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Contribution of the Middle Eastern dust source areas to PM_{10} levels in urban receptors: Case study of Tehran, Iran

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HIGHLIGHTS

- Modeled the Middle Eastern dust intrusions in 2009–2010 by HYSPLIT.
- Adjusted the model parameters including the threshold friction velocities.
- Potential origins of the Middle Eastern dust storm were identified.
- Contribution of the regional dust source areas to urban PM_{10} were determined.
- Deserts in Iraq and Syria were the main contributing dust sources to PM_{10} in Tehran.

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ABSTRACT

The origins and evolution of the Middle Eastern dust storms which frequently impact the residents of this arid region were studied. A methodology was adapted and developed to identify the desert regions of potential dust sources and determine their contributions to PM_{10} concentrations in the highly-populated receptor city of Tehran, Iran. Initially, the episodes of regional dust intrusion and the resulting amounts of increase in the particulate concentrations during these episodes were determined using a statistical analyzing methodology. The dust episodes were also inspected with the aerosol index information from the Ozone Monitoring Instrument (OMI). The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used as the main tool to determine the proportions of dust originating from different deserts during the dusty episodes of 2009–2010.

Daily 5-day back trajectories were obtained from the receptor stations during the dust outbreaks in order to find and confirm the location of potential sources. After the boundaries of the potential sources were determined by 5-day backward trajectories, this region was divided into different areas to quantify their contributions to the measured PM_{10} levels. The proximity between the measured and simulated data confirmed the ability of HYSPLIT in modeling the Middle Eastern dust intrusion and estimating the particulate concentration in the downwind receptor sites. Results showed that the deserts in Iraq and Syria are the main contributing dust sources which comprise more than 90% of the dust related PM_{10} concentrations in Tehran, during the studied dust episodes. The sources in northern Iraq and eastern Syria respectively represented 44% and 32% contributions on average.

1. Introduction

In the arid areas, dust storms release large amounts of particulate into the atmosphere every year, which could be transported to the downwind regions located hundreds of kilometers away (Fu et al., 2008). Dust storms can cause serious health problems such as lung irritation, allergic reactions, eye infections, meningitis and valley fever (Griffin and Kellogg, 2004; McKenna et al., 2008; Nieuwenhuijsen et al., 2007; Perez et al., 2012). Furthermore, mineral dust impacts the environment in many aspects including disturbance in the climate system, interrupting the balance of radiation, and adverse esthetic and visual effects (Tegen and Fung, 1994). This situation is particularly intense for the areas in the dust belt, which extends over North Africa, Middle East, Central and South Asia, and China (Chester et al., 1977; Mitsakou et al., 2008; Prospero et al., 2002).

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The development, evolution and transport path of mineral dust particles are affected by a complex system. A dust storm occurs when wind speed exceeds the threshold friction velocity and creates a suspended cloud of particles and carries it high into the air (Bagnold, 1941; Bréon et al., 2002; Stout, 2010). The threshold velocity of a region is affected by several parameters including the soil texture, humidity, vegetation, topography and particle diameter (Bréon et al., 2002; Fécan et al., 1999; Harris and Davidson, 2008; Marticorena et al., 1997). This cloud of suspended particles evolves and travels by various processes including advection, diffusion, turbulence, settlement and even chemical reactions. Hence, a proficient representation of a dust storm requires appropriate estimation of various parameters, particularly the threshold velocity, and proper simulation of aforementioned processes which define the dispersion and transformation of the dust particles.

Different approaches including satellite data processing, surface particulate monitoring, dust dispersion modeling and elemental tracers' analysis have been used to study the dust intrusions (Draxler et al., 2001; Engel-Cox et al., 2004; Liu et al., 2011; Schwikowski et al., 1995). Most of these studies have concentrated on finding the origins of the dust, and investigating the transportation of particulate dust storms. For instance, several researchers have processed Aerosol Index (AI) data from Total Ozone Mapping Spectrometer (TOMS) on the Nimbus 7 satellite, and Aerosol Optical Depth (AOD) data from Moderate Resolution Imaging Spectroradiometer (MODIS) to locate potential origins of the dust storms and identify areas where dust mobilization is more frequent (Esmailli et al., 2006; Liu et al., 2011; Miller, 2003; Prospero et al., 2002; Qu et al., 2006). More advanced studies have used different dispersion modeling and back trajectory approaches as well as processing satellite data to investigate dust storm paths and origins. Among different modeling tools, the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT) has been used for this purpose and has shown a superior potential (Draxler and Hess, 1998; Draxler and Rolph, 2012; Escudero et al., 2007a; Rodríguez et al., 2001; Querol et al., 2009). A few studies have been conducted to explore Mediterranean and North African dust storm origins and evolution using HYSPLIT as the main tool (Avila et al., 2007; Draxler et al., 2001; Escudero et al., 2005, 2006, 2011). However, most of these studies have shown that considerable uncertainties remain in these models of dust events. Hence, further investigations are required to improve the definition of the model's parameters and to enhance their accuracy.

The Middle East region has been described as a major dust source in several previous studies (Ginoux et al., 2012; Littmann, 1991; Middleton, 1986); however, limited work has focused on the Middle Eastern dust storms evolutions. One of these studies includes the attempt to estimate the soil roughness in the areas including Kuwait, Iraq, Syria, Saudi Arabia, the Emirates and Oman (Draxler et al., 2001). Also, a few studies were conducted to find dust sources in the Middle Eastern region (Ginoux et al., 2012; Prospero et al., 2002). Nonetheless, the dust storm evolution in the Middle East region has not been sufficiently explored, and the contribution of the dust storms to the observed Particulate Matter (PM) levels in the receptor cities has not been investigated.

Iran, like most other countries in the Middle East, is affected by multiple dust storms each year, especially in the western and central regions, including where the highly-populated capital city of Tehran is located (Shahsavani et al., 2011, 2012). Inhabitants in Tehran are generally exposed to high levels of urban background PM due to the large number of anthropogenic sources and the unique geographic characteristics of a city surrounded by a high altitude mountain chain on its boundary, downstream of the prevailing wind (Arhami et al., 2013; Atash, 2007; Halek et al., 2010; Madanipour, 2006; Sabetghadam et al., 2012). The particles from the dust storms are also being added to this high urban background level resulting in significantly elevated PM concentrations and reduced visibilities during the dust intrusion episodes (Vishkaee et al., 2011). Despite the significance of these phenomena, there is not sufficient information available about dominant dust origins and their contribution in particulate levels in Tehran.

In this paper, the dust storm origins and evolution which affect Tehran have been studied and the contribution of each dust origin to the measured PM_{10} levels has been determined. Initially the episodes of regional dust intrusion during the study period of 2009–2010 and the resulting amounts of increase in the particulate concentration during these episodes were determined. A methodology was developed for this purpose by means of statistical analyses of the recorded pollutant levels at the ambient monitoring stations. The occurrence of regional dust events was corroborated by inspecting AI data from the Ozone Monitoring Instrument (OMI) using a threshold index of 0.7. HYSPLIT was used as the main tool to model the dispersion and the route of dust particles. The model parameters including the threshold friction velocities have been adjusted and calibrated. The potential origins of dust storms were determined using back trajectory modeling. Finally, the contributions of different deserts in the region to the measured PM_{10} at Tehran's stations were estimated using the model simulation of dust contributed from each of the source regions. Results of this study can be used to improve decision-making and in determining more effective control strategies to deal with the dust intrusion crisis in the region.

2. Methodology

2.1. Dust episodes and their impact on PM_{10} levels

The hourly pollutant concentrations during 2009–2010 were extracted from the recorded data at 8 urban stations throughout the city of Tehran operated by Air Quality Control Company. Days affected by regional dust events (called "dusty days" from now on) were separated as described subsequently by applying a statistical analyzing procedure to the pollutant concentrations along with using satellite imagery. In several studies (e.g. Escudero et al., 2007b), just a threshold for PM_{10} concentration (e.g. 100 $\mu g/m^3$) was used to separate "dusty days" from other days (called "regular days" from now on). However, in Tehran other phenomena besides regional dust storms, such as inversion and stable weather conditions, could also cause high particulate levels. The difference between pollutant behavior in the days influenced by a regional dust storm and days of stable atmospheric/inversion conditions were used to separate these two events. During the dust storms the particulate matter levels are expected to substantially increase without a substantial increase in gaseous pollutant levels including Carbon Monoxide (CO), which is mainly formed from primary combustion, particularly in vehicle engines. On the other hand, during stable atmospheric/inversion conditions, there is expected to be a substantial increase in both particulate and gaseous pollutants including CO levels. In order to find the dusty days, the periods of substantially high PM_{10} levels (i.e. the daily levels were at least one standard deviation higher than average) were selected. Among the selected time frames, the periods for which daily CO levels were not more than one standard deviation above the average were retained for analysis. The AI maps from OMI for the selected periods were inspected both visually, and quantitatively using an AI threshold value of 0.7 to ensure the occurrence of regional dust events. The AI threshold of 0.7 is in the range of 0.6–1 which was suggested by previous studies to identify the regional dust events (Hsu et al., 1999; Prospero et al., 2002). The outcomes did not vary much by choosing a different threshold value in this range, since generally the AI values were considerably higher than the suggested threshold (up to more than 4.5) for a vast area of the studied region during the regional dust events. The findings were further verified due to the fact that the inversion events are mainly expected to occur during the colder seasons, which also correlated with the results.

The resulting numbers of dusty days were 16 and 15 for the years of 2009 and 2010, respectively. The AI's from OMI were greater than 0.7 during all of these days for a sizeable area in the studied region. The average PM_{10} levels recorded for each year and during dusty and regular days are shown in Fig. 1. Among the determined dusty episodes, four episodes of dust outbreaks caused higher PM_{10} levels (daily PM_{10} exceeded 200 μg/m^3) compared to the other episodes. These episodes, which are July 1–6, 2009, May 17–22, 2010, June 23–30, 2010, and July 14–19, 2010, were used in this study for modeling dust concentrations and determining the contribution of different regions to the particulate concentrations.

The PM_{10} data used in this study were measured at stations in urban areas surrounded by different sources. An urban background station far from local anthropogenic sources was not available. The following simple statistical analysis was performed on the data at these stations to separate the amount of PM_{10} increases during the episodes of major dust outbreaks from the urban background levels. Initial correlation coefficients (R^2) of hourly PM_{10} levels between all combinations of stations during dust events were calculated and one station, which had a significantly lower correlation coefficient (<0.6) than any of the other station combinations, was excluded. This station was excluded since it was expected to be influenced primarily by local sources, even during the episodes of major dust outbreaks.

Because of the weekly cycle in anthropogenic PM_{10} emissions, the contributions of dust storm to PM_{10} levels at stations were determined by subtracting the average of the same time frame (same hours and days) in the last week without dust event at each station. Using the same period in the week helped to avoid the effect of changes in anthropogenic emission patterns during different days of the week. However, some errors are expected for this method due to changes in meteorological conditions and sources during different weeks. In order to minimize the errors, the weeks with substantially different weather conditions such as rain, relative humidity and wind speed were replaced with the next closest week. With a lag of ±1 h, (for movement of dust between the stations in the city) all of the calculated PM_{10} levels from dust events at different stations were correlated with an R^2 value of more than 0.90. This high correlation indicates the accuracy of the calculated PM_{10} levels from the dust storms, using this approach.

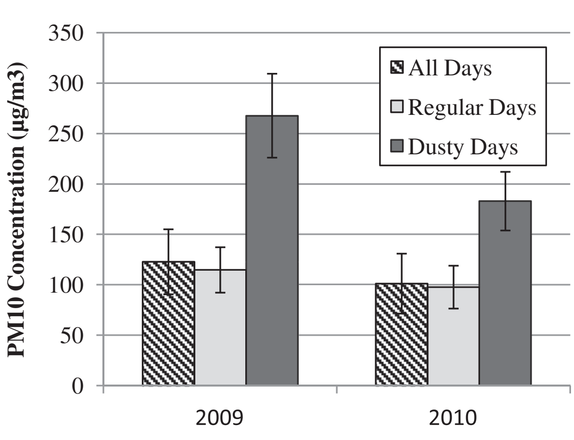

Fig. 1. Average PM_{10} concentration during the dusty and regular days in 2009–2010.

2.2. Dust origins and their contribution to PM_{10} levels

The vast deserts in the Middle East are mainly located on the western and southwestern part of this region, and the prevailing winds also blow from the west and southwest. This means the main dust origins affecting Tehran are expected to be located in these regions. To further verify this fact and to determine the boundaries of the areas containing the origins of the Middle Eastern dust affecting the city of Tehran, HYSPLIT model trajectories and satellite images were used. Daily 5-day backward trajectories were computed with HYSPLIT starting from four different altitudes with respect to a fraction (0.25, 0.5, 0.75, and 1.0) of the boundary layer depth at the starting time of 06:00 UTC each day. More details of running and calibrating the HYSPLIT model is described in Section 2.3.

The dust emission is initiated when the calculated friction velocity exceeds the threshold friction velocity, so it is crucial to determine the threshold velocities in the region as accurately as possible. Two alternative algorithms were examined for threshold velocities, which are called the original dust emission algorithm and the revised dust emission algorithm. In the original algorithm, a fixed threshold velocity is set for the whole region based on the properties of the soil in the region. In the revised algorithm, different threshold velocities are defined for different cells in the region for different months in the year (Draxler et al., 2010). The revised algorithm was chosen for this study because it resulted in a more accurate estimation of the dust outbreaks. In this algorithm, the threshold friction velocities were recommended by Draxler et al. (2010) based on the maps of AOD data from MODIS for each month of the year with 0.25° grid resolutions (http://www.meteozone.com/tutorial/dust/dust_global.zip). The cells for which the calculated AOD frequently exceeds 0.75 are defined as potential dust origins and the velocity corresponding to these AODs are defined as threshold friction velocity (Draxler et al., 2010). These recommended threshold friction velocities which are based on long term climatology data could have changed over the recent years due

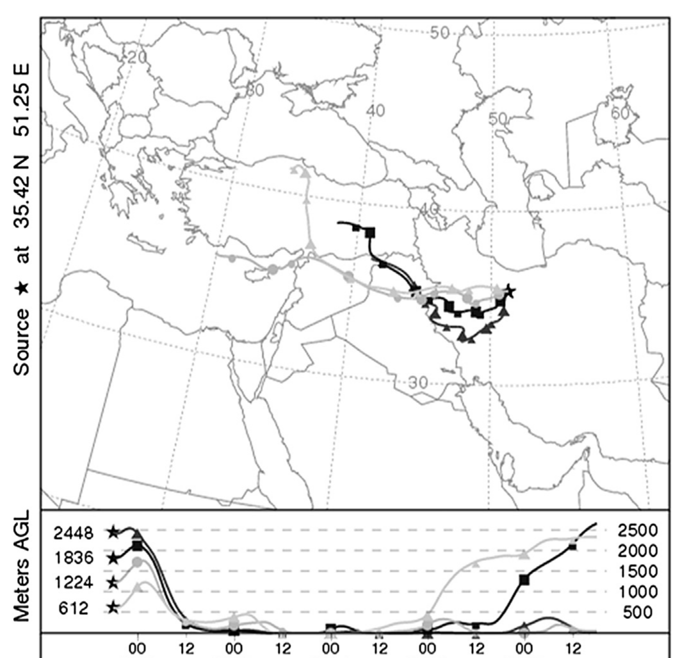

Fig. 2. 5-day backward trajectories initiating from different altitudes of Tehran, including 0.25, 0.5, 0.75 and 1 fractions of mixing height, with starting date of July 06, 2009.

to the changes in climate conditions, vegetation and related soil properties such as moisture content. So, different multiplications of the proposed threshold friction velocities were also examined by applying a multiplication factor (called *P10F* in HYSPLIT software). The multiplication factor leading to the most appropriate results of modeling PM_{10} concentration by HYSPLIT was determined, and the recommended threshold friction velocities were all multiplied by this factor.

The dust outbreak episode in early July 2009 was used to calibrate the model parameters. Other dusty episodes in the time span of 2009–2010 were used to verify the model performance using these parameters. All desert sources throughout the whole studied region were considered simultaneously for calibration. Once the model parameters were adjusted, the contribution of each desert area to the PM_{10} concentration in Tehran was determined. In order to apportion the contribution of each dust origin, the whole region was divided into different rectangular regions based on country borders and the desert areas, which is described later. Using the adjusted and verified model parameters, the model was run individually for each source region using the revised dust emission algorithm for all of the episodes. The regions which resulted in the major PM contributions were also divided into smaller rectangular sub-regions to determine the sources of dust with a finer resolution.

2.3. HYSPLIT inputs and parameters

Meteorological data from Global Data Assimilation System (GDAS), available every three hours at different pressure levels with grid resolutions of 1°, was used for modeling. Since the wind threshold velocities were obtained for grid sizes of 0.25°, this grid size was selected. Also, the grid resolution of 0.25° was deemed the proper size considering a tradeoff between the accuracy of results and the modeling calculation time. The default 3D particle distribution was used for the HYSPLIT dust simulations. Since a hybrid of numerical Eulerian and Lagrangian methods is used in HYSPLIT, an input value for the total number of particles released to simulate particle transport is required. The number of particles required for a simulation period was based upon a set of trial and error tests to improve the accuracy of the results while minimizing the increase in the computational time. Typically each dust event was represented by 5000 particles.

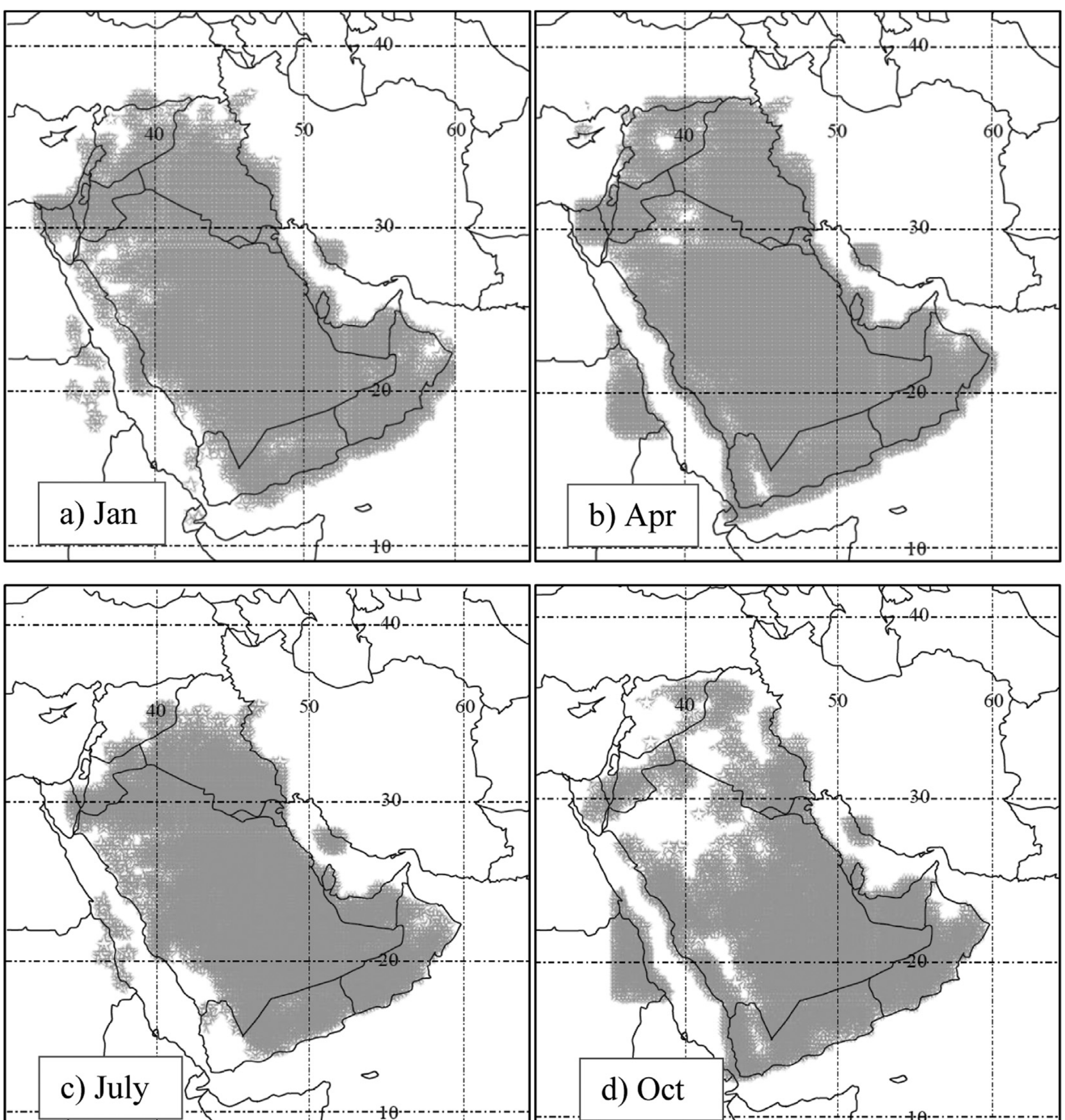

Fig. 3. Potential dust origins during different months of the year including: a) Jan, b) Apr, c) July, and d) October.

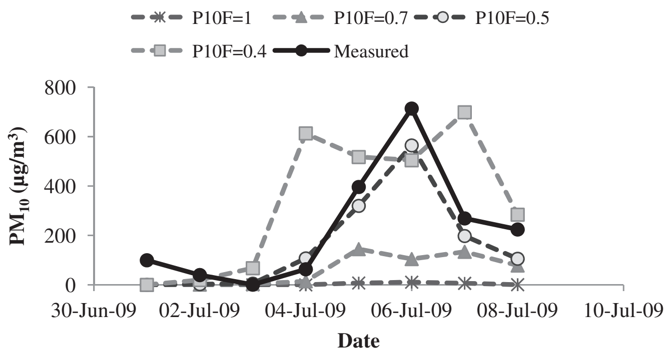

Fig. 4. Effect of reducing the NOAA suggested threshold friction velocities of the source grids by multiplying with different coefficients (P10F) on modeled PM_{10} during the dust episode of July 1st to 8th, 2009

The input height was selected to be 10 m, based on the recommendation of previous studies (e.g. Draxler et al., 2010), and performance of the models. In practice, the input height is assumed to be the elevation at which the particles are initially raised and completely mixed at the dust origin before the dust transportation begins. The average dust concentration is calculated between 0 and the mixing height which was approximately 1000 m above the ground level for most of the studied episodes. This approach may impact the accuracy of simulating the measured particles, particularly in case of considerable vertical dust gradients in this layer at the receptor sites. The same approach was adopted in the previous studies of dust modeling by HYSPLIT such as Escudero et al. (2006); however further investigations are required to analyze the resulting uncertainties. Dry deposition was taken into account and wet deposition was not, since the dust episodes were all during the dry and hot days of the year. In previous studies it was shown that particles originating from arid deserts and migrating in regional scales have the average aerodynamic size of about 3 μm and a density of about 2.5 gr cm^{-3} (Abdulla et al., 1988; Draxler et al., 2001). Using these values along with assuming spherical dust particles, the dry deposition velocities were estimated and added to the simulation processes.

3. Results and discussion

3.1. Main dust sources

Fig. 2 presents the results of 5-day back trajectory calculations, initiating from different altitudes including 0.25, 0.5, 0.75 and 1.0 fractions of boundary layer depth in the receptor city of Tehran, during the dust episode of early July 2009. It shows the path of particles hitting Tehran extends to the western direction during these dust outbreak episodes. The obtained trajectories show the path of air parcel movements and it does not exactly locate the origins of dust particles. Dust particles are entrained into the air, once the air parcels flow passes the surface level. During the dust episodes westerly air parcels traveled toward the east, passed over arid deserts lifting particles from the surface level, and transported them to Tehran. The particles back trajectories path for less than 5 days generally leaves the surface in the nearby countries. Hence, more dust displacement is expected from the nearby countries rather than from the far Saharan, as was also found in previous studies such as Vishkaee et al. (2011). The back trajectories obtained for the other dust episodes considered in this study also lead to a similar conclusion.

To determine the boundaries of the main potential dust sources, the revised dust emission module in HYSPLIT was used to locate the cells of potential dust origin in a meshed network. In this method, the cells of potential dust origin are extracted from the developed maps based on AOD data from MODIS as described by Draxler et al. (2010) (http://www.meteozone.com/tutorial/dust/dust_global.zip). To this end, the areas marked in Fig. 3 as potential dust origins are the cells whose calculated AOD's frequently exceed 0.75 for different months of the year (months of January, April, July, and October are shown as examples in this figure). Hence, the boundaries of the major areas with the potential of contributing to the dust storms of Tehran were determined. These areas include most of the neighboring countries of Iran on the west and the southern part of the Middle East. The origination of dust from these areas during the studied dust outbreaks were also verified by visually inspecting AI maps from OMI. Most parts of these areas were also identified as potential dust sources in the previous studies (Ginoux et al., 2012; Prospero et al., 2002; Walker et al., 2009). However, there are some areas marked as potential sources in Fig. 3, which are not found as dust sources in the previous studies. There are also some areas which are found as dust sources in one of the previous studies while not being identified in the other studies, as they used different methods. Since the marked areas represent the potential dust sources (not literal dust sources) in this figure, they generally cover a larger portion of this region in comparison with the previous studies. An area surrounding these countries was considered, to find the apportionment of different deserts in this area to the measured PM_{10} in Tehran. It should be noted that the plains on the borders of Iran with Afghanistan and Pakistan are also areas with a rather high dust storm frequency (Middleton, 1986); however,

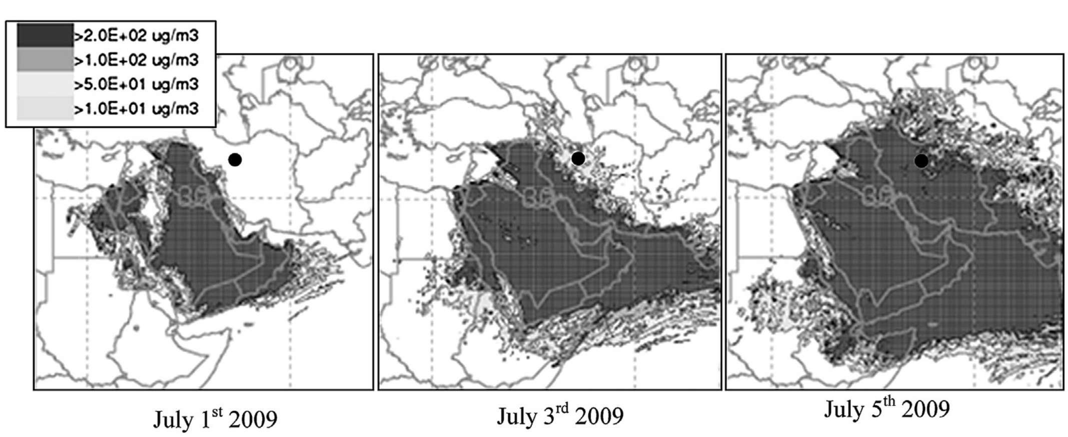

Fig. 5. The evolution of particles due to dust storm of early July 2009, between 0 and 1000 m.

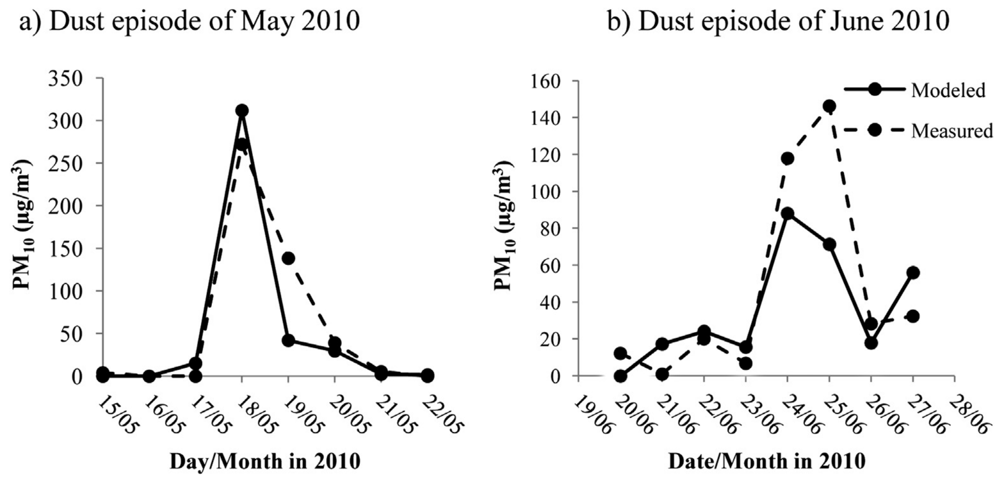

Fig. 6. Modeled versus measured PM_{10} originated from regional dust, during dust episodes of a) May 2010, and b) June 2010.

these areas were not included in our study of sources affecting Tehran due to the wind direction and particles path.

3.2. PM_{10} concentration originating from regional dust

In order to model the dust originated PM_{10} concentrations by HYSPLIT it is crucial to find the most appropriate threshold friction velocities for the different cells of dust origins. As mentioned in the methods section, dust sources over the entire study area were used to calibrate the model parameters, including the threshold velocities, for the dust intrusion episode of early July 2009. Results of incorporating different fractions of the threshold velocities suggested by NOAA into the revised module are shown in Fig. 4. The best results were obtained by reducing (multiplying the coefficient by 0.5) the NOAA suggested threshold velocities in the source regions. In this case the correlation coefficient (R^2) between the measured and modeled daily PM_{10} from dust outbreaks was 0.95. The reason that the adjustment to the original velocities was required could be due to the changes in the region conditions such as precipitation reduction which decreases the moisture content of the soil particularly in the arid areas. Moreover, the suggested threshold velocities which are based on AOD data could have been overestimated for the region and some uncertainty in the distribution of data could have occurred. Different factors could affect the relation between dust origins and AOD data, including cloud effects and physical and chemical properties of emitted dust (Draxler et al., 2010). Although the result of dust originated PM fits rather well with the measured data, further studies to analyze and lessen these uncertainties could result in more accurate models.

The results of modeling concentration distribution at three days during the episode of early July dust outbreaks are shown in Fig. 5. The evolution of dust and variations in PM_{10} concentrations in the studied area during the dust intrusion episodes could also be seen in this figure. It further verifies the development of dust plumes from the deserts on the western and southwestern part of the country and their movement toward eastern areas. The R^2 values between the modeled and measured daily PM_{10} originating from dust intrusion were between 0.60 and 0.86 for the four studied

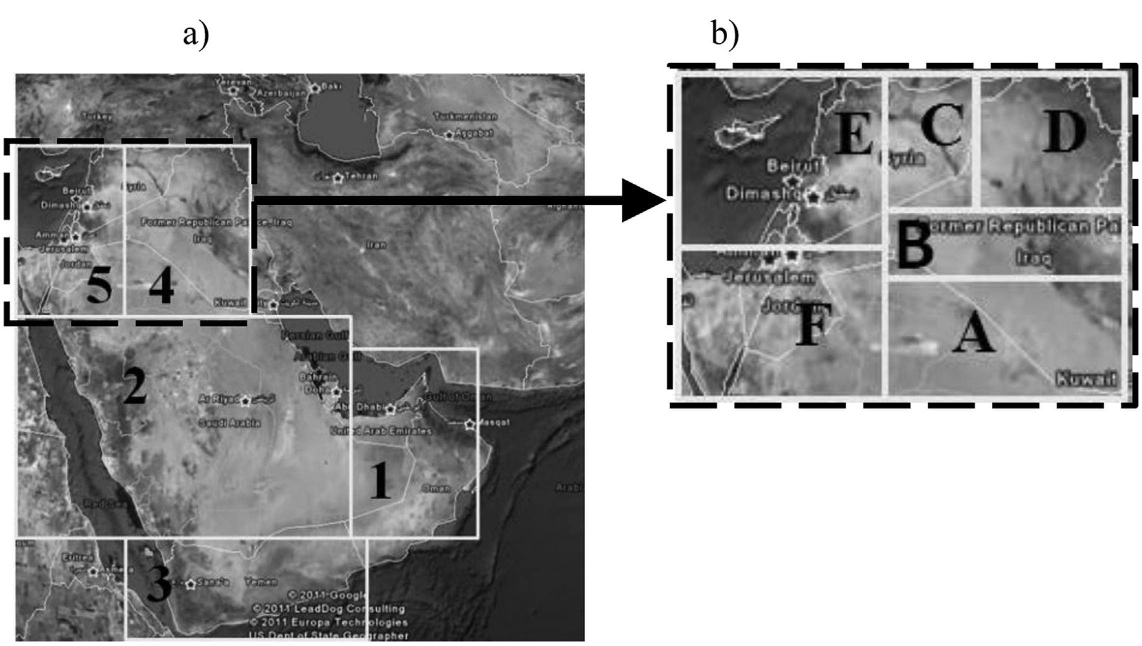

Fig. 7. a) The boundaries of 5 rectangular regions (regions 1–5) which the whole studied area was divided into, and b) the boundaries of 6 sub-regions (sub-regions A to F) which the area of regions 4 and 5 were divided into.

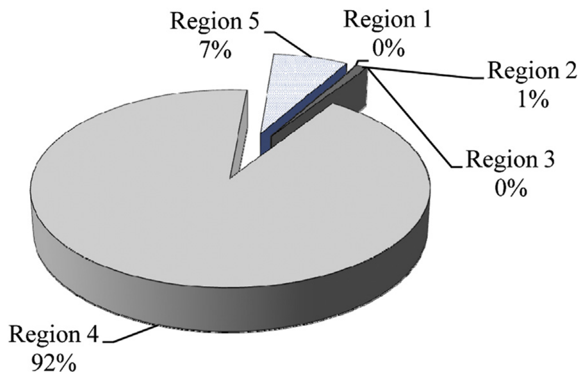

Fig. 8. Average contribution from different regions to the measured PM_{10} in Tehran during the studied period.

episodes. The results of modeled versus measured PM_{10} for two of these episodes in May and June 2010 are presented in Fig. 6. The dust emission and its evolution is affected by many different complex physical and even some chemical phenomena, and inaccuracy due to uncertainties, such as estimating threshold friction velocities for each region, is expected. The model performance varied to some extent during the different dust episodes. For instance, the May 2010 episode performed better with the model than the June 2010 event. Among other mentioned uncertainty causes, accuracy of the estimated threshold velocities could vary for different events. The threshold velocities change for different periods of the year, particularly due to changes in the soil moisture condition. Although different threshold velocities were assigned to the different months of the year, there is a possibility of a more accurate estimation in one episode compared to what was obtained in the other episodes. Although some differences between the measured and modeled PM_{10} levels exist, generally acceptable explanations of the measured particulate data were obtained.

3.3. Source apportionment

In order to apportion the contribution of each desert area, the whole area identified as a potential origin was divided into 5 rectangular regions based on the countries' and Sahara's borders as shown in Fig. 7a. The regions include the following countries: region 1- Oman and United Arab Emirates (~16.5°–25° N and 53°–56.5° E), region 2- Saudi Arabia, Bahrain, Qatar and Kuwait (~17.75°–28.75° N and 35.25°–52.25° E), region 3- Yemen (~12.5°–17.25° N and 42.75°–52.25° E), region 4- Iraq and the eastern part of Syria (~29.25°–36.75° N and 40.75°–43° E), and region 5- the western part of Syria, Jordan, Lebanon and the West Bank (~29.25°–36.75° N and 33.25°–38° E).

The source apportionment results averaged for all of the studied dust episodes are shown in Fig. 8. Although the results of the apportionment to some extent varied for different episodes in 2009 and 2010, the main contribution was shown to be from the deserts in regions 4 and 5. The contribution of regions 4 and 5 together accounted for more than 98% of the measured PM_{10} in Tehran. To further evaluate the contribution of different dust regions, the distribution of the resulting concentration pattern of PM_{10} originating from each of these 5 regions on July 6th, 2010, which is a peak day of dust intrusion, are presented in Fig. 9. These results also show the main dust storm impacting Tehran originated from region 4. These figures also reflect the fact that there are significant dust origins in other regions but the path of the produced dust from these regions does not pass over the targeted city of Tehran in this study. These regions could have major effects on the particulate

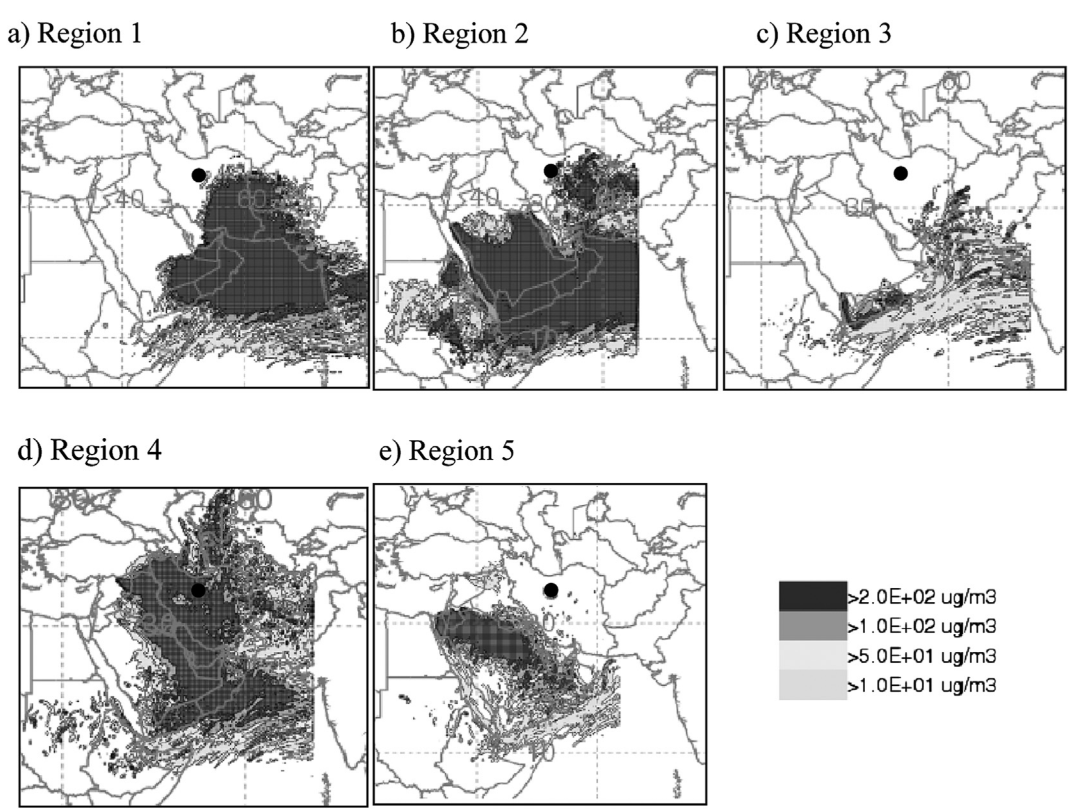

Fig. 9. The desert dust originated PM_{10} concentration gradients during early July episode of dust outbreaks (on July 6th) from a) region 1, b) region 2, c) region 3, d) region 4, and e) region 5.

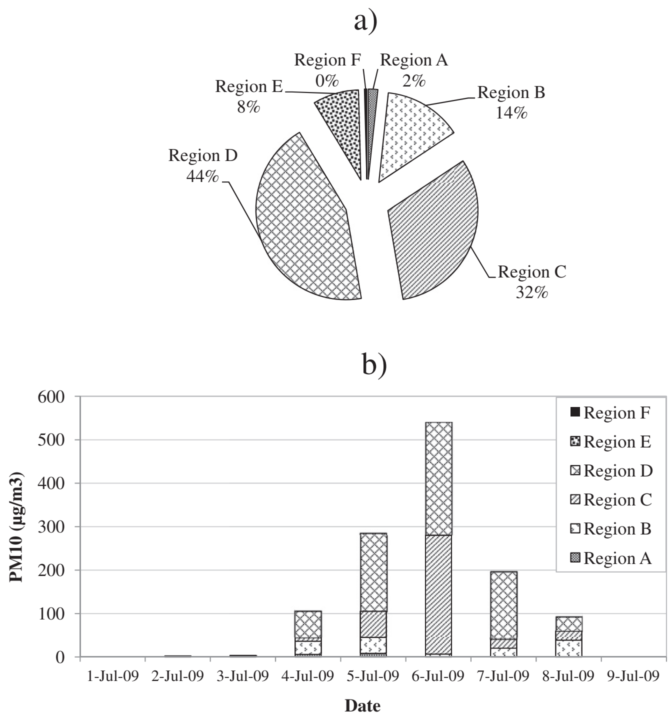

Fig. 10. Contribution of different sub-regions to the PM_{10} concentration in Tehran, a) averaged during all the studied episodes, and b) during early July 2009 dust episode.

levels on the other receptor cities around the country during the dust outbreaks.

Since nearly all of the contribution was found to be from the desert areas in regions 4 and 5, these areas were further divided into 6 smaller rectangular sub-regions, as shown in Fig. 7b, to model the dust origin sources with finer resolution. The results show the main contributions to particulate dust come from the sub-regions C and D (Fig. 10). These sub-regions include the areas in northern Iraq and eastern Syria. These results are also consistent with the path of back trajectory determined for Tehran as presented earlier in Fig. 2. The contributions from sub-regions C and D were on average 44% and 32% of the measured particulate from the dust intrusion during the four studied dust episodes, respectively. The central part of Iraq and western part of Syria, with contributions of 14% and 8%, were the next most significant contributing areas. A major part of the C and D regions contains elevated deserts or even mountains, so the emitted dust in the higher elevations could more effectively reach the receptor city of Tehran.

Abundant Middle Eastern dust origins in these identified source areas were also found in several previous studies (Ginoux et al., 2012; Middleton, 1986; Prospero et al., 2002; Walker et al., 2009). Most of these studies concurred on the presence of major dust sources in Iraq and Syria, which are located in region 4 and 5 as shown in Fig. 7 (Ginoux et al., 2012; Middleton, 1986; Prospero et al., 2002). In these countries, vast dust origins were spotted between the Tigris and Euphrates which generally lie in Region 4 (Ginoux et al., 2012; Middleton, 1986). In addition, the areas on the border of Iraq with Iran to the east of region 4 (particularly sub-region D) has shown to repeatedly generate dust plumes (Ginoux et al., 2012). A high-frequency releasing dust source was located by Walker et al. (2009) to the northeast of the city of Ar Raqqah (Syria) on the border of regions 4 and 5 (mostly sub-regions C and E). Another high-frequency dust generating source which corresponds to several salt flats (sabkhas in Arabic) is located on the border of Syria and Iraq in Region 4 (Ginoux et al., 2012). Other dust sources are located in various areas of Saudi Arabia (Fryberger et al., 1984) and the United Arab Emirates (Alsharhan and El-Sammak, 2004), which were also examined in this study as a major portion of regions 1 and 2. However, these areas did not show significant contribution to the transferred dust in the receptor city of Tehran during the studied major dust intrusion episodes. Moreover, several areas in the center of Afghanistan and Pakistan are also identified to have high dust storm frequencies (Ginoux et al., 2012; Littmann, 1991; Middleton, 1986), which are located further east of Iran. These potential dust source areas in the Eastern countries were not examined, since the back trajectory paths from Tehran was pointed toward west and southwest during the studied dust episodes. Note that our results are not intended to undermine the significance of other areas in generating dust plumes in the region. Our results specifically indicate the most significant contributing sources in the studied receptor city of Tehran. Other dust source origins can significantly impact the other receptor cities in this region.

4. Conclusions

A methodology was adapted and developed by statistically analyzing the recorded pollutant levels at ambient urban stations in Tehran to determine the episodes of regional dust intrusion and the resulting amounts of increase in particulate concentration. The episodes of regional dust outbreaks were further corroborated by inspecting the AI information from the OMI using a threshold index of 0.7. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to simulate the formation and dispersion of the Middle Eastern dust outbreaks. The agreement between the measured and modeled data in this study demonstrates the ability of HYSPLIT in modeling the dust evolution and estimating the particulate concentration in downwind receptor sites. However, it is crucial, in using this modeling tool, to properly define the threshold friction velocity. Decreasing the recommended velocities, by means of using AOD data from MODIS, with applying a multiplication factor led to higher R^2 values, while modeling the studied episodes.

The contributions of different deserts of potential dust origin to the measured PM_{10} at the receptor stations in Tehran were determined. Initially the dust origins were divided based on the countries' and Sahara's borders, and subsequently a finer resolution of source apportionments was performed to identify the regional dust sources. The results showed an area in Iraq and a part of eastern Syria to be responsible for some major dust episodes during the recent years in Tehran. The results of this study could be used in making decisions and setting up more effective control strategies for dealing with the dust crisis in the region.

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