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ABSTRACT

Vehicular emissions from arterials may present a risk to public health considering the type of surrounding built environments that can trap pollutants. In order to study the influence of urban morphometry on flow and dispersion of vehicular emissions, field measurements were performed in major arterials in 5 Southern Californian cities with different building geometries. Local mean wind, turbulence, virtual temperature, roadside fine particulate matter ($PM_{2.5}$) concentration, and traffic flow data were collected in summer 2008. In each city, data were collected for three days, covering two hours during the morning and evening commute and lighter mid-day traffic. First, the observation shows the influence of building geometry on street level concentration of particulates. Tall buildings cause a strong downdraft which upon impinging the street level flushes street canyon from pollutants. Second, field experiments help us understand the influence of local meteorological variables and their interaction with urban canopy to particle concentration. Concentrations at the windward side of buildings within urban canopy are extremely sensitive to wind direction. In addition to wind direction, turbulent flux, sensible heat flux and turbulent velocity are also affecting concentrations by enhancing vertical transport.

IMPLICATIONS

Transportation emissions in built environments surrounding major arterials can produce high concentration spots and have potential adverse health impact. Dispersion of pollutants within urban canopy is governed by flow and turbulence characteristics caused by building morphometry. Current dispersion models used for regulatory purpose have difficulties in simulating the flow and dispersion for complex building cases, especially when fine resolution is needed. Therefore, the investigation of roadside vehicular emissions in different types of built environments is needed. This work presents field experiments in 5 Southern Californian cities to investigate the influence of building geometry, local meteorological conditions and traffic flow on roadside particulate concentrations.

INTRODUCTION

In metropolitan cities, vehicular emissions are in close proximity to pedestrian, residences and local business. Compared with emissions from a highway passing through an open area, the study of local emissions from major arterials in urban area is more challenging and need to consider more factors, such as variation of traffic activity, local meteorological variables, built environments, urban heat island effect, etc. In street scale or neighborhood scale, the dispersion of pollutants is heavily depending on the mean flow and turbulence characteristics.[1-2]

The flow and dispersion through archetypal street canyons has been getting attentions for decades. Field experiments found the relationship between roof wind direction and canyon wind direction in street canyons,[3] and a clear pattern of vortex development and circulation.[4] Laboratory experiments observed the deformation of the recirculating flow with increasing canyon spacing with Particle Image Velocimetry (PIV) measurements.[5] Numerical models, such as k-ε model[6-7] and large-eddy simulation,[8-9] could also achieve the reasonable mean flow and turbulence characteristics within street canyon. The typical recirculating flow performing as a concentrated downdraft flow on the windward side and as an extensive updraft flow on the leeward side causes a larger concentration at the leeward side than at the windward side except for a step-down configuration,[1] which was already proved by numerical methods[8] and laboratory simulation.[10-11] There are several specific studies focusing on the dispersion of particles from vehicles within street canyon.[12-13]

The understanding of flow and dispersion within street canyon was used to create parameterized semi-empirical models, such as Operational Street Pollution Model (OSPM),[14] which usually has practical applications in air pollution management, mobile source control strategies, etc. Zhou and Levy[15] applied OSPM to study population exposure to traffic related primary pollutants in densely populated street canyons in mid-town Manhattan. Their findings indicated the street configuration (e.g. street width-to-height ratio) is a more sensitive factor in characterizing the intake fraction (iF) than traffic-related variables (e.g. traffic volume, traffic speed, and percent of truck traffic).

In recent years, there are series of field experiments conducted to study the flow and dispersion in urban area. URBAN 2000[16] was an urban tracer and meteorological field campaign conducted in Salt Lake City, Utah. This study was designed to investigate the urban nocturnal boundary layer (stable to neutral atmospheric condition). The strength of this study is that it provides a dataset that resolves interacting scales of motion from the individual building up through the regional scale under the same meteorological condition. Joint Urban 2003 (JU2003) field campaign which was designed to investigate the daytime boundary layer (neutral to unstable) was performed in Oklahoma City.[17] Velocity data obtained within a street canyon were used to explore the directional dependence of the mean flow and turbulence within a real-world street canyon.[18-19] The Madison Square Garden July 2004 (MSG04) field experiment was carried out in the deep urban canyons.[20-21] This experiment allowed continued improvement of the understanding of the atmospheric circulations and rapid vertical dispersion in the deep canyons of very large cities such as New York City. Other field experiments include: Basel Urban Boundary-Layer Experiment (BUBBLE) in Basel, Switzerland,[22] Dispersion of Air Pollution and its Penetration into the Local Environment (DAPPLE) in London, UK,[23-25] and Canyon Particle Experiment (CAPAREX) in Essen, Germany.[26]

The studies on the dispersion of vehicular emissions were also focusing on urban street canyon.[26-28] There is a major limitation on past field experiments: most field experiments have often focused on a single street canyon, and the vertical profile of velocity and turbulent flux within and above the street canyon. The variation of building geometry is hardly addressed. However, in build-up urban area, urban morphometry plays an important role on flow and dispersion, where most building geometries do not have the same features as street canyon. Understanding of flow and dispersion within street canyon or simple arrays is obtained under ideal situations. Application of these results in realistic case is difficult. Near source studies on dispersion of vehicle exhaust pollutants in built environments are still limited. The understanding of vehicular emissions in built environments surrounding major arterials has benefit on urban planning strategies, such as pedestrian-friendly community design, transportation planning, etc. Thus, the objectives of this study are to investigate a wider range of urban morphometry and more urban-like rough surface, and to study the influence of built environments on near source $PM_{2.5}$ concentration.

FIELD MEASUREMENTS

Site Description

The classification of building arrangements has no uniform standard. Theurer[29] suggested a classification scheme for wider urban areas in German towns. The building arrangements are divided into 9 types according to the function of buildings for urban air pollution modeling. Stewart and Oke[30] suggested 9 thermal climate zones in the city series for urban heat island study. In this study, the classification of building arrangements (shown in table 1) is due to development patterns and the proximity of buildings to the arterial. 5 typical building arrangements are selected from 5 southern Californian cities: 1) low density settlement, 1-2 stories; 2) low-rise settlement, 3-4 stories; 3) mid-rise settlement, 10-20 stories; 4) high-rise settlement, more than twenty stories and 5) a strip mall with surface parking separating the building and the arterial.

Sampling Description

The field measurements were conducted during the weekdays from June 19 2008 to August 1 2008 at five cities. Each city was equipped with a 3-D sonic anemometer (CSAT3, Campbell Sci.), measuring mean wind speed, turbulence and virtual air temperature, six DustTraks (TSI Inc.), measuring $PM_{2.5}$ concentration, and three digital cameras (JVC), recording traffic flow. For each city, parallel experiments were conducted for three days, covering the morning (7:00 a.m. ~ 9:00 a.m. local time) and evening (5:00 p.m. ~ 7:00 p.m. local time) commute and lighter mid-day (11:00 a.m. ~ 1:00 p.m. local time) traffic. Sonic anemometer collected 10 Hz data for 12 hours (7:00 a.m. ~ 7:00 p.m.) and DustTrak collected 1 Hz data for 6 hours. Table 2 described the sites in detail. All sites except P6 and LB6 are near ground level. For the sites near ground level, the height of DustTrak inlet is 2 m above the ground and the sonic anemometer was mounted at the height of 1.4 m at site 6, together with a DustTrak. Both

P6 and LB6 are at the roof of parking garage. P6 is 16 m above the ground and LB 6 is 24 m above the ground. Hence, for meteorological data, three sites (Huntington Beach, Anaheim and Los Angeles) are on the street level and the other two (Long Beach and Pasadena) are on the roof level. The locations of sonic anemometers for all 5 cities are chosen to be far away from arterials to avoid being affected by traffic induced turbulence. A quality assurance procedure was performed during each measurement period. Prior to measurements, zero calibration and synchronization of DustTraks were performed. In addition, in order to minimize the error made by difference of each DustTrak readings, all six DustTraks were sampling for 10 minutes at the same time and place to get the correct factor which was applied for accurate $PM_{2.5}$ concentration calibration.

RESULTS AND DISCUSSION

Mean Wind and Turbulent Characteristics in Observation

Table 3 shows summary of mean wind and turbulent characteristics for each city for 12 hours average data. U is mean wind speed, *WD* is wind direction, σ is standard deviation of wind component fluctuations. Subscripts u, v and w correspond to three wind components, south-north, east-west and vertical, respectively. Horizontal wind fluctuation is $\sigma_h = \left(\sigma_u^2 + \sigma_v^2\right)^{1/2}$, u_* is friction velocity, and turbulent kinetic energy is $TKE = \left(\sigma_u^2 + \sigma_v^2 + \sigma_w^2\right)/2$. Comparing three ground level sites, LA6, HB6 and A6, we can see that mean wind speed in Huntington Beach and Anaheim was about 3-4 times mean wind speed in Los Angeles and even a little higher than roof level measurements in Long Beach and Pasadena. Overall σ_w values on the roof level were higher than ground level and σ_w / u_* values in our measurement were greater than the results reported by Britter and Hanna[1]. They reported 1.1 in urban canopy and 1.3 near and above average building height *H*. Our data is more close to JU2003 data and MSG05 data[21]. σ_w / u_* values were in the range from 1.44~1.66 for JU2003 and 1.18~2.17 for MSG05.

Comparison of High-Rise Settlement and Strip Mall Case

The meteorological data collected by 3-D sonic anemometers were averaged each 30 minutes. Figure 1 shows averaged mean wind speed, U, and turbulent intensities, σ_w / U, for 2 cities, Los Angeles (high-rise settlement) and Huntington Beach (strip mall case). The maximum mean wind speed in Los Angeles was 0.7 m/sec, while in Huntington Beach the maximum mean wind speed was 1.7 m/sec. However, vertical velocity fluctuation in Los Angeles was comparable with Huntington Beach. Therefore, turbulent intensity, σ_w / U, in Los Angeles was much higher than that in Huntington Beach. This is reasonable since the building arrangement in Los Angeles is classified as high-rise settlement, with much rougher surface. Thus, although mean wind speed is low, high turbulence is easy to attain.

Figure 2 shows turbulent flux and sensible heat flux for two cities. For both cities, we can see the continuous increasing of turbulent flux and sensible heat flux during the morning and relatively high values during the afternoon and dropping down in the late afternoon. Although building arrangements in Los Angeles and Huntington Beach have huge difference, turbulent flux were not very different and the mean values for Los Angeles and Huntington Beach were 0.06 m^2/sec^2 and 0.07 m^2/sec^2, respectively. Sensible heat flux in Huntington Beach was a little higher than Los Angeles. The average values were 212 W/m^2 for the former and 124 W/m^2 for the latter. The lower sensible heat flux in Los Angeles is again caused by its building arrangements. High-rise settlement and more dense buildings create more shades of buildings on the ground, hence, less heating by sun.

The relationships between roadside $PM_{2.5}$ concentration and traffic count in Los Angeles and Huntington Beach are shown in figure 3. Traffic composition includes passenger car, bus and truck. The traffic data are collected from site LA2, LA3 and LA4 in Los Angeles and HB2, HB3 and HB4 in Huntington Beach. Although traffic flow in Los Angeles is about 3000 to 6000 vehicles per 20 minutes, that is much heavier than Huntington Beach, the concentration in Los Angeles is not higher than that in Huntington Beach. The average concentrations are 43±17 $\mu g/m^3$ in Los Angeles and 43±14 $\mu g/m^3$ in Huntington Beach. As we discussed before, turbulent intensity in Los Angeles is much higher than Huntington Beach. High turbulent level dilutes the pollutants concentration. This is agreement with what Britter and Hanna[1] discussed that the increased turbulence levels within the urban canopy result in larger dispersion coefficients and canopy ventilation. Our results demonstrate that shear produced turbulence caused by building roughness dominates the dispersion compared with buoyancy produced turbulence since sensible heat flux in Los Angeles is lower than in Huntington Beach.

$PM_{2.5}$ Concentration on Leeward Side and Windward Side

Figure 4 shows time series of $PM_{2.5}$ concentration with 1 Hz sampling frequency measured in Los Angeles from two opposite sites. Black lines represent site LA1 which is located at the windward side on 6th street and red lines represent site LA5 which is located at the leeward side on the same street facing LA1. $PM_{2.5}$ concentration peaks always appeared at leeward side. The performance of concentrations at windward side during the morning, noon and afternoon periods was different. In the morning (Figure 4a), concentration valley values appeared at windward side corresponding to the arising of concentration peaks at leeward side. At noon and in the afternoon, the fluctuations of concentration at windward side were not as obvious as that in the morning. At this location, buildings height at windward side (the highest one is 188 m) is much higher than that at leeward side (the highest one is 54 m).

Relation between $PM_{2.5}$ Concentration and Meteorological Variables

Figure 5 shows meteorological variables at site LB4, which was collected in Long Beach on July 2, 2008. The dominant wind direction measured by sonic anemometer on the roof of the building on that day is around 270° (westerly), almost perpendicular to the arterial. Under this wind condition, site S4 is located at the windward side of building and arterial is just at the upwind direction of DustTrak sampling. Figure 6 shows relation between $PM_{2.5}$ concentrations and meteorological variables. The plot of wind direction-$PM_{2.5}$ concentration relationship shows that all concentrations greater than 70 $\mu g/m^3$ appeared under the condition of wind direction around 270°. The plot of turbulent flux-$PM_{2.5}$ concentration relationship (Figure 6) shows high concentration appeared when wind speed, σ_w and turbulent flux was small. When wind speed, σ_w and turbulent flux became large, concentrations stayed at low level. These relationships were not found at other sites located in streets parallel to the dominant wind direction in which concentration stayed constant with changes in turbulence and fluxes.

SUMMARY

This study is a part of the University of California Transportation Center sponsored project 'Near source modeling of transportation emission in built environments surrounding major arterials'. The results presented here are based on analysis of field experiments conducted in 5 Southern Californian cities. Main highlights of the study are:

1) Mean wind speed measured on ground level in relatively open Huntington Beach and Anaheim are 3-4 times the mean wind speed in Los Angeles and even a little higher than roof level measurements in Long Beach and Pasadena. The average σ_w / u_* from our observation is 1.5, similar to MSG05 data reported by Hanna[21].
2) The comparison of Huntington Beach case and Los Angeles case indicated significant influence of building arrangement on the local meteorological condition and pollutant concentration. Although mean wind speed in Los Angeles is very low, much higher turbulent intensity is obtained caused by complex building geometry. Hence, the roadside $PM_{2.5}$ concentration in Los Angeles is not higher than Huntington Beach although the traffic flow in Los Angeles is 3-4 times heavier than Huntington Beach.
3) Particulate concentration data in Los Angeles shows leeward side of lower building could trap pollutants and produce high concentration while windward side with higher building has low concentration caused by clean air flushing.
4) Long Beach case helps us understand the influence of local meteorological variables on pollutants concentration and the role of receptor position within urban canopy. When monitor site is located at the windward side of building within urban canopy, wind direction has a significant influence on pollutions concentrations. In addition to wind direction, turbulent flux, sensible heat flux and turbulent velocity σ_w, can also affect concentrations, especially on producing extremely high concentration peaks.

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Table 1. The classification of building arrangements.

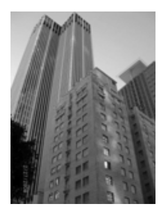
	Low density settlement	Low rise settlement	Mid-rise settlement	High-rise settlement	A strip mall
Stories	1 to 2 stories	3 to 5 stories	10 to 20 stories	>20 stories	1 to 2 stories
City	Anaheim	Pasadena	Long Beach	Los Angeles	Huntington Beach
Arterials	Harbor Blvd.	East Colorado Blvd.	East Ocean Blvd.	6th Ave.	Beach Blvd.
Typical buildings					

Table 2. Specification of each site.

City	Site	Instrument	Arterials	Distance to arterials (m)
Anaheim	A1	1DustTrak 1 Camera	Harbor Blvd.	3
	A2	1DustTrak 1 Camera	Harbor Blvd.	5
	A3	1DustTrak 1 Camera	Lampson Ave.	1
	A4	1DustTrak	Lampson Ave.	1
	A5	1DustTrak	Citruswood Ave.	1
	A6	1DustTrak 1 Sonic Anemometer	Harbor Blvd.	24
Pasadena	P1	1DustTrak	El Molino Ave.	1
	P2	1DustTrak	Colorado Blvd.	1

		1 Camera		
	P3	1DustTrak 1 Camera	Colorado Blvd.	1
	P4	1DustTrak 1 Camera	Colorado Blvd.	1
	P5	1DustTrak	El Molino Ave.	1
	P6 (Roof)	1DustTrak 1 Sonic Anemometer	Green St	34
Long Beach	LB1	1DustTrak	Ocean Blvd.	2
	LB2	1DustTrak 1 Camera	Ocean Blvd.	2
	LB3	1DustTrak	Broadway	1
	LB4	1DustTrak 1 Camera	Pine Ave.	1
	LB5	1DustTrak 1 Camera	Broadway	1
	LB6 (Roof)	1DustTrak 1 Sonic Anemometer	Pine Ave.	60
Los Angeles	LA1	1DustTrak 1 Camera	6th St.	1
	LA2	1DustTrak 1 Camera	Grand Ave.	1
	LA3	1DustTrak 1 Camera	Grand Ave.	1
	LA4	1DustTrak 1 Camera	6th St.	1
	LA5	1DustTrak	6th St.	1
	LA6	1DustTrak 1 Sonic Anemometer	Olive St.	50
Huntington Beach	HB1	1DustTrak	Garfield Ave.	1
	HB2	1DustTrak 1 Camera	Garfield Ave.	1
	HB3	1DustTrak 1 Camera	Beach Blvd.	1
	HB4	1DustTrak 1 Camera	Beach Blvd.	1
	HB5	1DustTrak	Beach Blvd.	22
	HB6	1DustTrak 1 Sonic Anemometer	Beach Blvd.	12

Table 3. Summary of mean wind and turbulent characteristics.

date	site	U	WD	σ_u	σ_v	σ_h	σ_w	TKE	u_*	σ_h / u_*	σ_w / u_*
		m/sec	degree	m/sec	m/sec	m/sec	m/sec	m^2/sec^2	m/sec		
6/19/2008	LA6	0.38	228.17	0.70	0.74	1.03	0.34	0.59	0.22	4.93	1.60
6/23/2008	LA6	0.31	239.39	0.75	0.85	1.14	0.34	0.72	0.26	4.64	1.36
6/30/2008	LA6	0.47	179.57	0.72	0.74	1.03	0.34	0.61	0.27	3.88	1.25
7/2/2008	LB6	1.00	260.08	0.78	0.64	1.01	0.54	0.70	0.34	3.09	1.67
7/7/2008	LB6	0.67	213.28	0.80	0.74	1.09	0.54	0.76	0.35	3.24	1.60
7/9/2008	LB6	0.92	216.12	0.81	0.71	1.08	0.56	0.80	0.37	3.09	1.61
7/16/2008	HB6	1.07	213.94	0.59	0.70	0.92	0.37	0.53	0.29	3.51	1.38
7/18/2008	HB6	1.02	229.31	0.68	0.60	0.91	0.36	0.48	0.25	3.69	1.48
7/21/2008	HB6	1.19	258.42	0.82	0.71	1.09	0.40	0.71	0.23	4.85	1.78
7/23/2008	P6	0.87	156.92	0.88	0.76	1.16	0.47	0.90	0.40	2.90	1.24

7/25/2008	P6	0.62	159.06	0.68	0.65	0.94	0.44	0.58	0.34	2.73	1.31
7/29/2008	P6	0.74	180.40	0.86	0.75	1.14	0.49	0.90	0.42	2.64	1.21
7/30/2008	A6	1.04	220.70	0.92	0.53	1.01	0.38	0.68	0.18	6.93	2.49
7/31/2008	A6	1.38	213.55	0.73	0.89	1.15	0.39	0.75	0.28	4.35	1.45
8/1/2008	A6	1.33	211.26	0.63	0.82	1.03	0.35	0.63	0.23	4.50	1.54

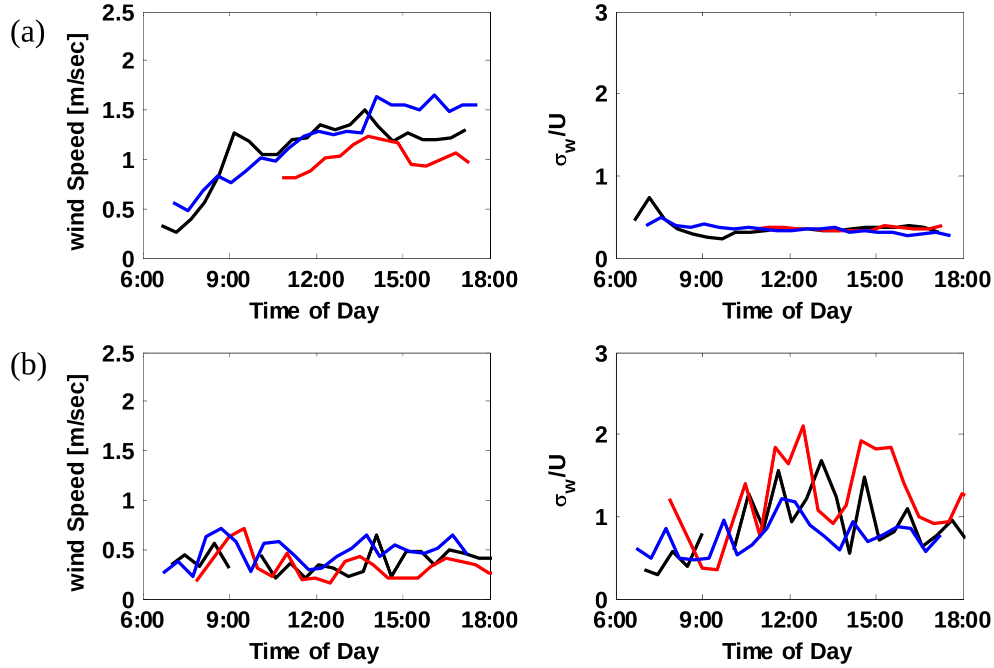
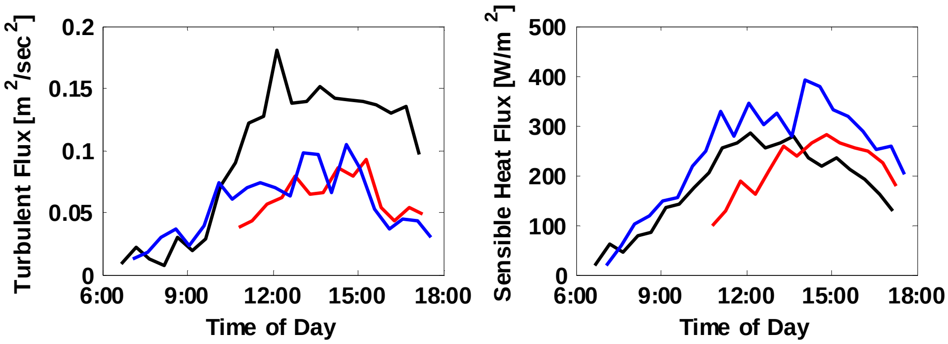


Figure 1. Mean wind speed and vertical velocity fluctuations in (a) Huntington Beach and (b) Los Angeles. (Note: black, red and blue indicate three different days.)

(a)



(b)

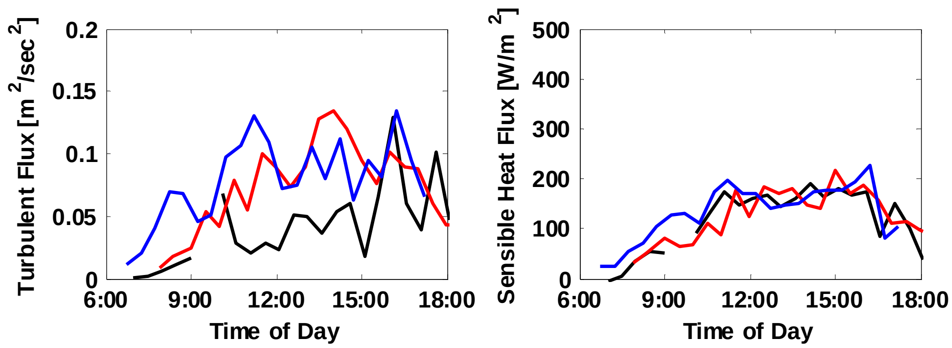


Figure 2. Turbulent flux and sensible heat flux in (a) Huntington Beach and (b) Los Angeles. (Note: black, red and blue indicate three different days.)

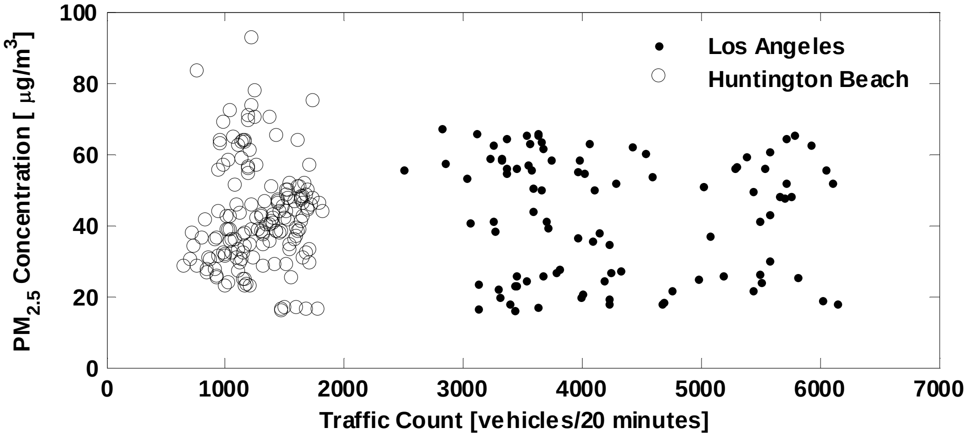


Figure 3. Relationship between traffic flow and $PM_{2.5}$ concentration in Los Angeles (dot) and Huntington Beach (circle)

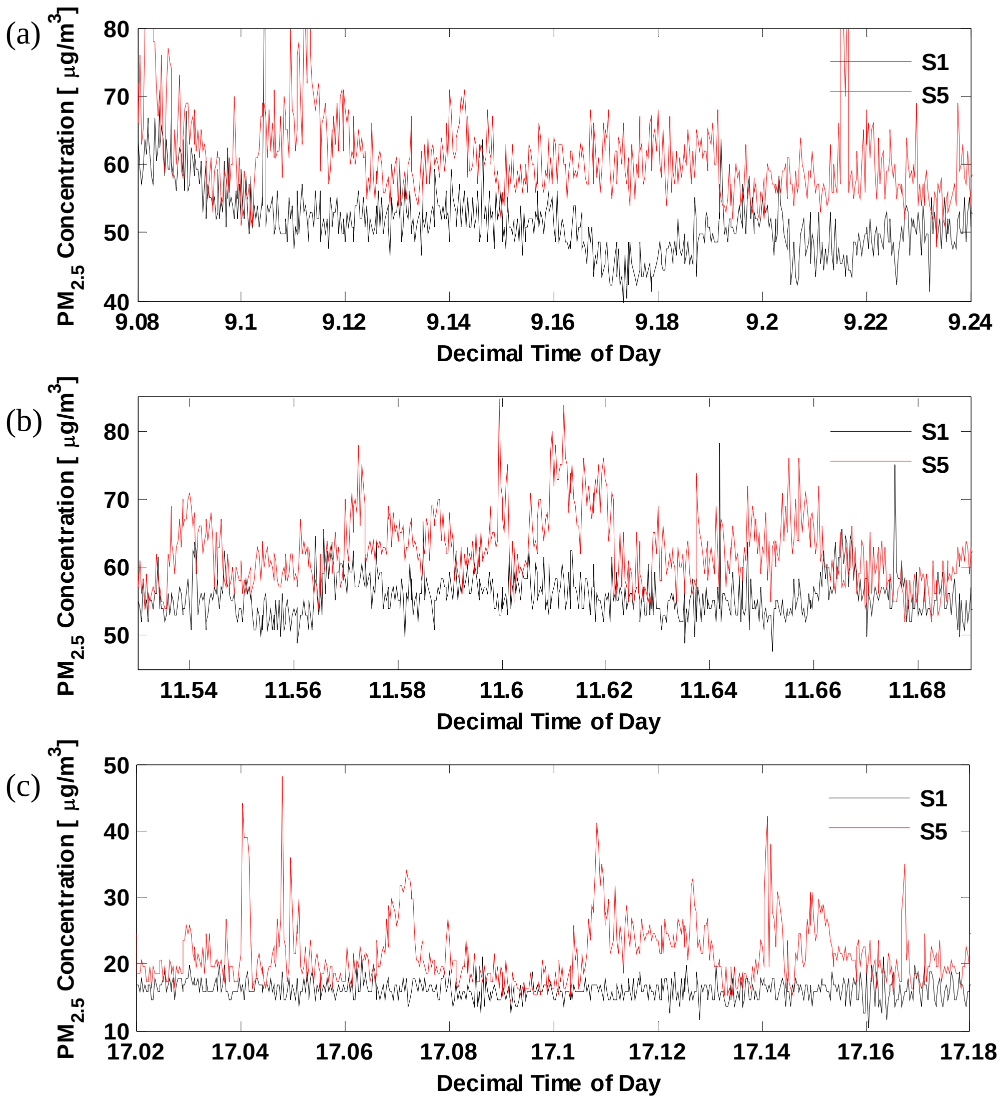


Figure 4. Time series (~ 10 minutes) of $PM_{2.5}$ concentration at site1 (windward side) and site 5 (leeward side) in Los Angeles during (a) morning, (b) noon and (c) afternoon. (Note: data are collected on 06/19/2008 in (a) and (b), 06/30/2008 in (c).)

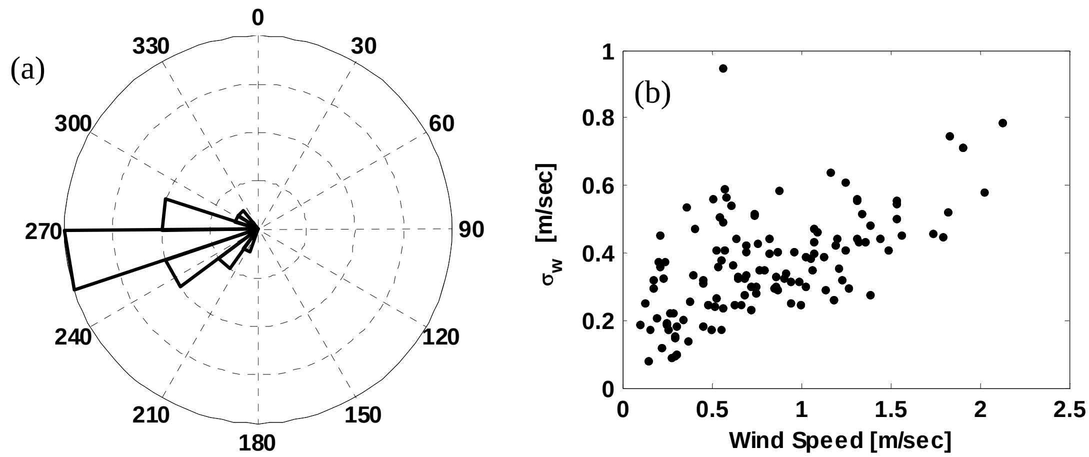


Figure 5. (a) Wind rose and (b) relation between wind speed and w_{rms} on 07/02/2008 at Long Beach.

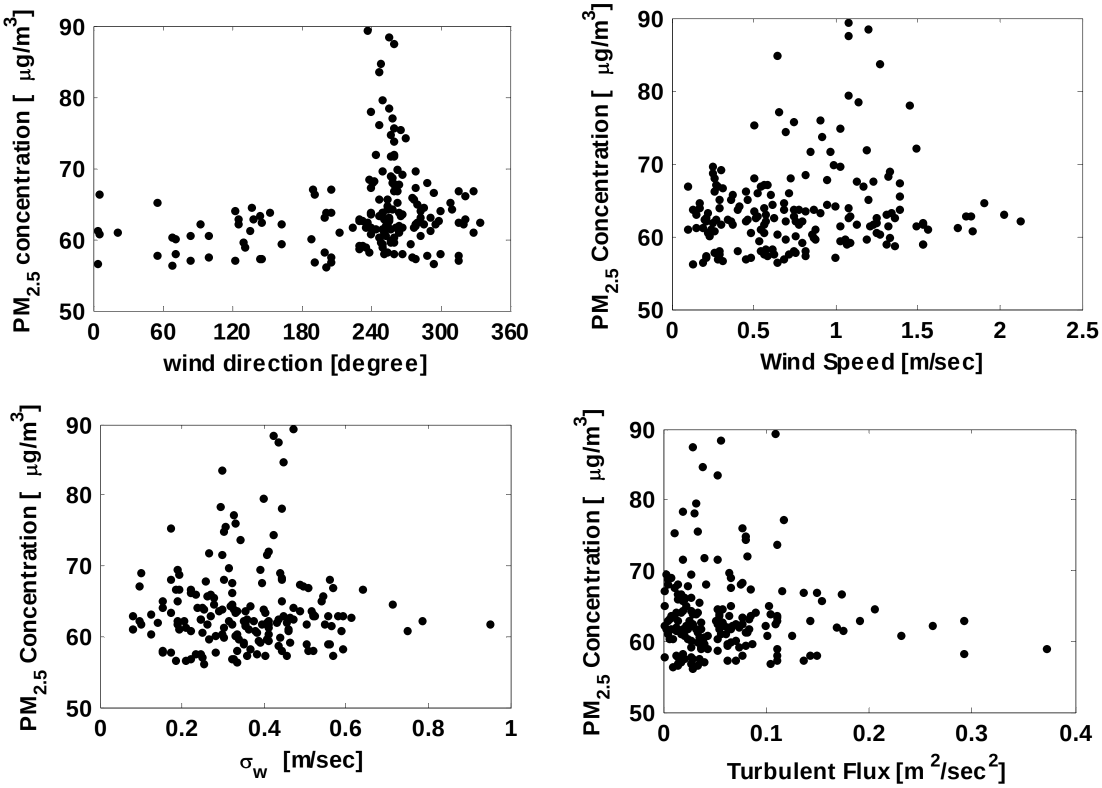


Figure 6. Relation between $PM_{2.5}$ concentrations and meteorological variables.