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Increasing trend of African dust, over 49 years, in the eastern Mediterranean

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[1] Dust observations in Israel were carried out since 1958. During 1958–2006, 966 dust days were observed. The dust days have been analyzed through their association with the regional eastern Mediterranean synoptic types, as classified by the Tel Aviv University method. Among the synoptic types, the most contributing were winter lows (with 368 days), Red Sea Troughs (214 days), and highs (211 dust days). Association of dust with highs is a new result, not found in the literature to date. Out of the total occurrences of Sharav lows, 36% are associated with dust, out of total winter lows 13%, with a winter low south to Cyprus having a 30% probability to produce a dust day, and of Red Sea Trough days 6% were associated with dust. Annual occurrence of dust days follows the changes in the occurrence of the regional synoptic systems: the number of dust days associated with Red Sea Troughs has increased by 2.3 d/10 yr, and with highs by 0.9 d/10 yr. The total incidence of dust days has increased with an average rate of 2.7 days per decade. This increasing trend in dust storm occurrence fits with previous results for the eastern Mediterranean and south Europe. Since dust storms are a regional phenomenon and reach south, central, and western Europe, this increase has implications for the entire Mediterranean and European regions. The results show potential for statistical forecasting of dust 1 day in advance. Such forecasts are important for public health warnings and for air transportation.

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1. Introduction

[2] The term "dust storms" refers here to clouds of mineral aerosols lifted into the atmosphere at sources in Algeria, Niger, Libya, Chad (Bodele Depression), Egypt, Sudan, Saudi Arabia, Jordan and Syria, and passing over the eastern Mediterranean and southern Europe at heights of up to 6 km above sea level [*Israelevich et al.*, 2002]. Dust has a residence time in the atmosphere ranging from hours to about 10 days, and is removed either through dry (contact) or wet (precipitation) deposition [*Ganor*, 1991, 1994; *Papayannis et al.* , 2008; *Kubilay et al.*, 2000]. Dust storms are a major atmospheric event in the eastern Mediterranean, and have a significant impact on public health [*Annesi-Maesano et al.*, 2007], transportation, cloudiness, rain, radiative transfer [*Goudie and Middleton*, 2001; *Rosenfeld et al.*, 2001; *Kaufman et al.*, 2005], and soil enrichment [*Rahn et al.*, 1979]. The dust may also have an impact on climate [*Andreae*, 1995; *Ramanathan et al.*, 2001; *Levin and Cotton*, 2009].

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[3] Dust was identified at ground level by measurements of PM10 (particulate matter with aerodynamic diameter of less than 10 μm), visually from visibility limits and sky color, or, for wet deposition, with rain collectors by evaporating water and checking the residue. In this work, a dust day (DD) was defined as a day when horizontal visibility was below 5000 m and/or dust was found in precipitation. The observations were made at Jerusalem and Tel Aviv.

[4] Most dust storm studies span a period of only a few years [*Dayan and Levi*, 2005; *Derimian et al.*, 2006], though some extend over a few decades [*Mahowald et al.*, 2007; *Dayan et al.*, 2008]. Since dust storms are a relatively rare event with high interannual variability, it is not clear that results from short periods are representative. In this work we analyze the 49 year period 1958–2006. The 49 year Tel Aviv University (TAU) synoptic classification based on the NCEP/NCAR reanalysis data, together with the database of dust observations since 1958, made it possible to significantly deepen the dust storm studies.

2. Methodology

2.1. Synoptic Classification

[5] Each day since the first of January 1958 was assigned a synoptic type using the TAU classification. The TAU classification is a semiobjective synoptic systems classification [*Alpert et al.*, 2004; *Osetinsky*, 2006], using the

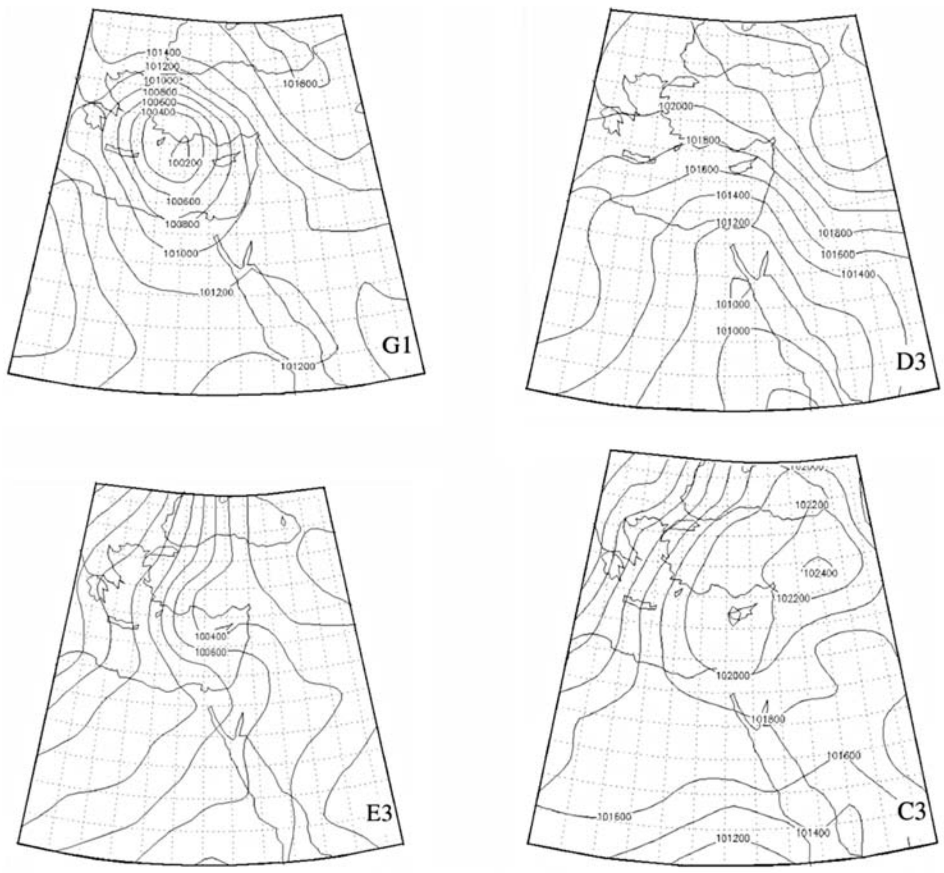

Figure 1. Sea level pressure maps of representative cases of TAU method synoptic systems at 12 UTC: Cyprus low (G1), Red Sea Trough (D3), Persian Trough (E3), high (C3).

NCEP/NCAR reanalysis data (available at http://www.cdc.noaa.gov/data/gridded/data.ncep.reanalysis.html). The automatic classification was originally applied to the daily data over 1948–2000 with the results shown to fit the true regional climate [*Alpert et al.*, 2004], and later extended to 2006.

[6] The TAU classification relies on a preliminary manual classification of a limited representative set of regional daily synoptic charts by a group of expert meteorologists. The daily sea level pressure charts at 1200 UTC for a representative period (one calendar year with one more meteorological winter season of DJF added) were manually classified into the typical regional synoptic groups (Figure 1). This manually classified set of the daily synoptic systems served as a training set for the TAU method called "a modified discriminant analysis." The method was then applied to the NCEP/NCAR reanalysis daily data. Each input vector consisted of the gridded parameters of geopotential height, temperature, zonal wind, and meridional wind (total four fields) over the eastern Mediterranean region of 30°E–40°E, 27.5°N–37.5°N (total 25 grid points), at 1000 hPa level at 1200 UTC. Thus, every daily vector consisted of $100 = 4 \times 25$ entries. For every daily vector, Euclidean distances between it and every member of the training set were calculated. The minimal distance decided the destination class.

[7] The TAU method has several advantages. It is simple in programming and application, and is applicable to any region, with the only requirement being a definition of a regional training set of synoptic systems, composed by the regional expert meteorologists. The method is extendable into the future, enabling addition of years to be classified, and applicable to GCM gridded data as well [*Osetinsky and Alpert*, 2004; *Samuels et al.*, 2007]. In this work, the TAU synoptic classes have been joined into synoptic types for a dust analysis, shown in Table 1.

2.2. Identification of Dust Days

[8] Dust was identified from the ground in Jerusalem during 1958–1973 and in Tel Aviv during 1974–2006. Measurements were made manually every day except for a week during Passover (April or May). Since the 1980s measurements were not taken for about 2 weeks per year, usually during summer (June to August) which is not dust season in Israel. Since 1995 identification has been possible by automatic continuous measurements of PM10.

[9] 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 of less than 5000 m, the WMO standard of low visibility [see also *Mahowald et al.*, 2007], and in addition brown, yellow or orange sky color.

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

Synoptic Types	Name	Synoptic Classes and Typical Cases
A	Sharav lows (SL)	A1, western SL; A2, central SL
B	Southern winter lows	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 (WL) 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

[10] Since 1968 a high volume sampler was operated from 0800 to 2000 h on days in which dust was identified in the morning, and the collected aerosols examined for color and under a microscope. Identification of dust in rainwater (wet deposition) was done 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. Usually dust was identified in dry conditions, sometimes the dust was later washed by rain, and it was also identified in rainwater, and sometimes the dust was only identified in rainwater.

[11] Cases were also identified by deposited dust. Every evening a one square meter clean glass was left outside at a height of one meter above the ground. 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. The results of all these measurements and identification methods were used to compile a list of days with dust for the years 1958 to 2006.

3. Probability of Dust Days in the TAU Classification

[12] During the 1958–2006 period, the total number of the observed DD was 966 [*Ganor et al.*, 2007] where, for example, in January there were 87 DD out of total 1519 days, and in April 205 DD out of total 1470 days (Table 2). Table 2 shows the monthly probabilities for a day with a given synoptic type to be a DD. For each given synoptic type, each monthly cell includes three values: "dust," number of DD; "total," total monthly type occurrences; "%," the ratio dust/total multiplied by 100, which gives the estimated probability for a DD to occur. For example, in January, there were 360 G-type days, in 53 out of which dust was observed. Therefore, the probability for dust to occur on a G-type day in January is about 15% (53/360 × 100).

Table 2. TAU Synoptic Types: Monthly Occurrence of Dust Days, Total Occurrence, and Dust Day Probability for 1958–2006

Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
A													
Dust	2	6	12	37	17	1	0	0	1	0	1	0	77
Total	12	18	36	80	42	6	1	0	5	5	3	5	213
Probability (%)	17	33	33	46	40	17	0	0	20	0	33	0	36
B													
Dust	2	3	3	0	0	0	0	0	0	0	0	0	8
Total	7	9	3	0	0	0	0	0	0	0	2	6	27
Probability (%)	29	33	100	0	0	0	0	0	0	0	0	0	30
C													
Dust	7	20	28	59	32	7	2	0	5	12	15	24	211
Total	500	517	655	682	682	371	234	211	352	476	495	557	5732
Probability (%)	1	4	4	9	5	2	1	0	1	3	3	4	4
D													
Dust	21	12	28	27	16	1	0	0	5	48	41	15	214
Total	492	337	341	271	158	19	5	10	104	610	711	524	3582
Probability (%)	4	4	8	10	10	5	0	0	5	8	6	3	6
E													
Dust	0	0	0	17	37	15	12	1	6	7	1	0	96
Total	0	1	16	120	494	1041	1273	1290	925	255	16	0	5431
Probability (%)	0	0	0	14	7	1	1	0	1	3	6	0	2
F													
Dust	2	8	13	16	2	0	0	0	0	3	4	5	53
Total	148	152	127	73	32	2	0	0	3	76	87	111	811
Probability (%)	1	5	10	22	6	0	0	0	0	4	5	5	7
G													
Dust	53	50	74	49	12	0	0	0	2	5	16	46	307
Total	360	350	341	244	111	31	6	8	81	97	156	316	2101
Probability (%)	15	14	22	20	11	0	0	0	2	5	10	15	15
All types													
Dust	87	99	158	205	116	24	14	1	19	75	78	90	966
Total	1519	1384	1519	1470	1519	1470	1519	1519	1470	1519	1470	1519	17897
Probability (%)	6	7	10	14	8	2	1	0	1	5	5	6	5

Table 3. Monthly Probabilities for Dust Given TAU Synoptic Type 1 Day Before and 2 Days Before[a]

Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					1 Day Before							
A	18	26	41	43	18	14	0	0	20	0	67	20
B	0	0	33	0	0	0	0	0	0	0	0	0
C	5	5	10	13	9	3	2	0	1	3	4	6
D	5	7	12	15	12	5	0	0	6	8	6	4
E	0	0	0	6	4	1	1	0	1	2	0	0
F	0	3	2	5	0	0	0	0	0	1	5	1
G	10	10	11	9	9	3	0	0	1	2	4	12
					2 Days Before							
A	9	16	16	25	6	14	0	0	25	0	0	20
B	0	0	33	0	0	0	0	0	0	0	0	0
C	7	8	12	16	8	2	2	0	2	3	4	7
D	5	7	13	15	11	0	0	0	1	8	6	5
E	0	0	9	12	6	1	1	0	1	5	6	0
F	1	4	4	3	0	0	0	0	0	1	0	3
G	7	6	6	6	8	0	0	0	1	1	6	8

[a]Probability values measured in percent.

[13] Table 2 shows that in November, in January–May, and in September–October, all synoptic types had a nonzero dust probability. In March, there were three occurrences of type B (southern winter lows), and dust was observed in all of them (100%). During June–August and in December, there were synoptic types with no dust. In July, 12 out of 14 observed DD were of E-type (Persian Trough), and 2 of C-type (subtropical high, or high to the west). Type G (winter lows) shows relatively high dust probabilities from December through April: 14% to 22%.

[14] Table 3 shows the monthly probability for DD given a certain synoptic type 1 day before and 2 days before the DD. The highest probability is for a DD in November preceded by type A 1 day before: 67%. For 2 days before probability, the highest probability is for a DD in March preceded by type B 2 days before: 33%.

[15] In 62% of cases the probability to have dust observed 1 day after a synoptic type is higher than 2 days after a type. For example, the annual dust probability on a day after a C-type day is 12% while the probability to have a DD 2 days after C-type is only 9%. Therefore, assuming computed dust probabilities to be valid in the future, we may conclude that a more successful dust forecast can be made 1 day in advance than 2 days in advance.

[16] It is important to note that high dust probabilities were sometimes obtained because of a small number of dust days during or after these type chains. These events should be treated with caution because of their low frequency. On the other hand, these are type chains with high probability of dust, and their frequencies are typical for the eastern Mediterranean. These synoptic types also keep their typical calendar dates of occurrence [*Osetinsky and Alpert*, 2006].

[17] The largest number of DD occurrences was for the G, C, and D types: 307 days, 211 days, and 214 days, respectively, while the highest dust probabilities were obtained for A, B, and G types: 36%, 30%, and 15%, respectively (Table 2). The high number of dust occurrences on days of C type (highs) is a new result to be added to those found in the dust storm studies to date.

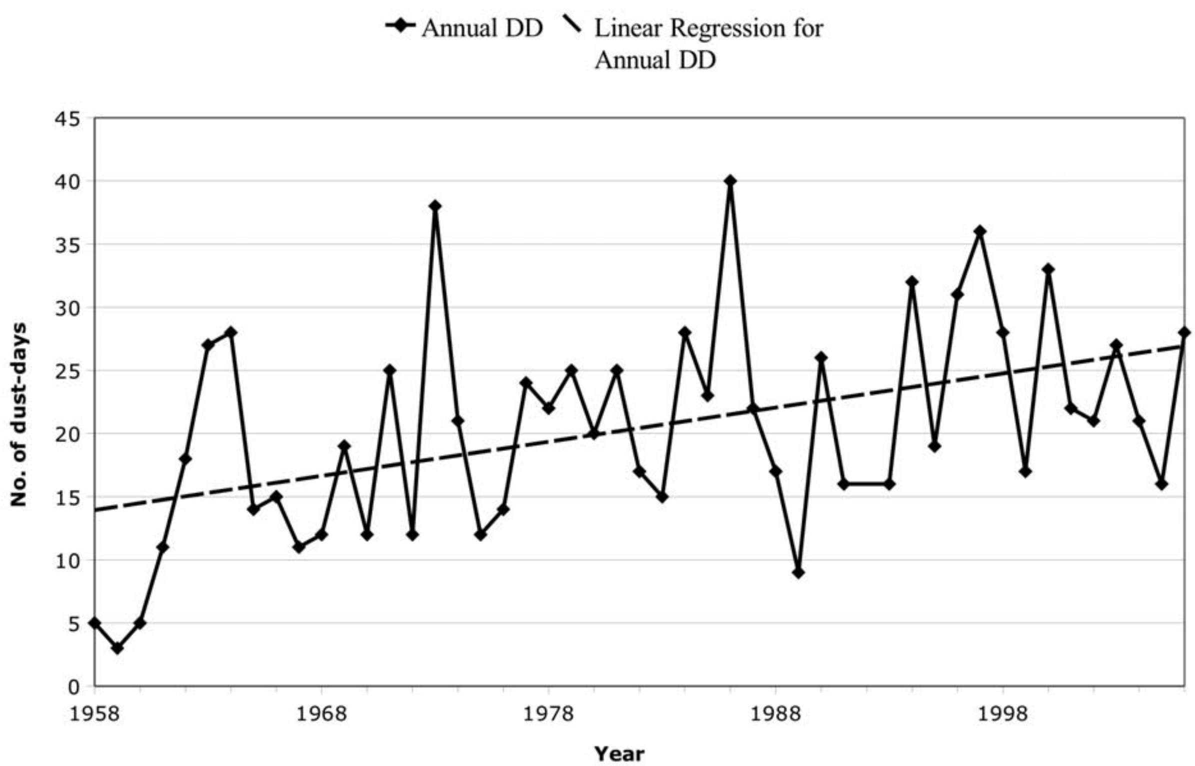

Figure 2. Annual numbers of days with dust (solid line), and linear trend (dashed line). Linear trend increases from 14 to 27 days. The slope of the linear regression is 0.27 DD/year.

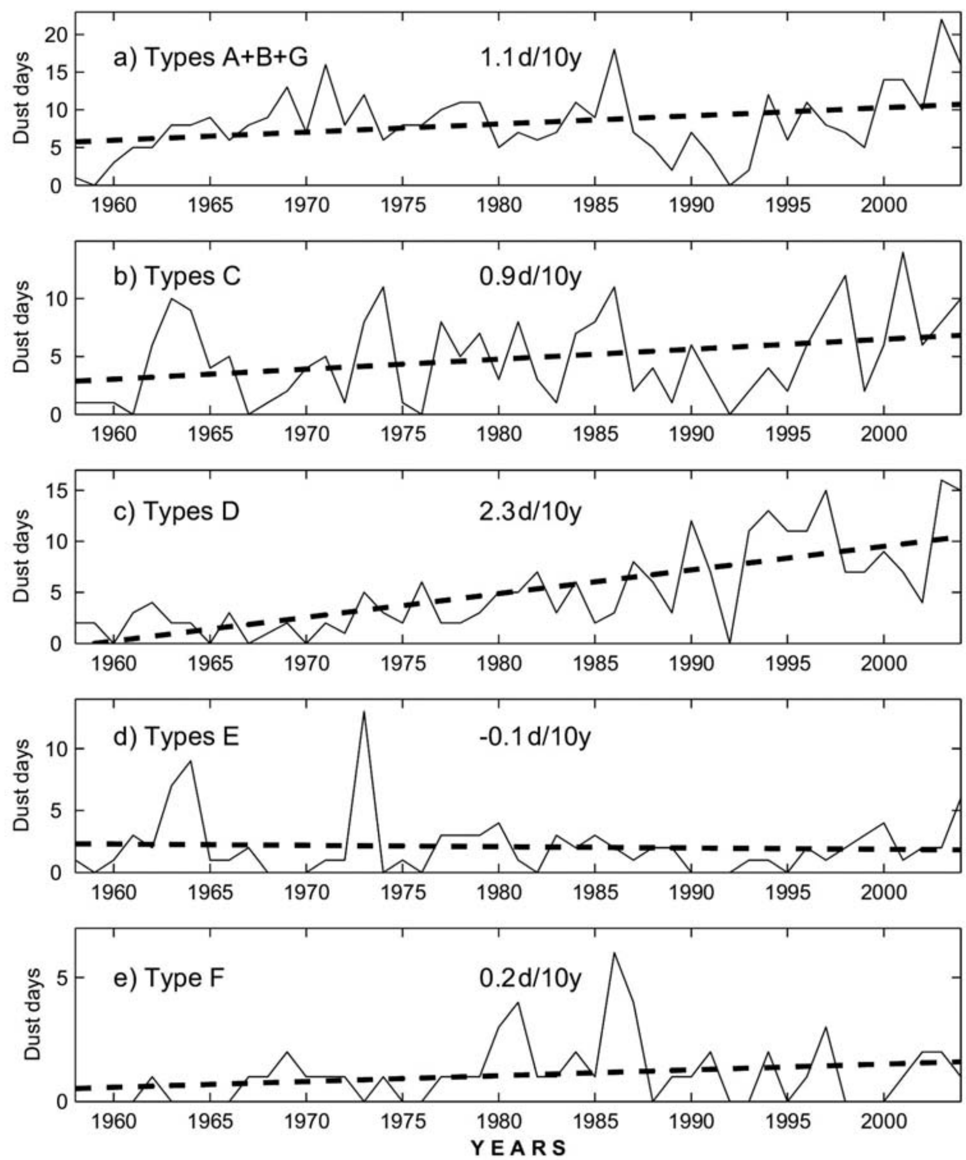

Figure 3. Annual number of days associated with dust storms in the TAU synoptic classification for 1958–2004 (solid line), and linear trends (bold dashed). Decadal slopes for linear trends are shown: (a) types A (Sharav lows) + B (winter lows south of Cyprus) + G (winter lows west/north/east to Cyprus, the latter only for a deep type); (b) types C (highs); (c) types D (Red Sea Troughs); (d) types E (Persian Troughs); (e) type F (shallow winter lows east of Cyprus).

[18] Measurements of PM10 increase during dust storms [*Ganor and Mamane*, 1982]. Taking into account the above synoptic associations with DD, this could explains the results of Dayan and Levi [*Dayan and Levi*, 2005] which show highest mean PM10 value during northern Cyprus (winter) lows (173.9 mcgr/m^3, 2% of cases), eastern highs (87.2 mcgr/m^3, 3% of cases), and Red Sea Troughs (54 mcgr/m^3, 20% of cases).

[19] During the summer, the dust usually moves over the eastern Mediterranean at heights above 2–3 km, with no dust near the ground, and is detected with remote sensing [*Israelevich et al.*, 2003; *Waisel et al.*, 2008]. Therefore, the number of DD during summer is very low, with only one dust storm recorded on the ground in August during the entire period.

4. Trends in Frequency of Dust Day Occurrence

[20] Trends in annual dust storm frequency have been identified previously in Spain, France, Corsica, and even Britain, and also over a period of just 12 years in Israel [*Ganor et al.*, 2007]. For the Middle East an increase in the frequency of low visibility, implying an increase in dust storms, has been found for 1973–2003, with a weaker trend found for 1940–2003 [*Mahowald et al.*, 2007]. A compilation of dust fallout cases since 1577 BC shows several increases and decreases, with the latest increase since about

1940 [*Bucher*, 1989]. Goudie and Middleton [*Goudie and Middleton,* 2001] claim an increase in dust storm frequency concurrent with drought periods in the Sahel, and cite others who claim an increase in frequency of occurrence and annual duration of dust storms since the 1950s. They also cite studies showing increase in dust rain days since the 1970s on the Mediterranean coast of Spain. Another study of an ice core for 1955–1985 showed increase in Saharan dust over the French Alps since the early 1970s. Fiol [*Fiol et al.*, 2005] concludes that dust rains in Palma de Mallorca are on the increase based on data from 1982 to 2003, and also cites other sources which show increasing frequency of dust in Spain from 1985 to 1994. These works indicate there is an increase of Saharan dust intrusions in the entire region around the Mediterranean.

[21] We find that the overall DD frequency in the eastern Mediterranean has increased. The number of annual DD in Tel Aviv has increased over the period 1958–2006 with a slope of 2.7 days per decade, from 5 days in 1958 to 28 days in 2006 (14 to 27 for the linear fit) (Figure 2).

[22] Figure 3 shows the trends for 1958–2004 by synoptic type. The highest increase is in the number of the dust storm–associated days of D type (Red Sea Trough) with a slope of 2.3 days per decade.

[23] The frequency of other dust storm–associated types has also changed. The number of DD of C type has increased by 0.9 d/10 yr, of types A+B+G together (lows originating from the west of the Levant) by 1.1 d/10 yr, and of F type by 0.2 d/10 yr. The number of DD of E type (Persian Trough, a typical summer synoptic type in Israel) has decreased by 0.1 d/10 yr.

[24] These results show a local synoptic change in this area, and could explain the increase in the total annual number of dust days in the eastern Mediterranean. Indeed, the annual frequency of Red Sea Trough days nearly doubled since the 1960s from 50 to about 100 days per year [*Alpert et al.*, 2004]. The annual frequency of winter low days was noticed to have dropped slightly in 1983–1998 to 26, compared with about 30 during 1967–1982 [*Alpert et al.*, 2004].

5. Conclusions

[25] During the 49 year period considered, 966 DD were recorded. The TAU classification uses automatic classification of large amounts of data, and revealed changes and trends over this long period. The method is easily applicable to any region and period for which reanalysis synoptic data and dust observations exist. Thus, the TAU method can be used for other regions.

[26] The analysis has added a high-pressure synoptic type (type C) to those known as dust-associated types. The TAU synoptic types may be used for a dust forecast in Israel, especially for a few rare types for which the dust probability is very high. For example, type A in November has 67% probability for dust on the day after it occurred. The A-G type chain in November has 100% probability for dust on the second day, i.e., on the G-type day.

[27] Overall for 62% of synoptic types, the probability for dust on the day after a given type is higher than for 2 days after the type occurred. Therefore, assuming computed dust probabilities remain valid in the future, we conclude that a more successful dust forecast can be made one day in advance than two days in advance.

[28] The TAU types G (winter low), C (high), and D (Red Sea Trough) made up 76% out of the 966 recorded dust days, while the types for which the dust probability is highest are the less common A (Sharav low) and B (southern winter low) types, with DD probability during the type of 36% and 30%, respectively.

[29] During the summer, the dust usually moves over the eastern Mediterranean at heights of above 2–3 km. Therefore, the number of dust days during the summer is very low, with practically no dust days recorded on the ground in August.

[30] An increasing trend in the total annual number of days with dust has been found, with a slope of 0.27 days per year. Trends in the annual number of days with dust during specific synoptic types have also been found: the number of DD occurring with a Red Sea Trough has increased by 0.23 days per year, for the lows by 0.11 days per year, and for the highs by 0.09 days per year.

[31] The above trends, taken together with trends identified previously in Europe, show the increasing availability of African dust in this region. This, in turn, is evidence for a regional synoptic change, and has implications for the entire Mediterranean and European regions.

[32] **Acknowledgment.** NCEP/NCAR reanalysis data were provided by the NOAA–CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site at http://www.cdc.noaa.gov.

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