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Dry deposition velocity of total suspended particles and meteorological influence in four locations in Guangzhou, China

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Abstract

Dry deposition velocity of total suspended particles (TSP) is an effective parameter that describes the speed of atmospheric particulate matter deposit to the natural surface. It is also an important indicator to the capacity of atmosphere self-depuration. However, the spatial and temporal variations in dry deposition velocity of TSP at different urban landscapes and the relationship between dry deposition velocity and the meteorological parameters are subject to large uncertainties. We concurrently investigated this relationship at four different landscapes of Guangzhou, from October to December of 2009. The result of the average dry deposition velocity is (1.49 ± 0.77), (1.44 ± 0.77), (1.13 ± 0.53) and (1.82 ± 0.82) cm/sec for urban commercial landscape, urban forest landscape, urban residential landscape and country landscape, respectively. This spatial variation can be explained by the difference of both particle size composition of TSP and meteorological parameters of sampling sites. Dry deposition velocity of TSP has a positive correlation with wind speed, and a negative correlation with temperature and relative humidity. Wind speed is the strongest factor that affects the magnitude of TSP dry deposition velocity, and the temperature is another considerable strong meteorological factor. We also find out that the relative humidity brings less impact, especially during the dry season. It is thus implied that the current global warming and urban heat island effect may lead to correlative changes in TSP dry deposition velocity, especially in the urban areas.

Key words: dry deposition velocity; total suspended particles; urban landscapes; meteorological parameters

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Introduction

The general term for the mixture of liquid droplets and the solid particles found in the air is the total suspended particles (TSP). TSP has wide range of sizes that originate from many different sources, including both stationary and mobile. Numerous studies have shown consistent correlation between the exposure to ambient particulates and the adverse health effects including mortality and respiratory disease (El-Fadel and Massoud, 2000; Laden et al., 2000; Liu and Zhang, 2009). Furthermore, particulates and aerosol have adverse effects to the environment such as reduced visibility, changing in the nutrient balance, affecting the earth's temperature and climate which will influence the global plant productivity and the land carbon sink (Aneja et al., 2001; Kaufman et al., 2002; Ramanathan and Carmichael, 2008; Mercado et al., 2009). In Guangzhou, TSP is one of the prominent pollutants in the ambient environment and is worth paying attention to (Zhou et al., 2007).

Atmospheric dry deposition is important for both the disappearance of air pollutants and their transfer between atmosphere and the nature surface. It is the predominant mechanism controlling the concentration of TSP, and may be particularly important in the urban and industrial areas (Shahin et al., 1999). Dry deposition velocity of atmospheric particulate matter is an effective index that describes the deposition speed of atmospheric particulate matter to the nature surface and an important indicator for the capacity of atmospheric self-depuration. It is often used to estimate the dry deposition flux. Usually, the dry deposition velocity is modeled under the controlled laboratory conditions. However, the understanding of how the physical and meteorological conditions as well as surface characteristics influence the dry deposition of particles is far from completion because of the complex interaction between those factors and deposition, there is no consistency on the dry deposition velocity obtained from the models due to its large variance (Caffrey et al., 1998; Odabasi et al., 1999; Odabasi and Bagiroz, 2002; Yang et al., 2005). Since the complicated composition is difficult to be described using traditional modeling, the knowledge about the dry deposition velocity of TSP is especially inadequate compared with others pollutants (Lin et al., 2010; Matsuda et al., 2010; Yasunari et al., 2010).

The micrometeorological methods such as eddy correlation, eddy accumulation and gradients which are widely used in particulate matter dry deposition research in the past decades can provide estimation on the submicron

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particle deposition with certain meteorological conditions, but not reliable if applied to larger particles influenced by sedimentation (Davidson et al., 1985). The method of surrogate surface is one approach that can provide a direct measurement on the minimum dry deposition flux and thereby is widely used to estimate the dry deposition velocity (Holsen et al., 1993; Franz et al., 1998; Shahin et al., 1999; Odabasi et al., 2002; Fang et al., 2003, 2006, 2010). It allows a better control over the exposure time, sampling extraction and other factors than that can be provided by measuring the natural vegetation, and enables the direct comparison between the measured and modeled data (Holsen and Noll, 1992; Paode et al., 1998; Kim et al., 2000). As a result, surrogate surface methods were extensively used to estimate the deposited materials include TSP (Holsen et al., 1993; Yang et al., 2005; Fang et al., 2006; Wu et al., 2006).

Spatial and temporal variability in dry deposition velocity strongly depends on the meteorological parameters such as wind speed, temperature, relative humidity; as well as the micro-meteorological parameters like the friction velocity, eddy diffusivity and atmospheric stability. It is also affected by the morphology characteristics from both pollutants (particle size, shape) and depositing surface (type of surface, roughness) (Caffrey et al., 1998; Franz et al., 1998; Vong et al., 2010). Studies on the dry deposition velocity of TSP in various types of landscapes and its correlation with meteorological parameters are essential. These studies help to understand the process of atmospheric particulate dry deposition and ultimately provide suggestions to the city planning especially at urban areas.

The objective of this study is to determine the variability of dry deposition velocity of TSP at different landscapes of Guangzhou, China. We also attempt to study the impact from some meteorological factors by investigating the correlations between the dry deposition velocity of TSP and the wind speed, temperature and relative humidity in the dry season of the year, when severe air pollution is most likely to occur.

1 Materials and methods

1.1 Sampling program

Guangzhou (latitude 22°26′N–22°26′N and longitude 112°57′E–114°13′E), is located to the north of the Pearl River Delta. The city is the capital of the Guangdong Province, China and has an area of about 7434 km^2 and a population of 10 million (Guangzhou Statistical Bureau, 2009). It has a subtropical oceanic monsoon climate in which the year can be divided into two distinct seasons. The wet season lasts from around April to October with hot, humid and rainy weather while the dry season lasts from late October to March with generally cool and dry weather.

Four sampling sites, Tianhe, Baiyunshan Forest Park (BFP), Higher Education Mega Center (HEMC) and Conghua, were selected to characterize the ambient particulates at different landscapes in Guangzhou (Fig. 1). The Tianhe Site, the BFP Site and the HEMC Site were chosen as the representatives of urban commercial landscape, urban forest landscape and urban residential landscape, respectively. The Conghua site was chosen to represent country landscape as a contrast to the urban landscapes and the background concentration of the major urban area (Hagler et al., 2006). These four sampling sites were selected because of their different local climate. Ye et al. (2007) found that the temperature, humidity and wind speed have exhibited a significant difference in these four types of landscapes. The sampling apparatus was placed on the roof of a building with no higher buildings around. The height of the buildings is much higher than the forest canopy and the difference varies from 15 to 20 m. The dry deposition flux of TSP was collected by dry deposition plates which is designed based on the surface method. Mass concentration of TSP was collected by the TSP sampler. Both the flux and the concentration of TSP at the four sites were collected simultaneously. The 24 hr consecutive sampling and meteorological observations were performed concurrently from October to December of 2009 and totally 148 samplers in 37 days were obtained. All samples were collected during the day when there was no precipitation.

1.2 Sampling apparatus

The TSP sampler is designed to collect the total suspended airborne particles with high-flow rate of (1.05% ± 3%) m^3/min (KC-1000, Laoshan Institute for Electronic Equipment, China). TSP from 1 m above the roof surface was collected on the glass fiber filters (200 mm × 250 mm, Laoshan Institute for Electronic Equipment, China). The filters were baked at 200°C for 2 hr to eliminate the volatile species. They were then conditioned for 24 hr in a clean room at (25 ± 1)°C and (50 ± 3)% humidity. After the conditioning, the plates were weighed. During transport and storage, the filters were folded with the dusty surface inwards and placed in a sealed plastic bag. The field blank for the background concentration of TSP was routinely detected by using operational blank (unexposed filters) which was processed simultaneously with field sample. In the study, the background contamination was insignificant and can be ignored.

The dry deposition plate was made of Polyvinyl Chloride (PVC). It was 200 mm long, 150 mm wide and 5 mm

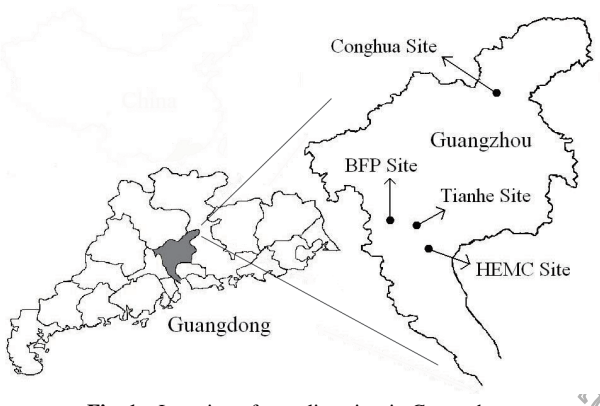

Fig. 1 Location of sampling sites in Guangzhou.

thick with a sharp leading edge (< 15° angle) pointing to the wind by a wind vane. A bearing structure was used to connect the plate and the wind vane, allowing the plate to swing freely into the wind. The plate was fitted with a stainless steel stand, keeping it at a height of 1.6 m. Three duplicate dry deposition plate samplers were placed side by side to collect samples during the sampling period. The top of each plate was covered with Mylar strips (100 mm × 90 mm) coated with thin Apezion L grease to collect the impacted particles and minimize the particle bounce. The strips were placed in clean room for 24 hr at (25 ± 1)°C temperature and (50 ± 3)% humidity, and weighed before and after the exposure. During transport and storage, every strip was placed in a sealed clean box. The deposition surface in this study was designed based on the surrogate surface measurement method to provide minimum airflow disruption, and the use of a smooth, horizontal, surrogate surface enabled a lower bound estimation of the dry deposition flux onto a horizontal surface (Holsen et al., 1993). This technique has been widely and successfully used to directly assess the deposited material in many previous studies (Kim et al., 2000; Fang et al., 2006, 2010).

1.3 Meteorological analysis

The ambient temperature and relative humidity at all sampling sites were measured using HOBO RH/Temperature sensors. The sensors were secured at a height of 2 m above the rooftop. To prevent the interference from solar radiation, every sensor was protected in a white painted wooden box with some ventilation holes on both sides. The wind speed and direction were measured at 1.5 m height above the roof using a FYF-1 which is a portable auto-recording wind detecting instrument (Shanghai Fengyun Meteorological Instrument Management Factory, China). Hourly data of temperature and relative humidity, as well as the 3-hr data point on wind speed and direction was measured and recorded.

1.4 Calculation and analysis

The dry deposition velocity of TSP was calculated by dividing the measured dry deposition flux within the surrogate surfaces with its ambient concentration. It can be expressed as Eq. (1) (Fang et al., 2006):

$$V_d = F_d / C \quad (1)$$

where, V_d (cm/sec) is the dry deposition velocity of TSP, F_d (μg/(m^2·day)) is the dry deposition flux of TSP and C (μg/m^3) is the air concentration of TSP. Multiple Linear Regression Analysis and Correlation Analysis were used to find the relationship between the variables by obtaining the prediction equations for certain chosen models. A SPSS software package was used to perform all the statistical analysis.

2 Results and discussion

2.1 Dry deposition velocity of TSP at four sampling sites

The total 148 dry deposition velocity samples of TSP were obtained from the following four sampling sites: Tianhe, BFP, HEMC and Conghua over 37 days, from October to December of 2009. Spatial and temporal changes of the data are shown in Fig. 2. The daily average dry deposition velocity shows a similar trend of changing at the four sites and in particularly at those three urban sites. During the sampling period, the average temperature, relative humidity, and wind speed was 20.2°C, 58% and 1.0 m/sec, respectively. Meteorological parameters and mean concentration of TSP at the four sampling sites are shown in Table 1.

Comparison on the maximum, minimum and mean values of dry deposition velocity of TSP is shown in Fig. 3. The mean values of dry deposition velocity from Tianhe, BFP, HEMC and Conghua are (1.49 ± 0.77) cm/sec, (1.44 ± 0.77) cm/sec, (1.13 ± 0.53) cm/sec and (1.82 ± 0.82) cm/sec, respectively. The highest dry deposition velocity values were 3.87 cm/sec in Tianhe, 4.25 cm/sec in BFP, 2.39 cm/sec in HEMC and 3.73 cm/sec in Conghua. Significant differences in the mean dry deposition velocity are found between Conghua and BFP (Conghua and HEMC, Tianhe and HEMC) (Fig. 3). The values from the three urban landscapes were generally lower than that in the country landscape.

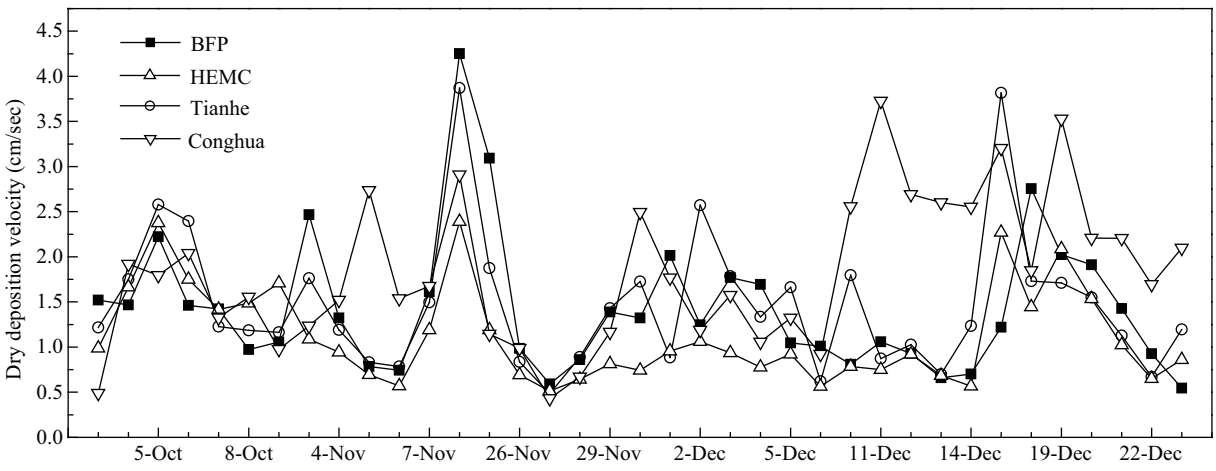

Fig. 2 Variations in dry deposition velocity of total suspended particles (TSP) at the four sampling sites.

Table 1 Meteorological parameters and mean concentration of TSP at the four sampling sites*

Sampling site	TSP concentration ($\mu g/m^3$)	Wind direction frequency (%)	Wind speed (m/sec)	Temperature (°C)	Relative humidity (%)
Conghua	55.9 ± 19.4	25-NE, 18-N, 18-SW, 17-W, 10-NW, 6-E, 4-S, 2-SE	1.2 ± 0.4 a	18.5 ± 5.6 b	62 ± 13 a
Tianhe	195.7 ± 91.6	50-SW, 42-SE, 6-NW, 2-NE	0.8 ± 0.3 b	21.7 ± 5.7 a	54 ± 14 b
BFP	168.9 ± 75.6	45-N, 15-NE, 12-S, 8-NW, 7-SW, 5-SE, 4-W, 4-E	1.0 ± 0.6 a	19.3 ± 5.4 ab	60 ± 13 a
HEMC	201.7 ± 101.1	50-NE, 38-NW, 7-N, 3-SW, 2-W	1.1 ± 0.5 a	21.1 ± 5.4 a	56 ± 36 ab

* Mean ± SD, different letters in the same column indicate the significant differences at $P < 0.05$ as determined by LSD test.

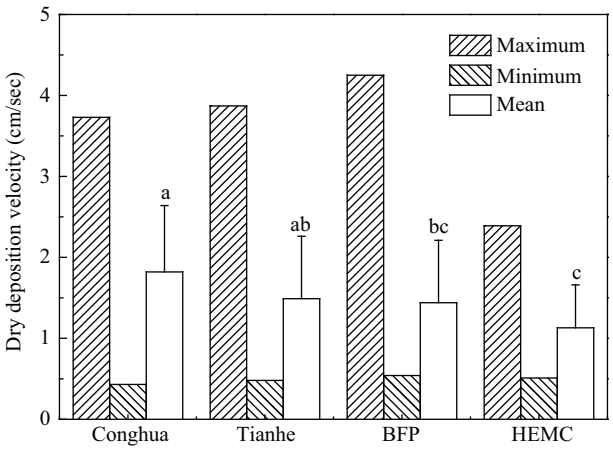

Fig. 3 Dry deposition velocity of TSP at the four sampling sites. Similar letters indicate non-significant differences while different letters indicate significant differences between landscapes.

The possible explanation for the difference in dry deposition velocity in four landscapes needs the information involving the particle size, friction velocity, atmospheric stability, wind speed, temperature and relative humidity of the landscapes. Unfortunately, there is not enough data on the particle size distribution of TSP and the micro-meteorological parameters of four landscapes available in this discussion. However, in order to provide insightful investigation into the influences from source area locations as well as particle size on dry deposition velocity of TSP, daily surface wind patterns and TSP concentration are analyzed together to roughly estimate the particle size variation at the four sites. It should be noted that surface wind measurements at one site do not necessarily represent the large-scale flow patterns, as local topography can affect the measurements. But, the wind measurements at four sites within a region can roughly represent regional rather than local winds.

As shown in Table 1, during the sampling period, northerly flow was prevalent since the frequency of N, NW and NE wind directions in Conghua, BFP and HEMC sites were the highest. However, Tianhe site showed a significant southerly flow, which indicates a strong mixed flow surrounding Tianhe compared with the other sites. Being the new commercial center of city, Tianhe has the densest high-rise in Guangzhou. A large numbers of buildings and streets tend to form canyon wind tunnel and weak wind shifting in direction throughout the day.

A spatial gradient of TSP concentration is seen among the downwind sites in Guangzhou Region, with the highest concentration at HEMC and the lowest one at Conghua as shown in Table 1. As the upwind site of urban area, the data from Conghua site can represent the background particle concentration of Guangzhou Region. Relative low TSP concentration in Conghua suggests that the contribution from local terrestrial source is dominate, which furthermore indicates that the coarse particulate concentration of TSP is the major species (Hagler et al., 2006). In general, larger particles have more weight leading to higher deposition velocity than fine particles. Conghua therefore tends to have the high dry deposition velocity of TSP. As the last downwind site in urban area, HEMC site is influenced by northerly winds transporting southward that causes the observed highest TSP concentration. It is attributed to the accumulation of fine particles and precursors transported from Tianhe and BFP. It also implies that the fine particulate concentration of TSP is the major species at HEMC, which causes low dry deposition velocity of TSP. As the center area of Guangzhou, Tianhe and BFP have the relatively highest TSP concentration level. This is not surprising given the size of the area and the intense traffic congestion. The accumulation of particulate matter is due to the transport of precursors from the north; the locally emitted organic species; the construction dust from both primary and secondary. The higher coarse particle concentration of TSP in these two sites therefore causes the larger dry deposition velocity of TSP.

Meteorological parameter is another important influence to the dry deposition velocity. Characteristics of wind speed, temperature and relative humidity of a particular landscape can influence the friction velocity and the atmospheric stability. Different landscapes cause variances in these meteorological and micro-meteorological parameters, and lead to different dry deposition velocity. In order to determine whether the spatial difference of dry deposition velocity is partially influenced by meteorological parameters, the analysis on the relationship between the dry deposition velocity and meteorological parameters is needed.

Interestingly, these results do not agree with a previous study in Taiwan (Yang et al., 2005), where it was found that the dry deposition velocity values of total particulates were 2.5, 1.5, and 1.2 cm/sec for highway intersection, coastal area, and suburban area, respectively. The author suggested that the highest value in highway intersection could be explained by dust resuspension and particulates from vehicles into the ambient air. But, this explanation may not be effective in our experiment. Particulate species composition difference between the inland and the coastal cities tend to have different characteristic in dry deposition velocity of particulates.

2.2 Relationships between deposition velocity and meteorological factors

The relationships between the dry deposition velocity of TSP and meteorological parameters were investigated by means of regression analysis and correlation analysis. The dry deposition velocity as a function of meteorological parameters is shown in Fig. 4.

A preliminary classification on the meteorological conditions was carried out using dichotomy to deeply explore the relationship between the dry deposition velocity and single meteorological parameters. In this study, temperature, relative humidity and wind speed were segmented into two levels according to the arithmetic average value of the data. These meteorological parameters were therefore segmented into six types of meteorological conditions.

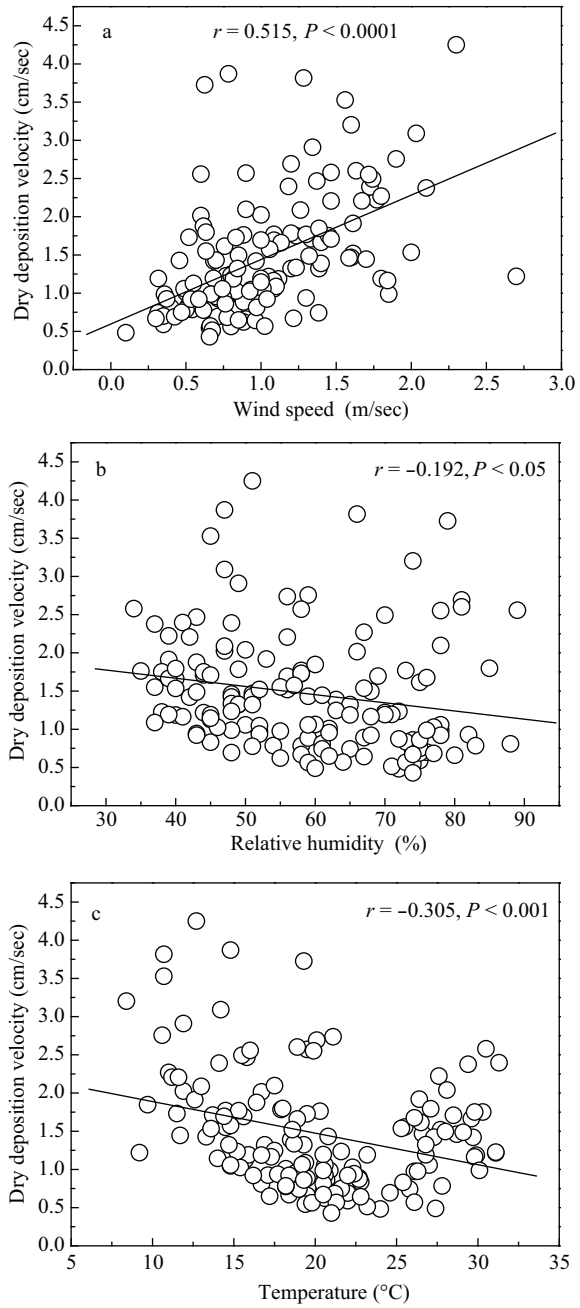

Fig. 4 Relationships between the dry deposition velocity and coherent wind speed (a), relative humidity (b) and temperature (c).

A strong positive correlation exists between dry deposition velocity and wind speed ($P < 0.0001$) as shown in Fig. 4a. Dry deposition velocity increases effectively with increasing wind speed in every meteorological condition (Table 2). This result is consistent with previous studies (Odabasi et al., 2002). Lo et al. (1999) found that the magnitude of the deposition velocity strongly depends on the wind speed, in certain conditions. Particulate matter transportation is highly affected by the aerodynamic driving force of the wind. High wind speed tend to increase the friction velocity, which accelerates the transport of particulate matter. During the sampling period, we found that Conghua tend to have the relative highest wind speed level (Table 1), which can partially explain the highest dry deposition velocity in Conghua (Fig. 3), and BFP is the same as Conghua. This may suggest the wind speed is the determinant factor influencing the dry deposition velocity, especially in the urban forest landscape and country landscape which is covered with vast vegetation.

There is a negative correlation between the dry deposition velocity and the relative humidity ($P < 0.05$), as shown in Fig. 4b. This influence is strong only when the environmental temperature is above 20°C. Furthermore, a weak positive correlation exists when the wind speed is above 1 m/sec (Table 2). Numerous studies have investigated the effects of particle growth on dry deposition velocity due to humidity effects during the atmospheric dry deposition. Hygroscopic growth can significant increase the particle deposition rates, especially during the period with high relative humidity (Winkler, 1973; Tang et al., 1978; Hänel, 1982; Quinn and Ondov, 1998). The dry deposition velocity of S can increase 8.5 times while increasing the relative humidity (Hillamo et al., 1993). However, the humidity effect was considered to be minor because particle growth had been shown to be of little correlation with the relative humidity when the level is below 90% (Lo et al., 1999). The presented result of this study is partially consistent with this theory. Additionally, it is likely that the temperature plays an important role in influencing the effect of relative humidity that changes the dry deposition velocity of TSP. A higher temperature might be a more contributing factor that is responsible for the decrease of the dry deposition velocity.

The negative correlation between the temperature and the dry deposition velocity of TSP is strong ($P < 0.001$), as shown in Fig. 4c. High relative humidity and wind speed might strengthen this negative correlation between dry deposition velocity and temperature (Table 2). But, this result is contradictory to other studies. Dasch and Cadle (1986) reported that the higher values of dry deposition velocity of particles could be caused by higher air temperature which increases atmospheric mixing. Wyers and Duyzer (1997) found that the dry deposition velocity of the nitrate over a coniferous canopy was larger than the maximum theoretical value when the temperature was above 20°C. Higher temperature was expected to have a stronger atmospheric mixing which decreases the stability of atmosphere. Vertical gradient of the temperature could lead to vertical transition and turbulence effect of the air, particularly in

Table 2 The correlation coefficients of dry deposition velocity with wind speed (m/sec), RH (%) and temperature (°C)

Wind speed		Relative humidity		Temperature	
Classification	Pearson correlation	Classification	Pearson correlation	Classification	Pearson correlation
0 < RH < 58	r = 0.507**	0< Wind speed <1	r = –0.117	0 < Wind speed <1	r = –0.276*
58 < RH < 100	r = 0.457**	Wind speed >1	r = 0.067	Wind speed >1	r = –0.348**
Temperature < 20	r = 0.409**	Temperature < 20	r = –0.021	0 < RH < 58	r = –0.281*
Temperature > 20	r = 0.644**	Temperature > 20	r = –0.471**	58 < RH < 100	r = –0.481**

* Significant at 0.05 level; ** significant at 0.01 level. RH: relative humidity.

the cold season. Higher surface temperature might increase the upward transition and the mixing of the particles when the deposition surface particle concentration is high. Thus, dry deposition velocity would be expected to decrease due to the rising of the deposition aerodynamic resistance, especially for the fine particles whose deposition mainly depends on the diffusion effect and the Brownian Motion (Lo et al., 1999). During the sampling period, we found HEMC tends to have a relatively higher air temperature level while Conghua has the lowest (Table 1), which can explain the relatively low dry deposition velocity in HEMC and the highest dry deposition velocity in Conghua (Fig. 3).

2.3 Regression analysis of dry deposition velocity and meteorological factors

Based on the experimental results, the relationship between TSP deposition velocity and these meteorological parameters can be expressed by the following multiple linear regression equation:

$$V_d = 1.755 + 0.717\,\mathrm{WS} - 0.005\,\mathrm{RH} - 0.037\,\mathrm{Temp} \quad (2)$$

where, WS means wind speed; RH means relative humidity; Temp means temperature.

The regression coefficients indicate that the relationship between the dry deposition velocity of TSP and the meteorological parameters is consistent with the results. Furthermore, the accuracy can be validated by comparing the measured and the calculated data. The data set from the BFP site was used to test the model. This simulation matches the measurements in general, and the regression coefficient of the model is 0.331 ($P < 0.0001$), which shows the effectiveness of the model. It is likely that more accurate prediction could be obtained by considering more parameters such as the particle size distribution and the micro-meteorologcial parameter. In summary, high wind speed and low temperature are the factors that increase the dry deposition velocity of TSP.

3 Conclusions

Spatial and temporal changes in the dry deposition velocity of TSP at different landscapes were measured by a surrogate surface method, from October to December of 2009 in Guangzhou. The mean values of dry deposition velocity for Tianhe, BFP, HEMC and Conghua cites are (1.49 ± 0.77) cm/sec, (1.44 ± 0.77) cm/sec, (1.13 ± 0.53) cm/sec and (1.82 ± 0.82) cm/sec, respectively. The highest dry deposition velocity is found in the urban commercial landscape, followed by the urban forest landscape and the urban residential landscape. This spatial variation can be explained by the difference of particle size composition of TSP as well as the meteorological parameters from sampling site.

The results show a significant positive correlation between the dry deposition velocity and the wind speed, while the temperature and the relative humidity are negatively correlated. Wind speed could be one of the strongest factors that determine the magnitude of particle dry deposition velocity. Relative humidity is not the critical impact to the dry deposition velocity of TSP especially in dry season. It may affect the dry deposition velocity only under certain meteorological conditions. Temperature is also a considerably important meteorological factor responsible for the change of the dry deposition velocity.

Overall, this study attempts to determine the impacts from some meteorological factors to the dry deposition velocity of TSP. It is shown that these influences are realistic and complex and significant. Changing in the meteorological parameters will affect the particles' dry deposition velocity within the turbulent layer so that it plays an important role in influencing atmospheric particle dry deposition process. The global and regional climate change, arising from either anthropogenic emissions or improper urban planning, tends to alter the meteorological parameters sustained in different scales. For instance, the urban heat island tends to raise the air temperature extensively while also reduce the relative humidity and wind speed in urban areas. Therefore, it may consequently lead to the changes in the TSP dry deposition velocity even in world widely.

Our experiments were performed in an area with low sub-tropic climate during the dry season. It is not clear whether the similar results would be obtained during the wet season or in other locations. Further research, especially the long term observation on dry deposition velocity of TSP is needed.

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References

Aneja V P, Agarwal A, Roelle P A, Phillips S B, Tong Q S, Watkins N et al., 2001. Measurements and analysis of criteria pollutants in New Delhi, India. *Environment International*, 27(1): 35–42.

Caffrey P F, Ondov J M, Zufall M J, Davidson C I, 1998. Determination of size-dependent dry particle deposition velocities with multiple intrinsic elemental tracers. *Environmental Science and Technology*, 32(11): 1615–1622.

Dasch J M, Cadle S H, 1986. Dry deposition to snow in an urban area. *Water, Air, and Soil Pollution*, 29(3): 297–308.

Davidson C I, Lindberg S E, Schmidt J A, Cartwright L G, Landis L R, 1985. Dry deposition of sulfate onto surrogate surfaces. *Journal of Geophysical Research*, 90(D1): 2123–2130.

El-Fadel M, Massoud M, 2000. Particulate matter in urban areas: health-based economic assessment. *The Science of the Total Environment*, 257(2-3): 133–146.

Fang G C, Chang C N, Chu C C, Wu Y S, Fu P P C, Yang I L et al., 2003. Characterization of particulate, metallic elements of TSP, $PM_{2.5}$ and $PM_{2.5-10}$ aerosols at a farm sampling site in Taiwan, Taichung. *The Science of the Total Environment*, 308(1): 157–166.

Fang G C, Wu Y S, Chang S Y, Rau J Y, Huang S H, 2006. Dry deposition, ionic species measured and source interpretation during seasonal cycle at offshore areas near Taiwan Strait. *Chemosphere*, 64(8): 1253–1263.

Fang G C, Yang I L, Liu C K, 2010. Measure and modeling the ambient air particles and particle bound mercury Hg(p) at a traffic sampling site. *Atmospheric Research*, 97(1-2): 97–105.

Franz T P, Eisenreich S J, Holsen T M, 1998. Dry deposition of particulate polychlorinated biphenyls and polycyclic aromatic hydrocarbons to lake Michigan. *Environmental Science and Technology*, 32(23): 3681–3688.

Guangzhou Statistical Bureau, 2009. Guangzhou Statistical Yearbook. Guangzhou Statistical Bureau Press, Guangzhou. 185–193.

Hagler G S W, Bergin M H, Salmon L G, Yu J Z, Wan E C H, Zheng M et al., 2006. Source areas and chemical composition of fine particulate matter in the Pearl River Delta region of China. *Atmospheric Environment*, 40(20): 3802–3815.

Hänel G, 1982. Influence of relative humidity on aerosol deposition by sedimentation. *Atmospheric Environment*, 16(11): 2703–2706.

Hillamo R E, Kerminen V M, Maenhaut W, Jaffrezo J L, Balachandran S, Davidson C I, 1993. Size distributions of atmospheric trace elements at dye 3, Greenland – I. Distribution characteristics and dry deposition velocities. *Atmospheric Environment*, 27(17-18): 2787–2802.

Holsen T M, Noll K E, 1992. Dry deposition of atmospheric particles: application of current models to ambient data. *Environmental Science and Technology*, 26(9): 1807–1815.

Holsen T M, Noll K E, Fang G C, Lee W J, Lin J M, Keeler G J, 1993. Dry deposition and particle size distributions measured during the lake Michigan urban air toxics study. *Environmental Science and Technology*, 27(7): 1327–1333.

Kaufman Y J, Tanre D, Boucher O, 2002. A satellite view of aerosols in the climate system. *Nature*, 419(6903): 215–223.

Kim E, Kalman D, Larson T, 2000. Dry deposition of large, airborne particles onto a surrogate surface. *Atmospheric Environment*, 34(15): 2387–2397.

Laden F, Neas L M, Dockery D W, Schwartz J, 2000. Association of fine particulate matter from different sources with daily mortality in six U.S. cities. *Environmental Health Perspectives*, 108(10): 941–947.

Lin C H, Lai C H, Wu Y L, Chen M J, 2010. Simple model for estimating dry deposition velocity of ozone and its destruction in a polluted nocturnal boundary layer. *Atmospheric Environment*, 44(35): 4364–4371.

Liu L, Zhang J L, 2009. Ambient air pollution and children's lung function in China. *Environment International*, 35(1): 178–186.

Lo A K F, Zhang L M, Sievering H, 1999. The effect of humidity and state of water surfaces on deposition of aerosol particles onto a water surface. *Atmospheric Environment*, 33(28): 4727–4737.

Matsuda K, Fujimura Y, Hayashi K, Takahashi A, Nakaya K, 2010. Deposition velocity of $PM_{2.5}$ sulfate in the summer above a deciduous forest in central Japan. *Atmospheric Environment*, 44(36): 4582–4587.

Mercado L M, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M et al., 2009. Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, 458(7241): 1014–1017.

Odabasi M, Bagiroz H O, 2002. Sulfate dry deposition fluxes and overall deposition velocities measured with a surrogate surface. *The Science of the Total Environment*, 297(1-3): 193–201.

Odabasi M, Muezzinoglu A, Bozlaker A, 2002. Ambient concentrations and dry deposition fluxes of trace elements in Izmir, Turkey. *Atmospheric Environment*, 36(38): 5841–5851.

Odabasi M, Sofuoglu A, Vardar N, Tasdemir Y, Holsen T M, 1999. Measurement of dry deposition and air-water exchange of polycyclic aromatic hydrocarbons with the water surface sampler. *Environmental Science and Technology*, 33(3): 426–434.

Paode R D, Sofuoglu S C, Sivadechathep J, Noll K E, Holsen T M, 1998. Dry deposition fluxes and mass size distributions of Pb, Cu, and Zn measured in southern lake Michigan during AEOLOS. *Environmental Science and Technology*, 32(11): 1629–1635.

Quinn T L, Ondov J M, 1998. Influence of temporal changes in relative humidity on dry deposition velocities and fluxes of aerosol particles bearing trace elements. *Atmospheric Environment*, 32(20): 3467–3479.

Ramanathan V, Carmichael G, 2008. Global and regional climate changes due to black carbon. *Nature*, 1(4): 221–227.

Shahin U, Zhu X, Holsen T M, 1999. Dry deposition of reduced and reactive nitrogen: a surrogate surfaces approach. *Environmental Science and Technology*, 33(12): 2113–2117.

Tang I N, Munkelwitz H R, Davis J G, 1978. Aerosol growth studies - IV. Phase transformation of mixed salt aerosols in a moist atmosphere. *Journal of Aerosol Science*, 9(6): 505–511.

Vong R J, Vong I J, Vickers D, Covert D S, 2010. Size-dependent aerosol deposition velocities during BEARPEX' 07. *Atmospheric Chemistry and Physics*, 10(12): 5749–5758.

Winkler P, 1973. The growth of atmospheric aerosol particles as a function of the relative humidity-II. An improved concept of mixed nuclei. *Journal of Aerosol Science*, 4(5): 373–387.

Wu Y S, Fang G C, Chen J C, Lin C P, Huang S H, Rau J Y et al., 2006. Ambient air particulate dry deposition, concentrations and metallic elements at Taichung Harbor near Taiwan Strait. *Atmospheric Research*, 79(1): 52–66.

Wyers G P, Duyzer J H, 1997. Micrometeorological measurement of the dry deposition flux of sulphate and nitrate aerosols to coniferous forest. *Atmospheric Environment*, 31(3): 333–343.

Yang H H, Hsieh L T, Cheng S K, 2005. Determination of

atmospheric nitrate particulate size distribution and dry deposition velocity for three distinct areas. *Chemosphere*, 60(10): 1447–1453.

Yasunari T J, Bonasoni P, Laj P, Fujita K, Vuillermoz E, Marinoni A et al., 2010. Estimated impact of black carbon deposition during pre-monsoon season form Nepal Climate Observatory – Pyramid data and snow albedo changes over Himalayan glaciers. *Atmospheric Chemistry and Physics*, 10(14): 6603–6615.

Ye Y H, Zhou K, Song L Y, Jin J H, Peng S L, 2007. Dew amounts and its correlations with meteorological factors in urban landscapes of Guangzhou, China. *Atmospheric Research*, 86(1): 21–29.

Zhou K, Ye Y H, Liu Q, Liu A J, Peng S L, 2007. Evaluation of ambient air quality in Guangzhou, China. *Journal of Environmental Sciences*, 19(4): 432–437.

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