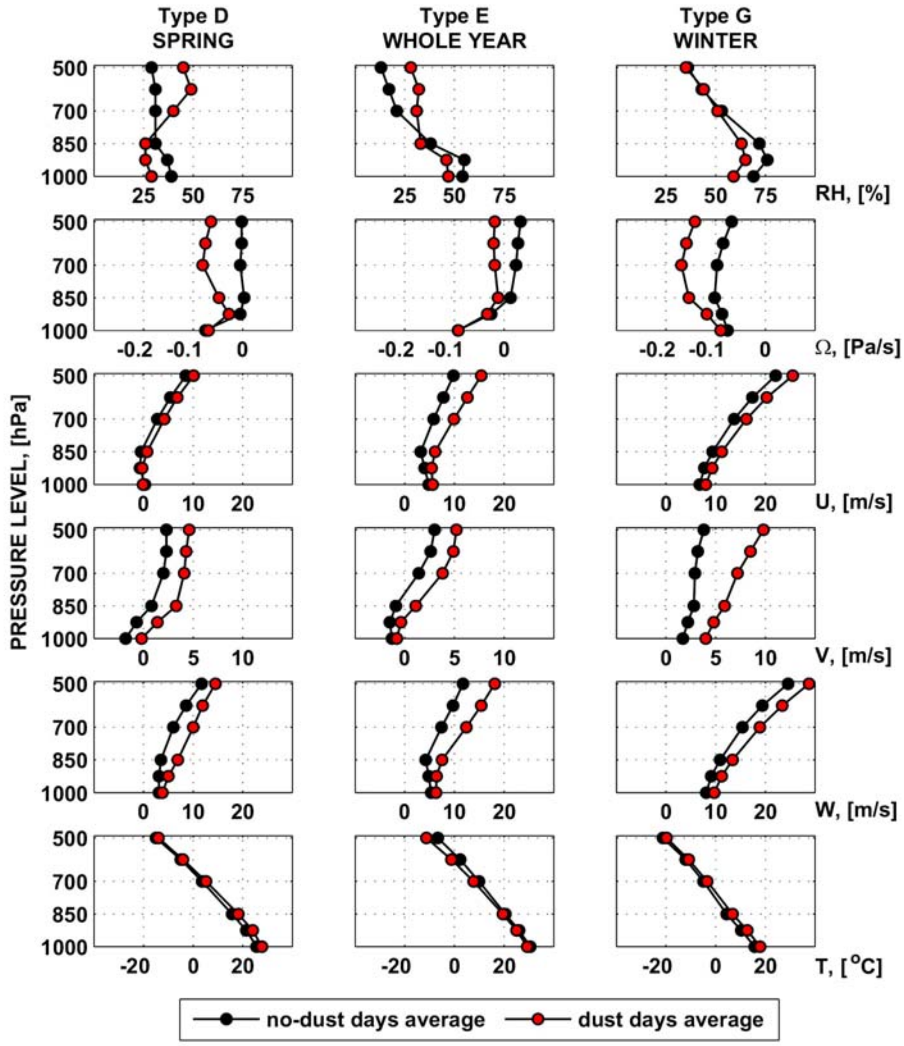

Figure 4. Main differences between dust and no-dust days. (left) D-type in spring, (middle) E-type for a whole year, and (right) for G-type in winter. *RH* is relative humidity in percent, Ω is *Omega* in Pa/s, *U* is *U-wind* in m/s, *V* is *V-wind* in m/s, *W* is absolute horizontal wind in m/s, and *T* is for temperature in Celsius. Red circles are for days with dust, and black circles are for days without dust.

(Table 2). However, *t* test is formally only valid for close-to-normally distributed (Gaussian) parameters. Therefore, we also used the bootstrapping technique described in section 3. The population sizes for no-DD were C-type 5522, D-type 3372, G-type 1795, E-type 5336. The population sizes for DD were C-type 210, D-type 210, G-type 306, E-type 95. Types C, D, G were chosen because they have the most DD, and type E was added to complete the set used for Figure 4.

[43] It was found that for most cases, *t* test shows significance better than 1%. In fact, even if the averages (Figure 1) appear identical, as for example, for synoptic G-type for *RH* at 500 hPa to 700 hPa, the *RH* distributions may be significantly different. Table 2 shows this to be the case for *RH* during G-type at 600 hPa and 500 hPa (with significance 1.4%). Table 2 shows that for most cases, the DD and no-DD *RH* distributions are significantly different. The conclusion is that the populations for DD and no-DD days are different for every pressure level. This justifies showing only the averages in the profile Figures 1–4. The profiles give much more information by showing the relations between pressure levels throughout the troposphere.

[44] The bootstrapping method results (Table 3) are given in the form of the distance between the average of non-DD means and the DD average in units of the standard deviation of the distribution of non-DD means. This distance is an indicator of how different the DD and no-DD populations are. These results show the DD population to be distinct from the no-DD population by at least 3 sigma (1% significance) for most sets, except the following: (1) between 2 and 3 sigma: D-500*U-wind*, G-500*RH*; (2) between 1 and 2 sigma: D-500*Abswind*, G-700*RH*, D-600*U-wind*, D-850*U-wind*, C-925*U-wind*; (3) below 1 sigma: C-1000*U-wind*, D-700*U-wind.*

[45] These exceptions are the same as those with the *t* test (Table 2). We conclude that *t* test is a good enough measure

and could be used in the future to further test the difference between the populations.

5. Summary

[46] The analysis of meteorological profiles for relative humidity (*RH*), and wind (*Omega*, *U-wind*, *V-wind*, *Abswind*), has been carried out for the period of 1958 to 2006 over the eastern Mediterranean–Israel. During this period, about 1000 dusty days were observed. It has been found that relative humidity and wind components show significant differences between dust and no-dust conditions.

[47] The *RH* is higher by 11–15% at the three upper levels, 700, 600, 500 hPa, during the dust episodes as compared to no-dust conditions. In Israel, high *RH* at these levels is associated with cumulonimbus, altocumulus, or stratocumulus clouds, and precipitation, and is presumably applicable for dust forecast and probability of precipitation following a dust event.

[48] Vertical component *Omega* during dust days is always more negative than for no-dust days. The *V-wind* for dust days is more positive (southerly), or in cases of negative wind (northerly wind) is weaker. Absolute horizontal wind is stronger during dust days than during no-dust days.

[49] Below 700 hPa level, temperature is equal or higher for dust days than for no-dust days, except for G-type during fall. Average temperature is above minus 20°C at 500 hPa, and is higher still for lower levels (higher pressures).

[50] A previous work [*Ganor et al.*, 2010] has shown an increase in days with dust since 1958. If this trend continues, we expect the average lower troposphere profiles of the above parameters to change, as the effect of the dust-day profiles becomes more pronounced.

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References

Alpert, P., P. Kishcha, A. Shtivelman, S. O. Krichak, and J. H. Joseph (2004a), Vertical distribution of Saharan dust based on 2.5-year model predictions, *Atmos. Res.*, *70*, 109–130, doi:10.1016/j.atmosres.2003.11.001.

Alpert, P., I. Osetinsky, B. Ziv, and H. Shafir (2004b), Semi-objective classification for daily synoptic systems: Application to the eastern Mediterranean climate change, *Int. J. Climatol.*, *24*, 1001–1011, doi:10.1002/joc.1036.

Alpert, P., I. Osetinsky, B. Ziv, and H. Shafir (2004c), A new seasons definition based on classified daily synoptic systems: An example for the eastern Mediterranean, *Int. J. Climatol.*, *24*, 1013–1021, doi:10.1002/joc.1037.

Alpert, P., P. Kishcha, Y. J. Kafuman, and R. Schwarzbard (2005), Global dimming or local dimming? Effect of urbanization on sunlight availability, *Geophys. Res. Lett.*, *32*, L17802, doi:10.1029/2005GL023320.

Andreae, M. O. (1995), Climatic effects of changing atmospheric aerosol levels, in *World Survey of Climatology*, vol. 16, *Future Climate of the World*, edited by A. Henderson-Sellers, pp. 341–392, Elsevier, Amsterdam.

Annesi-Maesano, I., F. Forastiere, N. Kunzli, and B. Brunekref (2007), Particulate matter, science and EU policy, *Eur. Respir. J.*, *29*, 428–431, doi:10.1183/09031936.00129506.

Ansmann, A., I. Mattis, D. Müller, U. Wandinger, M. Radlach, D. Althausen, and R. Damoah (2005), Ice formation in Saharan dust over central Europe observed with temperature/humidity/aerosol Raman lidar, *J. Geophys. Res.*, *110*, D18S12, doi:10.1029/2004JD005000.

Barkan, J., H. Kutiel, P. Alpert, and P. Kishcha (2004), Synoptics of dust intrusion days from the African continent into the Atlantic Ocean, *J. Geophys. Res.*, *109*, D08201, doi:10.1029/2003JD004416.

Carmona, I., Y. J. Kaufman, and P. Alpert (2008), Using numerical weather prediction errors to estimate aerosol heating, *Tellus, Ser. B*, *60*, 729–741.

Dayan, U., B. Ziv, T. Shooba, and Y. Enzel (2008), Suspended dust over southeastern Mediterranean and its relation to atmospheric circulations, *Int. J. Climatol.*, *28*, 915–924, doi:10.1002/joc.1587.

Derimian, Y., A. Karnieli, Y. J. Kaufman, M. O. Andreae, T. W. Andreae, O. Dubovik, W. Maenhaut, I. Koren, and B. N. Holben (2006), Dust and pollution aerosols over the Negev desert, Israel: Properties, transport, and radiative effect, *J. Geophys. Res.*, *111*, D05205, doi:10.1029/2005JD006549.

Ganor, E. (1975), Atmospheric dust in Israel: Sedimentological and meteorological analysis of dust deposition, 224 pp., Ph.D. thesis, Hebrew Univ. of Jerusalem, Jerusalem, Israel.

Ganor, E. (1994), The frequency of Saharan dust episodes over Tel Aviv, Israel, Atmos. *Environ.*, *28*(17), 2867–2871, doi:10.1016/1352-2310(94)90087-6.

Ganor, E., I. Osetinsky, A. Stupp, and P. Alpert (2010), Increasing trend of African dust, over 49 years, in the eastern Mediterranean, *J. Geophys. Res.*, *115*, D07201, doi:10.1029/2009JD012500.

Goudie, A. S., and N. J. Middleton (2001), Saharan dust storms: Nature and consequences, *Earth Sci. Rev.*, *56*, 179–204, doi:10.1016/S0012-8252(01)00067-8.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-Year Reanalysis Project, *Bull. Am. Meteorol. Soc.*, *77*, 437, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2.

Kaufman, Y. J., I. Koren, L. A. Remer, D. Rosenfeld, and Y. Rudich (2005), The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean, *Proc. Natl. Acad. Sci. U. S. A.*, *102*, 11,207–11,212, doi:10.1073/pnas.0505191102.

Levin, Z., and W. Cotton (2007), Aerosol pollution impact on precipitation: A scientific review, Int. Aerosol Precip. Sci. Assess. Group, Int. Union of Geod. and Geophys., World Meteorol. Org., Geneva.

Levin, Z., A. Teller, E. Ganor, and Y. Yin (2005), On the interactions of mineral dust, sea salt particles and clouds: A measurement and modeling study from the MEIDEX campaign, *J. Geophys. Res.*, *110*, D20202, doi:10.1029/2005JD005810.

Mahowald, N. M., J. A. Ballantine, J. Feddema, and N. Ramankutty (2007), Global trends in visibility: Implications for dust sources, *Atmos. Chem. Phys.*, *7*, 3309–3339.

Markowicz, K. M., P. J. Flatau, M. V. Ramana, P. J. Crutzen, and V. Ramanathan (2002), Absorbing Mediterranean aerosols lead to a large reduction in the solar radiation at the surface, *Geophys. Res. Lett.*, *29*(20), 1968, doi:10.1029/2002GL015767.

Osetinsky, I. (2006), Climate changes over the eastern Mediterranean—A synoptic systems classification approach, 153 pp., Ph.D. thesis, Tel Aviv Univ., Tel Aviv, Israel.

Rahn, K. A., R. D. Borys, G. E. Show, L. Schutz, and R. Jaenicke (1979), Long range impact of desert aerosols on atmospheric chemistry: Two examples, in *Saharan Dust Mobilization, Transport, Deposition*, edited by C. Morales, pp. 243–266, John Wiley, New York.

Ramanathan, V., P. J. Crutzen, J. T. Kiehl, and D. Rosenfeld (2001), Aerosols, climate and the hydrological cycle, *Science*, *294*, 2119–2123, doi:10.1126/science.1064034.

Rosenfeld, D., Y. Rudich, and R. Lahav (2001), Desert dust suppressing precipitation: A possible desertification feedback loop, *Proc. Natl. Acad. Sci. U. S. A.*, *98*, 5975–5980, doi:10.1073/pnas.101122798.

Stanhill, G., and S. Cohen (2001), Global dimming: A review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences, *Agric. For. Meteorol.*, *107*, 255–278, doi:10.1016/S0168-1923(00)00241-0.

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