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Influences of Traffic Emissions and Meteorological Conditions on Ambient PM_{10} and $PM_{2.5}$ Levels at a Highway Toll Station

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ABSTRACT

The PM_{10} and $PM_{2.5}$ levels at a highway toll station were monitored from October to December 2008. Experimental results show that hourly average PM_{10} and $PM_{2.5}$ levels at the highway toll station were 10.6–208.4 $\mu g/m^3$ and 6.6–187.9 $\mu g/m^3$, respectively. Additionally, the $PM_{2.5}$-to-PM_{10} ratio at the highway toll station was 0.73, indicating that emissions from traffic sources are dominant in $PM_{2.5}$ fraction. At the highway toll station, the time variations of the PM_{10} and $PM_{2.5}$ levels were not strongly correlated with traffic volumes; however, traffic on the highway markedly elevated ambient PM_{10} and $PM_{2.5}$ levels. The PM_{10} and $PM_{2.5}$ levels at the highway toll station are higher than those at monitoring stations in the vicinity to the toll station by factors of 1.3–1.4 and 1.4–1.8 times, respectively. The low wind speeds and low mixing-layer heights lead to relatively high PM_{10} and $PM_{2.5}$ levels. Moreover, high wind speed also could have resulted in high PM_{10} and $PM_{2.5}$ levels due to the re-suspension of particulate matter under well dispersed conditions. Measurements indicate that both traffic emissions and meteorological conditions drive PM_{10} and $PM_{2.5}$ levels at the highway toll station.

Keywords: PM_{10}; $PM_{2.5}$; Traffic emission; Meteorological condition; Highway toll station.

INTRODUCTION

Atmospheric particulate pollution is a major public concern in urban areas because particulate matter has a strong impact on the human health. The particulate matter PM_{10} and, in particular, $PM_{2.5}$ fractions can reach conductive airways and adversely affect the respiratory system (Duhme *et al.*, 1998). Pope *et al.* (2002) demonstrated associations between fine particles and numerous health problems, including asthma, bronchitis, acute and chronic respiratory symptoms.

Road transport is one of the main sources of particulate matter in urban areas (Artíñano *et al.*, 2004; Charron and Harrison, 2005; Abu-Allaban *et al.*, 2007). Particulate emissions from road transport include tail exhaust, products of abrasion processes and re-suspended road dust (Gertler *et al.*, 2000; Charron and Harrison, 2003). Road transport may also be responsible for a large proportion of the formation of particulate matter by gas-to-particle conversion (Mysliwiec and Kleeman, 2002). However, several studies showed that ambient PM levels are not only related with local transport emission characteristics but also driven by local meteorological conditions (Gebhart *et al.*, 2001; Harrison *et al.*, 2004; Wise and Comrie, 2005). Rost *et al.* (2009) suggested that precipitation and mixing-layer height are the meteorological variables that most markedly influence near-surface PM_{10} levels within cities. The absence of precipitation and the low value of the mixing-layer height lead to relatively high PM levels. In addition, Chu *et al.* (2004) showed that PM_{10} levels were high when the mixing-layer height was < 150 m.

Since highways have much more traffic than local access roads, highway transport seems to be critical role as a pollution source of particulate matter in air. However, information on PM levels at highway toll stations is limited. The aim of this study is to examine the influences of traffic emissions and meteorological conditions on ambient PM levels at a highway toll station.

MATERIALS AND METHODS

Monitoring Site and Data Collection

The monitoring site in this study is at a toll station on Highway 1, 10 km west of the Taipei City center (Fig. 1). According to the records from the Bureau of Highway, this toll station has the highest traffic volume among all toll stations in Taiwan.

In this study, an optical particle counter (Grimm Series 1.108 Aerosol Spectrometer, Grimm Technologies, Inc., Douglasville, GA, USA) was placed at the toll plaza to

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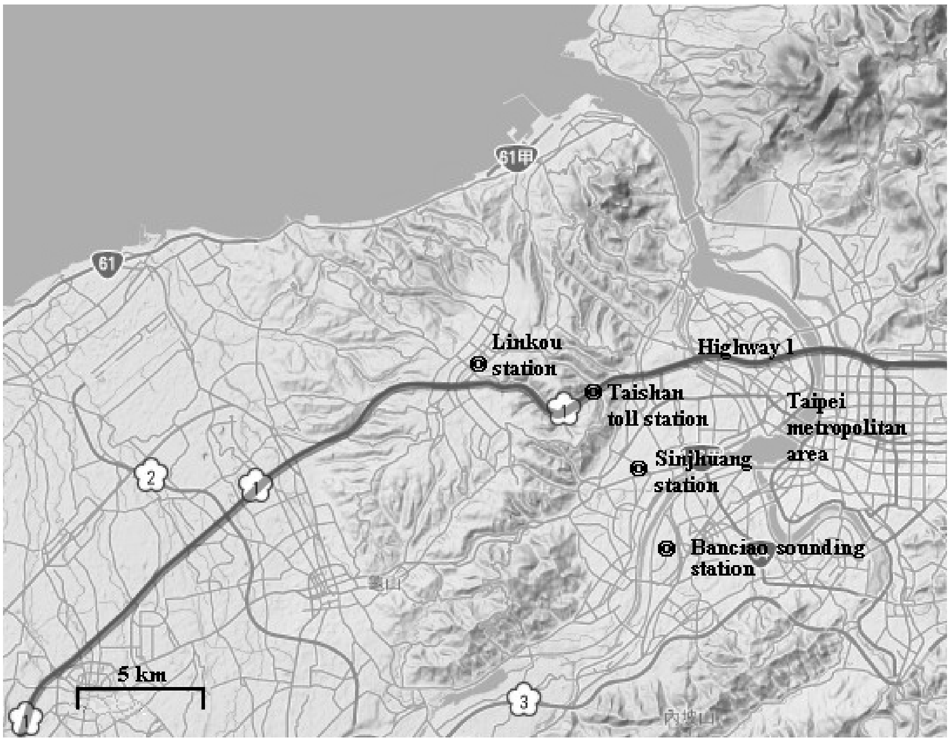

Fig. 1. Locations of highway toll station, sounding station and monitoring stations in North Taiwan.

measure particle mass concentrations and size distributions. The optical particle counter was operated continuously at each on-site monitoring period. On-site measurements were conducted during 3 monitoring sessions from October to December 2008. Local meteorological data were recorded by a Vantage Pro 2^{TM} Weather Station (Davis Instruments, Hayward, CA, USA), which was set up next to the optical particle counter. Moreover, the sounding data used to evaluate the mixing-layer heights were collected by the Banciao sounding station daily at 00:00 and 12:00 coordinated universal time (UTC) and available from Taiwan's Central Weather Bureau. Mixing-layer heights were calculated from the sounding profiles of the potential temperatures, as suggested by Marsik *et al.* (1995). Hourly traffic data at the highway toll station were obtained from the Toll Station Administration. Additionally, hourly PM_{10} and $PM_{2.5}$ levels measured by ambient air-quality monitoring stations at Linkou station and Sinjhuang station in the vicinity of the highway toll station were used to compare with those measured at the highway toll station. These hourly PM_{10} and $PM_{2.5}$ concentrations were measured using automatic Met One BAM 1020 beta gauge monitors (Met One, Inc., Grants Pass, OR, USA) in Taiwan's air-quality monitoring network.

Data Quality Assurance

The Grimm Aerosol Spectrometer measures the particle mass concentrations in an optical size of 0.23–20 μm with 15 differently size ranges. The detail information of this monitor can be found in Cheng (2008) and Cheng and Lin (2010). PM_{10} and $PM_{2.5}$ levels were calculated from particle mass size distribution concentrations as follows:

$$PM = \sum_{i=1}^{15} m(d_{pi}) f(d_{pi}) \tag{1}$$

where PM represents PM_{10} or $PM_{2.5}$; i is channel number of the optical particle counter; d_{pi} is the arithmetic mean diameter of the upper and lower boundaries for channel i; $m(d_{pi})$ is the mass concentration in channel i; and $f(d_{pi})$ is the fraction of PM_{10} or $PM_{2.5}$ at d_{pi} (Hinds, 1999).

However, the responses of light-scattering dust monitors are influenced by the aerosol parameters, such as the refractive index, and the particle shape, density and size. Cheng and Lin (2010) demonstrated that the Grimm Aerosol Spectrometer overestimated PM levels by a factor of about 1.69 times, relative to the actual concentration measured using a Met One E-BAM sampler at an underground station. Therefore, to obtain values closer to true PM values from Grimm Aerosol Spectrometer, all readings from the Grimm Aerosol Spectrometer were calibrated against a Met One E-BAM sampler (Met One, Inc., Grants Pass, OR, USA). Calibration experiments were conducted at the highway toll station under the same environmental conditions. The $PM_{2.5}$ concentrations were measured simultaneously over a 3-day period using a Grimm Aerosol Spectrometer and a Met One E-BAM sampler.

Fig. 2 demonstrates the relationship between 1-h average $PM_{2.5}$ concentrations calculated from mass size distribution data obtained using the Grimm Aerosol Spectrometer with the $PM_{2.5}$ fraction (Eq. 1) and those directly measured by the Met One E-BAM sampler at the highway toll station. Statistical results indicate that the calibration factor for mass concentrations obtained using the Grimm Aerosol Spectrometer is 0.87 ($R^2 = 0.99$). The

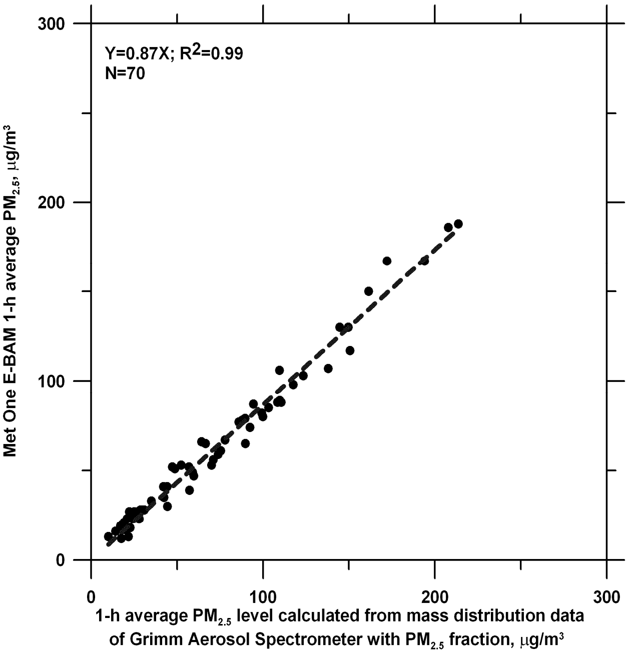

Fig. 2. Comparative scatter plots of the 1-h average $PM_{2.5}$ made using Grimm Aerosol Spectrometer and the Met One E-BAM sampler.

raw data obtained by the Grimm Aerosol Spectrometer in mass size distributions were calibrated using a correction factor of 0.87, to yield "actual" PM levels and mass size distributions at the highway toll station.

RESULTS AND DISCUSSION

PM Levels and Mass Size Distribution at Highway Toll Station

Table 1 presents the hourly average PM_{10} and $PM_{2.5}$ at the highway toll station. Experimental results show that PM_{10} and $PM_{2.5}$ levels at the highway toll station were 10.6–208.4 μg/m^3 (mean = 78.9 μg/m^3) and 6.6–187.9 μg/m^3 (mean = 56.1 μg/m^3), respectively. Lai *et al.* (2004) reported that exposure levels of $PM_{2.5}$ for toll station workers at the same highway toll station on the tickets-only lane and the ticket/cash lane were about 109.6 ± 48.7 μg/m^3 and 115.6 ± 41.8 μg/m^3, respectively. Measurements made by Lai *et al.* (2004) for $PM_{2.5}$ levels on the highway toll station were about 2.0 times those measured in this study. The high exposure levels of $PM_{2.5}$ for toll station workers may be caused by the poor ventilation in tollbooths.

Chen *et al.* (1999) measured PM_{10} and $PM_{2.5}$ levels at nine sites in Taipei, Taichung and Kaohsiung, the three largest cities of Taiwan. The measurement results noted that PM_{10} and $PM_{2.5}$ levels in the Taipei urban area were about 15.4–115.9 μg/m^3 (mean = 42.2 μg/m^3) and 11.6–66.3 μg/m^3 (mean = 23.1 μg/m^3), respectively. The PM_{10} and $PM_{2.5}$ levels at the highway toll station were higher than those obtained by Chen *et al.* (1999) approximately 1.9 and 2.4 times, respectively, indicating that PM_{10} and $PM_{2.5}$ levels at the highway toll station were significantly higher than those measured at the urban area due to traffic emissions. Ho *et al.* (2004) also demonstrated that mean PM_{10} levels at five monitoring stations in the Taipei urban area were about 42.2–49.9 μg/m^3. The mean values of this five examined stations were nearly equal, indicating that the spatial differences in PM_{10} levels in Taipei urban area were rather small. Moreover, Chang *et al.* (2010) demonstrated that PM_{10} and $PM_{2.5}$ levels at the Taipei Aerosol Supersite from 2002 to 2008 were about 2.9–176.5 μg/m^3 (mean = 44.0 μg/m^3) and 1.4–109.0 μg/m^3 (mean = 30.3 μg/m^3), respectively. Those measurement results suggested that the highest levels of PM_{10} and $PM_{2.5}$ appear in spring (mean = 53.3 μg/m^3 for PM_{10}; mean = 34.5 μg/m^3 for $PM_{2.5}$), which is closely related to the influence of long-range transport of Asian dust and manmade pollutants from Mainland China on Taiwan. However, the PM_{10} and $PM_{2.5}$ levels at the highway toll station were significantly higher than those obtained by Ho *et al.* (2004) and Chang *et al.* (2010).

Fig. 3 shows the average particle mass size distribution measured at the highway toll station. This size distribution over the size range of 0.23–20 μm was obtained by averaging data for all monitoring sessions. The upper and lower limits of the concentration error bar represent one standard deviation of particle mass concentrations. Measurements reveal that the lognormal mass size distribution at the highway toll station had two modes (accumulation mode and coarse mode), in which the mode diameters were about 0.35 and 4.5 μm, respectively. In addition, the $PM_{2.5}$-to-PM_{10} ratio at the highway toll station was 0.73 (R^2 = 0.98).

Measurements of the size distribution and $PM_{2.5}$-to-PM_{10} ratio are similar to those made in typical urban roadside environments (Horvath *et al.*, 1996; Osrt and Chestunt, 1998; Gertler *et al.*, 2000; Harrison *et al.*, 2004; Sillanpää *et al.*, 2005; Yin and Harrison, 2008), indicating that emissions from traffic sources are dominant in $PM_{2.5}$ fraction in urban areas.

Effect of Traffic Emission on PM Levels

Fig. 4 plots the time variations of PM_{10}, $PM_{2.5}$ and traffic volume throughout the monitoring period. Measurements show that PM_{10} and $PM_{2.5}$ levels at the toll station varied markedly and irregularly, but regular

Table 1. Hourly PM_{10} and $PM_{2.5}$ levels at the highway toll station

	Average^a (S.D.^{b})	Min–Max^c	Median	Q_1–Q_3^{d}
PM_{10}, μg/m^3	78.9 (39.8)	10.6–208.4	74.1	45.9–109.5
$PM_{2.5}$, μg/m^3	56.1 (34.4)	6.6–187.9	49.5	28.1–79.4

a. Observation number N = 238, b. S.D.: standard deviation, c. Min–Max: minimal value–maximal value, d. Q_1–Q_3: first quartile value–third quartile value.

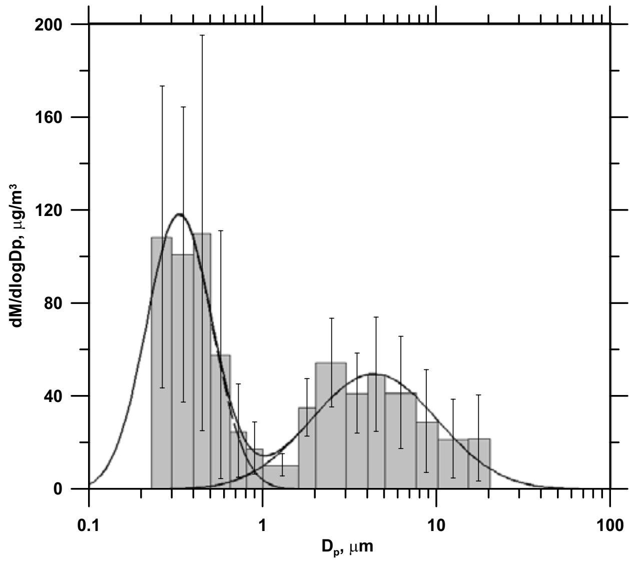

Fig. 3. Average particle mass size distribution measured at highway toll station during monitoring periods.

variation existed in total traffic volumes. Traffic volumes usually peaked markedly during the morning (7:00–8:00) and evening (17:00–18:00) rush hours on weekdays. According to the measurements, the variations of PM_{10} and $PM_{2.5}$ levels were not strongly correlated with traffic volumes at the toll station ($R_{pearson}$ = –0.06 for PM_{10} vs. traffic volume and $R_{pearson}$ = –0.11 for $PM_{2.5}$ vs. traffic volume). Based on statistical results, one can reasonable suppose that traffic volume is not the major dominant factor for the variations of the PM levels. Fig. 5 plots the time variations of PM_{10} and $PM_{2.5}$ levels at the Linkou station, Sinjhuang station and the highway toll station. Measurements show that PM_{10} and $PM_{2.5}$ levels at the highway toll station were significantly higher than those at the monitoring stations ($p < 0.01$ for both PM_{10} and $PM_{2.5}$). Despite the differences between the PM levels at the toll station and the monitoring stations, the variations in PM_{10} and $PM_{2.5}$ level between the highway toll station and these two monitoring stations are similar ($R_{pearson} \geq 0.8$ for both PM_{10} and $PM_{2.5}$ at toll station vs. Linkou station and toll station vs. Sinjhuang station), indicating that the variations of the PM levels at the highway toll station are not only caused by the particulate matter that is emitted from traffic but are also influenced by the local meteorological conditions, such as wind speed and the stability of the atmosphere boundary layer. Nevertheless, the PM_{10} and $PM_{2.5}$ levels at the highway toll station are higher than those at the monitoring stations in the vicinity of the toll station by factors of about 1.3–1.4 and 1.4–1.8 times, respectively, indicating that traffic on the highway markedly elevated ambient PM_{10} levels and, in particular, $PM_{2.5}$ levels. Charron and Harrison (2005) obtained a similar result near a heavily trafficked London highway, noted that hourly average $PM_{2.5}$ levels at Marylebone Road near a busy London highway were significantly higher than those measured at Bloomsbury 2 km from Marylebone Road by a factor of about 1.3 times. Moreover, the $PM_{2.5}$-to-PM_{10} ratios at the Linkou and Sinjhuang stations were 0.56 (R^2 = 0.95) and 0.66 (R^2 = 0.98), respectively. The $PM_{2.5}$-to-PM_{10} ratio at the Sinjhuang station was higher than that at the Linkou station due to the Sinjhuang station is more close to a local main traffic road than the Linkou station. Chen *et al.* (1999) also noted that $PM_{2.5}$-to-PM_{10} ratios at the Taipei urban area were about 0.54–0.59. Compared with $PM_{2.5}$-to-PM_{10} ratios at the Linkou and Sinjhuang stations and those obtained by Chen *et al.* (1999), the $PM_{2.5}$-to-PM_{10} ratio at the toll station was significantly higher than those at monitoring stations and in the urban area, indicating that a considerable amount of fine particles was exhausted directly from vehicles at the toll station.

Effect of Meteorological Conditions on PM Levels

During the sampling periods, the wind speed was 0.3–3.5 m/s (mean = 1.3 m/s); the prevalent wind direction was between north-northeast (NNE) and southwest (SW); the temperature was 13.6–33.5°C (mean = 23.5°C), and the relative humidity was 45–88 % (mean = 70 %).

Table 2 presents the mixing-layer heights at 00:00 UTC and 12:00 UTC during the monitoring periods. The mixing-layer heights varied markedly among the each on-site monitoring session. To analyze the behavior of PM levels

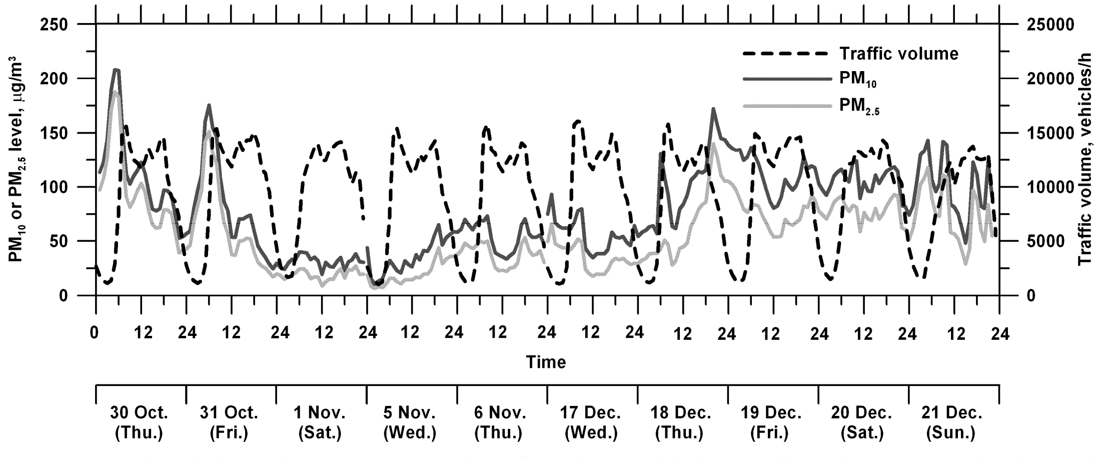

Fig. 4. Temporal variations of PM_{10}, $PM_{2.5}$ and traffic volume at highway toll station over monitoring period.

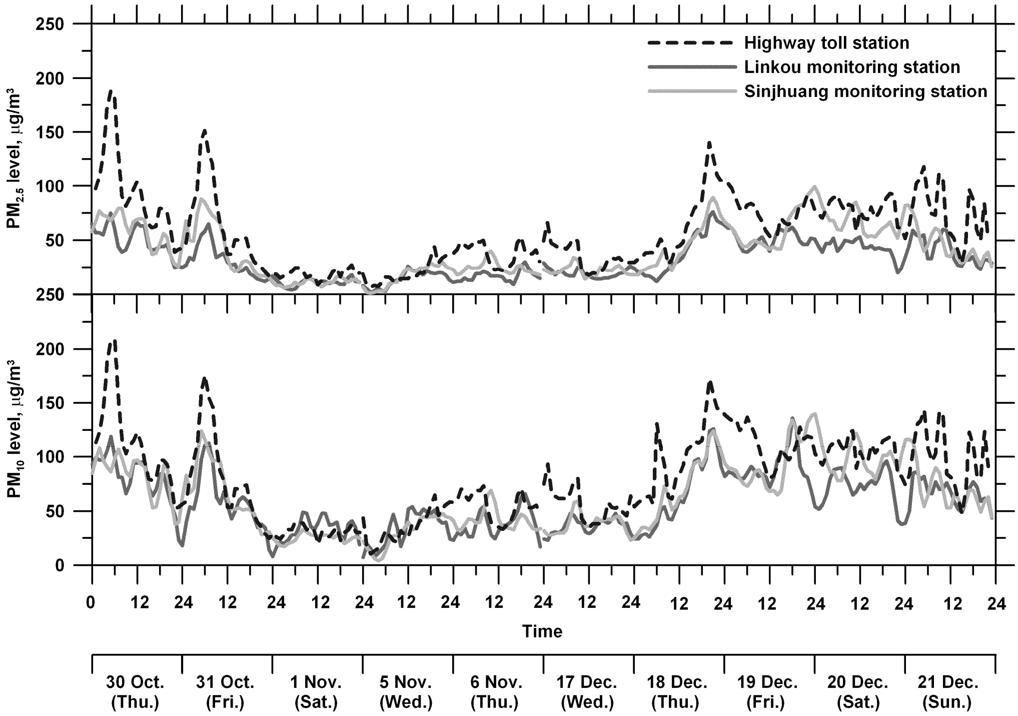

Fig. 5. Temporal variations of $PM_{2.5}$ and PM_{10} at highway toll station, Linkou monitoring station and Sinjhuang monitoring station.

Table 2. Mixing-layer heights at 00 UTC and 12 UTC.

Date	Mixing-layer height, m	
	00 UTC	12 UTC
30 Oct.	364	1553
31 Oct.	827	1319
1 Nov.	1493	822
5 Nov.	824	1548
6 Nov.	651	810
17 Dec.	1913	204
18 Dec.	191	1657
19 Dec.	143	300
20 Dec.	220	676
21 Dec.	148	515

with respect to particular meteorological conditions, Fig. 6(a)–(d) plots the PM_{10}, $PM_{2.5}$, coarse PM ($PM_{2.5-10}$) levels and $PM_{2.5}$-to-PM_{10} ratios at various mixing-layer heights and wind speeds. Here, the hourly variations of the mixing-layer heights were treated as a linear relationship between 00:00 UTC and 12:00 UTC. Measurement results demonstrated that PM_{10}, $PM_{2.5}$, coarse PM levels and $PM_{2.5}$-to-PM_{10} ratios depended on the wind speed and the mixing-layer height. High PM_{10} and $PM_{2.5}$ levels could be observed at low wind speed when mixing-layer height < 500 m. When wind speed increasing, the levels of PM_{10} and $PM_{2.5}$ decreased. This implies that dilution and dispersion due to the wind. However, high PM_{10} and $PM_{2.5}$ levels appeared at high wind speed when mixing-layer height > 1000 m. At this situation, high PM_{10} and $PM_{2.5}$ levels may be caused by greater ventilation for the long-range transport of emissions from distant sources at high wind speed and mixing-layer height conditions. Moreover, the coarse PM levels increased when the wind speed increased. This pattern clearly reveals that at least a part of this particulate matter is from wind driven re-suspension processes, and that is why $PM_{2.5}$-to-PM_{10} ratios decreased when the wind speed increased, in particular, at mixing-layer height < 1000 m. Compared with the effect of the traffic emissions on the time variations of PM levels, the time variations of PM levels are more strongly driven by local meteorological conditions than traffic emissions. Chu *et al.* (2004), Hooyberghs *et al.* (2005), Wise and Comrie (2005), and Rost *et al.* (2009) also found a strong correlation between daily PM levels and mixing-layer heights. Wise and Comrie (2005) suggested that meteorological variability typically accounted for 20–50% of PM variability.

CONCLUSIONS

The measurements indicate that traffic volume, wind speed and mixing-layer height are the variables that most strongly influence near-surface PM levels at the highway toll station. The PM_{10} and $PM_{2.5}$ levels at the highway toll station exceed those at monitoring stations in the vicinity of the toll station by factors about 1.3–1.4 and 1.4–1.8 times, respectively. Measurements reveal a significant increase in PM_{10} and $PM_{2.5}$ levels close to the surface as the wind speed or the mixing-layer height decrease, because of reduced turbulent exchange. Additionally, the raising of road dust caused by high-speed winds counteracts the improved turbulent exchange, such that high coarse PM levels are observed at high wind speed.

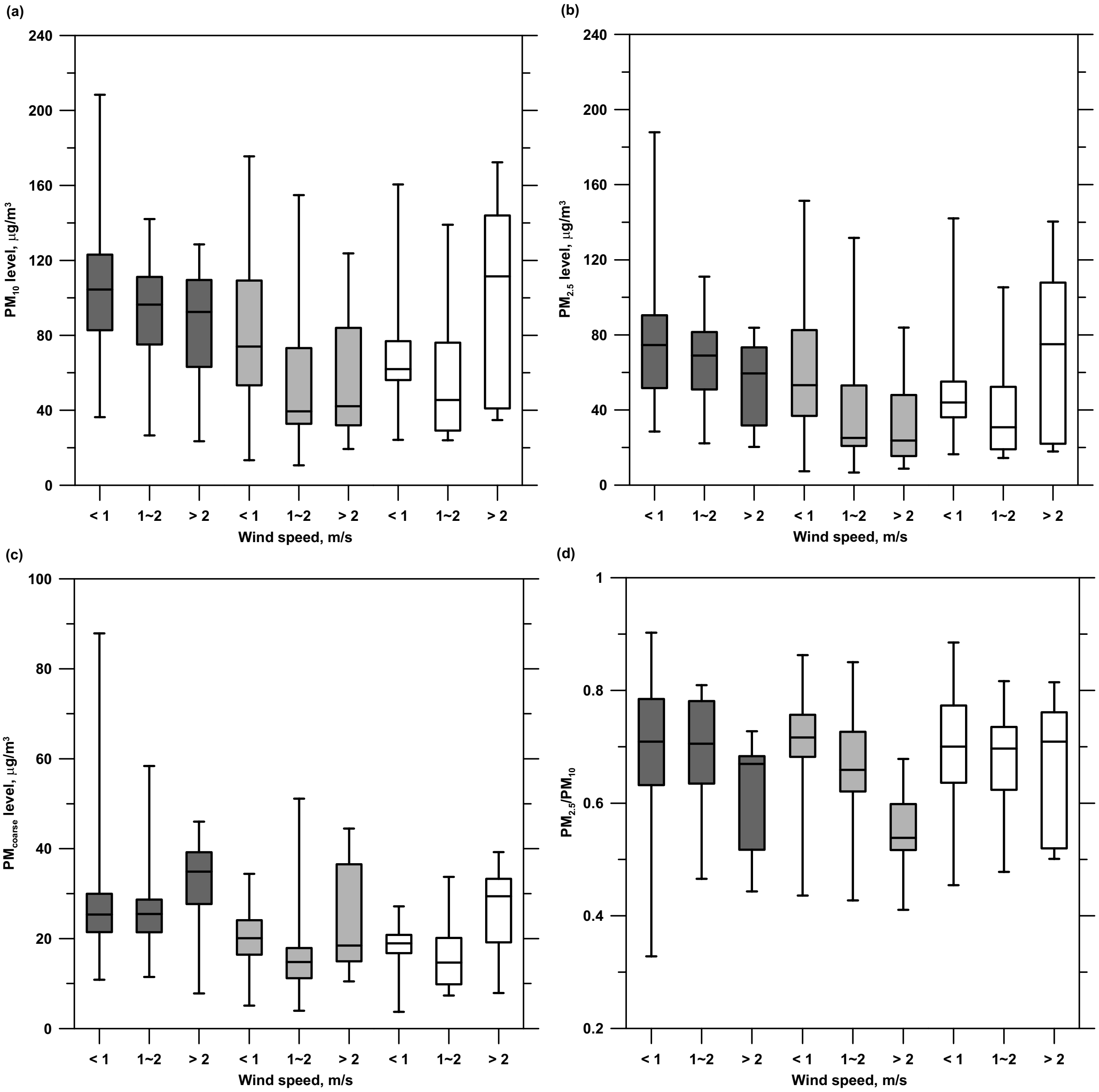

Fig. 6. Box and whisker plot showing the lowest, lower quartile, median, upper quartile, and maximum PM levels at various wind speeds and mixing-layer heights. Here, dark gray box showing PM levels at mixing-layer height < 500 m; light gray box showing PM levels at mixing-layer height between 500–1000 m; white box showing PM levels at mixing-layer height > 1000 m. (a) PM$_{10}$ levels, (b) PM$_{2.5}$ levels, (c) coarse PM levels and (d) PM$_{2.5}$-to-PM$_{10}$ ratios.

REFERENCES

Abu-Allaban, M., Gillies, J.A., Gertler, A.W., Clayton, R. and Proffitt, D. (2007). Motor Vehicle Contribution to Ambient PM$_{10}$ and PM$_{2.5}$ at Selected Urban Areas in the USA. *Environ. Monit. Assess.* 132: 155–163.

Artíñano, B., Salvador, P., Alonso, D.G., Querol, X. and Alastuey, A. (2004). Influence of Traffic on the PM$_{10}$ and PM$_{2.5}$ Urban Aerosol Fractions in Madrid (Spain). *Sci. Total Environ.* 334–335: 111–123.

Chang, S.C., Chou, C.C.K., Chan C.C. and Lee, C.T. (2010). Temporal Characteristics from Continuous Measurements of PM$_{2.5}$ and Speciation at the Taipei Aerosol Supersite from 2002 to 2008. *Atmos. Environ.* 44: 1088–1096.

Charron, A. and Harrison, R.M. (2003). Primary Particle Formation from Vehicle Emissions during Exhaust Dilution in the Roadside Atmosphere. *Atmos. Environ.* 37: 4109–4119.

Charron, A. and Harrison, R.M. (2005). Fine (PM$_{2.5}$) and Coarse (PM$_{2.5–10}$) Particulate Matter on a Heavily Trafficked London Highway: Sources and Processes. *Environ. Sci. Technol.* 39: 7768–7776.

Chen, M.L., Mao, I.F. and Lin, I.K. (1999). The PM$_{10}$ and PM$_{2.5}$ Particles in Urban Areas of Taiwan. *Sci. Total*

Environ. 226: 227–235.

Cheng, Y.H. (2008). Comparison of the TSI Model 8520 and Grimm Series 1.108 Portable Aerosol Instruments Used to Monitor Particulate Matter in an Iron Foundry. *J. Occup. Environ. Hyg.* 5: 157–168.

Cheng, Y.H. and Lin, Y.L. (2010). Measurement of Particle Mass Concentrations and Size Distributions in an Underground Station. *Aerosol Air Qual. Res.* 10: 22–29.

Chu, S.H., Paisie, J.W. and Jang, B.W.L. (2004). PM Data Analysis—A Comparison of Two Urban Areas: Fresno and Atlanta. *Atmos. Environ.* 38: 3155–3164.

Duhme, H., Weiland, S.K. and Keil, U. (1998). Epidemiological Analyses of the Relationship between Environmental Pollution and Asthma. *Toxicol. Lett.* 102–103:307–316.

Gebhart, K.A., Kreidenweis, S.M. and Malm, W.C. (2001). Back-Trajectory Analyses of Fine Particulate Matter Measured at Big Bend National Park in the Historical Database and the 1996 Scoping Study. *Sci. Total Environ.* 276: 185–204.

Gertler, A.W., Gillies, J.A. and Pierson, W.R. (2000). An Assessment of the Mobile Source Contribution to PM_{10} and $PM_{2.5}$ in The United States. *Water Air Soil Poll* 123: 203–214.

Harrison, R.M., Jones, A.M. and Barrowcliffe, R. (2004). Field Study of the Influence of Meteorological Factors and Traffic Volumes upon Suspended Particle Mass at Urban Roadside Sites of Differing Geometries. *Atmos. Environ.* 38: 6361–6369.

Hinds, W.C. (1999). *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles.* 2nd ed., Wiley, New York.

Ho, D.S., Juang, L.C., Liao, Y.Y., Wang, C.C., Lee, C.K, Hsu, T.C., Yang, S.Y. and Yu, C.C. (2004). The Temporal Variations of PM_{10} Concentration in Taipei: a Fractal Approach. *Aerosol Air Qual. Res.* 4: 38–55.

Hooyberghs, J., Mensink, C., Dumont, G., Fierens, F. and Brasseur, O. (2005). A Neural Network Forecast for Daily Average PM_{10} Concentrations in Belgium. *Atmos. Environ.* 39: 3279–3289.

Horvath, H., Kasahara, M. and Pesava, P. (1996). The Size Distribution and Composition of the Atmospheric Aerosol at a Rural and Nearby Urban Location. *J. Aerosol Sci.* 27: 417–435.

Lai, C.H., Liou, S.H., Shih, T.S., Tsai, P.J., Chen, H.L., Chang, Y.C., Buckley, T.J., Strickland, P. and Jaakkola, J.J.K. (2004). Exposure to Fine Particulate Matter ($PM_{2.5}$) among Highway Toll Station Workers in Taipei: Direct and Indirect Exposure Assessment. *Arch. Environ. Health* 59: 138–148.

Marsik, F.J., Fischer, K.W., McDonald, T.D. and Samson, P.J. (1995). Comparison of Methods for Estimating Mixing Height Used during the 1992 Atlanta Field Intensive. *J. Appl. Meteorol.* 34: 1802–1814.

Mysliwiec M.J. and Kleeman M.J. (2002). Source Apportionment of Secondary Airborne Particulate Matter in a Polluted Atmosphere. *Environ. Sci. Technol.* 36: 5376–5384.

Osrt, B. and Chestnut, L. (1998). Assessing the Health Benefits of Reducing Particulate Matter Air Pollution in the United States. *Environ. Res.* 76: 94–106.

Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K. and Thurston, G.D. (2002). Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution. *J. Am. Med. Assoc.* 287: 1132–1141.

Rost, J., Holst, T., Sähn, E., Klingner, M., Anke, K., Ahrens, D. and Mayer, H. (2009). Variability of PM_{10} Concentrations Dependent on Meteorological Conditions. *Int. J. Environ. Pollut.* 36: 3–18.

Sillanpää, M., Saarikoski, S., Hillamo, R., Pennanen, A., Makkonen, U., Spolnik, Z., Grieken, R.V., Koskentalo, T. and Salonen, R.O. (2005). Chemical Composition, Mass Size Distribution and Source Analysis of Long-Range Transported Wildfire Smokes in Helsinki. *Sci. Total Environ.* 350: 119–135.

Wise, E.K. and Comrie, A.C. (2005). Meteorologically Adjusted Urban Air Quality Trends in the Southwestern United States. *Atmos. Environ.* 39: 2969–2980.

Yin, J. and Harrison, R.M. (2008). Pragmatic Mass Closure Study for $PM_{1.0}$, $PM_{2.5}$ and PM_{10} at Roadside, Urban Background and Rural Sites. *Atmos. Environ.* 42: 980–988.

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