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Increase in dust storm related PM_{10} concentrations: A time series analysis of 2001–2015☆

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ABSTRACT

Over the last decades, changes in dust storms characteristics have been observed in different parts of the world. The changing frequency of dust storms in the southeastern Mediterranean has led to growing concern regarding atmospheric PM_{10} levels. A classic time series additive model was used in order to describe and evaluate the changes in PM_{10} concentrations during dust storm days in different cities in Israel, which is located at the margins of the global dust belt. The analysis revealed variations in the number of dust events and PM_{10} concentrations during 2001–2015. A significant increase in PM_{10} concentrations was identified since 2009 in the arid city of Beer Sheva, southern Israel. Average PM_{10} concentrations during dust days before 2009 were 406, 312, and 364 μg m^{-3} (median 337, 269,302) for Beer Sheva, Rehovot (central Israel) and Modi'in (eastern Israel), respectively. After 2009 the average concentrations in these cities during dust storms were 536, 466, and 428 μg m^{-3} (median 382, 335, 338), respectively. Regression analysis revealed associations between PM_{10} variations and seasonality, wind speed, as well as relative humidity. The trends and periodicity are stronger in the southern part of Israel, where higher PM_{10} concentrations are found. Since 2009 dust events became more extreme with much higher daily and hourly levels. The findings demonstrate that in the arid area variations of dust storms can be quantified easier through PM_{10} levels over a relatively short time scale of several years.

1. Introduction

Desert dust storms have played an increasingly pronounced physical and chemical role in the global system (Shao et al., 2011). One of the environmental consequences of atmospheric dust is the significance for climate through a range of possible influences and mechanisms. It is also possible that dust may affect climate through its influence on marine primary productivity (Jickells et al., 1998), and may also affect air temperatures through the absorption and scattering of solar radiation (Li et al., 1996; Moulin et al., 1997; Alpert et al., 1998). Numerous studies have shown high concentrations of ambient particulate matter (PM) during dust events in different parts of the world (Rodrıguez et al., 2001; Krasnov et al., 2014). Mineral dust also strongly affects public health in arid environments with frequent dust storms (Vodonos et al., 2014; Yitshak-Sade et al., 2015). Studies have shown that particulate matter with an aerodynamic diameter of less than 10 μm (PM_{10}) significantly increases pollution levels above the standard values of air quality during dust storm events (Mitsakou et al., 2008; Querol et al., 2009; Krasnov et al., 2014).

Due to the placement of Israel in the global dust belt, dust events are a common phenomenon. Dust events have shown to increase daily PM_{10} 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). In the desert Negev region (southern Israel) hourly PM_{10} concentrations can reach levels above 5000 μg m^{-3} (Krasnov et al., 2014). The suggested increasing frequency of dust storms in the southeastern Mediterranean (Ganor et al., 2010) over the past few decades has led to growing concern regarding PM_{10} levels. Changes in the amounts of dust and associated dust storm were shown to occur in several regions (Zhu et al., 1997; Zhang et al., 2003; Fiol et al., 2005; Mahowald et al., 2007). 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 dust storms occurrence since the 1950s. A study based on 63 years of dust data

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in Iceland showed that the highest frequency of dust events was found during the 2000s in south and north-east Iceland (Dagsson-Waldhauserova et al., 2014).

These studies however, did not refer to the atmospheric concentration during these dust events. The aim of the present study was to examine changes in PM concentrations associated with dust events over the last 15 years (2001–2015) in different parts of Israel. Israel is located, between 29° and 33° north of the equator, which is characterized as a subtropical region, between the temperate zone and the tropical zone. The unique setting creates a situation where the northern and coastal regions of Israel show Mediterranean climate (characterized by hot and dry summers and cool rainy winters). Whereas the southern and eastern areas are characterized by an arid climate. This remote area is between the major dust sources and should be better identified on the world dust map. Results from the arid city of Beer Sheva (southern Israel) were compared to Rehovot (central Israel) and Modi'in (eastern Israel) in order to evaluate spatial changes on a small scale (Fig 1).

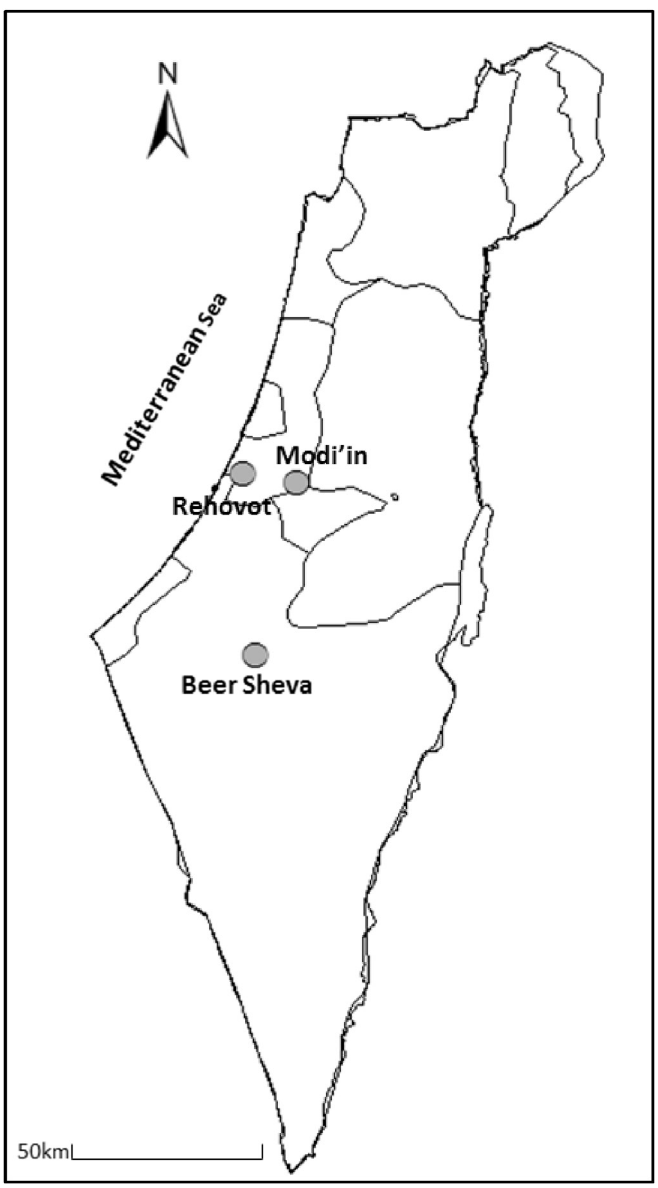

Fig. 1. Map of the study area (Israel). The study is based on three cities in Israel- Beer Sheva (southern Israel); Rehovot (central Israel) and Modi'in (eastern Israel).

2. Materials and methods

2.1. Study area

The study is based on three cities in Israel- Beer Sheva (southern Israel); Rehovot (central Israel) and Modi'in (eastern Israel). The city of Beer-Sheva (31.2498° N, 34.7997° E), population of 196,300, is located in the Negev desert, southern Israel. The area is characterized by hot, dry summers dominated by daily land and sea breeze circulation and wet, cool winters with considerable cyclonic activity. The semi-arid northern Negev desert has an average annual rainfall of about 100 mm, most of which falls from December to March. The region's average annual temperature is 19.8 °C, with large differences between winter and summer and between day and night. Atmospheric humidity varies between 5% and 93%. Rehovot (31.8980° N, 34.8081° E) is a city in the center district (population 199,999) of Israel, about 20 km south of Tel Aviv. Rehovot's climate is classified as warm and temperate. The winter months are rainy while the summer months are dry. The average annual temperature is 20 °C with average relative humidity of 65%. The rainfall average is 537 mm. Modi'in (31.9077° N, 35.0076° E) is located about 35 km southeast of Tel Aviv and 30 km west of Jerusalem (population 90,000). During the summer season there is intense solar radiation, and relatively high temperature and relative humidity, although lower than the coastal strip (Rehovot). During the winter, the temperatures are relatively low especially at night. The annual rainfall is 400–650 mm.

Dust events in Israel are dominated by a specific synoptic system prevailing during each season (Alpert et al., 1990; Kahana et al., 2002; Alpert and Ziv, 1989; Ganor et al., 2010). In the winter, cold low-pressure systems penetrate Israel— with the Cyprus Low being the dominant system (Alpert et al., 1990). The Red Sea Trough is the most common system in the autumn (Kahana et al., 2002), whereas highs and warm low-pressure system – Sharav Low – is specific to 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 system (Alpert et al., 1990). Israel has two origins for the aeolian material. The primarily is in North Africa (about 60%–80%) and some minor contribution from the deserts in the east and south-east of Israel. The main synoptic system contributing dust is the Cyprus low that enters Israel from the south-west.

2.2. Environmental data

Data for Beer Sheva, Rehovot and Modi'in were obtained from the monitoring stations of the Ministry of Environmental Protection (http://www.sviva.gov.il) within the framework of the National Air Monitoring System. The monitors are located on top of school buildings in the middle of each city. The data were recorded every 5 min by a dichotomous ambient particulate monitor (Thermo Scientific 1405DF; Thermo Fisher Scientific Inc.) that provides a continuous direct mass measurement of particle mass utilizing two tapered element oscillating microbalances. The database consists of sequential time series of daily records including: daily and hourly atmospheric PM_{10} concentrations (μg m^{-3}), wind speed (m s^{-2}), air temperature (C°), relative humidity (%) and rain (mm). The monitoring station are all placed in a relatively "clean" areas far from industry and other possible anthropogenic dust sources.

Each day was classified as either a dust day or a non-dust day. A dust day was defined as PM_{10} daily average above 200 μg m^{-3} for the purpose of this study; followed by Krasnov et al. (2014) and Vodonos et al. (2014). The records were collected over 14 years between January 2001 and December 2014 (in total: 5115 daily records). Descriptive statistics of the different parameters is

Table 1
Data section of measured covariates for the study period (2001–2015) from the Beer-Sheva; Rehovot and Modi'in monitoring stations of the Israel Ministry of Environmental Protection. There is missing data on rain in Modi'in.

Model parameters [mean (SD)]	Beer Sheva		Rehovot		Modi'in	
	Non dust	Dust	Non dust	Dust	Non dust	Dust
PM_{10} (μg m^{-3})	44.2 (28.1)	462.9 (329.8)	41.1 (26.1)	389.9 (276.1)	50.7 (30.5)	388.8 (214.8)
Wind speed (m/s)	2.6 (0.8)	3.9 (1.3)	2.3 (0.8)	3.4 (1.8)	2.1 (1.0)	2.7 (1.4)
Temperature (°C)	19.9 (5.6)	16.5 (5.5)	20.7 (5.8)	18.2 (5.4)	20.8 (5.3)	18.8 (4.9)
Relative humidity (%)	67.7 (15.3)	59.4 (15.4)	61.6 (15.9)	52.5 (18.4)	65.7 (12.7)	55.1 (15.5)
Rain (mm)	0.4 (2.3)	0.8 (3.4)	1.4 (10.1)	2.3 (6.1)	(–)	(–)

presented in Table 1.

2.3. Statistical analysis

This time series study is based on the daily PM_{10} concentration for three cities over 14 years (2001–2014). For univariate analysis appropriated statistical tests such as t-tests and one way ANOVA were performed; Pearson correlation and Spearman coefficient were also calculated. To describe and evaluate the trends and periodicity of PM_{10} concentration, we used a classic time series additive model in which the time series are composed of the sum of three components: trend, periodicity, and error ("white noise"). Generally, the trend represents a long-term tendency, the periodicity component represents regular oscillations about a trend and the 'white noise' is a random component, an error of the modeling. We tested the following priori cycles: annual, 4-month (seasons) with emphasis on months with dust storms events and elevated PM_{10} concentrations. The cycles were tested simultaneously, and the regression estimate exponential and *p* values from the single runs for the statistically significant cycles were reported. As realization of this approach we built a *cosinor* model based on Gaussian generalized linear model regression for each of the considered cities (Halberg et al., 1967). The final model is as follows:

$$Y_t = a_0 + a_1*t + a_2*t^2 + a_3*t^3 + (b_i\cos(w_i t) + C_i\sin(w_i t)) + c_1 S_w + c_2 S_a + c_3 S_s + M + \varepsilon_t, \quad (1)$$

where t is the time variable; ωi is frequency of wave number i; for presentation of seasonality we used indicator (dummy) S variables based on season definition for Israel (Alpert et al., 2004). The summer is the "dust free" season in the area (Alpert et al., 1990), and was used as the reference. S_w S_a, S_s are indicator variables for winter, autumn and spring respectively; M is vector of meteorological variables (temperature; wind speed; relative humidity) and

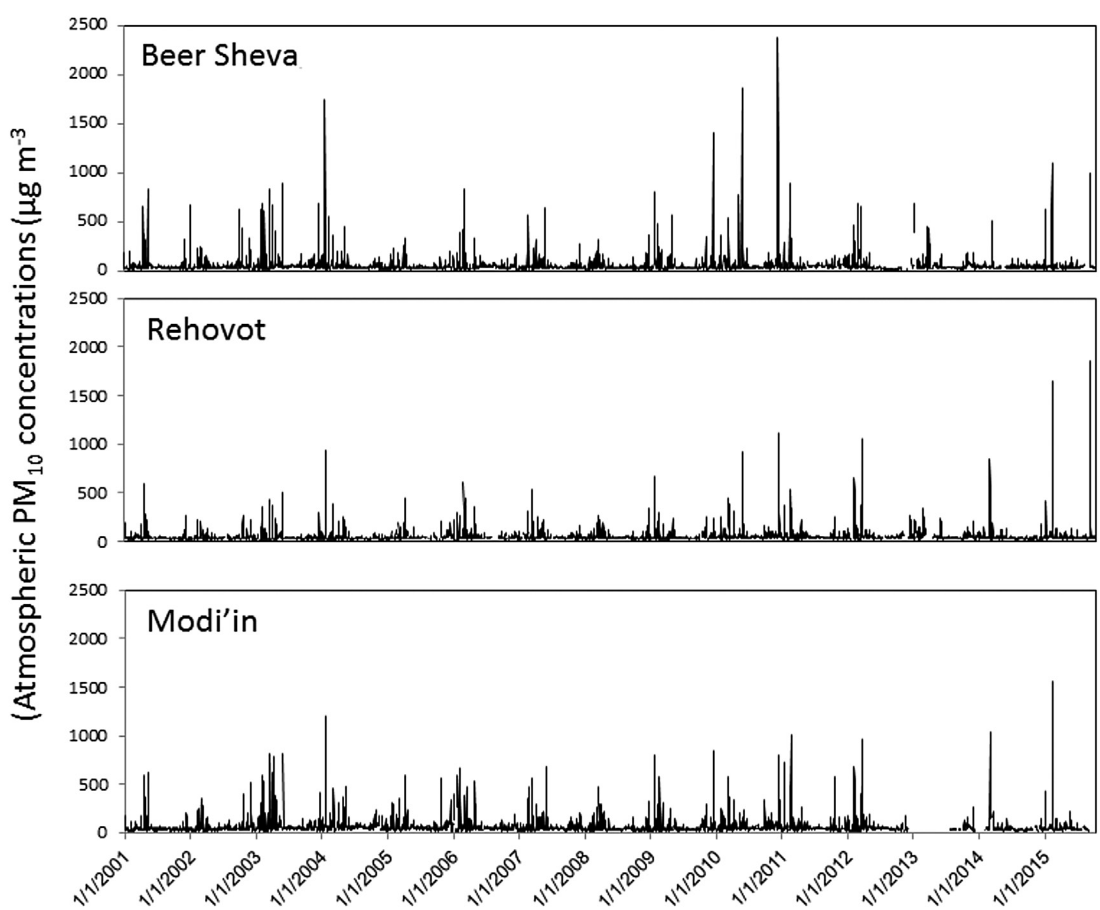

Fig. 2. Average daily concentrations of PM_{10} (μg m^{-3}) over 15 years (Jan 1st 2001–Oct 12th 2015) recorded in the Beer-Sheva, Rehovot and Modi'in monitoring stations.

ε_t is an error. The trend $T_r(Y_t)$ is presented in the following form:

$$T_r(Y_t) = a_0 + a_1{*}t + a_2{*}t^2 + a_3{*}t^3 \quad (2)$$

For the presentation of the periodic component of the time series, we use the pairs of sine and cosine functions representing the annual cycle:

$$\cos\left(t{*}\frac{2\pi}{365.4}\right) \text{ and } \sin\left(t{*}\frac{2\pi}{365.4}\right) \quad (3)$$

Results were considered to be statistically significant if the relevant p-value was less than 0.05. Statistical analyses were performed using SPSS (version 21; SPSS, Chicago, IL).

3. Results and discussion

The overall description of the daily (24-hr) time series of PM_{10} concentrations over the period of 2001–2015 for the three cities is presented in Fig. 2. The daily PM_{10} averages in Beer-Sheva ranged from 6 to 2379 μg m^{-3}; for Rehovot from 6 to 1459 μg m^{-3} and for Modi'in from 6 to 1562 μg m^{-3}. The dust days (days with PM concentration > 200 μg m^{-3}) in Fig. 2 are represented by the peaks of PM_{10} concentrations which are higher for Beer Sheva (note especially 2004 and 2011). The city of Beer Sheva is located in an arid zone close to dust sources. The dust particles originating from the source areas are easily transported to Beer Sheva to elevate the atmospheric PM concentrations significantly above the background value (Krasnov et al., 2014). However, the particle concentrations decreases along the aeolian transport path, which is mostly south western in the area (Tsoar and Blumberg, 1991), therefore lower concentrations reach the distal locations (Rehovot and Modi'in) resulting in lower PM_{10} levels in other cities during dust events. This is true for all events except an unusual event in September 2015 that originated from the north source (Syria) and contributed higher PM_{10} values to Modi'in and Rehovot (Fig. 2).

Fig. 3a demonstrates the changes in the number of dust days per year in the three cities during 2001–2015. The highest number of dust days in Beer Sheva was observed in 2003 and 2010, 15–16 dust days while only 2 days were recorded during 2014. The highest number of dust days in Modi'in was also found in these years (18 during both 2003 and 2010) but only five dust days in 2014. In Rehovot, 2006 was the year with the largest number of dust days (11 in total) and 2014 with the lowest (3 days). Previous studies on changing frequencies of dust events, showed an increase in overall dust storm frequency. In the Middle East an increase in dust event frequency has been reported for the years 1973–2003 (Mahowald et al., 2007). In Israel, the number of annual dust days in Tel Aviv has increased from 5 days in 1958 to 28 days in 2006 (Ganor et al., 2010). These changes were attributed to changes in local synoptic systems. Our results however, reveal that the number of dust events per year is decreasing from 2010 for all cities.

Although the year 2003 had the highest number of dust events

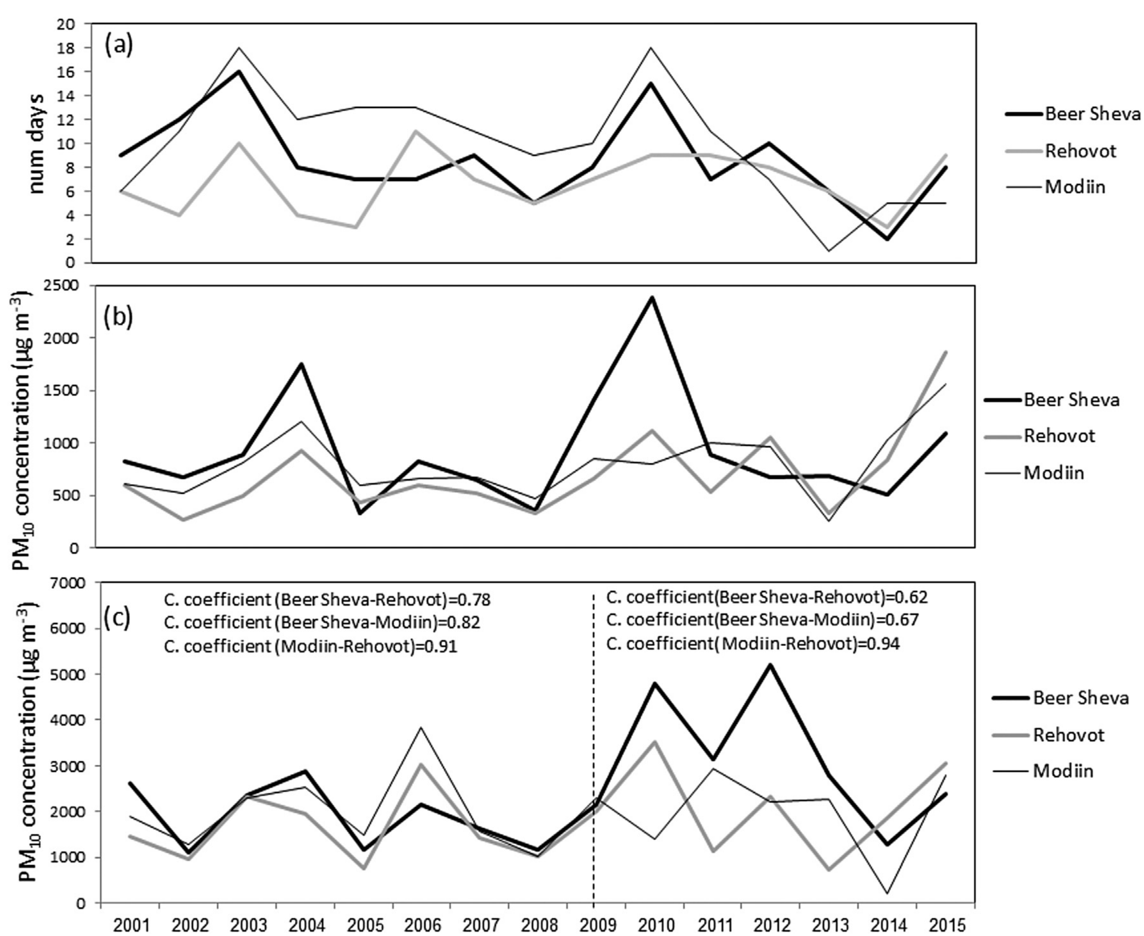

Fig. 3. (a) Number of dust days per year. (b). Maximum daily PM_{10} average (c) highest hourly PM concentration, per year for Beer Sheva, Rehovot and Modi'in. An increase in concentrations is evident for Beer Sheva from 2009 and marked by a dashed line representing the separation of the data into two periods. C.coefficient = Spearman correlation coefficient.

in Beer Sheva and Modi'in, the strongest dust event of that year had daily values of 886, 499 and 812 μg m^{-3} in Beer Sheva, Rehovot and Modi'in, respectively (Fig 3b). These are low values compared to other dust storms that reached daily values above 1000 μg m^{-3} – such as during 2010 and 2015.

Analysis of hourly concentrations (Fig 3c), revealed that the highest concentration per hour occurred during a dust event in 2010 (4797 μg m^{-3} ± 452) and 2012 (5198 μg m^{-3}) in Beer Sheva. The increase in dust storms severity based on hourly concentrations was recently presented in Krasnov et al. (2014), where five out of six presented dust events with extremely high hourly levels occurred during 2009–2012. PM_{10} concentrations in other regions show similar hourly concentrations during dust events. In Australia, a dust event from 2009 reached values of 6460 μg m^{-3}. In Phoenix, Arizona, a dust event from July 2011 resulted in peak hourly PM_{10} concentrations of 1974 μg m^{-3} (Raman et al., 2014) while in the Canary Islands (Querol et al., 2004), daily PM_{10} values during Saharan dust events reach up to 1000 μg m^{-3}.

An increase in hourly concentrations for Beer Sheva, from the year 2009 was noticed – marked as a dashed line in Fig. 3c. This gave the motivation to split the data into two groups (before and after 2009) for further analysis. The first thing noticed is that this increase in hourly concentrations is not significant for Rehovot and Modi'in. Independent t-tests between the two periods however showed that there was a strong significant difference in daily PM_{10} concentrations due to dust events between the two periods for all cities. In addition, there is a strong correlation (Pearson correlation coefficient ~0.9) in daily PM_{10} concentrations between Rehovot and Modi'in for both periods, but the correlation between these two cities to Beer Sheva decreased to ~65% after 2009 (Fig 3c). This suggests that the PM_{10} concentrations in Beer Sheva behave differently than the two other cities, especially after 2009.

Time series analysis revealed that the trend in daily PM_{10} concentrations is not linear over the years. Average PM_{10} concentrations (both dust and non-dust) before 2009 were 53, 62 and 43 μg m^{-3} in Beer Sheva, Rehovot and Modi'in respectively (median 37, 45, 43 respectively). After 2009 the respective average concentrations were 56, 60 and 53 μg m^{-3} (median 3, 41, 36). For dust days, average PM_{10} concentrations before 2009 were 406, 312 and 364 μg m^{-3} (median 337, 269, 302) in Beer Sheva, Rehovot and Modi'in respectively. After 2009 the average dust storm concentrations were 536, 466 and 428 μg $m^{-3\ 3}$ (median 382, 335, 338) indicating an overall increase in 24-h PM_{10} concentrations for the three cities. In Beer Sheva, these dust days comprised 42 (4.8%) days in winter and 23 (4.9%) days in spring before 2009 with highest daily average of 1746 μg m^{-3}. After 2009, 39 (6.2%) of days were dust days in winter and 6 (1.8%) in spring while highest daily average was 2379 μg m^{-3}. For Rehovot and Modi'in respectively, dust days comprised 28 (3.4%) and 51 (5.8%) of all days in winter and 19 (4.2%) and 31 (6.6%) in spring before 2009 with 929 and 1205 μg m^{-3} maximum daily concentrations. After 2009, 33 (5.3%) and 41 (8.4%) of days were dust days in winter and 5 (1.4%) and 4 (1.4%) in spring. Maximum daily concentrations after 2009 were 1859 and 1562 μg m^{-3} for Rehovot and Modi'in respectively. The change in the frequency of dust events in Israel is due to the prevalence of specific synoptic systems during the different seasons. Results suggest that there is an increase (%) in winter dust events (Cyprus low) with a significant decrease in spring dust storms (resulting from Sharav lows). The synoptic systems in the winter are characterized by stronger winds and lower relative humidity that enable to transport higher amounts of dust particles from the sources and the increase in PM_{10} levels. This is in agreement with a study by Ganor et al. (2010) that showed the increase in winter lows occurrence since 1958. Despite the decrease in overall number of dust days since 2010, the maximum daily PM_{10} concentrations after 2009 are higher for the three cities. This phenomenon has been previously presented in studies such as in Tai et al. (2012a,b). They show that in the Midwest years with less frequent cyclones had higher annual average $PM_{2.5}$.

A multivariate regression analysis revealed the factors that may affect the PM_{10} levels in the different cities (Tables 2–4). Air temperature was found to have significant effect only for Rehovot and Modi'in while wind speed was found to positively affect the PM_{10} concentrations at all times. Relative humidity was found to effect negatively on PM_{10} concentrations after 2009.

These finding may be related to the increase in winter dust events as during these events are characterized by stronger winds

Table 2
Results of trend-harmonic analysis for daily PM_{10} in Beer Sheva.

Variables	Before 2009 (adjusted R^2 = 14.8%)		After 2009 (adjusted R^2 = 15.9%)	
	Beta	P-value	Beta	P-value
Intercept	−137.38	<0.001	−567.4	<0.001
day	0.75	<0.001	1.38	<0.001
day2	−1.71	<0.001		
day3	0.85	<0.001	−1.34	<0.001
ycos	0.35	<0.001	0.02	0.761
ysin	0.16	<0.001	−0.14	0.008
Air temperature	0.42	<0.001	−0.03	0.466
Wind speed	0.27	<0.001	0.36	<0.001
Relative humidity (%)	−0.02	0.526	−0.11	<0.001
Spring	0.1	<0.001	0.06	0.173
Winter	0.09	0.138	0.15	0.046
Autumn	0.03	0.409	−0.002	0.959

Table 3
Results of trend-harmonic analysis for daily PM_{10} in Rehovot.

Variables	Before 2009 (adjusted R^2 = 16.6%)		After 2009 (adjusted R^2 = 15.2%)	
	Beta	P-value	Beta	P-value
Intercept	−97.12	<0.001	−372.13	<0.001
day	−0.33	0.076	0.93	<0.001
day2	1.41	0.002		
day3	−1.06	<0.001	−0.86	<0.001
ycos	0.652	<0.001	0.44	<0.001
ysin	0.45	<0.001	0.28	<0.001
Air temperature	0.72	<0.001	0.54	<0.001
Wind speed	0.07	<0.001	0.21	<0.001
Relative humidity (%)	−0.02	0.362	−0.12	<0.001
Spring	0.06	0.086	0.02	0.622
Winter	−0.002	0.980	0.20	0.012
Autumn	−0.006	0.871	0.09	0.031

Table 4
Results of trend-harmonic analysis for daily PM_{10} in Modi'in.

Variables	Before 2009 (adjusted R^2 = 14.9%)		After 2009 (adjusted R^2 = 15.3%)	
	Beta	P-value	Beta	P-value
Intercept	−167.56	<0.001	−428.80	<0.001
day	0.90	<0.001	0.83	<0.001
day2	−1.70	<0.001		
day3	0.80	0.017	−0.82	<0.001
ycos	0.49	<0.001	0.27	<0.001
ysin	0.33	<0.001	0.20	<0.001
Air temperature	0.61	<0.001	0.46	<0.001
Wind speed	0.20	<0.001	0.20	<0.001
Relative humidity (%)	0.05	0.072	−0.04	0.228
Spring	0.09	0.008	0.05	0.257
Winter	0.02	0.805	0.29	<0.001
Autumn	0.02	0.606	0.11	0.047

and lower relative humidity that enable to transport higher amounts of dust particles.

The decrease in dust storm frequencies during increase in PM_{10} hourly and daily levels and the effect of the different meteorological factors on PM_{10} concentrations might be a result of the change in the climate. A study by Dawson et al. (2014), discusses the potential sensitivity of PM episodes to climate-change-related changes in air pollution meteorology. Dust events and the following increase in PM results from distinct synoptic-scale conditions that have strong, but as yet uncertain, links to climate change. Indeed, climate-induced changes in synoptic scale weather patterns, such as cyclones, frontal passages, and location and frequency of high pressure systems, have been suggested as major drivers of future changes in PM episodes (see, e.g., Leung et al., 2005). In addition PM levels are affected by changes in land use and land cover, from farming or development. PM derived from dust events however, are not yet well captured in climate change studies and requires more attention in modeling studies of future climate. There are several understudied links between climate and aerosol research that, if pursued, could significantly increase our understanding of the implications of climate change for PM.

4. Conclusions

Studies have shown the impact of dust events on atmospheric PM concentrations. Israel is located on the margin of the global dust belt and is subjected to frequent dust events. This remote area is between the major dust sources and should be better identified on the world dust map. The study suggests analysis of daily and hourly PM_{10} concentrations over a time series of 15 years. The findings indicate increase in PM_{10} concentrations due to dust storms in Israel, especially over the last five years. Although a decrease in number of dust days per year were noticed (especially during spring season), significant changes over time were found in PM_{10} concentrations. Dust events in Israel since 2009 became more extreme with much higher daily and hourly levels. The higher values were recorded in the arid city of Beer Sheva. The analysis of daily and/or hourly PM_{10} concentrations can be appropriate to examine changes in dust storm levels. These changes in PM_{10} concentrations are pronounced in areas that are proximal to the dust sources, since these are immediately influenced by particles emitted from these sources. The changes in PM_{10} concentrations over the years are likely attributed to changes in synoptic-scale conditions driven by climate. Yet, the link between PM and climate change is still uncertain. In addition the changes in land use and land cover, from farming or development may also contribute high PM during the dust events. There is growing concern about the potentially detrimental impact that environmental pollution can have on human health as drylands (arid and semi-arid zones) that are subject to frequent dust events constitute about 40% of the Earth's total land surface and contain an estimated 2.1 billion people.

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