# Particle Matter (PM) air pollution in the metropolitan area of Haifa, Israel - Correlation with synoptic conditions and climatic stress

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## 1. Introduction

High Particle Matter (PM) concentrations are detected over the Middle East and Israel, attributed to natural dust outbreaks as well as to local and remote anthropogenic sources (e.g., Erel et al. 2007, 2013, Pey et al. 2013). Epidemiological studies demonstrated that PM has a clear correlation with the number of daily deaths and hospitalizations (e.g., Karanasiou et al. 2012) as well as with environmental variables, such as poor visibility (Erel et al. 2013). EPA (2013) states that inhalable particles, including coarse ($PM_{10}$) and especially fine ($PM_{2.5}$) particles, originate mostly from anthropogenic sources and $PM_{10}$ concentrations are highly correlated with these of $PM_{2.5}$.

The spatio-temporal distribution of air pollution is highly dependent on the atmospheric conditions determined by the combined local, meso- and synoptic-scale circulations, together with the geographical characteristics of the region, i.e., the complex terrain of Haifa metropolitan area and the nearby bay structure (Fig. 1). Yuval and Broday (2006) showed that while dust outbreaks are excluded, heavy traffic load is the main source for $PM_{10}$ in the Haifa metropolitan area, though this area has major industrial plants, including the national petroleum refineries, petrochemical and agrochemical industries.

The present research analyzes the relationships between synoptic conditions and the distribution of $PM_{10}$ and $PM_{2.5}$ in Haifa metropolitan area. The relationships are studied also with regard to the summer climatic stress. The 'environment to circulation' and 'circulation to environment' approaches are adopted following Yarnal (1993), Yarnal et al. (2001) and Dayan et al. (2012), shown as efficient tools relating synoptic systems to air pollutants. The objectives of the study are:

- To analyze the distribution of $PM_{10}$ and $PM_{2.5}$ on a seasonal, weekly and daily bases
- To identify the synoptic systems responsible for pollution events and define their 'pollution potential'
- To identify the relations between the degree of summer climatic stress and $PM_{2.5}$ concentration

## 2. Material and Methods

Study region: The Haifa metropolitan area is located at the eastern Mediterranean coastline (Fig. 1), is the third largest metropolitan area of Israel, with a population of almost 1 million, and is the major regional center of northern part of the country. The city is built mostly on the northern slopes of Mount Carmel, reaching an altitude of ~500 m above sea level. The Haifa Bay is the center of commerce and industry, including the Port of Haifa.

Database: Daily average $PM_{10}$ and $PM_{2.5}$ concentrations are taken from the 9 active monitoring stations and wind data - from 5 stations (see Fig. 1), for 10 years, 2003-2012. The daily synoptic type is defined according the semi-objective classification of Alpert et al. (2004a) for the Levant region, which differentiates among 5 main systems, further classified into 19 specific types. For the summer season, we also use a new classification that is based on a climatic stress index (CSI) for the summer days. This index, developed by Savir (2014), is calculated by a prediction equation for a combination of the normalized standardized heat stress and the height of the upper-level marine inversion base.

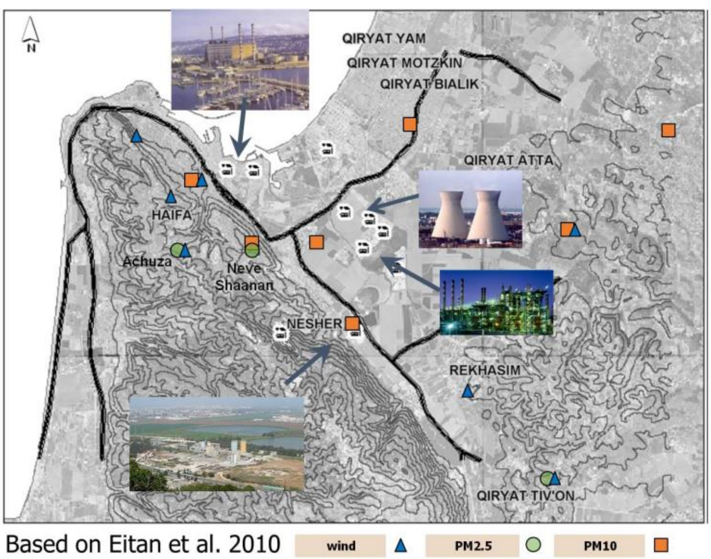


*Fig. 1: The Haifa metropolitan area, together with the location of the wind, $PM_{10}$ and $PM_{2.5}$ monitoring stations and main local pollution sources*

Methods: Boxplot charts are used to present the seasonal distribution of daily $PM_{10}$ and $PM_{2.5}$ concentrations through their quartiles. Exceeding days are defined as days in which the daily average concentration exceeded the Israeli standard, being 130 $\mu g/m^3$ for $PM_{10}$ and 37.5 $\mu g/m^3$ for $PM_{2.5}$, in at least one station. Their distribution is studied on a daily, weekly and seasonal basis as well as according the regional synoptic systems/types. The 'pollution potential', regarded as percentage of exceeding days for each of the regional synoptic system/type, is calculated. This expresses the 'environment to circulation' approach. In order to get insight into the relevant mechanisms, the diurnal evolution of the wind field for each synoptic type is derived and analyzed, expressing the 'circulation to environment' approach (not shown).

## 3. Results

### 3.1 Seasonal distribution and trends

The seasonal distribution of $PM_{10}$ and $PM_{2.5}$ (Fig. 2) indicates the homogeneity of the summer season (JJA) with the lowest concentration, against the large distribution and the highest concentrations in the winter (DJF) and spring (MAM) seasons. Daily maximum $PM_{10}$ concentration of 1366$\mu g/m^3$ was measured during a severe dust event of 25-27 of February 2006 (maximum 30-min. $PM_{10}$ reached 3849$\mu g/m^3$) and the daily $PM_{2.5}$ concentration was 493$\mu g/m^3$ (maximum 30-min. $PM_{2.5}$ reached 1059$\mu g/m^3$). The spring season has the highest number of exceeding days, 9.8% and 16.2% for $PM_{10}$ and $PM_{2.5}$, respectively, compared to 7.4% and 12.6% of the days for the winter. In spite of the persistent stability and absence of rain during the entire summer season, the PM concentration are the lowest, and only 3 exceeding days (in 10 seasons, 0.3%) for $PM_{10}$ were measured, with maximum daily concentration of 151.7$\mu g/m^3$. These were mostly dust events on June. For $PM_{2.5}$ there were 4.2% exceeding days with maximum daily concentration of 54.6$\mu g/m^3$. Erel et al. (2007) shows summer transport of anthropogenic PM from Greece and east Europe. The autumn season (SON), though experiencing dust events, has lower rate of exceeding days compared to the winter and spring, 2.9% and 7.9% for $PM_{10}$ and $PM_{2.5}$, respectively. The differences in the average concentration between the seasons are statistically significant (according *t-test*) for both $PM_{10}$ and $PM_{2.5}$.

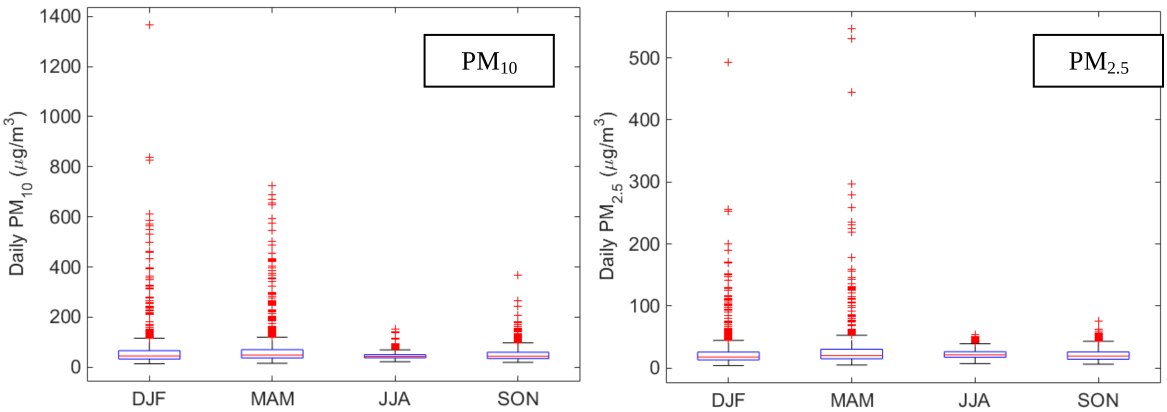


*Fig. 2: Boxplot charts of the seasonal distribution of daily $PM_{10}$ (left) and $PM_{2.5}$ (right) concentration of the most polluted station in the Haifa metropolitan area*

When the exceeding days are excluded, a different seasonal distribution of $PM_{10}$ and $PM_{2.5}$ is noted (Fig. 3). The summer becomes the most polluted season with $PM_{2.5}$, attributable to anthropogenic sources, whereas for $PM_{10}$ the highest average and maximum concentrations remains in the winter and spring seasons.

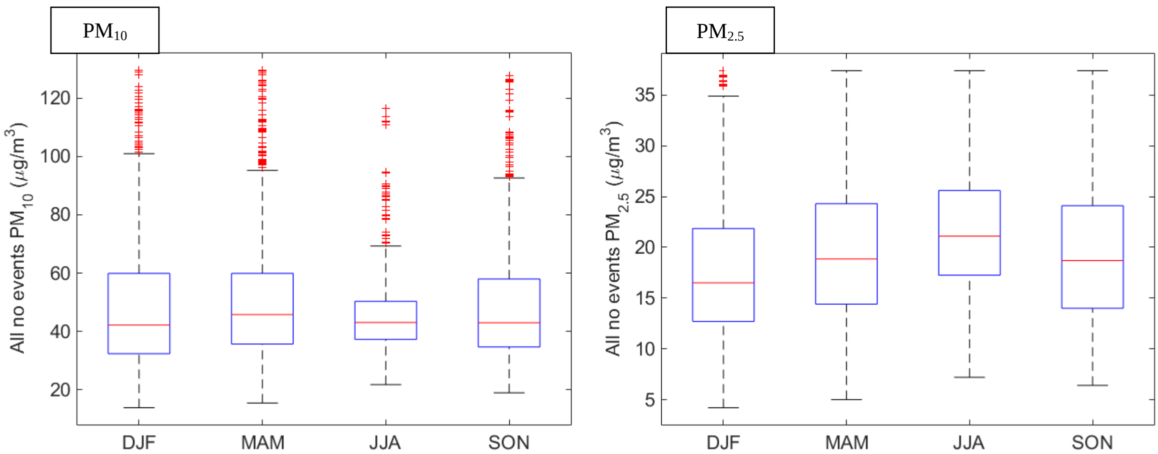


*Fig. 3: As in Fig. 2 but without exceeding days*

The spatial distribution depends on the sources of the pollution, the synoptic system that dominates the wind regime, the meso-scale factor (mainly the breeze circulation) and the complex terrain of the study region. Following the 'circulation to environment' approach, maps of the wind regime for each of the 5 main regional synoptic systems and 19 specific types (based on Alpert et al. 2004a) were derived (not shown).

Figure 4a presents the correlation between the maximum daily concentrations of $PM_{10}$ against $PM_{2.5}$ for each season. It further indicates that extreme dust events characterize the spring and winter season, but it also indicate two different correlations. One is a high concentration of $PM_{10}$ accompanied by relatively lower $PM_{2.5}$ concentrations and second, in which high concentrations of $PM_{2.5}$ are most noticeable. It was found that the later scenario appears only when the high concentrations of $PM_{2.5}$ are measured in a specific station (Qiryat Tiv'on, see Fig. 4b) located at the southeastern part of the study region, whereas for the former, the highest $PM_{2.5}$ is measured in Neve Shaanan station, located at the northeastern face of the Carmel Mountain. These two scenarios are associated with different wind regimes (not presented).

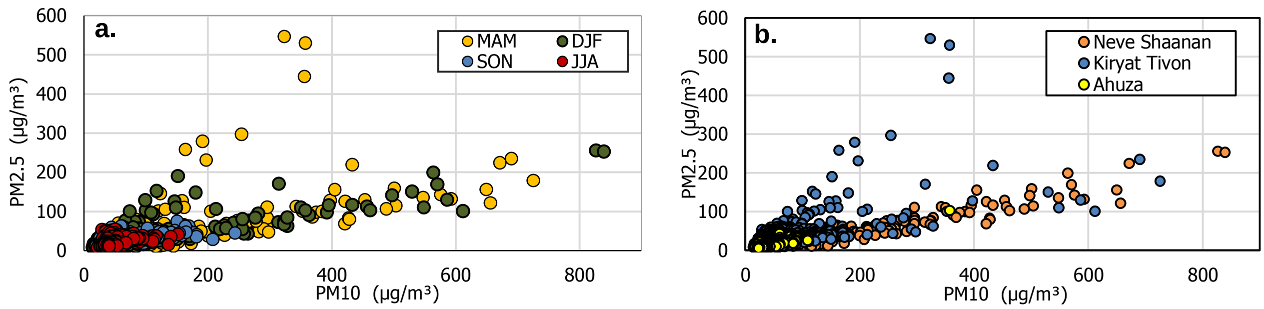


*Fig. 4: Scatter plot of the mean daily concentration of $PM_{10}$ against $PM_{2.5}$, at the most polluted station, as a function of season (a) and as a function of the station measuring the highest $PM_{2.5}$ concentration (b)*

In order to further validate the difference in the temporal distribution between $PM_{10}$ and $PM_{2.5}$, the linear trend along the study period is calculated for each season for the subsample that excludes the exceeding days. Table 1 shows a decreasing trend, for $PM_{2.5}$ in all seasons, significant in 3 of them, in spite of the short period, unlike the $PM_{10}$, being positive for the winter and autumn (not significant in any of the seasons). This is attributed to the improvement in local air pollution due to the mitigation applied on local PM sources, including the cement industry and transportation. The decreasing trend of $PM_{2.5}$ while excluding exceeding days does not agree with the insignificant trend of the annual $PM_{2.5}$ at the Neve Shaanan station, for the period 1999-2006, shown in Yuval et al. (2012, Fig. 8d).

| | Winter (DJF) | Spring (MAM) | Summer (JJA) | Autumn (SON) |
|---|---|---|---|---|
| $PM_{10}$ | +3.3 | -5.4 | -2.1 | +2.4 |
| $PM_{2.5}$ | **<u>-2.8</u>** | **<u>-8.0</u>** | <u>-7.7</u> | -1.8 |

*Table 1: Linear trends for the seasonal $PM_{10}$ and $PM_{2.5}$ along the study period (2003-2012),* excluding the exceeding days. *The trends are calculated based on the daily maximum concentrations, and are presented in $\mu g/m^3$ per decade. Values significant at the 95% level (two-tailed) are bold and underlined, and those significant at the 90% level are underlined*

### 3.2 Synoptic systems associated with pollution events and their 'pollution potential'

PM pollution events in the study region are associated with different synoptic systems, including cyclonic and anticyclonic ones. Extreme dust events result from natural dust outbreaks originating from the Sahara desert (see Figs. 5a, 5b, 5d, 5e) mostly associated with Cyprus and North African ('Sharav') lows (see Alpert and Ziv 1989, Dayan et al. 1991, Dayan et al. 2008). Nevertheless, days exceeding the Israeli standard occur also under stable weather conditions, associated with various synoptic systems, but they are characterized by much lower PM concentrations. A MODIS satellite image and backward air mass trajectory of the summer day (July 1st, 2003) with the highest $PM_{2.5}$ concentration, 54.6$\mu g/m^3$ ($PM_{10}$ was 50$\mu g/m^3$), indicate the large difference from a typical dust event (see Figs. 5c and 5f).

The 'pollution potential' of each of the synoptic systems characterizing the Levant region, together with the number of exceeding days for the study period, is presented in Fig. 6. It indicates the highest potential of Sharav Low for exceeding days, over 20% and 30% of the days for $PM_{10}$ and $PM_{2.5}$ respectively. However, note the low occurrence of this synoptic system, only 1.2% on an annual basis and 5.4% in April, the richest month with Sharav lows. Cyprus lows, responsible for 90% of the rainfall in Israel (Saaroni et al. 2010a), has also relatively high potential for PM pollution. Their contribution to the exceeding days belonging to this system is 7 times higher than Sharav lows due to their higher frequency. Moreover, the highest concentration observed was associated with a Cyprus low. The annual occurrence of Cyprus lows is 17% and its occurrence during the rainy period, November-March, is 30%. All exceeding days of the above two synoptic systems result from natural dust outbreaks originating from the Sahara desert that penetrated the region with strong southwesterly flow.

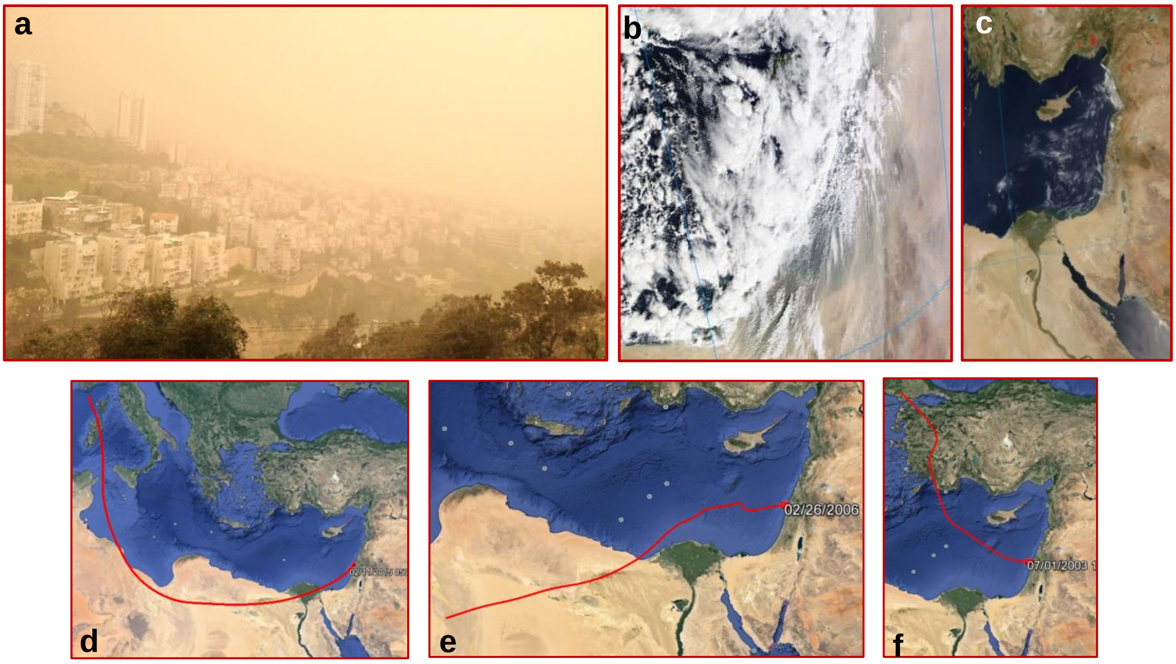


*Fig. 5: Haifa during the most severe dust event of 11 Feb. 2015 (a) the MODIS satellite image of 11 Feb. 2015 (b) the MODIS satellite image of the summer day with the highest $PM_{2.5}$ concentration, 1 July 2003 (c) and 72-h backward air mass trajectories at 500 m AGL calculated using the Hybrid Single-Particle Lagrangian Integrated model (Draxler and Rolph 2003, Kahl and Samson 1986) for 26 Feb. 2006 (d), 11 Feb. 2015 (e) and 1 Jul. 2003 (f)*

The remaining synoptic systems, typically associated with static stability, have lower pollution potential, of <5% for $PM_{10}$ and 5-10% for $PM_{2.5}$. The Red Sea trough, a non-migratory pressure trough extending from the south, characterized by easterly flow, can produce dust events penetrating from the Mediterranean deserts, especially from Saudi Arabia. Nevertheless, days belonging to this system may also be characterized by stable and calm weather conditions, and thus are accompanied by local pollution most similar to high pressure systems (see Saaroni et al. 2009). The summer season is dominated by the Persian Trough (Saaroni et al. 2010b), over 80% of the days. It is a non-migratory lower-level trough extending from the Asian Monsoon over the Persian Gulf toward southern Turkey and the Aegean Sea, inducing the northwesterly maritime Etesian wind that transports relatively cool and humid air toward the EM. Together with the upper-level subsidence, no dust events develop during the summer, explaining the lowest rate of exceeding days.

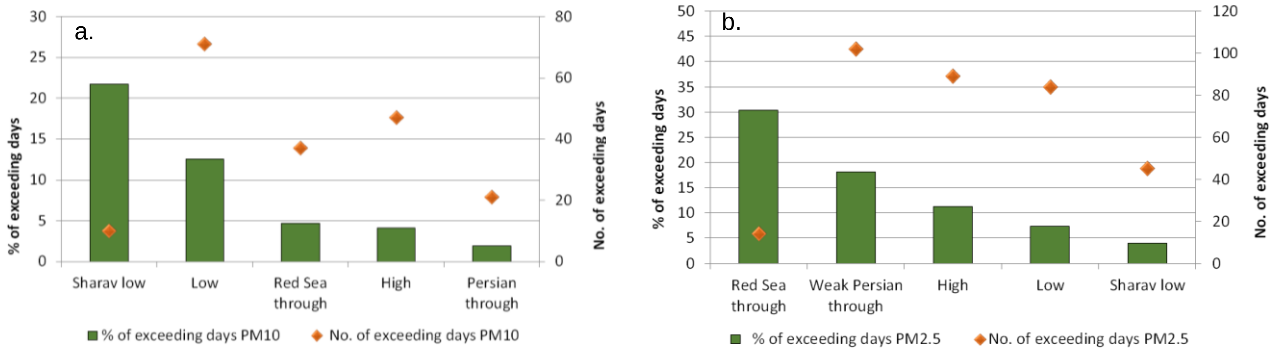


*Fig. 6: The 'pollution potential' and no. of exceeding days for the study period, for $PM_{10}$ (a) and $PM_{2.5}$ (b)*

### 3.3 Summer PM concentrations and its relation to climate stress

The summer season is characterized by heat stress conditions associated with high relative humidity, persisting over the study area. The heat-stress is aggravated while the permanent marine inversion that caps the lower-level humid air is lower than normal. This condition also traps the air pollution. Moreover, the seasonal Persian Trough prevents development of dust outbreaks. Following the above, a positive correlation is expected between summer PM concentrations and both heat stress and the inversion height., With regard to climate stress conditions, the summer season is defined here according the synoptic season definition when the Persian Trough dominates above 80% of the days, i.e., the period between the 25th of June and the 7th of September (following Alpert et al. 2004b).

Adopting the 'environment to circulation' approach, we analyzed the $PM_{10}$ and $PM_{2.5}$ distributions as a function of the climate stress conditions, using the CSI index (Fig. 7), which is a combination of the inversion height and the heat-stress (both normalized and standardized). CSI 1-3 are defined as 'comfort', 'medium' and 'discomfort' conditions, respectively. The increase in PM concentrations with the discomfort conditions is well seen, indicating that discomfort conditions are associated also with higher PM pollution, in accordance with our expectations.

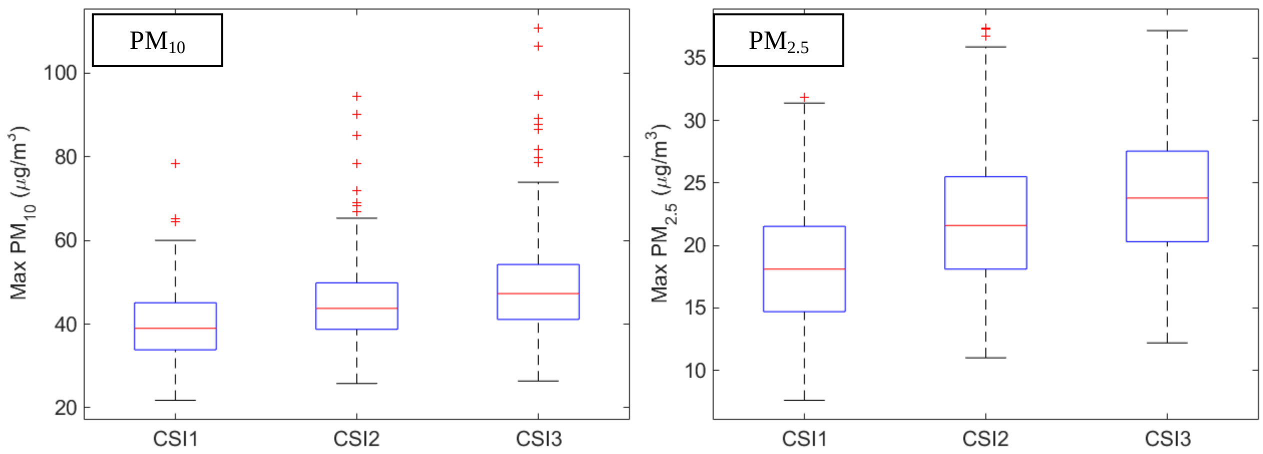


*Fig. 7: As in Fig. 2 but for CSI 1, 2 and 3 for the summer season (based on the synoptic season definition)*

The daily $PM_{10}$ against $PM_{2.5}$ as a function of the CSI index (Fig. 8) is presented for Neve Shaanan station (the only station that measures both $PM_{10}$ and $PM_{2.5}$, see location in Fig. 1). It further indicates the higher pollution especially that of $PM_{10}$ associated with severe heat stress conditions.

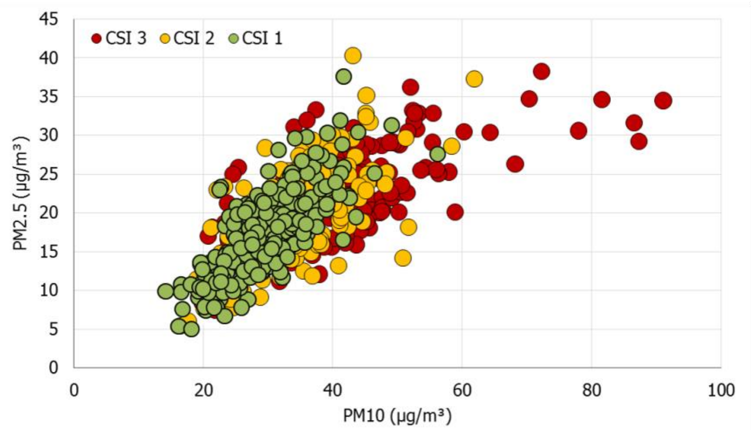


*Fig. 8: Scatter plot of daily $PM_{10}$ against $PM_{2.5}$ as a function of the CSI index for Neve Shaanan station*

## 4. Summary and conclusions

Haifa metropolitan area is subjected to high particle Matter (PM) concentrations attributed to natural dust outbreaks as well as to local and remote anthropogenic sources. The analysis of seasonal course shows that the winter and spring are the richest with PM pollution, with days of severe dust outbreaks, the autumn is in the third place, with several severe outbreaks, and the summer, when no outbreaks develop and therefore the average concentration and the variability are the smallest. While excluding events in which the PM concentrations exceed the Israeli standard, the highest average of fine particles, $PM_{2.5}$, appears in the summer season. Moreover, in spite of the high correlation found between daily $PM_{10}$ and $PM_{2.5}$, the latter is more dominated by anthropogenic sources. This is concluded through the significant decreasing trend in $PM_{2.5}$ concentrations along the study period, unlike that of $PM_{10,}$ especially when analyzing the trends excluding exceeding days.

The 'pollution potential' for exceeding the Israeli standard was calculated for each of the synoptic systems that characterizes the Levant region. The highest potential has the 'Sharav' Low, but the occurrence of this synoptic system is very low. On the contrary, Cyprus Lows, responsible for 90% of the rainfall in Israel, has the highest number of exceeding days. These two synoptic systems are responsible for most natural dust outbreaks, originating from the Sahara desert. The Red Sea trough can be also associated with dust events, penetrating from the Mediterranean deserts. The summer season is dominated by the Persian Trough associated with the persistent maritime Etesian winds and upper-level subsidence that prevents dust outbreaks into the region.

For the summer season, when anthropogenic sources are assumed to dominate, we looked for potential relations with the climate stress conditions. As expressed, the new CSI index developed for mid-summer days, the PM concentrations is found to be correlated with the discomfort conditions, indicating that sever discomfort conditions are accompanied by higher PM pollution. This is attributed to the lower base of the marine inversion and therefore more stable weather conditions preventing efficient vertical dispersion of PM.

Defining and understanding the relations between synoptic-scale atmospheric variables and local pollution potential can be further evaluated for future conditions using outputs of climate models.

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## References

Alpert P., Osetinsky I., Ziv B., Shafir H., 2004a: Semi-objective classification for daily synoptic systems: application to the eastern Mediterranean climate change. *International Journal of Climatology*, 24, 1001-1011

Alpert P., Osetinsky I., Ziv B., Shafir H., 2004b: A new seasons definition based on classified daily synoptic systems: an example for the eastern Mediterranean. *International Journal of Climatology*, 24, 1013–1021

Alpert, P., Ziv B., 1989: The Sharav cyclone: Observations and some theoretical considerations. *Journal of Geophysical Research,* 94, 18 495–18 513

Dayan U., Heffter J., Miller J., Gutman G., 1991: Dust intrusion events into the Mediterranean Basin. *Journal of Applied Meteorology,* 30, 185-199

Dayan U., Ziv B., Shoop T., Enzel Y., 2008: Suspended Dust over South-Eastern Mediterranean and its Relation to Atmospheric Circulations. *International Journal of Climatology*, 28, 915-924

Dayan U., Tubi A., Levy I., 2012: On the importance of synoptic classification methods with respect to environmental phenomena. *International Journal of Climatology*, 32, 681-694

Draxler RR., Rolph G D., 2003: *HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory Model*); National Oceanic and Atmospheric Administration Air Resources Laboratory. Available at the NOAA ARL Website (http://ready.arl.noaa.gov/HYSPLIT_traj.php).

Eitan O., Yuval., Barchana M., Dubnov J., Linn S., Carmel Y., Broday D., 2010: Spatial analysis of air pollution and cancer incidence rates in Haifa Bay, Israel*. Science of the Total Environment,* 408, 4429–4439

Epa 2013: United States Environmental Protection Agency website. http://www.epa.gov/airquality/particlepollution/

Erel Y., Kalderon-Asael B., Dayan U., Sandler A., 2007: European atmospheric pollution imported by cooler air masses to the Eastern Mediterranean during the summer. *Environmental Science&Technology*, 41, 5198-5203

Erel Y., Tirosh O., Kessler N., Dayan U., Belkin S., Stein M., Sandler A., Schauer J.J., 2013: Atmospheric Particulate Matter (PM) in the Middle East: Toxicity, Trans-boundary Transport, and Influence of Synoptic Conditions. *Medical Geochemistry: Geological Materials and Health*, 31-46

Kahl JDW., Samson PJ., 1986: Uncertainty in trajectory calculations due to low resolution meteorological data. *Journal of Climate and Applied Meteorology*, 25, 1816-1831

Karanasiou A., Moreno N., Moreno T., Viana M., Leeuw F.,Querol X., 2012: Health effects from Sahara dust episodes in Europe: Literature review and research gaps. *Environment International*, 47, 107–114

Pey J., Querol X., Alastuey A., Forastiere F., Stafoggia M., 2013: African dust outbreaks over the Mediterranean Basin during 2001–2011: PM10 concentrations, phenomenology and trends, and its relation with synoptic and mesoscale meteorology. *Atmospheric Chemistry and Physics*, 13, 1395–1410

Saaroni H., Ziv B., Uman T., 2009: Does a synoptic classification indicate the Nox pollution potential? The case of the Metropolitan area of Tel-Aviv, Israel. Water Air and Soil Pollution, 207, 139-155

Saaroni H., Halfon H., Ziv B., Alpert P., Kutiel H., 2010a: Links between the rainfall regime in Israel and location and intensity of Cyprus lows. *International Journal of Climatology*, 30*, 1014–1025*

Saaroni H., Ziv B., Osetinsky I., Alpert P., 2010b: Factors governing the interannual variation and the long-term trend of the 850 hPa temperature over Israel. *Quarterly Journal of the Royal Meteorological Society* 136, 305-318

Savir, A., 2014: Downscaling Synoptic Data as a Tool for Analysing and Predicting Israeli Summer Conditions. PhD Thesis, accepted in Tel Aviv University, 93 p.

Yarnal B., 1993: *Synoptic Climatology in Environmental Analysis*. Belhaven Press: London.

Yarnal B., Comrie A.C., Frakes B., Brown D.P., 2001: Developments and prospects in synoptic climatology - Review. . *International Journal of Climatology*, 21, 1923–1950

Yuval, Broday D.M., 2006: High-resolution spatial patterns of long-term mean concentrations of air pollutants in Haifa Bay area. *Atmospheric Environment*, 40, 3653-3664

Yuval, Broday D.M., Alpert P., 2012: Exploring the applicability of future air quality predictions based on synoptic system forecasts. *Environmental Pollution*, 166, 65-74