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Journal of the Air & Waste Management Association
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uawm20

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Accepted author version posted online: 23 Sep 2013.Published online: 18 Dec 2013.

To cite this article: Helena Krasnov , Itzhak Katra , Petros Koutrakis & Michael D. Friger (2014) Contribution of dust storms to PM_{10} levels in an urban arid environment, Journal of the Air & Waste Management Association, 64:1, 89-94, DOI: 10.1080/10962247.2013.841599

To link to this article: http://dx.doi.org/10.1080/10962247.2013.841599

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TECHNICAL PAPER

Contribution of dust storms to PM_{10} levels in an urban arid environment

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*Quantitative information on the contribution of dust storms to atmospheric PM_{10} (particulate matter with an aerodynamic diameter ≤ 10 μm) levels is still lacking, especially in urban environments with close proximity to dust sources. The main objective of this study was to quantify the contribution of dust storms to PM_{10} concentrations in a desert urban center, the city of Beer-Sheva, Negev, Israel, during the period of 2001–2012. Toward this end, a background value based on the "dust-free" season was used as a threshold value to identify potentially "dust days." Subsequently, the net contribution of dust storms to PM_{10} was assessed. During the study period, daily PM_{10} concentrations ranged from 6 to over 2000 μg/m^3. In each year, over 10% of the daily concentrations exceeded the calculated threshold (BV_t) of 71 μg/m^3. An average daily net contribution of dust to PM_{10} of 122 μg/m^3 was calculated for the entire study period based on this background value. Furthermore, a dust storm intensity parameter (*Ai*) was used to analyze several storms with very high PM_{10} contributions (hourly averages of 1000–5197 μg/m^3). This analysis revealed that the strongest storms occurred mainly in the last 3 yr of the study. Finally, these findings indicate that this arid urban environment experiences high PM_{10} levels whose origin lies in both local and regional dust events.*

Implications: The findings indicate that over time, the urban arid environment experiences high PM_{10} levels whose origin lies in local and regional dust events. It was noticed that the strongest storms have occurred mainly in the last 3 yr. It is believed that environmental changes such as global warming and desertification may lead to an increased air pollution and risk exposure to human health.

Introduction

Numerous studies have reported high concentrations of ambient particulate matter (PM) during dust events in different parts of the world (e.g., Dayan et al., 1991; Gertler et al., 1995; Rodriguez et al., 2001; Kallos et al., 2006; Escudero et al., 2007; Koçak et al., 2007a; Mitsakou et al., 2008; Contini et al., 2010; Alolayan et al., 2013). More importantly, several studies have found excess in mortality and morbidity during dust storm episodes (e.g., Chen et al., 2004; Gyan et al., 2005; Perez et al., 2008; Neophytou et al., 2013).

Due to the proximity of Israel to the global dust belt, which extends from West Africa to the Arabian Desert, dust events can increase daily PM_{10} (PM with an aerodynamic diameter ≤ 10 μm) levels in the center of Israel (Tel Aviv) to as high as 2100 μg/m^3 (Ganor et al., 2009; Kalderon-Asael et al., 2009), which is significantly above all air quality standards. The Negev region in southern Israel is frequently impacted by dust storms (Dayan et al., 1991; Erell and Tsoar, 1999; Offer et al., 2008; Ganor et al., 2010). Hourly average PM_{10} concentrations can reach 4200 μg/m^3 during storms in the northern Negev (Offer and Azmon, 1994). The intense dust storms in the Negev are associated with specific synoptic systems. In the winter, cold low-pressure systems with the Cyprus Low are most prevalent (Alpert et al., 1990b). The Red Sea Trough (RST) is the most common system in the autumn (Kahana et al., 2002), whereas high- and warm low-pressure systems, Sharav Low, are frequent in the spring (Alpert and Ziv, 1989). The summer period is considered as a dust-free season (Ganor et al., 2010) due to the influence of the quasi-stationary Persian Trough (PT) system (Alpert et al., 1982, 1990a; Dayan et al., 1988). Dust particles reach the southeastern Mediterranean by two main trajectories: one from the west (North Africa–Sinai–Negev) and the second from east (Arabian Desert–Negev) (Dayan et al., 1991; Ganor and Foner, 1996; Israelevich et al., 2002; Ganor et al., 2010), with dust particles having somewhat different mineralogical and chemical compositions (Kalderon-Asael et al., 2009; Ganor et al., 2009).

The increasing frequency of dust storms in the southeastern Mediterranean (Ganor et al., 2010) over the past few decades has led to growing concern regarding the levels of PM_{10}. However, quantitative information on the contribution of dust storms to atmospheric PM_{10} is still lacking, especially in urban environments that are proximal to dust sources. Only a few methods

Journal of the Air & Waste Management Association, 64(1):89–94, 2014. Copyright © 2014 A&WMA. ISSN: 1096-2247 print
DOI: 10.1080/10962247.2013.841599 Submitted June 12, 2012; final version submitted August 2, 2013; accepted September 2, 2013.

have been developed to estimate the dust contribution. Escudero et al. (2007) determined the daily contribution in Spain based on statistical treatment of PM time-series data recorded at regional background sites. Ganor et al (2009) employed in Tel Aviv (center of Israel) an automatic algorithm with three threshold criteria: the half-hour PM_{10} average is higher than 100 $\mu g/m^3$; this level is maintained for at least 3 hr; and the maximum hourly concentration recorded is above 180 $\mu g/m^3$. As shown by Viana et al. (2010), Ganor et al.'s method might not be directly applicable to areas where the maximum PM_{10} hourly values recorded are relatively low.

Because there is only a single monitoring PM station in the Negev, the method of Escudero et al. (2007) is not applicable. Due to the low contribution of anthropogenic PM in the Negev and frequent dust storms compared with nonarid areas (Ganor et al., 2009), a new method is required to determine dust thresholds and net contribution to PM levels. The main objective of this study was to analyze PM_{10} atmospheric concentrations in a desert urban center (the city of Beer-Sheva, Negev region of Israel) over the past decade, with the aim to quantify the contribution of dust storms to the particle levels.

Data Analysis

Data set

PM_{10} data for the period 2001–2012 were obtained from the monitoring station of the Ministry of Environmental Protection (http://www.sviva.gov.il) within the framework of the National Air Monitoring System. The data were recorded every 5 min by a dichotomous ambient particulate monitor (Thermo Scientific 1405-DF; Thermo Fisher Scientific Inc.) that provides a continuous direct mass measurement of particle mass utilizing two tapered element oscillating microbalances (TEOMs). Data on $PM_{2.5}$ are available only from May 2012. Finally, daily concentrations were estimated by averaging hourly mean concentrations.

Background value

A background value (BV) was calculated solely on the basis of the summer time, which is a "dust-free" season in the study area (Dayan, 2008; Ganor et al., 2010). Although the universal summer season in the northern hemisphere lasts from 22 June to 21 September (American Meteorological Society [AMS], 2001), the summer time in this study was limited to the months of July and August in order to exclude dust events that may occur at the beginning and/or the end of the summer. The BV was determined for 12-hr periods from 6 a.m. to 6 p.m. (since the majority of natural dust storms take place mainly during the daytime) based on a curve-area calculation as shown below.

For a time-series curve of hourly PM_{10}, the area under the curve (AUC) based on concentration values is defined as follows:

$$\varepsilon(t_{1,}t_n) = \int_{t_1}^{t_n} A(t)dt \qquad (1)$$

where $A(t)$ is the hourly AUC between two specific hours t_1 and t_n and $\varepsilon(t_1, t_n)$ is the daily AUC during the time period t_1 to t_n (t_1 and t_n are times at the beginning and the end of the observations, respectively; $n = 12$). This estimate may be expressed in the following form:

$$\varepsilon(t_1, t_n) = \int_{t_1}^{t_n} A(t)dt = \sum_{i=t_1}^{t_n} \frac{(b_1 + b_2) \cdot h}{2} \qquad (2)$$

where h is the height (distance between the parallel sides), which equals 1, as the distance represents 1 hr, and b_1 and b_2 are the lengths of the parallel sides, i.e., the PM_{10} concentration per hour. Because $h = 1$, we obtained

$$\varepsilon(t_1, t_n) = \sum_{i=t_1}^{t_n} \frac{(b_1 + b_2)}{2} \qquad (3)$$

By dividing the ε by 12, average PM_{10} concentration values can be obtained. The $\varepsilon(t_{1,}, t_n)$ area was calculated for each day of the summer period during the 12-yr period covered by the study. An average value was constructed for each year (BV_{2001} to BV_{2012}). No significant differences ($P > 0.05$) were found among the summers, thus a total value for the entire period (BV) was derived. However, the threshold (BV_t) for the classification between potentially "dust days" and non-dust days during the dust seasons was determined as 2 standard deviations above the average BV to reduce errors. Accordingly, a day with PM_{10} that is higher than BV_t will be considered potentially as a "dust day."

Desert-dust-derived PM_{10}

The next step was to examine whether all classified "dust days" were associated with dust events. Observed synoptic systems were reviewed for all these days, considering several systems that are typical to dust events (Dayan et al., 2008; Ganor et al., 2010). Back trajectories were retrieved using the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model (Draxler and Rolph, 2003) for three different altitudes (500, 1000, and 1500 m above ground level [AGL]). In addition, we compared the PM_{10} concentrations of the "dust days" in Beer-Sheva with those in Tel Aviv on the same dates, assuming that during regional storms the dust is also transported to the center of Israel with a trend of decreasing concentrations (Ganor and Foner, 2001). Tel Aviv PM_{10} data were obtained from the Israel Ministry of Environmental Protection and from the work of Ganor et al. (2010).

In order to assess the net contribution (NC) of the dust in the "dust days" to the daily PM_{10} concentrations, the BV_t value was subtracted from the PM_{10} concentration of each dusty day during the dust period. The NC values over time were classified based on percentile thresholds 10th, 25th, 50th, and 75th to classify dust storm levels, as "low," "medium," "high," and "severely high," respectively. NC values of the strongest dust storms that occurred during the study period (2001–2012) were examined in detail. To compare between different storms, we used a parameter that represents storm intensity (A_i) The A_i value was calculated on an hourly basis as the area under the storm curve, which takes into account the concentration values and the storm duration.

Results and Discussion

The daily (24-hr) average PM_{10} values in Beer-Sheva ranged from 6 to 2568 $\mu g/m^3$ (Figure 1). Annual averages (2001–2012) ranged from 43 to 77 $\mu g/m^3$, with no increasing trend. These levels are significantly higher than the World Health Organization (WHO) guideline (20 $\mu g/m^3$) and other PM_{10} levels observed across the Mediterranean basin (Querol et al., 2009). The calculated background values of the "dust-free" seasons (BV_{2001} to BV_{2012}) ranged from 27 to 61 $\mu g/m^3$, with an average BV value of 42 $\mu g/m^3$. Considering 2 standard deviations above, the determined threshold (BV_t) used to classify between potentially "dust days" and non-dust days during the dust seasons was 71 $\mu g/m^3$.

During the study period, daily PM_{10} concentrations exceeded the BV_t for over 10% of the days (538 out of a total of 4384). In all the summer "dust-free" seasons together (2001–2012), the PM_{10} was above the BV_t on 34 days, with a peak value of 99 $\mu g/m^3$ (in one day of summer 2002). These 34 summer days were not counted as a part of the total 538 days, as they were not associated synoptically with dust storms. A detailed examination of the synoptic conditions over time revealed that all 538 identified days were influenced by one of the major synoptic systems that are associated with dust storm events in this region. The dominant system was found to be the Cyprus (cold) Low, followed by the Sharav Low and Red Sea Trough. The role of the Cyprus Low system in leading dust storms was also described by Dayan et al. (2007) in a climatic study in Beer-Sheva during 1967–2003. The comparison of the PM_{10} concentrations recorded in Beer-Sheva during the identified dust days with those of Tel Aviv at the same dates showed a similar pattern of PM_{10} changes (Figure 2). The relatively low correlation of the two time series (43%) is explained by nonconstant trend of increasing PM_{10} level in Beer-Sheva and Tel Aviv due to dust storms. In addition, more dust events occurred in Beer-Sheva during that time compared with Tel Aviv. This indicates local dust storms, as was confirmed also by the HYSPLIT models. Note, for example, the three-peak storm in Beer-Sheva compared with a one-peak storm in Tel Aviv at the same date (rectangle in Figure 2). Since all the days with $PM_{10} > 71$ $\mu g/m^3$ were found to be associated with dust events, a constant anthropogenic contribution to PM_{10} can be assessed from the background values of the "dust-free" seasons (34 $\mu g/m^3$ in average for the whole studied period).

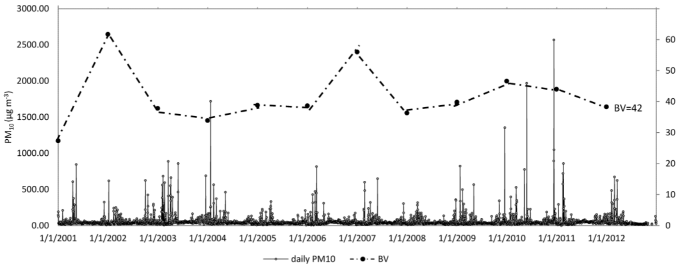

Figure 1. Distribution of daily PM_{10} averages in Beer-Sheva during the study period 2001–2012. Observations of PM_{10} from the monitoring station were available for 97% of the days across the period. Calculated background values for the "dust-free" summer seasons (BV_{2001} to BV_{2012}) are presented in a dashed line on the secondary *y*-axis (right side) along with the average value (BV).

The (1-day) average NC for all dust days in Beer-Sheva (2001–2012) ranged from 1 to 2643 $\mu g/m^3$, with an average value of 122 $\mu g/m^3$ ($n = 538$), which is about 3.5 times higher than the BV (42 $\mu g/m^3$). In order to estimate the percent annual NC, a weight ratio based on the annual average PM_{10} (ranged from 43 to 77 $\mu g/m^3$ during 2001–2012) and that of the non-dust days was calculated as follow: (1) subtract the PM_{10} average of the non-dust days from the annual average PM_{10} to retrieve the weight of the dust; (2) deviation of this value by the annual PM_{10} average provides the NC in percentage. We found that percent

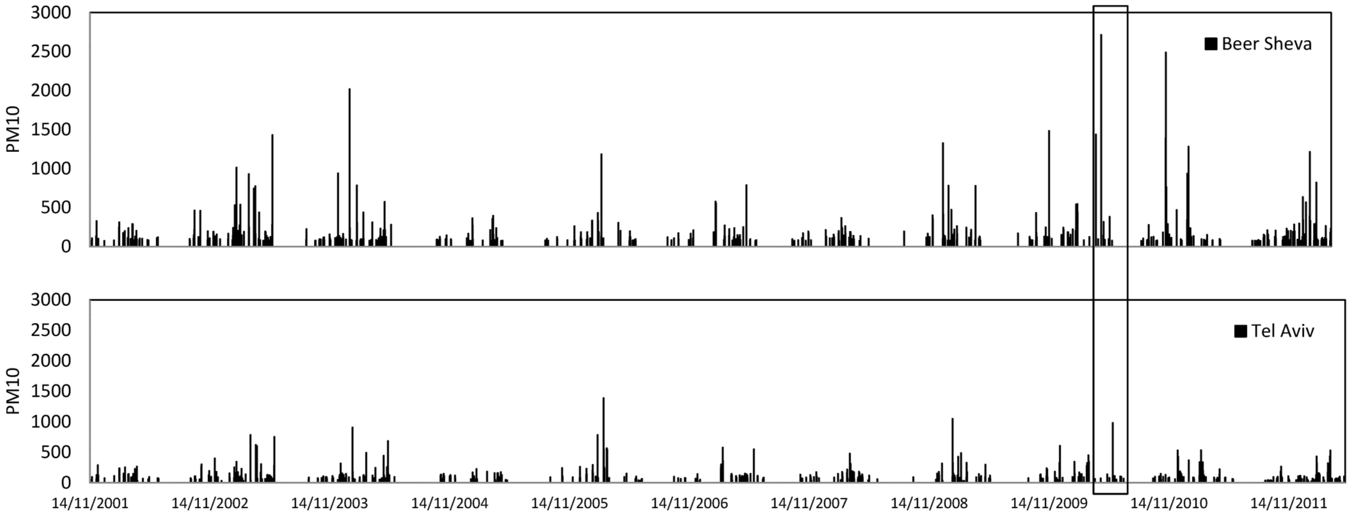

Figure 2. Association between higher PM_{10} concentrations ($>BV_t$) identified in Beer-Sheva and those observed in Tel Aviv at the same dates during 2001–2012. An example of differences in the dust intensity of simultaneous peaks is given in the rectangular.

annual NC to PM_{10} of dust storms in Beer-Sheva ranged from 22% to 52%. The results of Ganor et al. (2009) in Tel Aviv for the years 1995–2006 suggested lower percent annual net contributions (9.4–29.5%). The NC derived for the dust days were grouped based on percentile thresholds (10th, 25th, 50th, and 75th) from the distribution of the daily PM_{10} values >71 $\mu g/m^3$ of the research period ($n = 2650$) (Table 1). This makes it possible to classify dust storm events according to their levels: "low" 264 $\mu g/m^3$; "medium" 661 $\mu g/m^3$; "high" 1322 $\mu g/m^3$; and "severely high" 1983 $\mu g/m^3$. Goossens and Offer (1995) suggest a threshold of 200 $\mu g/m^3$ as a criterion to define dust storms in the northern Negev desert, which corresponds to the "low" level of this study. However, they did not suggest a further classification. Other PM_{10} classifications in Israel have been related to PM_{10} pollution (anthropogenic and nonanthropogenic), with the addition of the background values to the total concentration in each level. Ganor et al. (2009) grouped PM_{10} concentrations in Tel Aviv into four pollution levels "low" 5–40 $\mu g/m^3$; "medium" 35–65 $\mu g/m^3$; "high" 65–150 $\mu g/m^3$; and "very high" 100–3000 $\mu g/m^3$. For our data set, 12% of the total days exceeded the NC of 300 $\mu g/m^3$ ("low" level), 5% >700 $\mu g/m^3$, 2.5% >1000 $\mu g/m^3$, and 0.6% (about 24 days) >2000 $\mu g/m^3$. Ganor et al. (2009) attributed 3% of the cases in Tel Aviv to the "very high" class (100–3000 $\mu g/m^3$), whereas in Beer-Sheva 3.1% of cases had values above 1000 $\mu g/m^3$.

The method presented here was also used to assess the ratio of NC to PM_{10} during strong storms ("high"; "severely high"). In such events, PM_{10} can reach high hourly concentrations over several consecutive hours. Six storms are presented in Figure 3. Daily (24-hr average) contributions above 1000 $\mu g/m^3$ were found in three of them (one in 2009 and two in 2010). In all storms, maximum PM_{10} hourly values exceeded 2000 $\mu g/m^3$, and in May 2010 the PM_{10} concentrations exceeded 4000 $\mu g/m^3$ (Figure 3d). The storm of February 2012 showed a daily concentration of 680 $\mu g/m^3$, but the maximum hourly PM_{10} concentration reached more than 5000 $\mu g/m^3$ (Figure 3f). Although the most extreme PM_{10} value (5197 $\mu g/m^3$) was recorded in the storm of 2012 (Figure 3f), which lasted (on and off) for 52 hr, the calculated storm intensity, based on the A_i parameter, showed that the strongest dust storm had occurred in December 2010 (Figure 3e). Its long duration of 61 h (almost 3 days) with high PM_{10} values (maximum of 3873 $\mu g/m^3$) resulted in the highest A_i value. Thus the most intense storm does not always have the highest 1-hr maximum PM_{10} concentration. Finally, five of the six storm events occurred during the past 3 yr, showing further evidence of the increasing trend of desert dust storms in the southeastern Mediterranean during the past few decades (Ganor et al., 2010).

Conclusion

An analysis of PM_{10} concentration data was performed for an urban arid environment that is located at the margin of the global dust belt. The method presented in this study to quantify the contribution of dust storms to PM levels using a single monitoring station and adjusted threshold criteria could be applicable to other areas with a limited number of stations as well as to situations with lower PM_{10} concentrations and less intense dust

Table 1. Classification of the net contribution (NC) of dust storms to daily PM_{10} levels ($\mu g/m^3$) in each year

Percentile	2001–2002	2002–2003	2003–2004	2004–2005	2005–2006	2006–2007	2007–2008	2008–2009	2009–2010	2010–2011	2011–2012	Classification
10th percentile	26	136	194	32	111	71	29	125	264	241	114	"Low "
25th percentile	65	340	486	81	278	179	74	313	661	604	286	"Medium "
50th percentile	129	680	973	162	556	358	149	627	1322	1209	572	" High "
75th percentile	193	1020	1460	243	834	537	223	940	1983	1813	858	"Severely high"

Notes: Thresholds were determined by the percentile class weight (for the entire period 2001–2012): "Low" (10th percentile, 264 $\mu g/m^3$), "Medium" (25th percentile, 661 $\mu g/m^3$), "High" (50th percentile, 1322 $\mu g/m^3$), and "Severely high" (75th percentile, 1983 $\mu g/m^3$).

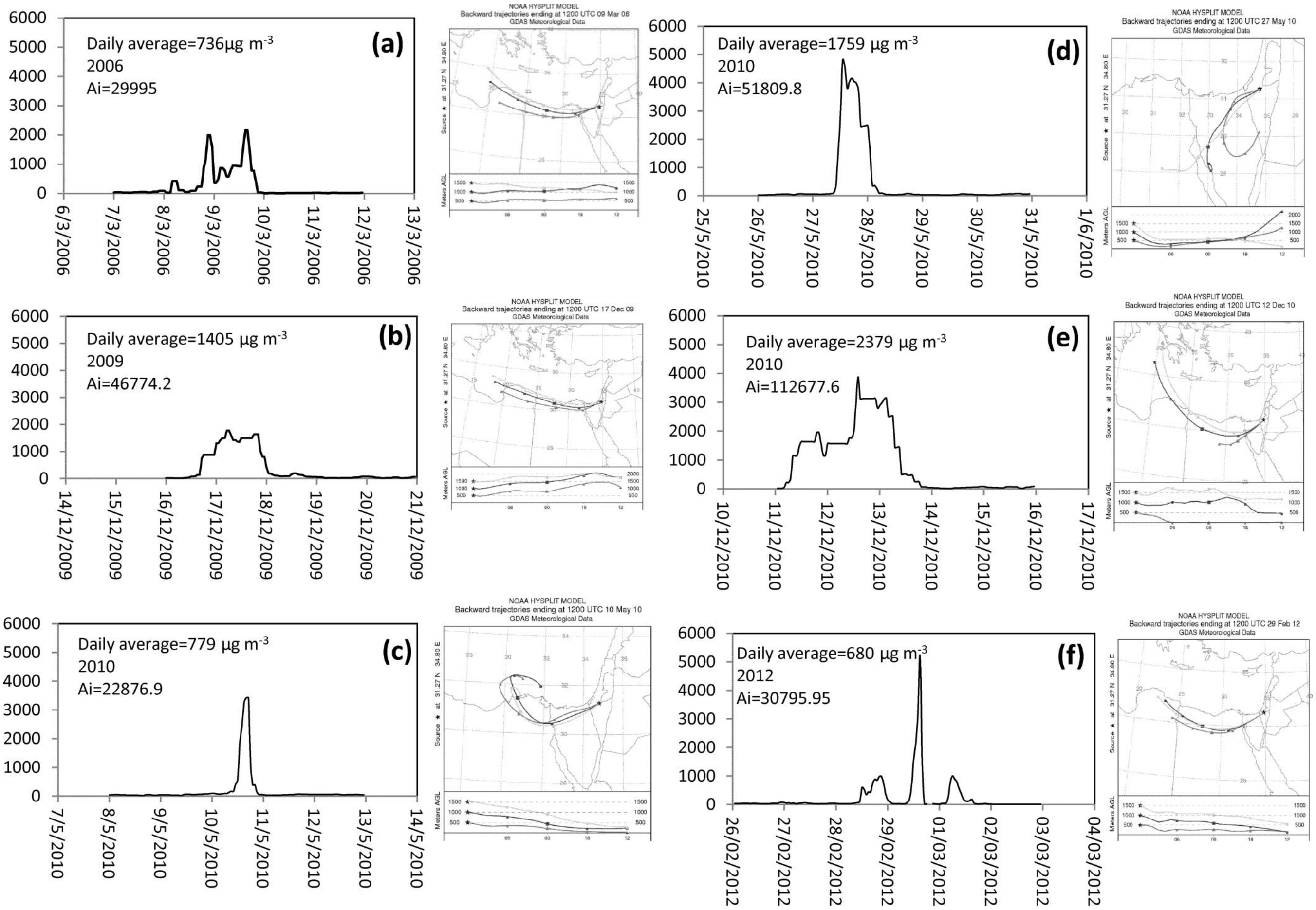

Figure 3. High net contribution (NC) to PM_{10} levels (hourly averages) during strong dust storms recorded in the northern Negev. The value (Ai) represents the storm's intensity. Air mass trajectories (HYSPLIT) during each storm (presented at the right side) associated with typical synoptic systems in the east Mediterranean: Cyprus Low (a, b, e, f), Sharav Low (c), and Red Sea Trough (d).

events. The results on hourly and daily time scales indicate that frequently Beer-Sheva experiences high PM concentrations, which originate mostly from desert dust storms. In addition, a background value of 42 $\mu g/m^3$ (that is higher than the WHO guideline) was calculated for the "dust-free" season. Calculations yielded net daily dust storm contributions of 1–2643 $\mu g/m^3$, with an annual average of 122 $\mu g/m^3$ during the study period. The contribution of dust storm events to PM_{10} can reach hourly averages of 1000–5197 $\mu g/m^3$. These findings suggest that dust storms in the southeastern Mediterranean are a major source of high PM_{10}. Using the intensity parameter Ai, it was noticed that the strongest storms have occurred mainly in the last 3 yr. It is believed that environmental changes such as global warming and desertification may lead to an increased impact of dust storm events.

Funding

The research was supported by the Environment and Health Fund (no. RGA1004).

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