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A COMPREHENSIVE OVERVIEW OF PM_{10} LEVELS IN İSTANBUL: ANNUAL AND SEASONAL SPATIO-TEMPORAL VARIATIONS AND THE LONG-DISTANCE TRANSPORT

Meral DEMİRTAŞ *

Department of Meteorological Engineering, Faculty of Aeronautics and Astronautics,
University of Ondokuz Mayıs, Samsun, Turkey

ABSTRACT

This study provides a comprehensive overview of the particulate matter with diameters equal or smaller than 10 μm (PM_{10}) levels in the megacity İstanbul. PM_{10} concentrations of ten ambient air quality monitoring stations in İstanbul were studied for the period of 2007-2016. The study focuses on: (i) similarities and differences among PM_{10} monitoring areas, (ii) spatial and temporal variations of PM_{10}, (iii) long-distance PM_{10} transport for four selected cases. PM_{10} concentrations show significant variations across the megacity, with high PM_{10} levels at heavy traffic points and industrial zones. Results indicate that the number of exceedances allowed by the EU standards is violated daily and annually at all monitoring sites which indicate serious air quality problem in İstanbul. Monthly mean PM_{10} analysis indicated the most polluted month being November in eight stations, and December is the second most polluted month. The seasonal variation is characterized by high concentrations in the winter, and low concentrations in the summer. Analyses of high PM_{10} episodic events shed light on possible long-distance emission sources and key atmospheric flow patterns which transport PM_{10} from the Atlantic, Europe, the Balkans, the Black Sea, North Africa-the Saharan Desert and the Eastern Mediterranean.

Keywords: PM_{10}, High PM_{10} episodic cases, Long distance transport, Backward trajectory, İstanbul-Turkey

1. INTRODUCTION

PM_{10} air pollution is very important since it adversely influences human health, leading to or aggravating cardiovascular and lung diseases, heart attacks and arrhythmias. It can also have an impact on the central nervous system and the reproductive system, and can lead to cancer [1]. Some epidemiological studies remarked that PM_{10} is correlated with mortality and hospitalizations from respiratory complaints [2, 3]. In Turkey, epidemiological incidents are not well documented. However, a few studies [4, 5, 6, and 7] have pointed out a significant relationship between elevated air pollution concentrations and the number of patients admitted to the hospitals. The association between air pollution and admissions for asthma and other respiratory diseases among children who were younger than 15 yr of age was investigated, and results showed that the highest association was 18% rise in asthma cases correlated with a 10 mgm^{-3} increase in PM_{10} [6]. In another study, the risk of respiratory admissions was found to increase by 0.7% for a 10 mgm^{-3} increase in PM_{10} [7]. In the last decades, air pollution in megacities and their impacts on the surrounding environment and the regional air quality (AQ) has gained extensive scientific interest [8].

İstanbul is one of the largest megacities in Europe with a population over 16 million. With an area of 5400 km^2, İstanbul is the largest urban area of Turkey. The megacity İstanbul extends on two continents: the European part and the Asian part. The city is separated from the Asian continent by Bosporus strait of 30 km length that connects the Marmara Sea at the south with the Black Sea at the north (Figure 1). The orography modulates the atmospheric flow. Simulations of the export of air pollution to downwind locations via long-range transport have shown different transport patterns. İstanbul is located on a crossroad of air masses coming from Europe and Africa, where anthropogenic emissions, mostly from Europe, the Balkans and the Black Sea, meet with natural emissions from the

*Corresponding Author: mdemirtas@omu.edu.tr

Saharan Desert dust, vegetation and the sea, in addition to biomass burning which has a seasonal trend [9]. Climatological studies suggest that north-easterly and south-westerly winds prevail in the winter and north-easterly winds in the summer [10]. İstanbul is exposed to sea and land breeze local circulations. During summer, the southern part of the city which is close to the Marmara Sea experiences such circulation patterns that influence pollutants transport and accumulation in the boundary layer [11]. The northern part is usually under the influence of the colder northern air masses and the cooler Black Sea.

İstanbul was affected by several serious AQ problems in the past [10]. The main sources of PM_{10} in İstanbul are: traffic, residential heating, industrial processes and street dust [10,12,14], and a large contribution comes from ship emissions in the city since on average 60,000 ships pass yearly through the Bosphorus Channel [10]. High PM_{10} episodes can also occur when favourable atmospheric flow transports high PM_{10} from remote source locations to over İstanbul [10, 12, 13, 14, 15]. Plumes from large dust storms and wildfires can be transported on large scales. Dust emitted from desert surfaces by wind erosion of soil can be transported in the atmosphere over thousands of kilometres. Transport of PM_{10} from the source locations depends on atmospheric flow. Long-range transport (LRT) may substantially increase PM_{10} concentrations. LRT may also lead to episodic events when air masses arrive during favourable meteorological conditions from regions with high emissions of particles or from the Saharan Desert dust plumes [13, 14]. It is important to understand the underlying atmospheric flow patterns that lead to episodic air pollution events at local and long range scales. Previous LRT studies have shown that İstanbul is affected from Western Europe, the Balkans and the eastern part of Russia in the winter, from Eastern Europe in the summer, and from central North Africa in the spring [13, 14, 19]. This study considers four high episodic PM_{10} events in which two of them seem to be originating from the Saharan Desert dust plumes.

Previous PM_{10} studies of İstanbul [10, 13, 14, 15] -which are referred in related parts of Section 3- addressed its various aspects with varying number of stations and shorter temporal coverage. By using measurements of ten AQ stations with ten year coverage (2007-2016), this study aims (i) to quantify spatial and temporal distribution of PM_{10} in the megacity İstanbul; (ii) to evaluate exceedances; (iii) to examine high PM_{10} episodic events with underlying mean atmospheric conditions and the role played by the long-range transport.

2. DATA AND METHODOLOGY

2.1. Air Quality Data

Over the years, authorities have adopted legislations in order to improve ambient AQ, such as the European Union Directive 2008/50/EC [16] (hereafter the EU2008 Directive) which corresponds to the main AQ legislation for twelve regulated pollutants, including PM_{10}. To comply with the EU2008 Directive, İstanbul is covered by several AQ monitoring stations, with major incidence on areas where health protection and spatial coverage are fundamental, *i.e.* large urbanized-traffic-industrial regions.

Air quality data wes retrieved from the database of Ministry of Environment and Urbanization, the government agency in charge of collection of air pollution data in Turkey. These AQ stations are operated by the Environmental Protection and Control Centre of İstanbul Metropolitan Municipality. At these stations, PM_{10} concentrations are measured using an ambient suspended particulate monitor system (Model MP101M of Environment S.A), and the instrument's measuring principle is based on Beta Gauge monitoring and it is approved by the US Environmental Protection Agency (EPA) [14].

İstanbul's ten ambient AQ monitoring stations used in this research are listed in Table 1 and their locations are depicted in Figure 1. Selection of these stations is based on the availability of data for the desired study period and also location of AQ monitoring stations throughout the city. Data from the above mentioned monitoring stations from 2007 to 2016 were analyzed with reference to the EU standards (Table 2). The dataset comprises PM_{10} hourly mean concentrations. The daily mean of PM_{10} concentrations were calculated for each day provided that at least 18 h data was available. Monthly means were computed if available data covered at least 21 days. Seasonal means for winter (December-January-February), spring (March- April-May), summer (June-July-August) and autumn (September-October-November) periods were computed if at least 2 months of data were present.

Table 1. Air quality monitoring stations

Station name	Site environment type	Altitude (m)	Latitude (N)	Longitude (E)
Alibeyköy	Urban-heavy traffic	6	41° 03' 27"	28° 56' 44"
Aksaray	Heavy traffic	40	41° 00' 52"	28° 57' 16"
Beşiktaş	Heavy traffic	95	41° 03' 14"	29° 00' 36"
Esenler	Heavy traffic-industrial	52	41° 02' 17"	28° 53' 17"
Kartal	Heavy traffic-industrial	31	40° 53' 24"	29° 12' 26"
Kadıköy	Urban-traffic	13	40° 59' 30"	29° 02' 00"
Sarıyer	Urban-traffic	104	41° 07' 44"	29° 02' 58"
Ümraniye	Urban-traffic	153	41° 00' 48"	29° 09' 43"
Üsküdar	Urban-traffic	69	41° 00' 55"	29° 01' 29"
Yenibosna	Heavy traffic-industrial	27	40° 59' 56"	28° 49' 36"

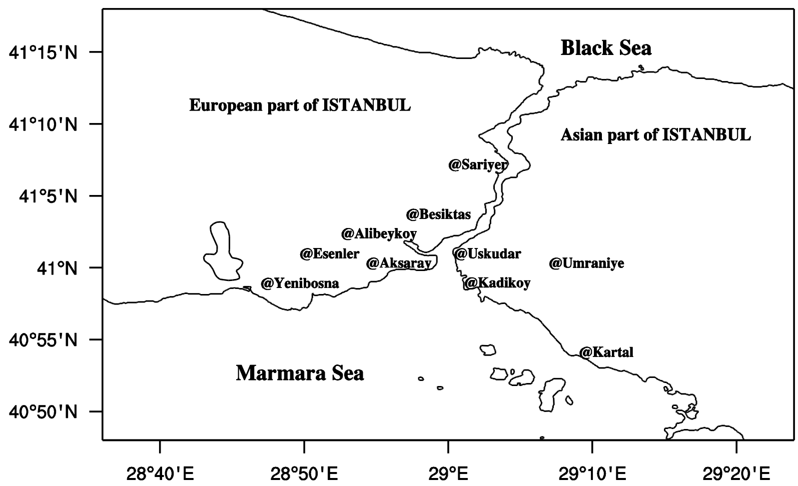

Figure 1. Locations of ten air quality monitoring stations of İstanbul are depicted.

Table 2. PM_{10} air quality standards based on the European Union Directive 2008/50/EC

Pollutant	Concentration	Averaging period	Legal nature	Permitted exceedances each year
PM_{10}	50 µg/m^3	24 hours	Since 1.1.2005	35
	40 µg/m^3	1 year	Since 1.1.2005	

2.2. Atmospheric Fields

Atmospheric datasets used in this study are from the European Centre for Medium-Range Weather Forecasts (ECMWF): (i) ERA-Interim (ECMWF-EI) reanalysis [17] is used for computing seasonal climatological means (1979-2009), and associated meteorological parameters are interpolated on to 0.5°x0.5° longitude-latitude grids. (ii) ECMWF operational analysis dataset is used for examining meteorological conditions of high PM_{10} episodic events, and parameters are interpolated onto 0.25°x0.25° longitude-latitude grids.

In order to obtain a more in-depth understanding of the dynamical and physical mechanisms behind the relationship between PM_{10} and atmospheric conditions, seasonal composite maps of mean sea level pressure (MSLP), wind at 10 m and 850 hPa geopotential height and wind at this level were calculated from 1979-2009 reference period for each season (winter, spring, summer, and autumn). The wind at 850 hPa is considered since it is far less influenced by surface conditions. It also underlies presence of low level jets which are very important for transporting PM_{10} from distant places. The climatological mean of each season is mapped on large scale to give a big picture with emphasis given to the area of interest (Figure 1).

i. Winter: Prominent winds at 10 m are northerly and north-easterly over the area of interest (Figure 2a). At 850 hPa (Figure 3a); winds are westerly and south-westerly. High PM_{10} episodes usually occur in winter, these winds transport PM_{10} from Europe and the Balkans.

ii. Spring: The dominant wind direction is north-easterly at 10 m over the İstanbul area (Figure 2b), and westerly at 850 hPa level (Figure 3b). These winds have the potential to advect PM_{10} emissions from the west and as well as from the north-east.

iii. Summer: The winds at 10 m are strong and north-easterly over the area of interest (Figure 2c), and at 850 hPa they are north-north-easterly (Figure 3c). PM_{10} concentrations are not so high in summer, but when mega heat waves are accompanied by large wildfires, these winds can transport PM_{10} from the source locations to over İstanbul.

iv. Autumn: the winds at 10 m (Figure 2d) are similar to those of summer, but the winds at 850 hPa are westerly and north-westerly (Figure 3d). These winds can advect PM_{10} sources from Europe and Eastern Russia.

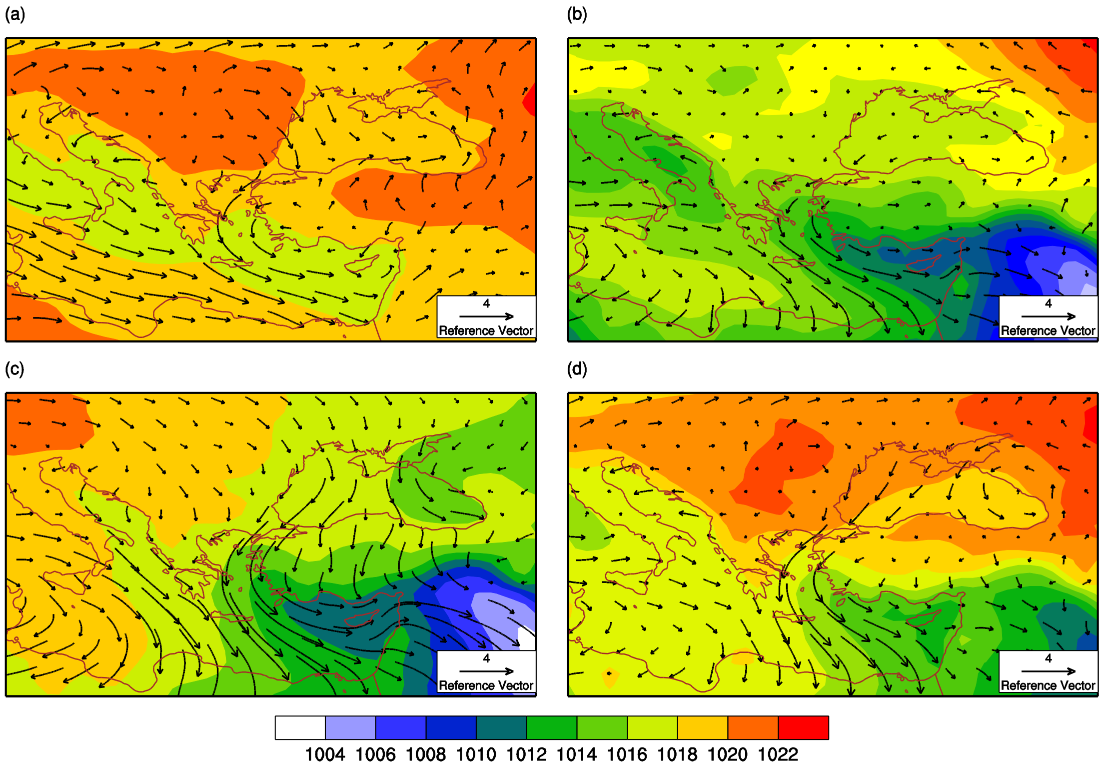

Figure 2. Seasonal mean of MSLP (hPa) in shading and wind vectors (m/s) at 10 m: (a) Winter; (b) Spring; (c) Summer; (d) Autumn

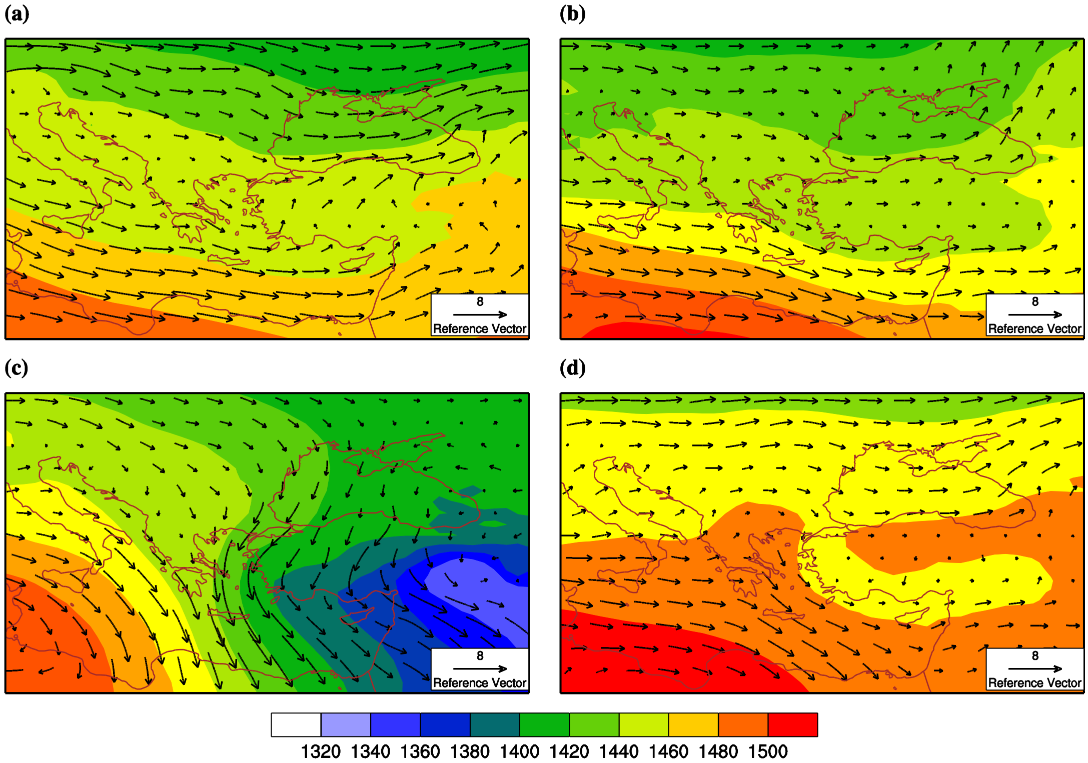

Figure 3. Seasonal mean of 850hPa geopotential height (m) in shading and wind (m/s): (a) Winter; (b) Spring; (c) Summer; (d) Autumn

2.3. Air Mass Backward Trajectory Analysis

Backward trajectories from İstanbul were computed by employing a commonly used [10, 13, 14] the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (2016-version) which is a complete simulation system to determine air parcel trajectories, calculate single scattering processes and perform complex simulations of deposition [18, 19]. HYSPLIT was developed at the Air Resources Laboratory (ARL) [19] of the National Oceanic and Atmospheric Administration (NOAA). It is a complete system for computing trajectories of complex dispersion and deposition simulations using either puff or particle approaches. The HYSPLIT transport and dispersion model and its web-based interface (the READY) are used in this study. The HYSPLIT model uses archived meteorological data and dispersion of a pollutant is calculated by assuming either puff or particle dispersion [18, 19]. The required meteorological fields have been driven employing National Centers for Environmental Prediction re-analysis data on 1°x1° longitude-latitude grids.

The air-mass trajectories were generated using the HYSPLIT model in order to have a better insight on possible sources of high PM_{10} episodic cases (Section 3.3). A backward tracking time of 72 h was applied at 500 m, 1000 m and 1500 m heights, and for each episodic day the terminus of the trajectories was considered to be located at İstanbul (41.06°N, 28.97°E), and the arrival time corresponds to the previous midnight of the date of the maximum pollutant value measured to consider the contribution from the closest time. This study did not consider performing backward trajectories for each monitoring stations, it is beyond the scope of current study, and a future comprehensive study on long-range transport could include all stations.

3. RESULTS AND DISCUSSION

3.1. Analyses of Ten Ambient Air Quality Monitoring Stations

The data analysis is based on the 24-h averages of PM_{10} concentrations. The study period (2007-2016) annual mean PM_{10} concentrations are presented in Figure 4 for all monitoring stations. It gives a snap-shot of the spatial distribution of PM_{10} concentrations over İstanbul.

PM_{10} concentrations show significant variations across the city. Stations close to industrial zones and heavy traffic show higher PM_{10} levels compared to stations located in residential areas. Also, topography and prominent atmospheric conditions can strongly influence resulting PM_{10} concentrations. Analyses of annual, monthly and seasonal distributions of PM_{10} show that monitoring stations can be categorized into various groups depending on their underlying PM_{10} concentrations. Accordingly, results are grouped in three categories and presented in Table 3.

Table 3. Mean PM_{10} categories and corresponding monitoring stations

PM_{10} Mean concentrations ($\mu g/m^3$)	Monitoring stations
Category 1: 80-100	Kartal
Category 2: 60-80	Esenler, Yenibosna, Aksaray, Alibeyköy
Category 3: 30-50	Beşiktaş, Sarıyer, Kadıköy, Ümraniye, Üsküdar

Kartal station has the largest PM_{10} concentrations which range from 55-90 $\mu g/m^3$ throughout the study period (Figure 4 and Figure 5), and its seasonal variability is quite different to the other stations, with relatively high values even in summer (Figure 6). These results are in line with the previous studies that pointed out high PM_{10} concentrations of Kartal [10, 14]. The main anthropogenic sources of PM_{10} emissions in Kartal can be outlined as; heavy traffic, industry and residential heating in winter. Traffic which includes diesel powered heavy duty vehicles is the leading component of the emission sources in this area [10, 14]. The PM_{10} pattern in Kartal is also under the influence of topographical conditions. Kartal's elevation ranges from 1 m to 537 m. The used land area is situated between the hills on the northern side [10].

Esenler, Yenibosna, Aksaray and Alibeyköy form the second highest PM_{10} concentration category as also remarked by previous studies [10, 14]. Alibeyköy, Yanibosna and Kartal were not affected by any typical direct source, except busy traffic [14]. Other daily fluctuations that did not continuing for more than few hours are considered to be directly related to regional and local dust generation mechanisms [14]. Esenler hosts an intercity bus terminal which is quite busy throughout the year, and it is also under the influence industrial emissions. Yenibosna AQ station is located in a business and industrial location which is very close to the Atatürk International Airport and a major heavy traffic conjunction with an estimated traffic flow of about 220,000 vehicles per day (40,000 of which are heavy duty vehicles) [10]. Aksaray is surrounded by commercial sites and associated heavy traffic. Alibeyköy is a developing urban area with a growing traffic load since it also hosts a very active intercity bus terminal. The low-quality domestic heating is also still being used in Alibeyköy. The second group's annual, monthly and seasonal distributions are similar (Figures 4-6).

Beşiktaş, Kadıköy, Sarıyer, Ümraniye and Üsküdar form the low PM_{10} concentration group (Figures 4-6). These stations are located in residential districts, but they are very close to roads with heavy traffic. Besiktaş AQ station is placed on the side of a Bosphorus Bridge connection road which around 50,000 vehicles pass per day on its six lanes [10]. Therefore, Beşiktaş has higher PM_{10} values compared with other members of this group. PM_{10} concentrations are on the rise in Kadıköy and Ümraniye. Üsküdar has the lowest PM_{10} annual, monthly and seasonal mean concentrations as reported by previous studies [10, 14], since it is exposed to less busy traffic compared with other stations. The third PM_{10} concentration group has the lowest PM_{10} concentrations compared the other two groups, it is mainly because these locations are less expose to heavy traffic and industrial emissions that give rise to high PM_{10} concentrations.

Monthly mean PM_{10} analysis reveals the most polluted month for each station (Figure 5). Over all, November is the most PM_{10} polluted month in eight stations, and December is the second most polluted month. These results support the highest PM_{10} concentrations of winter.

There are sharp seasonal variations in the data for all stations as also pointed out by previous studies [10, 14]. This implies that the stations are affected by local sources as well as meteorological conditions during particular time periods. This is especially noted equally across all the stations during winter and summer. In all stations, the lowest concentrations are noted for summer, while pronounced concentrations are seen in winter, spring and autumn (Figure 6). The summer, when almost all the monitoring stations show lower PM_{10} concentrations, is considerably different to the winter. This could be attributed to the result of diminished residential heating and addition of airborne dust, natural dust and soil [10, 13, 14]. It should also be noted that construction work increases during summer and large amounts of airborne and street dust are transported from construction sites.

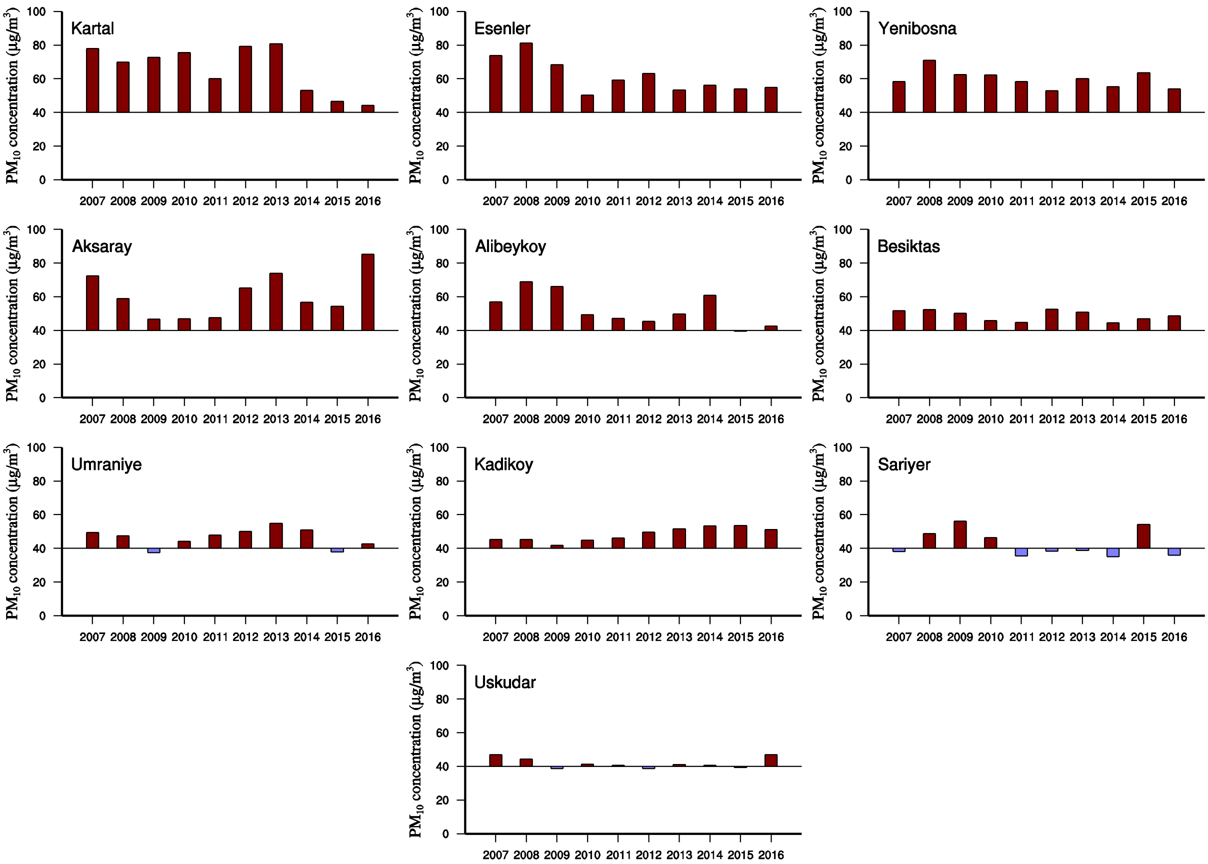

Figure 4. PM_{10} annual mean concentrations ($\mu g/m^3$) are shown for ten monitoring stations. The reference line is drawn to indicate annual limit (40 $\mu g/m^3$) as outlined in the Table 2.

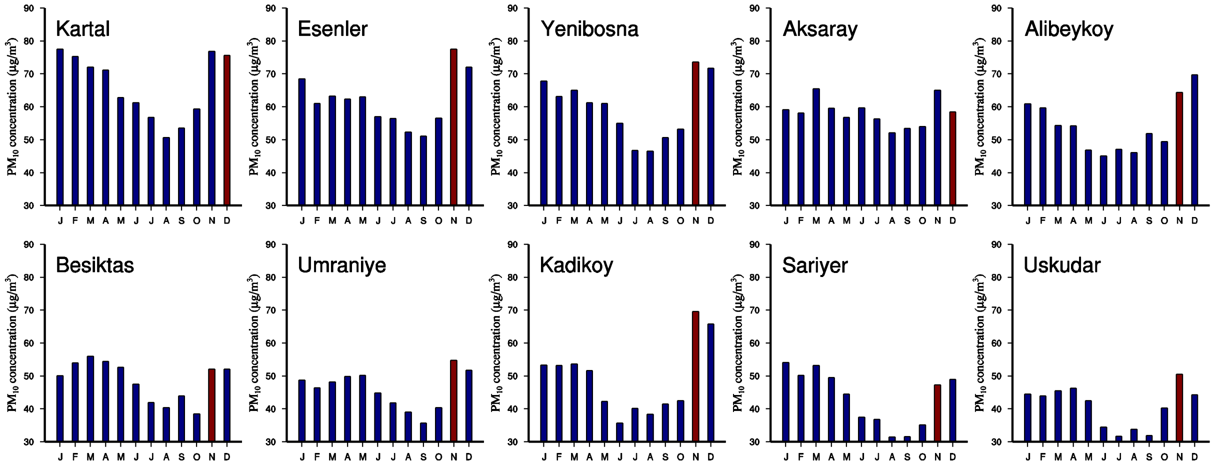

Figure 5. The study period averaged PM_{10} monthly concentrations ($\mu g/m^3$) are shown for ten monitoring stations. The highest concentration exhibiting months is shown in a different colour.

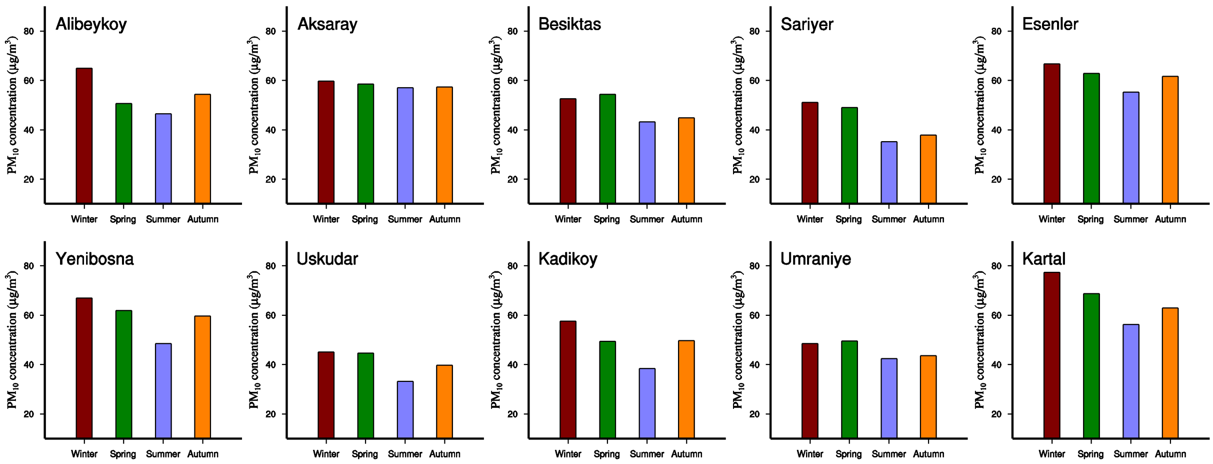

Figure 6. The study period averaged seasonal mean PM_{10} concentrations ($\mu g/m^3$) are shown for ten monitoring stations

The 24 h mean PM_{10} threshold of $50 \mu g/m^3$ should not be exceeded more than 35 times a year according to the EU2008 Directive. Daily mean exceedances in PM_{10} concentrations have been investigated with respect to Table 2. The EU limit of PM_{10} was exceeded in all regions of İstanbul during the study period (2007-2016).

Exceedances vary both temporally and spatially; they are more frequent in winter and autumn seasons which may be attributable to intensified anthropogenic activities such as domestic heating and traffic [10, 14]. Exceedance percentages of each year for PM_{10} mass concentrations observed by each station are presented in Figure 7. Kartal station exhibits daily mean exceedance of 80% in 2010, 2012 and 2013, but results also suggest decreasing trend since 2014. Esenler, Yenibosna and Aksaray monitoring stations have high exceedances as pointed out by some previous studies [10, 14]. On the other hand, lower exceedances are noted for Sarıyer, Ümraniye and Üsküdar monitoring stations, maybe due to not being so much exposed to industrial emission sources and heavy traffic [10, 14].

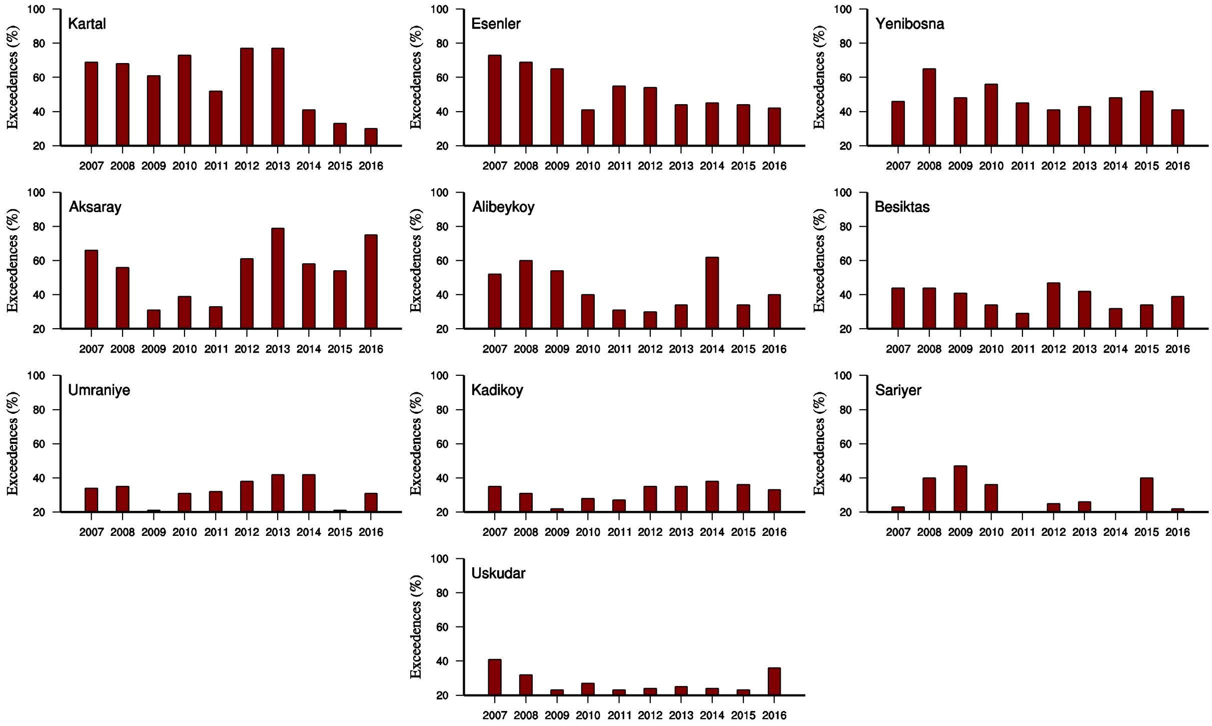

Figure 7. Percentage of PM_{10} exceedances are shown for ten monitoring stations for the study period.

İstanbul's annual mean and seasonal mean PM_{10} concentrations are computed by averaging over ten monitoring stations. The annual mean PM_{10} of İstanbul is above the annual limit (40µg/m^3) throughout the study period (Figure 8a). The annual mean is 55-60 µg/m^3 (Figure 8a) and seasonal levels range from 35 to 70 µg/m^3 (Figure 8c-f).

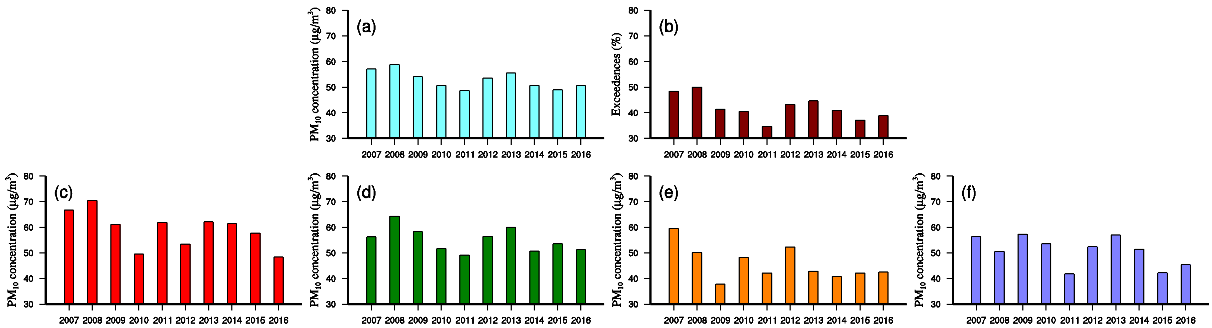

Figure 8. Annual mean, annual exceedances and the study period averaged seasonal mean PM_{10} concentrations (µg/m^3) of İstanbul: (a) Annual, (b) Annual exceedances (%), (c) Winter, (d) Spring, (e) Summer, (f) Autumn.

Seasonal variations indicate that winter (Figure 8c), spring (Figure 8d) and autumn (Figure 8f) seasons have high PM_{10}concentrations, while summer has the lowest (Figure 8e). İstanbul's annual exceedance is computed by taking an average over ten monitoring stations. İstanbul exceeds the EU limit throughout the study period (Figure 8b).

3.2. Case Studies of High PM$_{10}$ Episodic Events

This study considers four high episodic PM$_{10}$ events in which two of them seem to be originating from the Saharan Desert dust plumes.

3.3.1. High PM$_{10}$ episodic event of 12-14 April 2008

PM$_{10}$ levels were well above the daily limit of 50 µg/m^3 on 13th April 2008 at all stations, with some stations' hourly concentrations exceeding 180 µg/m^3 (Figure 9). Esenler, Yenibosna and Kartal stations were the top three highest PM$_{10}$ (120-180 µg/m^3) stations, while Kadıköy station reported the lowest concentration (58 µg/m^3). It is interesting to note how all the stations were affected on the same date, and this prompts the question of a common emission source.

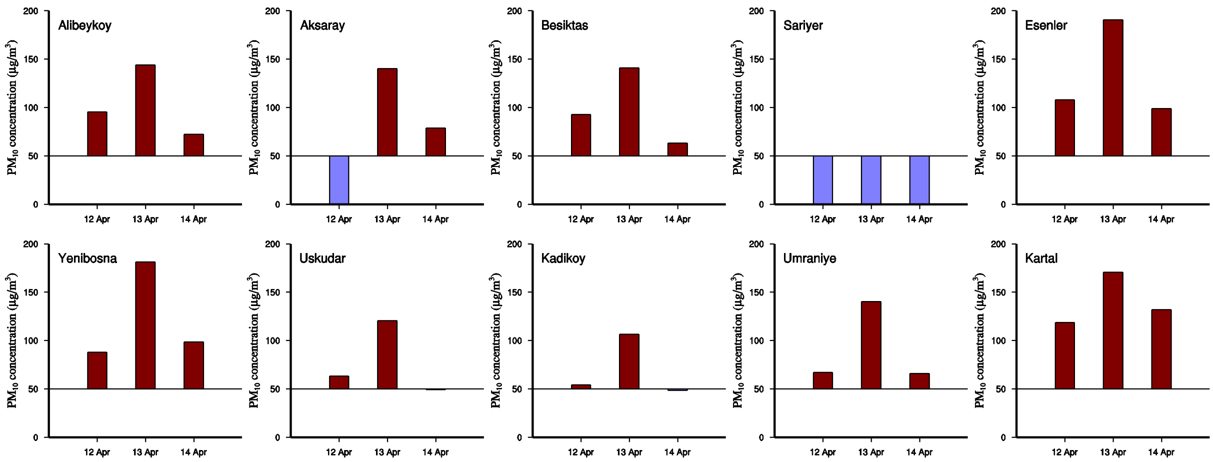

Figure 9. Time series of daily mean PM$_{10}$ concentrations (µg/m^3) are shown for ten monitoring stations for 12-14 April 2008 case. The reference line is drawn to indicate 24-h limit (50 µg/m^3) as outlined in the Table 2.

The HYSPLIT backward trajectory analyses at 500, 1000 and 1500 m levels were conducted to investigate the long range transport of PM$_{10}$. Over a 72-h run time, the obtained trajectories extended to south western Europe and North Africa (Figure 10a) –which is in line with previous studies of the same case [13, 14]. A study focusing on the source apportionment of Saharan dust event of 13 April 2008 reported that 57% of the observed PM$_{10}$ originates from mineral dust [14].

Atmospheric conditions of the period shed light on the atmospheric driving mechanisms. Figure 11a shows an anticyclone over the Eastern Mediterranean, and its southern extent being over North Africa. Strong easterly winds travelled over North Africa and from there, via south westerly winds, arrived over İstanbul. The direction of the prominent strong winds suggests that natural soil dust might have been transported from the Sahara Desert.

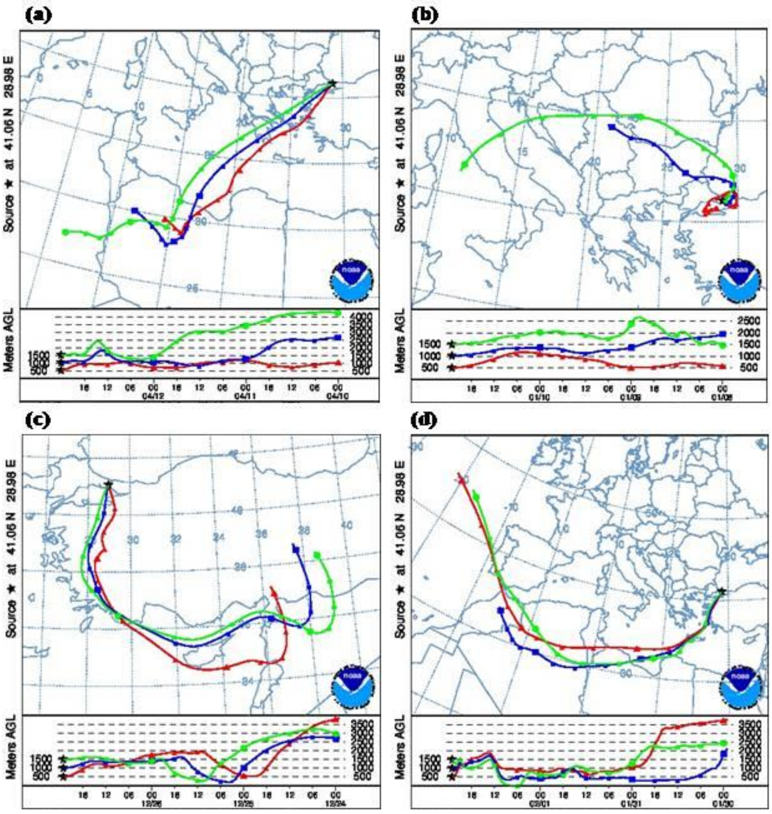

Figure 10. The 72-h backward trajectories are shown for the long-distance transport of air masses to İstanbul: (a) 13 April 2008; (b) 10 January 2011; (c); 26 December 2013; (d) 1 February 2016

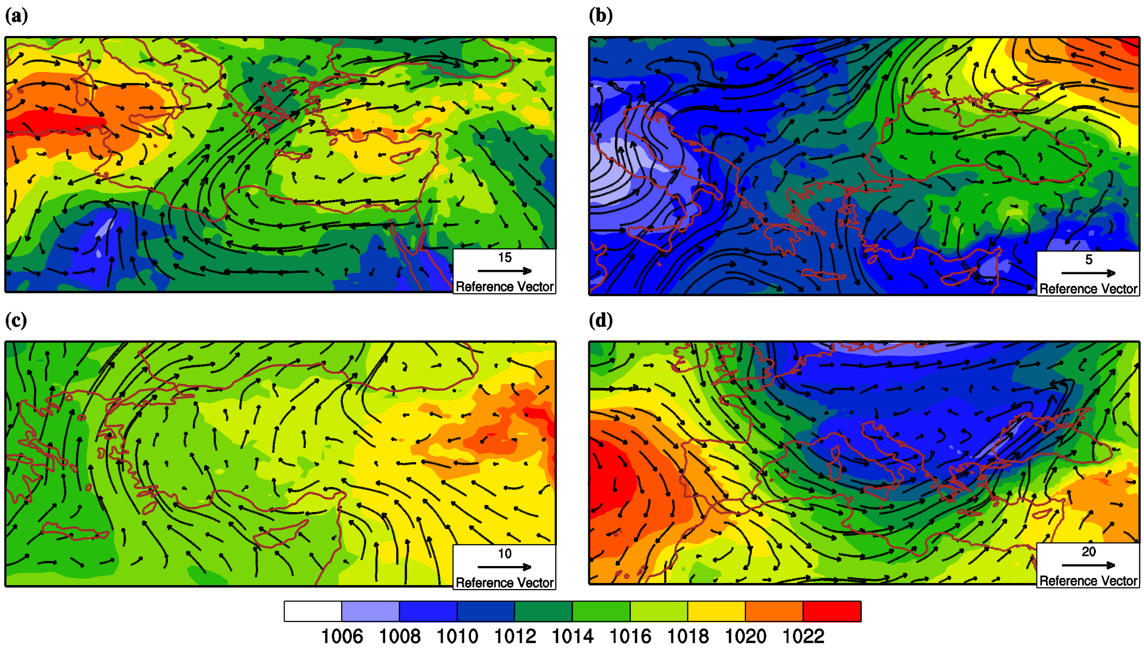

Figure 11. MSLP (hPa) in shading and wind vectors (m/s) at the 850 hPa are plotted for: (a) 13 April 2008; (b) 10 January 2011; (c); 26 December 2013; (d) 1 February 2016

3.3.2. High PM_{10} episodic event of 8-10 January 2011

PM_{10} concentrations exceeded the daily limit at all stations, with some hourly mean concentrations being above 200 µg/m^3 which is four times higher than the daily limit (Figure 12). All stations recorded high PM_{10} concentrations on both 8th and 10th January 2011 and, Yenibosna exhibited the highest PM_{10} levels (over 200 µg/m^3) on both days, and the Kartal station followed the suite with 180-200 µg/m^3. Ümraniye, Aksaray and Esenler were also among high PM_{10} concentration reporting stations, while Alibeyköy and Beşiktaş had lower levels (50-60 µg/m^3) compared to other monitoring stations. Since they were affected at the same period, emission sources could be very similar.

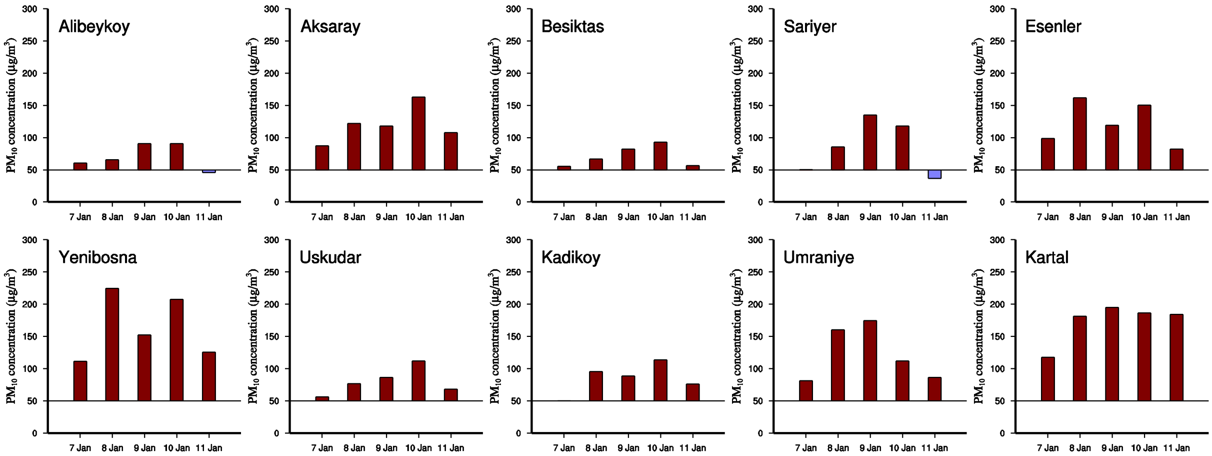

Figure 12. As in Figure 9, but for 7-11 January 2011 case.

Backward trajectory analyses were performed at 500, 1000 and 1500 m levels to explore the origin of far distance PM_{10} emission sources. The HYSPLIT model trajectory paths (Figure 10b) show that air masses reaching İstanbul originate from Italy, the North Eastern Europe and the Western Black Sea. The role of meteorological factors was analyzed and is presented in Figure 11b. A cyclonic circulation over southern Italy and an anticyclonic circulation to its south generated strong horizontal wind gradients. Some of these strong winds arrived over Eastern Europe and the Balkans, and after that reached over to İstanbul. Considering where these winds travelled though, it is plausible that they had transported industrial emission sources.

3.3.3. High PM_{10} Episodic Event of 24-26 December 2013

Recorded PM_{10} concentrations exceeded the daily limit during 24-26 December 2013, with some hourly concentrations being six times above the EU limit (Figure 13). Yenibosna exhibited the highest levels (300 µg/m^3) on 24th -25th, and the Kartal station closely followed it. On 26th the Esenler station had the highest PM_{10} concentration (300 µg/m^3), the Kartal station was the second highest, and the Yenibosna being the third. Sarıyer and Üsküdar stations reported the lowest PM_{10} levels (100 µg/m^3) compared to others. The very high PM_{10} concentrations suggest a closer emission source.

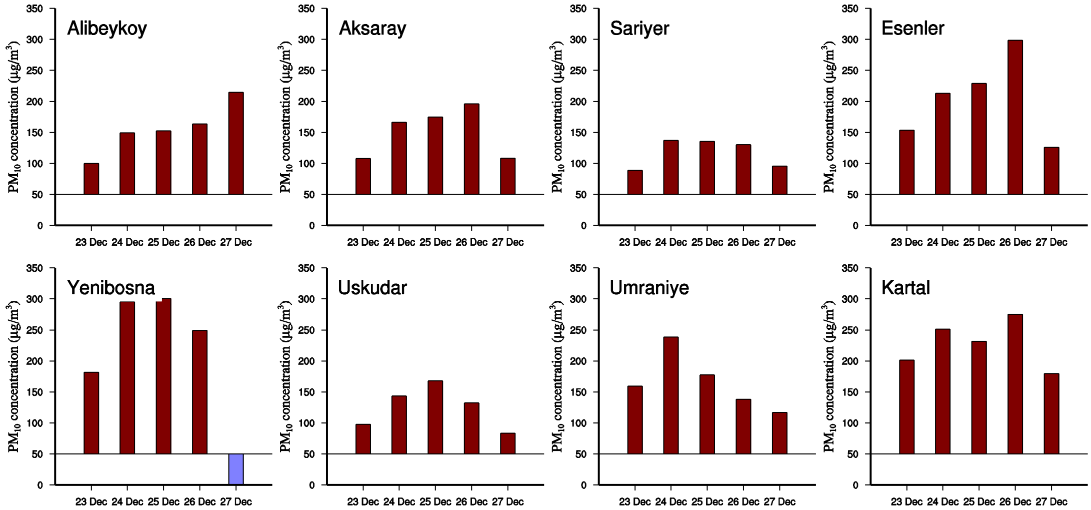

Figure 13. As in Figure 9, but for 23-27 December 2013 case.

Backward trajectory analyses were conducted at 500, 1000 and 1500 m levels to find out whether the emission source was from a closer location compared to other cases. The HYSPLIT model results indicate that air masses reaching İstanbul originated from the south eastern Mediterranean countries (Figure 10c) where dust storms commonly occur [9, 14]. Meteorological analysis indicates underlying atmospheric driving mechanisms that can lead to such high PM_{10} concentrations (Figure 11c). An anticyclone on the south east of Turkey had advected soil dust from the Eastern Mediterranean emission sources over to İstanbul. The direction of the prominent strong winds indicates that natural soil dust might have been transported from Middle Eastern deserts.

3.3.4. High PM_{10} episodic event of 31 January – 2 February 2015

This is the highest PM_{10} concentration episodic day among the four cases considered in this study. PM_{10} levels were above the daily limit at all stations, with daily mean concentration surpassing 350 (μg/m^3) in Beşiktaş (Figure 14). It is very interesting to note Sarıyer station being the second highest PM_{10} level (286 μg/m^3) recording station which usually has lower PM_{10} concentrations. Yenibosna and Kartal stations -which are belonging to the second highest PM_{10} group-, followed the suite. Alibeyköy - which belongs to the high PM_{10} category group two (Table 3) – had the lowest PM_{10} level (100 μg/m^3).

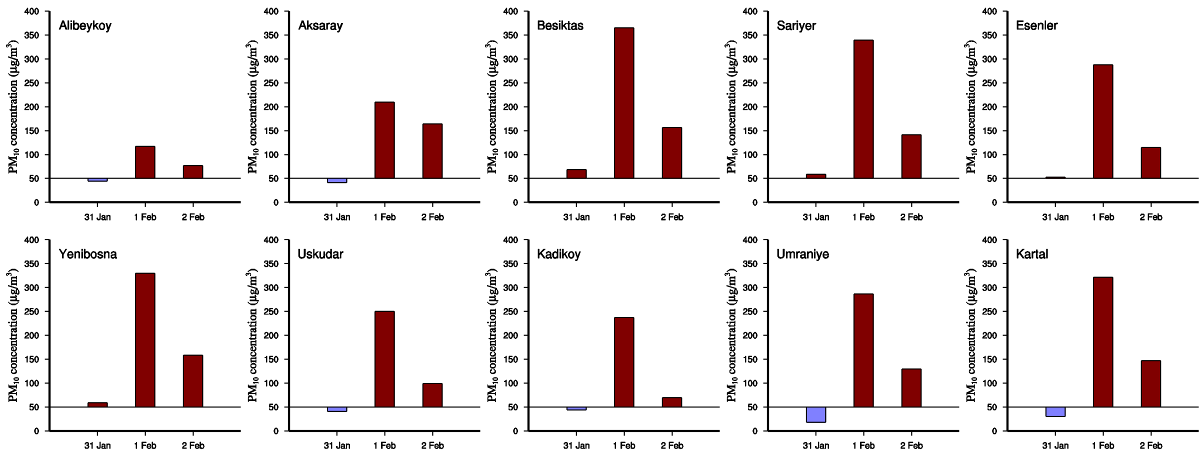

Figure 14. As in Figure 9, but for 31 January – 2 February 2016 case.

The HYSPLIT backward trajectory analyses at 500, 1000 and 1500 m levels were performed to investigate the long range transport of PM_{10}. Over a 72-h simulation time, the obtained trajectories implied that air masses reaching İstanbul originated from the east Atlantic and travelled across North Africa (Figure 10d). Meteorological analysis gives more insight into how such high PM_{10} concentrations were transported to İstanbul (Figure 11d). A deep cyclone located to the north-west of Turkey provided the necessary strong wind, and south westerly low-level jets carried high PM_{10} concentrations from a very long-distance. Taken into account where these winds passed though, it can be argued that they had transported industrial emission from remote industrial sources and natural soil dust from the Sahara Desert. A source apportionment analysis is beyond the scope of this paper, maybe future studies can explore mixed PM_{10} contributions from remote sources quantitatively.

4. CONCLUDING REMARKS

Spatial distribution of PM_{10} concentrations shows significant variance over the city. As can be expected, the stations away from the heavy traffic and industrial hot spots present very different distributions of PM_{10} concentrations throughout the year. The analysis of annual and seasonal means of the study period revealed three PM_{10} concentrations groups. The Kartal station has the highest PM_{10} concentrations as remarked by previous studies [10, 14]. The second group comprises Esenler, Yenibosna, Aksaray and Alibeyköy. These stations are affected from heavy traffic, industrial emissions and the burning of low-quality domestic fuels. The third group consists of Beşiktaş, Sarıyer, Kadıköy, Ümraniye and Üsküdar. AQ with respect to PM_{10} is the best in Kadıköy, Ümraniye, and Üsküdar compared with other stations.

Monthly mean PM_{10} analysis indicated the most polluted month being November in eight stations, and December is the second most polluted month. PM_{10} concentrations of the monitoring sites greatly exceed the EU PM_{10} AQ standards [10, 14]. Analysis of percentages of PM_{10} exceedance of İstanbul indicates that they are around 50 % throughout the study period. The most PM_{10} polluted Kartal station exceed the limits more than 80 % of the time, while the least polluted station Üsküdar has exceedance rate around or below 40%. PM_{10} violations are strongly associated with local sources which exhibit a seasonal pattern with maxima in the winter and minima in the summer.

Four PM_{10} episodic cases were evaluated in order to have a better insight into remote origin of PM_{10} concentrations and the role played by the meteorological conditions. These episodic events represent the most outstanding cases in terms of hourly mean PM_{10} concentrations in the majority of AQ monitoring stations for a certain day or days. High PM_{10} episodic cases shed light on the role played by the atmospheric driving mechanisms. The HYSPLIT back-trajectory analysis showed that during the high PM_{10} days, transport is mainly from Europe, the Balkans, the Black Sea, the North Africa/ the Saharan Desert and the Middle Eastern desserts to İstanbul. PM_{10} extreme events are associated predominantly with situations characterized by a western, south-western, south-eastern and north-wind component and advection of air masses from remote emission sources. The highest PM_{10} episodic day (1st February 2015) was found to be related to the strong low level jets that carried air parcels from the Atlantic across North Africa which possibly contained dust from the Saharan Desert. Two episodic events (12-14 April 2008 and 24-26 December 2013) were under the influence of anticyclones which were located to the south east of Turkey and provided the necessary atmospheric driving mechanisms that carried PM_{10} from the south eastern Mediterranean and central North Africa.

The results suggest that PM_{10} levels in megacities like İstanbul should be continuously monitored in a wide network of ambient air monitoring sites with different characteristics based on local and remote emission sources, population and geography. Low PM_{10} levels at the urban sites may not represent the rural PM_{10} profiles in the extended area of a megacity due to the distribution of the emission sources, the local and short-to-long range transport of PM_{10} and its associated precursors.

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