11A.3 MESOSCALE CONTROLS ON PARTICULATE MATTER POLLUTION FOR A MEGA-CITY IN A SEMI-ARID MOUNTAINOUS ENVIRONMENT: TEHRAN, IRAN

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1. INTRODUCTION

Urban air pollution is a major environmental problem, especially for developing countries where emission standards are not stringent or enforced well. Tehran, the capital of the Islamic Republic of Iran has a population of approximately 10 million people and is situated in a semi-enclosed basin just south of the Alborz Mountain chain (with average height of 2000 mASL; Figure 1). It has suffered from poor air quality since the oil boom decade of 70s, but a rapid population growth in the past 15 years has made matters even worse. On some days, the pollution loading of the atmosphere is so high that the impressive Alborz Ranges become invisible from most vantage points. It has been recently stated by Tehran's Clean Air Committee that 10,000 people die every year due to air pollution related cardio-pulmonary disease.

Compared to the size of the air quality problem, there are only a few internationally published scholarly work that focus on particulate levels and its environmental impacts in Tehran. For example, Shafie-Pour and Ardestani (2007) estimated that the total health damage from air pollution in major urban centres of Iran cost US$7 billion; equivalent to 8.4% of Gross Domestic Productivity (GDP); clearly making air quality a serious concern for this country. Shirazi and Harding (2001) provide information on trends for some common pollutants such as Carbon Monoxide (CO) and particulate matter (PM) for the period between 1988 and 1993. They indicate a rapid upward trend for most pollutants except NO_2, where approximately 2 million registered motor vehicles contribute significantly to the poor air quality. The role of the transport sector on ambient levels of particulates is considered by Halek et al (2004) where the age distribution and polluting potential of the car fleet is examined in conjunction with seasonal variation in PM levels.

Due to Tehran's location at the foot of the Alborz mountains, it can be expected that local thermal wind regimes with their associated frontal features as described by Monti et al. (2002) and Brazel et al. (2005) play a major role in controlling and dispersing particulate matter in the city. Furthermore, given the size of Iran's capital, a heat island effect is expected which is likely to modify topographically induced winds as described by Brazel et al. (2005). However, analysis of this, is beyond the scope of this paper.

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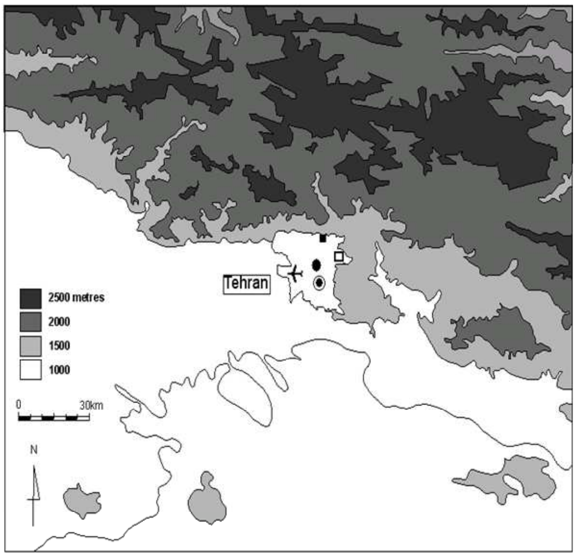

FIGURE 1: Map of Tehran Metropolitan Region. Air Quality Stations: The Foothills Station (Aghdasieh) is shown by the black square, the Central Station (Fatemi) is shown by the black circle, the Southern Station (Bazaar) is shown by the white circle. Meteorological Towers: The Met-West (Tehransar) is shown by the sign for a plane (since it is near the airport), and the Met-East (Resalat) is shown by the white square.

The aim of this paper is to present an in-depth analysis of mesoscale controls – particularly on a diurnal scale – on PM_{10} (particles less than 10 µm in aerodynamic diameter) concentrations for Tehran through examining its spatial and temporal patterns as measured by 5 permanent monitoring stations. Three of the monitoring stations measure pollutants and meteorology and are roughly aligned on a north-south axis, the other two stations, located in the eastern and western parts of the city, only measure meteorological variables.

2. GEOGRAPHICAL SETTING AND LOW-LEVEL CLIMATOLOGY

Tehran (35° 42'N, 51° 25'E) has an area of 700 km^2 and is situated in a semi-enclosed basin south of the Alborz Mountains. Its location for a major city is unusual since it is not near a river or even close to sea. The average annual rainfall is approximately 230 mm, with most precipitation falling in autumn and winter months.
Due to high elevation (approximately 1140 m), aridity, and latitude, the city experiences four seasons. Climate can be extremely hot in the summer (with midday temperatures ranging between 30 to 40°C), and cold in winter when night time temperatures can be below the freezing point (Figure 2). Local precipita-

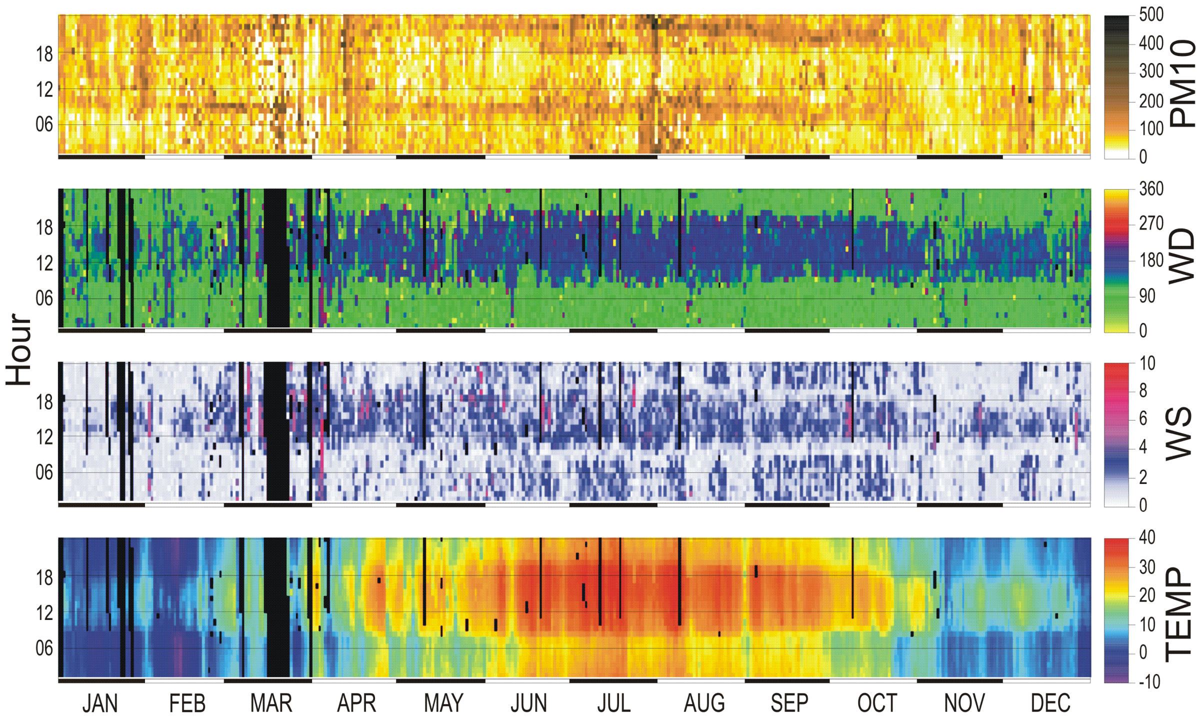

FIGURE 2: Hourly values for PM_{10} (μg/m^3) averaged over 2001 – 2005, Wind Direction (WD; degrees), Wind Speed (WS; m/s), and Temperature (TEMP; °C) measured at Foothills Station for 2005. Each hour is represented by a coloured pixel, where each day is shown as a vertical strip.

tion is absent for 6 months of the year on the low lying areas. Synoptic scale low pressure systems that originate from the Mediterranean propagate over the region in spring and autumn, while in winter the southward extension of the Siberian high pressure system can advect cold temperatures over the Iranian Plateau. A large scale easterly flow dominates the area in the summer, thought to be associated with a circulation pattern named 'the winds of 120 days' caused by a thermal low over Pakistan (Zawar-Reza 2008). Therefore aside from the summer when large scale flow is easterly, a westerly direction is preferred at other times but is thought to be modified by the mountains.

3. METHODOLOGY – AIR QUALITY NETWORK AND DATASETS

Recognising the dire situation with the poor air quality, Tehran Municipality and the Department of Environment (DOE) have in recent years established a monitoring network through a subsidiary called the Air Quality Control Company (AQCC). One of the pollutants routinely measured by most stations is PM_{10}. For this paper we focus our analysis on three stations that roughly bisect the city in a north-south direction (Figure 1). The Aghdasieh Station is the northern most station situated on the steep foothills of the Alborz Mountains (hereafter referred to as the Foothills Station), in the mostly affluent residential sector of the city. The Fatemi station is close to central Tehran, on a relatively flatter slope, but still mostly residential (hereafter referred to as Central). The Bazaar Station – as the name implies – is situated at the commercial heartland of the city and is the southern most station, in a more congested and socio-economically poorer region (hereafter referred to as Southern). Since the climate close to the foothills is milder during summer, historically there has been a north-south socioeconomic gradient in Tehran.

Although the air quality monitoring stations also measure meteorology, because of poor sitting, they do not provide reliable meteorological datasets (i.e. wind speed and direction) useful for analysis of mesoscale wind regime, therefore analysis of regional meteorology uses two different stations. The Tehransar Station situated close to the Airport west of the city (Met-West), and the Resalat Station which is situated in the east (Met-East; Figure 1). Both stations are located in open fields where at least a 100 m fetch in each direction provides data that is not as contaminated by the urban landscape. Pre-2006 hourly data for all stations has been generously provided to us by AQCC and has been quality assured by them.

4. RESULTS AND DISCUSSION

4.1 Air Quality

To illustrate how poor the air quality of Tehran actually is, Table 1 shows the number of days the World Health Organisation (WHO) standard of 50 μg/m^3 for a 24 hour average value was exceeded for PM_{10}. With the best efforts of AQCC, significant gaps in the dataset still exit; therefore the percentage of days with complete hourly data is also shown. The Foothills Station came online more recently and has been

TABLE 1: Annual exceedences of PM_{10} at Foothills and Central Stations, showing number of days WHO guideline was exceeded, number of days with complete data, and percentage of days guideline exceeded.

	1998	1999	2000	2001	2002	2003	2004	2005
Foothills								
Exceedences (days)			77	253	179	225	224	295
complete data (days)			144	271	207	306	323	349
exceeded (%)			53	93	86	74	69	85
Central								
Exceedences (days)	304	300	308	344	281	303	266	238
complete data (days)	333	325	339	365	332	332	339	356
exceeded (%)	91	92	91	94	85	91	78	67

logging data since 2000. It is quite evident that the PM_{10} standard is frequently exceeded at both stations, with percentages well above 70 in most years. The lowest percentage is recorded at the Foothills in 2000 at 53; however this might be due to the high number of missing data. In general, PM_{10} is exceeded more frequently in Central Tehran. Both stations show a record number of exceedences in 2001. It will be interesting to further investigate why 2001 stands out, it might be linked to the severe drought that gripped the region in that period and may be more related to dust than PM emissions from transport.

Figure 2 illustrates hourly measured PM_{10}, wind direction, wind speed, and temperature at the Foothills Station. Clearly two daily peaks exist for PM_{10}, one at approximately 0800 LT (GMT+3.5), and the other at around 1900 LT which can be linked to the traffic volume (Figure 2a). Figure 3 illustrates calculated hourly emission strengths where hourly aggregate traffic volumes were used (Halek et al. 2004) to obtain an hourly breakdown of the estimated daily emission of 11 tonnes of PM_{10} due to transport (Shirazi and Harding 2001). It is important to note that this constructed emission profile does not consider seasonal or weekday/weekend variation in emission strengths and is highly idealised. In addition, seasonal variation in background values is not known for Tehran, but might be a substantial portion relative to anthropogenic sources, especially in drier seasons.

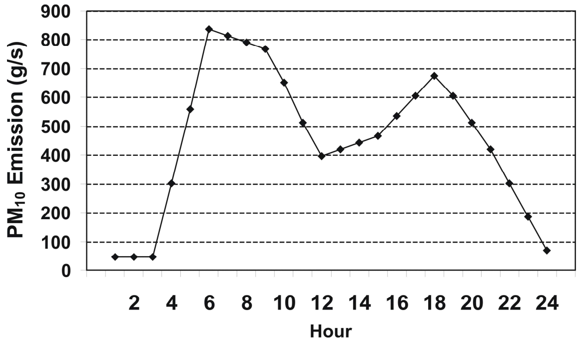

FIGURE 3: Estimated hourly PM_{10} emissions due to transport.

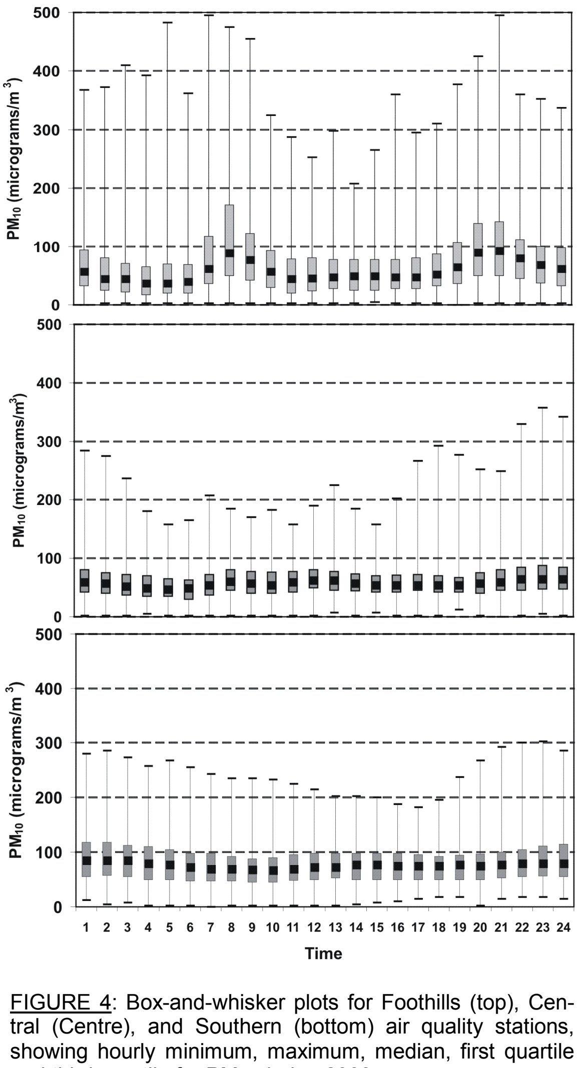

FIGURE 4: Box-and-whisker plots for Foothills (top), Central (Centre), and Southern (bottom) air quality stations, showing hourly minimum, maximum, median, first quartile and third quartile for PM_{10} during 2003.

However, examination of wind direction and speed also reveals that emission peaks coincide with times where the low-level meteorology goes through a transition phase. The morning peak is associated with a shift from an easterly to a southerly; while the evening peak is associated with the reversal of this flow.

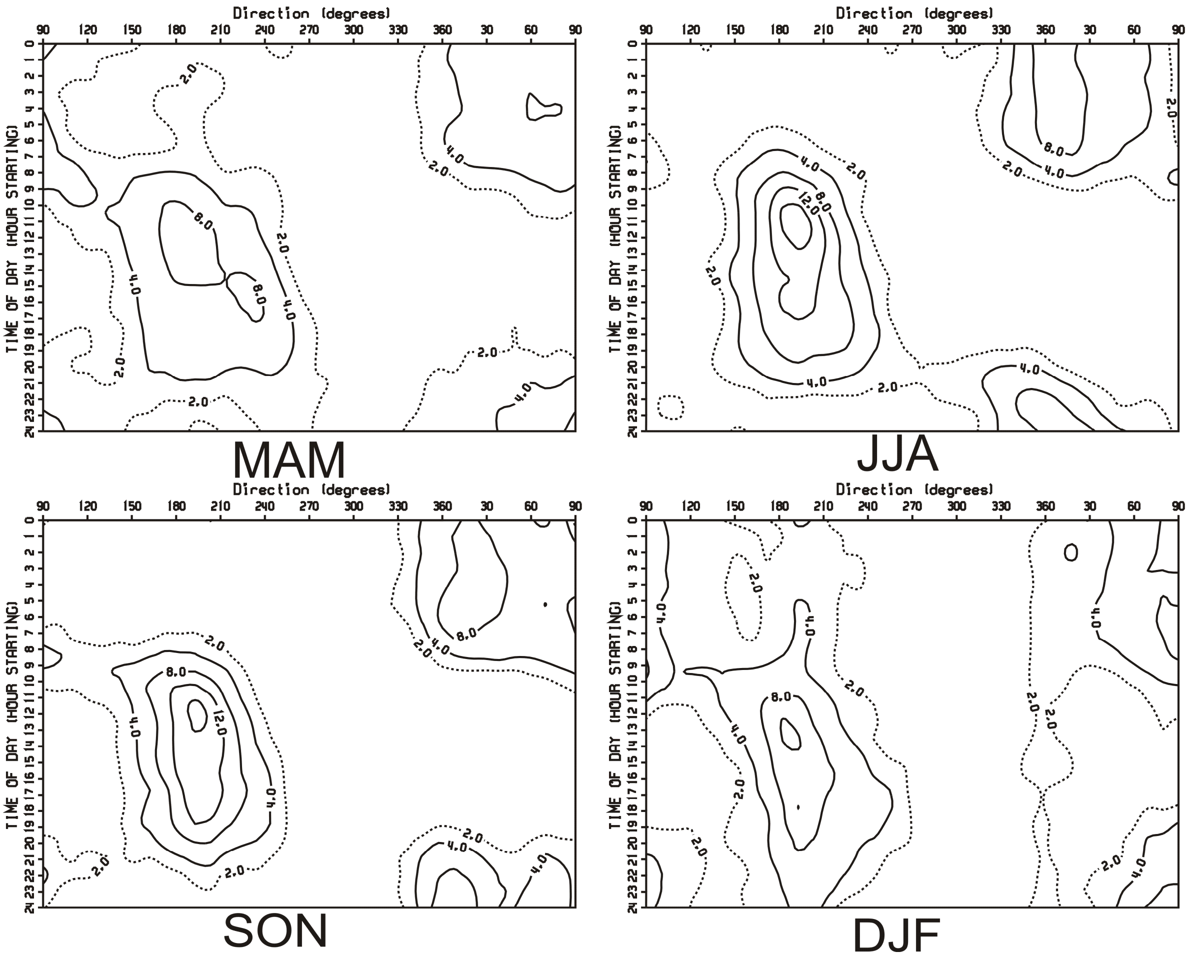

FIGURE 5: Seasonal frequency distribution for wind direction for the Met-East Station. Contour lines start at 2% (dashed line); contours interval is set at 4% for solid lines.

Wind speed is reduced during these transition periods, which is a normal frontal feature (Monti et al. 2002; Brazel et al. 2005). Alongside wind speed, the stability of the atmosphere also controls air pollution levels. Information on mixing depth is not available, but, as will be described in the next section, an attempt has been made to assess atmospheric stability using temperature gradients very close to the ground (derived from temperature measurements at two heights at the meteorological tower of the Met-East station). As will be shown later, the low-level wind regime over Tehran is strongly influenced by the diurnal pattern due to daytime up-slope flow and nocturnal down-slope wind. This diurnal pattern is more prominent in the summer with the more intense solar insolation and higher temperatures, but can happen at other times also. In the spring and winter periods it can be disrupted by passage of low pressure systems as is evident particularly in January and February (Figures 2 b, c, d).

Figure 4 shows hourly statistics for PM_{10} at all stations as a box-and-whisker plot. The morning and evening peaks in PM_{10} are not as prominent for the Central and Southern Stations suggesting that other factors beside emissions from local traffic might be at play. Although the diurnal reversal in wind direction occurs at similar times at these locations also (not shown), it is striking that the traffic volume does not affect the concentration as much. The hourly median is relatively monotonic throughout the day, and higher concentrations are more likely from late evening till morning. This could suggest regional transport of PM, where the nocturnal down-slope flow slowly drains PM_{10} from the more elevated parts of Tehran (as discussed in the next section).

4.2 Mesoscale Features

The mountainous physical geography of Tehran has a dominating control on low level wind climatology. The northern half of Tehran is situated in the semi-enclosed basin, whereas the southern portion intrudes into the low lying flat terrain. Figure 5 shows the hourly wind direction frequency distribution for different seasons (March, April, May (MAM; spring); June, July, August (JJA; summer); September, October, November (SON; autumn); December, January, February (DJF; winter) for 2003 at the Met-East Station. As mentioned above, this station is located on the eastern fringes of Tehran, well inside the basin. It is apparent that wind has a bi-modal behaviour at this site. During the day, a south south-westerly direction is preferred, while at night the direction of flow is mostly from a north north-east quadrant. The daytime up-slope winds are most frequent in the summer and

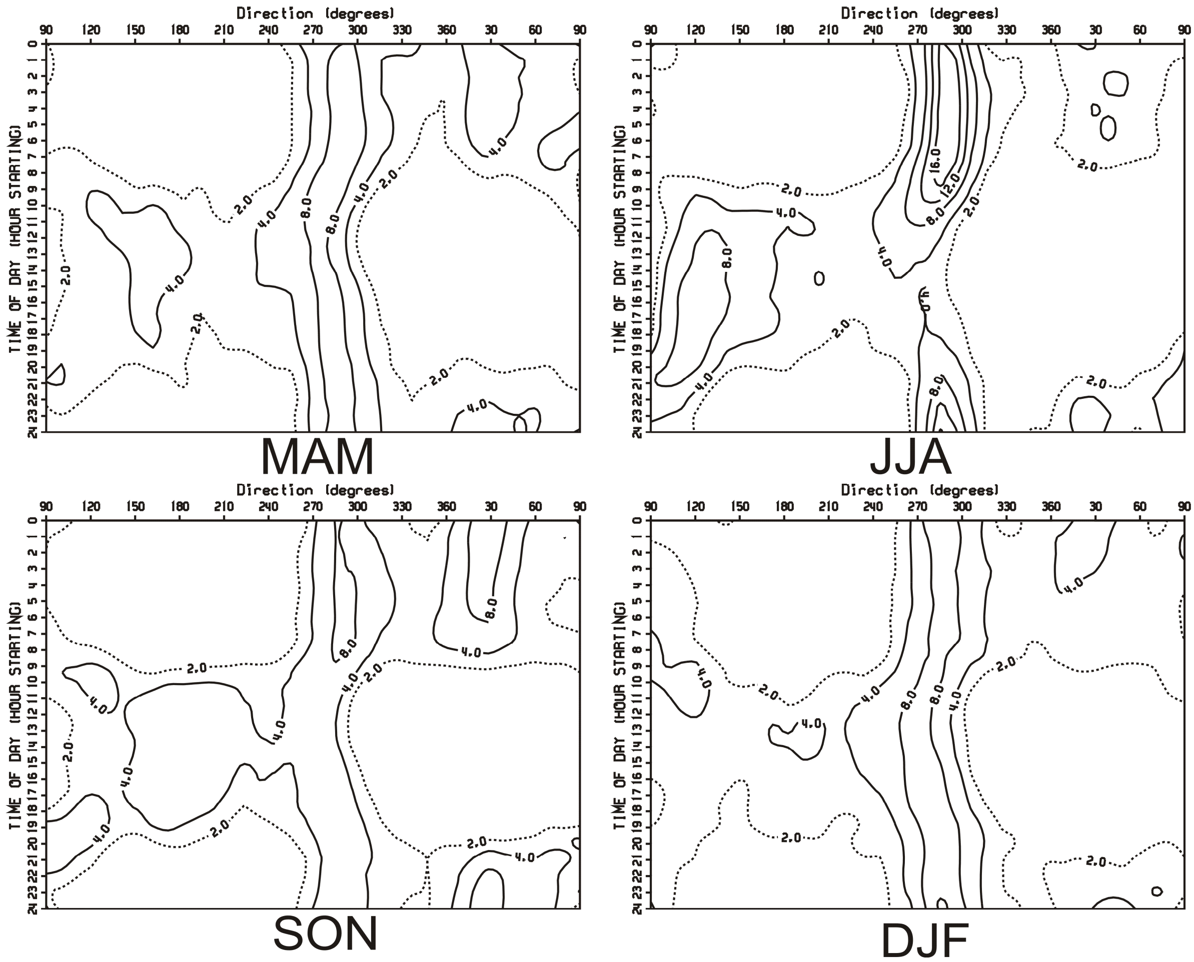

FIGURE 6: Seasonal frequency distribution for wind direction for the Met-West Station. Contour lines start at 2% (dashed line); contours interval is set at 4% for solid lines.

autumn seasons. If we consider the 8% contour to signify a prominent wind flow, in the summer season the up-slope current starts at 0800 LST and ceases at 2000 LST. The nocturnal northerly drainage winds are also most prominent during summer and autumn. The combined effect of less insolation to drive thermally generated flows and the regular passage of the eastward propagating depressions that pass over Tehran make the bi-modal behaviour of wind more diffuse in spring and winter. The upslope flow usually starts after 1000 LT and flows for 5 hours only. Diurnally reversing wind systems due to orography have been observed in many other areas, for a comprehensive review of the subject see Whiteman (2000).

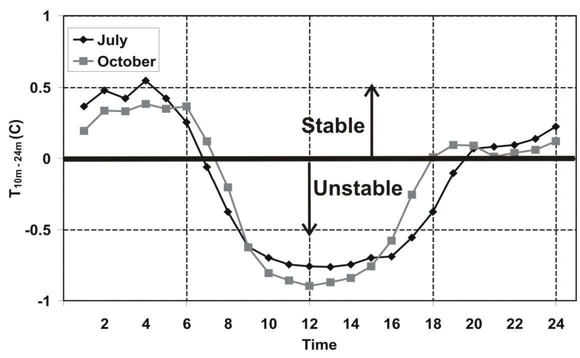

FIGURE 7: Hourly averaged low-level stability for July and October at Met-East station.

The Met-West Station, which is located on the more low-lying area of Tehran, exhibits a different pattern with the influence of thermally generated flow not as clear cut (Figure 6). This might be due to the fact that this location is not as sloped or close to the foothills. The spring and winter periods are mostly dominated by westerly flow parallel to the major axis of the Alborz Mountains. The diurnal pattern is most evident in summer, where upslope winds are from the east south-east quadrant, and the drainage winds blow from the north-west. Therefore in summary, any study of air pollution in Tehran should consider that, during the day, the upslope winds will carry pollutants to the northern parts of the city close to the foothills, whereas at nights, the southern parts will be where the pollutants should concentrate. Other important information regarding seasonal and diurnal fluctuation in boundary-layer depth is not available at the moment, but an attempt has been made to produce a surrogate for atmospheric stability. Vertical temperature profiles obtained from the meteorological tower of the Met-East station provide useful information on atmospheric stability near the ground. In semi-arid environments such as Tehran, the climatic conditions regularly produce fine, cloudless weather conditions with weak winds which can approximately be considered ‘ideal’ as defined by Oke (1987). This is especially true during summer when synoptic influences are reduced and depression disturbances are less frequent. Figure 7 shows hourly statistics of the temperature difference between 10m and 24m for July and October. When compared with wind speed at 24m (Fig. 8), these measurements reflect the typical diurnal cycle of an unstable, turbulent PBL during the day, where downward momentum flux is high and hence wind speeds are increased. Towards the evening, a stable boundary layer with decreased wind speeds develops and keeps on growing throughout the night due to long-wave radiative loss producing a sensible heat flux directed away from the surface (Oke 1987). This is important, as it emphasises the high potential of a poorly ventilated nocturnal PBL that contributes to elevated pollution levels.

Another feature that is likely to play a significant role in the presented low level wind field and its associated controls on particulate pollution in Tehran is a heat island effect. It may be a possible explanation for the rather monotonous diurnal concentrations without clearly observable peaks in the central and southern fringes of Tehran. However, an in-depth analysis of this feature is beyond the scope of this paper and will be investigated in future research. A comprehensive discussion on interactions between heat island effects and topographically induced slope circulations can be found in Brazel et al. (2005).

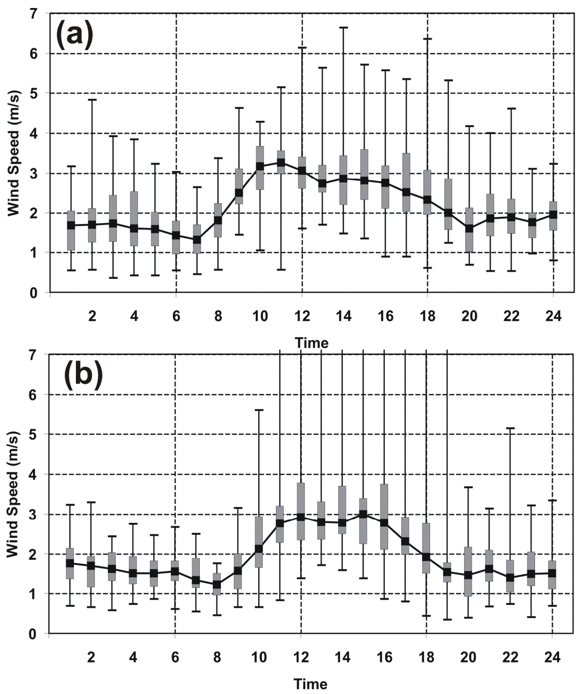

FIGURE 8: Hourly statistics showing minimum, maximum, median, first quartile and third quartile for wind speed at 24 m for (a) July, and (b) October at Met-East station.

5. CONCLUSION

Analysis of data from permanent air quality monitoring stations show that Tehran regularly exceeds the WHO guideline of 50 µg/m^3 for PM_{10}. There are inter-annual differences in percentage of times that exceedences occur, but in general exceedences occur more than 70% of times.

The frequency distribution of wind direction over Tehran is highly bi-modal, where the up-slope southerly flow dominates during the day, and a night-time down -slope flow occurs most nights. Therefore topography has an influential role in pollution dispersal.

Close to the foothills of the Alborz mountains two daily peaks in PM_{10} concentrations are observed which can be linked to traffic volume and associated emissions. Additionally, the low level meteorology goes through a transition phase that coincides with times of peak traffic and contributes to elevated particulate concentrations. Central and southern parts of Tehran do not show these peak concentrations due to local transport of pollutants.

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