Aerosol Science and Technology

ISSN: 0278-6826 (Print) 1521-7388 (Online) Journal homepage: http://www.tandfonline.com/loi/uast20

Intra-Community Variability in Total Particle Number Concentrations in the San Pedro Harbor Area (Los Angeles, California)

Katharine Moore , Margaret Krudysz , Payam Pakbin , Neelakshi Hudda & Constantinos Sioutas

To cite this article: Katharine Moore , Margaret Krudysz , Payam Pakbin , Neelakshi Hudda & Constantinos Sioutas (2009) Intra-Community Variability in Total Particle Number Concentrations in the San Pedro Harbor Area (Los Angeles, California), Aerosol Science and Technology, 43:6, 587-603, DOI: 10.1080/02786820902800900

To link to this article: http://dx.doi.org/10.1080/02786820902800900

View supplementary material

Published online: 24 Mar 2009.

Submit your article to this journal

Article views: 351

View related articles

Citing articles: 24 View citing articles

Full Terms & Conditions of access and use can be found at
http://www.tandfonline.com/action/journalInformation?journalCode=uast20

Download by: [University of North Texas] **Date:** 05 January 2017, At: 22:59

Aerosol Science and Technology, 43:587–603, 2009
Copyright © American Association for Aerosol Research
ISSN: 0278-6826 print / 1521-7388 online
DOI: 10.1080/02786820902800900

Intra-Community Variability in Total Particle Number Concentrations in the San Pedro Harbor Area (Los Angeles, California)

Katharine Moore,[1] Margaret Krudysz,[2] Payam Pakbin,[1] Neelakshi Hudda,[1] and Constantinos Sioutas[1]

[1]*Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, California, USA*

[2]*School of Public Health, Department of Environmental Health Sciences, University of California, Los Angeles, Los Angeles, California, USA*

Recent evidence links elevated ultrafine particle (UFP) concentrations with adverse health effects, but exposure assessments based upon $PM_{2.5}$ mass concentrations may be misleading. In order to better understand and quantify intra-community variability in UFP concentrations, a dense network of 14 monitoring sites was set-up in Los Angeles in two clusters—San Pedro/Wilmington and West Long Beach—in communities surrounding the Ports of Los Angeles and Long Beach. The network measured total particle number concentrations greater than 7 nm in diameter. In this range, UFP comprise approximately 90% of the total. Port-related activities—particularly goods movement associated with high volumes of heavy-duty diesel vehicle (HDDV) traffic—represent significant UFP sources. The field study was conducted from mid-February through mid-December 2007 to assess diurnal, seasonal, and spatial patterns and intra-community variability in total particle number concentrations. For sites within a few km of each other, simultaneous particle number concentrations can vary up to a factor of 10 (<10,000 cm^{-3} up to 90,000 cm^{-3} for hourly averages calculated by month). The median hourly correlation coefficient (r) across all sites was modest and varied from 0.3 to 0.56. Specific site locations, particularly proximity to roadways used for goods movement, strongly affect observations. Clear diurnal and seasonal patterns are evident in the data. A diurnal pattern associated with high HDDV volumes and goods movement was identified. Coefficients of Divergence calculated for the site pairs suggest moderate heterogeneity overall (median study COD $\approx$ 0.35). The intra-urban variability observed in this study is comparable to and exceeds the inter-urban variability observed in a previous study in Los Angeles. UFP concentrations can vary considerably on short spatial scales in source-rich environments strongly influencing the accuracy of exposure assessments.

Received 15 October 2008; accepted 15 January 2009.

Support for this study was provided by the California Air Resources Board (ARB contract 05-317) and by the United States Environmental Protection Agency through the Science to Achieve Results (STAR) graduate fellowship program (#R832157). This study would not have been possible without substantial assistance from the South Coast Air Quality Management District (PM Fine, S Wilson) and extensive voluntary community involvement. This includes the Ports of Los Angeles and Long Beach, the City of Los Angeles, the City of Long Beach, Battalion 6 of the Los Angeles Fire Department, B. Alvarez, G. Bertolin (SAIC), J. Cross, J. Marquez (Coalition for a Safe Environment (Wilmington)), D. Berns and D. Seymour (The Berns Company), A. Hricko (USC), C. Janocha (Superior Electrical Advertising), D. Mohda (Long Beach Job Corps Center), R. Veyna and T. Diaz (Orange County Nursery), Southern California Edison, and G. Johnson (Westside Baptist Church). We also acknowledge the assistance of our colleagues in the HCMS from the Desert Research Institute, UCLA and ARB. All members of the USC Aerosol Group, particularly Z. Ning, M.D. Geller, and M. Arhami, assisted with the successful completion of this project.

Address correspondence to Constantinos Sioutas, Department of Civil and Environmental Engineering, University of Southern California, 3920 South Vermont Avenue, KAP 210 MC 2531, Los Angeles, CA 90089, USA. E-mail: sioutas@usc.edu

INTRODUCTION

The relationship between elevated ambient particulate matter (PM) mass concentrations and adverse human and environmental health impacts is well established (Dockery and Pope 2006). Determining the relationship between particle size and composition and specific health endpoints, however, is an active area of research. Pro-inflammatory response at the cellular level as well as increased incidence of asthma, among other diseases, are linked to exposure to ultrafine particles (approximately <100 nm in diameter)(UFPs) (Pekkanen et al. 1997; Li et al. 2003; Xia et al. 2004; Delfino et al. 2005). UFPs have been shown to be more toxic than larger particles of the same composition (Gong et al. 2007; Xia et al. 2007), and deposit with high efficiency in the lower human lung due to their size. UFPs constitute a small fraction of fine $PM_{2.5}$(<2500 nm in diameter) mass; ambient particle number concentrations tend to increase sharply as diameters decrease into the UFP range (Hinds 1999). Therefore, number concentration is a more appropriate measurement metric for UFPs. Readily available $PM_{2.5}$ mass concentrations from centrally located sites are often used as surrogates for UFP

concentrations (Wilson and Zawar-Reza 2006), despite the fact that poor correlation has been found between UFP number and $PM_{2.5}$ mass concentrations (Harrison and Jones 2005, among others). Further, the presumption that one measurement is representative of concentrations across the entire region of interest may not be valid (Wilson et al. 2005; Pinto et al. 2004). These two issues can lead to exposure misallocation and introduce bias and considerable uncertainty into exposure assessments (Wilson et al. 2005; Wilson and Zawar-Reza 2006).

In urban environments, motor vehicle traffic is the dominant source of primary UFP (Kim et al. 2002; Westerdahl et al. 2005), although other sources such as food cooking and wood burning can also contribute (Kleeman et al. 1999; Schauer et al. 2001). Secondary atmospheric production of new UFP and additional UFP mass can also be important in some conditions (Kulmala et al. 2004; Fine et al. 2004; Moore et al. 2007). While primary UFPs should dominate on local scales, secondary production may be an important factor on regional scales and promote spatial homogeneity (Turner and Allen 2008). As their atmospheric lifetimes are short, strong gradients in UFP concentrations can be expected in areas with multiple sources of primary UFP (Sioutas et al. 2005). A series of studies under many different conditions in the vicinity of Los Angeles–area freeways (Zhu et al. 2002a,b; 2005; 2006) show that UFP concentrations can decrease exponentially downwind although the decay rate depends strongly on factors such as source strength, wind speed, temperature, relative humidity, and time of day. Typical scales of impact are 100–500 m. Improved characterization of UFP gradients requires concurrent high temporal resolution measurements of number concentration at multiple sites within a limited geographic area on the scale of the observations by Zhu and colleagues in order to better assess intra-community variability, potential UFP exposures and health outcomes. While observations may be city-, source-, and sink-dependent (Freiman et al. 2006; Turner and Allen 2008, and references therein), baseline measurements like these will be useful to the development of potential number-based UFP standards to protect against UFP-induced or -exacerbated illness (Nel 2005).

Limited data sets exist of inter- and intra-urban variability in particle number concentrations. During 2002 and 2003, the USC Children's Health Study (CHS) made extended measurements of particle number and co-pollutant concentrations in several "city center" locations primarily in the Los Angeles air basin. Each site was separated by 10s–100s of km. The seasonal and diurnal patterns in particle concentrations were relatively consistent, but a comparison of particle number concentrations between sites found weak to modest spatial correlations and site proximity to local vehicular traffic strongly influenced the results (Sardar et al. 2004; Singh et al. 2006). Extended monitoring in several European cities also found strong seasonal and local traffic impacts on observations (Aalto et al. 2005). In a companion study, spatial variation in particle number exceeded that for particle mass and varied between the cities (Lianou et al. 2007). Factors such as traffic intensity, sampling location (as a surrogate for proximity to and availability of UFP sources), sources, and local meteorology have been shown to introduce substantial differences in particle number concentrations observed in intra-city studies (Lianou et al. 2007; Puustinen et al. 2007; Cyrys et al. 1998; Buzorius et al. 1999; Tuch et al. 2006; Harrison and Jones 2005).

Here we present the results from a high-density network of monitoring sites designed to characterize intra-community variability in UFP number concentrations in a Los Angeles–area community. The 2007 study was conducted in the communities surrounding the San Pedro Harbor as part of the multi-investigator and -platform Harbor Communities Monitoring Study (HCMS). Sponsored by the California Air Resources Board, the HCMS' goal is to investigate temporal and spatial variability in selected air quality parameters, including the identification of "hot spots" in this "source" region of the Los Angeles basin. The combined Ports of Los Angeles and Long Beach are the fifth largest in the world and represent a significant source of air pollution. For example, the most recent emissions inventory (2005) estimates that 50% of all ambient diesel particulate matter in the air basin arises from port and port-related activities, particularly goods movement (Port of Long Beach 2007, Port of Los Angeles 2007). There are additional industrial UFP sources (e.g., refineries, power plants) near the ports, although companion measurements performed during this same time period and subsequent modeling indicate that motor vehicle and motor vehicle–related emissions strongly predominate (Arhami et al. 2009; Minguillon et al. 2008). Strong growth in cargo volume and its associated goods movement are expected for the foreseeable future, giving rise to substantial local community concern regarding the air quality impacts of the ports (Hricko 2008). Recent studies of size-resolved particulate matter near the ports indicate high spatial variability for the elements associated with motor vehicle and ship emissions, among other sources (Krudysz et al. 2008; Arhami et al. 2009). Total particle number concentrations alone are reported here—size distribution measurements are presented in a companion paper (Krudysz et al. 2009).

EXPERIMENTAL METHODS

This study was conducted at 14 sites in the Los Angeles air basin from February 12, 2007 through December 11, 2007 in coordination with the other investigators participating in the HCMS. Site information is provided in Table 1 and the relative positions of the sites to each other are shown in Figure 1. As mentioned above, previous work has identified motor vehicles to be the dominant source of UFPs in the Los Angeles area. Principal roadways, including major interstate freeways and heavily travelled surface streets are shown in Figure 1 and criss-cross the study area. Sites in the vicinity of the Ports—described in detail below—were chosen in urban industrial and mixed industrial/residential areas by taking into consideration meteorology and the strength and location of probable nearby sources while

TABLE 1

Site information including the designation code, geographic co-ordinates, site and equipment elevations, sampling period, and (CPC) data recovery

Site designation†	Latitude	Longitude	Site elevation (m)	Inlet elevation (m)*	Anemometer elevation (m)*	Sampling period	Data recovery (%)
LA1	34° 1′ 9″ N	118° 16′ 39″ W	61	4.6	9.1	2/15–12/15/2007	97%
SP1	33° 42′ 54″ N	118° 16′ 28″ W	1	3.0	3.4	6/1–12/12/2007	91%
W1	33° 45′ 57″ N	118° 15′ 22″ W	3	13.7**	14.0**	2/22–12/11/2007	95%
W2	33° 46′ 16″ N	118° 15′ 52″ W	4	3.2	3.4	4/27–12/12/2007	87%
W3	33° 46′ 48″ N	118° 14′ 55″ W	4	4.6	3.4	2/24–12/12/2007	92%
LB1	33° 44′ 40″ N	118° 13′ 5″ W	5	3.0	3.4	3/12–12/12/2007	87%
LB2	33° 46′ 57″ N	118° 13′ 0.7″ W	2	5.6	6.9	2/16–12/11/2007	84%
LB3	33° 46′ 54″ N	118° 12′ 49″ W	2	3.0	3.4	3/7–5/30/2007, 11/21–12/11/2007	98%, 45%
LB4	33° 47′ 0.9″ N	118° 12′ 13″ W	4	3.4	3.4	8/2–12/11/2007	99%
LB5	33° 47′ 16″ N	118° 12′ 29″ W	4	5.6	5.9	2/14–12/11/2007	88%
LB6	33° 47′ 35″ N	118° 13′ 7″ W	4	3.4	5.2	2/13–11/12/2007	88%
LB7	33° 47′ 55″ N	118° 12′ 44″ W	5	5.9	6.9	2/23–12/11/2007	91%
LB8	33° 48′ 9″ N	118° 13′ 12″ W	6	4.6	5.2	3/7–12/11/2007	86%
LB9	33° 48′ 18″ N	118° 13′ 21″ W	6	2.7	3.4	3/13–12/11/2007	88%

†The site codes include a city identifier and number. The sites are numbered roughly from S – N (LA = Los Angeles, SP = San Pedro, W = Wilmington, and LB = Long Beach).

*height relative to ground.

**roof elevation estimated to be 10.7 m.

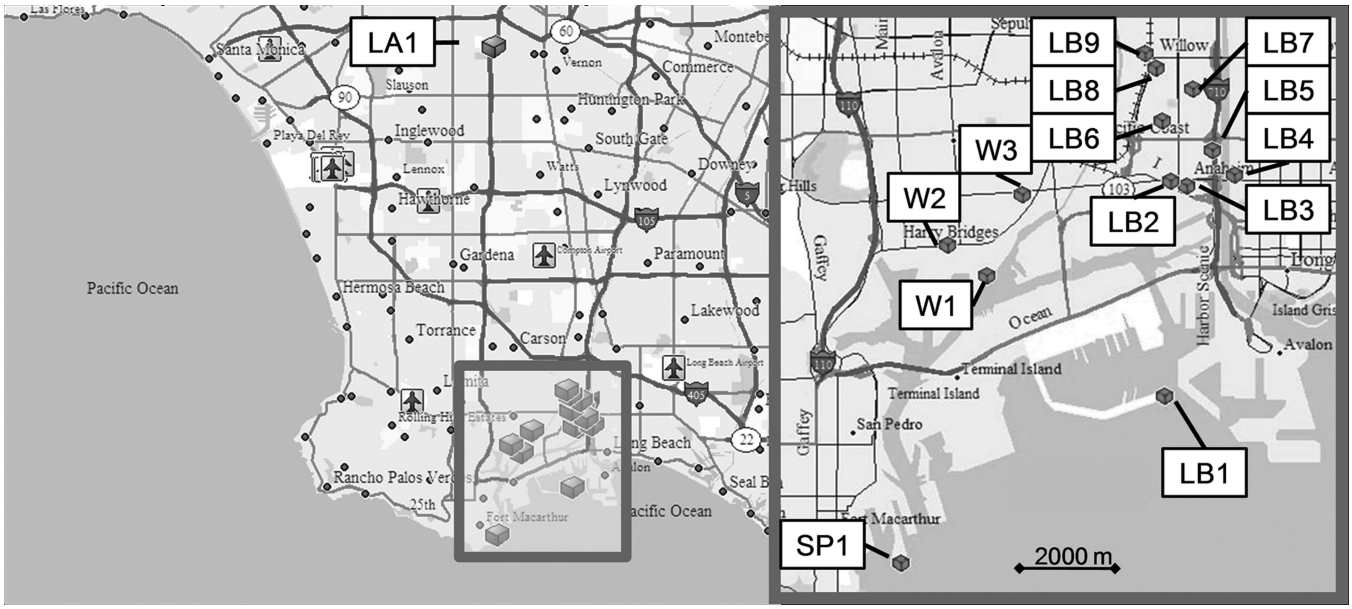

FIG. 1. Site locations—the exploded view of the San Pedro Harbor area in the grey box is shown on the right. Specific distances between sites are provided in the text. Note the numerous important roadways in the study area (described further in the text). (Figure provided in color online.)

also maintaining the study goal of monitoring in a limited area. With the possible exception of the two "harbor" background sites in/on San Pedro Harbor itself, the mix of probable sources at any given study site was reasonably representative of multiple locations within the Harbor communities. It is important to recognize that distinguishing between residential and commercial sites as a meaningful framework to interpret the data presented here is of limited utility as the majority of the sites are located in close proximity to each other and the predominant local sources (e.g., motor vehicle or similar). Quantifying variability within this limited spatial scale is the goal of this study. A detailed description of the atmospheric processes governing the loss of UFPs is beyond the scope of this article. However, given the dominant sources, the sinks suggested for urban and near-roadway environments (e.g., evaporation of semi-volatile aerosols following dilution) are likely (Zhu et al. 2002a,b; 2005; 2006; Zhang et al. 2004; Jacobson and Seinfeld 2004). Due to delays in obtaining access, sampling did not start at all sites on February 12 (see Table 1).

Site Descriptions

One site ("LA1") was selected near downtown Los Angeles to provide a regional context to the observations being made in the vicinity of the Ports (Figure 1, Table 1). LA1, located ca. 32 km north of the Ports, is the Southern California Particle Center Supersite located at the University of Southern California (USC) where extensive air quality measurements have previously been reported (Sardar et al. 2005; Moore et al. 2007; Ning et al. 2007). It is an urban background site influenced by traffic from the I-110 freeway located approximately 150 m to the west. There are two clusters of sites in the Port area—San Pedro/Wilmington and West Long Beach. With the exception of the harbor background sites in/at the Harbor itself, the sampling sites in the two clusters are all located within approximately 2000–2600 m of each other near multiple sources of ultrafine particles. These sources include light-duty motor vehicle, rail, and heavy-duty diesel vehicle (HDDV) traffic as well as other Port and Port-related activities (see Figure 1). These sites are shared with the concurrent particle size distribution study (Krudysz et al. 2009) and use identical nomenclature.

Site SP1 is located at the only typically vacant berth (Berth 47) in the Port of Los Angeles (PoLA) and ships/other harbor craft are not regularly docked there. It is a harbor background site surrounded by San Pedro Harbor on two sides, typically upwind of Port activities and not near significant motor vehicle traffic. Sites W1–W3 are within ca. 2200 m of each other. Site W2 is located approximately 7200 m NNE of site SP1 at the intersection of Harry Bridges Boulevard and Fries Avenue directly north of the PoLA and 2000 m south of the Wilmington city center. Harry Bridges is a major arterial roadway with significant HDDV traffic. Site W1 is located ca. 1300 m SE of W2 on a rooftop at Pier 195. It is across a shipping channel and approximately 600 m north of the PoLA. While W1 is located in an industrial area, it is not located near heavily traveled roadways. Site W3 is located in a mixed residential/commercial area approximately 1800 m NE of site W2. It is 300 m N of Alameda Street and 300 m WSW of the intersection of Anaheim and Alameda Streets. Both of these roadways have significant motor vehicle and HDDV traffic. Rail lines servicing the Ports also follow Alameda Street.

The eight West Long Beach sites are primarily located within a rectangle approximately bounded by the Terminal Island

Freeway (SR-103) to the west, Willow Avenue to the north, the I-710 on the east, and Anaheim Street to the south. The north-south and east–west gradients in the site locations were chosen to take advantage of known wind patterns (discussed below) and sources. Site LB1 is a companion harbor background site to SP1 located in the Port of Long Beach (PoLB). It is ca. 4300 m south of the major arterial intersection of Santa Fe Avenue, and Anaheim Streets with substantial HDDV traffic (Houston et al. 2008). Sites LB2 and LB3 are located in a commercial area 50 m E and 150 m WSW of this intersection. Site LB4 is an industrial area 10 m north of Anaheim Street, adjacent to the Los Angeles River, 1200 m E of Santa Fe Avenue, and 400 m east of the I-710 where HDDV traffic is up to 25% of the total (Zhu et al. 2002a). I-710 is a major conduit for HDDV leaving the Ports with cargo for inland locations. Site LB5 is 580 m north of Anaheim Street in an industrial area adjacent to the west side of the I-710. Site LB6 is 200 m north and 50 m east of the intersection of the Pacific Coast Highway and Santa Fe Streets. The Terminal Island Freeway (SR-103)—another major conduit for HDDV leaving the Ports—is located another 800 m west. Continuing 1000 m N on SR-103, site LB8 is located adjacent to a school immediately to the east of the roadway, and site LB9 is located approximately 20 m to the north of SR-103's termination at Willow Street. Site LB7 is located on a roof adjacent to the playground of another school approximately 1000 m west of the Terminal Island Freeway and 490 m east of the I-710. Sites LB7 and LB8 are in primarily residential neighborhoods near the commercial strip on Santa Fe Avenue. Proximity to roadways given the results of the previously mentioned studies (Arhami et al. 2009; Minguillon et al. 2008) is emphasized in these site descriptions. Additional information specific to each Harbor Community Monitoring Study site is available online through the California Air Resources Board's website.

Equipment

The standard equipment package installed at most sites included a temperature-controlled, insulated, all-weather enclosure, condensation particle counter (CPC), weather station, and laptop computer. Fifteen identical butanol-based CPCs (Model 3022A, TSI, Inc., Shoreview, MN) were obtained for this study and have a nominal 50% detection efficiency diameter of 7 nm increasing to approximately 100% for particles > 20 nm. All fifteen CPCs were returned to the manufacturer for factory re-calibration prior to the start of the study. The CPCs were controlled and the total number concentration recorded using Aerosol Instrument Manager software (v7.3, TSI, Inc., Shoreview, MN). The sampling inlet for each CPC was typically 2 m in length and 0.63 cm in diameter. At selected sites, inlets up to 3.25 m in length were used to locate the sampling point above local obstructions. The sampling stream was not conditioned prior to measurement and the sampling flow rate was 1.5 liters min^{-1} (lpm). Davis Vantage Pro2 or Pro2 Plus weather stations (Davis Instruments, Hayward, California) were installed at each site except LA1 where data were collected by an existing meteorological station. A single CPC was used to perform measurements at each site as far as possible.

Both the CPC and weather station data were logged continuously at one-minute intervals using Pacific Standard Time (PST). The standard operating protocol required weekly visits to download data, check equipment performance, and perform maintenance (instrument operation could not be checked remotely). The low and high flow rates of each CPC were measured and the flow rates adjusted if they exceeded 0.3 ± 0.03 lpm and 1.5 ± 0.2 lpm, respectively. During the summer, the routine CPC maintenance procedure was revised to include repeated drain/refill cycles of the butanol reservoir to remove condensed water.

Following factory re-calibration prior to the start of field sampling, side-by-side operation of the CPCs was conducted measuring ambient concentrations at site LA1. One-minute data were collected over several days for sets of 4–6 CPCs. The average slope of an individual CPC against the "mean" CPC is 1.04 ± 0.08 (mean $\pm$ standard deviation, range 0.93–1.21) with very high correlation (r^2 range 0.9–1.0) (Figure S1, supplemental data). Variations in performance between the CPCs could not be readily explained by measured differences in the low or high CPC flow rates or the re-calibration data supplied by the manufacturer. The side-by-side tests were repeated at the end of the sampling campaign (Figure S2, supplemental data). There is more scatter in the post-HCMS data, but the average slope changes little (0.98 ± 0.16, range 0.72–1.26) and the correlation remains high (r^2 is 0.98 ± 0.3). The ratio of post- to pre-study slope is $94 \pm 14\%$ (75–121% range). Given the relative consistency in these results, no corrections to account for variations in individual CPC performance were made to the mean data reported here. Observations using the longest inlet (3.2 m) were 3% less than those using a standard inlet, consistent with theoretical predictions using the Gormeley-Kennedy equations and particle size distribution data (Krudysz et al. 2009). No corrections for inlet length were made, but a 10% increase for data obtained while sampling at low flow rates (approximately 0.3 lpm) was added in the few instances applicable. Further, theoretical calculations suggest inertial losses for larger particles (e.g., 1 μm in diameter) in the inlets are negligible and are also ignored.

In this study, total particle number concentrations are measured. This is a reasonable surrogate for ultrafine particle number concentrations. Limited ambient aerosol particle size distribution data obtained as part of an earlier study at LA1 (Moore et al. 2007) and measurements during this study at W2 indicate that greater than 80% and 95% on average of the particles from 15 nm–20 μm are <100 nm and <200 nm in diameter, respectively. Additionally extensive particle number size distributions measurements from ca. 15–700 nm in mobility diameter were performed throughout this study with co-located equipment (reported in Krudysz et al. 2009). These data also indicate that

80–90% of observed particles were in the UFP size range. Earlier studies in the Los Angeles basin (Fine et al. 2004; Singh et al. 2006) at different locations also support this observation. Furthermore, in contrast to observations in other cities, extensive particle size distributions in the Los Angeles basin—particularly in the "source" region near the Harbor—exhibit minimal multimodality in the UFP size range (Krudysz et al. 2009; Fine et al. 2004; Singh et al. 2006). In the urban environment studied here, significant concentrations of particles less than 7 nm are likely to be present (e.g., Shi et al. 2001, among others) from both motor vehicle/combustion emissions and possibly new particle formation events. Indirect evidence from eastern locations downwind from these study sites in the Los Angeles basin suggest new particle formation occurs (Fine et al. 2004), although to date no direct evidence of these events has been obtained. Studies in other urban locations suggest that new particle formation events may be likely, particularly during warm, sunny periods (Petaja et al. 2007; Wehner and Wiedensohler 2003), although the conditions responsible for new particle formation events in all locations are not well known. As most observations of these events indicate they are regional in nature (Kulmala et al. 2004 and references therein) it is possible if they are occurring that they are affecting all study sites—with the possible exception of site LA1—similarly. There is some evidence (discussed later) of secondary UFP production at LA1. In the context of the goals of this study, it is important and relevant to note that it has not yet been established that sub-7 nm diameter particles—particularly given their very short atmospheric lifetimes on the order of minutes—play a significant role in the adverse health effects associated with UFPs (Donaldson et al. 1998; 2002; Delfino et al. 2005; Sioutas et al. 2005; Li et al. 2003), although this may well warrant further investigation (Shi et al. 2001). Therefore we chose to use the 3022As as this allowed us to directly compare our observations to earlier studies as well as to obtain data simultaneously at 13–14 sites which is necessary for subsequent modeling work. Despite these caveats and the differences observed between CPC performance during side-by-side operation discussed above, our assumption that the total particle number concentration is a representative surrogate for the UFP number concentration associated with health impacts is reasonably valid.

All one-minute weather and CPC data were reviewed and screened for irregularities using a procedure similar to that reported elsewhere (Puustinen et al. 2007) with comparable data removal rates. In this paper, only hourly averages are reported. Overall, data are available for approximately 90% of the sampling periods at each site. For most months and sites, data availability exceeds 90%, but water condensation in the butanol reservoir in June and July (75% data availability overall, 65% minimum value) reduce the campaign's average. February and December data are not reported in this article, but it should be emphasized that these data are consistent with the trends observed in March and November, respectively.

Statistical Analysis

The correlation coefficient (r) is a standard method used to evaluate the (linear) relationship between paired data points. The coefficient can vary from 0 (no correlation, independent data points) to $\pm$ 1 indicating perfect positive or negative correlation. In this study, the correlation coefficient is calculated monthly between specific site pairs using hourly mean number concentration values. This analysis helps to determine what fraction of the number concentrations at any particular site can be explained by the concentrations simultaneously measured at the other sites. One limitation of this method, however, is that perfect correlation can be observed between two sites where the concentrations vary by a consistent factor. In other words high correlations between paired sites would only imply uniform temporal variation (Lianou et al. 2007). Therefore, calculating r alone would not necessarily provide sufficient information to characterize the variability between two sites.

Another useful method to characterize the spatial variability between site pairs is the coefficients of divergence (COD) method. The COD is defined as:

$$\mathrm{COD}_{jk} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_{ij} - x_{ik}}{x_{ij} + x_{ik}}\right)^2}$$

where x_{ij} is the ith concentration measured at site j for a given sampling period, j and k are two different sites, and n is the number of observations (Krudysz et al. 2009). By inspection, the COD for a given site pair will vary from 0—where concentrations are identical at both sites—to 1—where concentrations are highly different. The COD therefore specifically addresses the limitation to the correlation coefficient described above. A low COD value indicates a high level of homogeneity in concentrations between site pairs, and a high COD, the opposite. CODs larger than 0.2 can be considered heterogeneous (Wilson et al. 2005). CODs have been used to quantify the variability in $PM_{2.5}$ and PM_{10} mass concentrations between specific site pairs in several studies—for example in the Los Angeles region where CODs varied from 0.07–0.48 (Pinto et al. 2004). Most maximum values reported in California and at other locations in the United States and the world were on the order about 0.2 and less (Pinto et al. 2004; Kim et al. 2005; Wilson et al. 2006). Overall, these results imply a fair amount of spatial homogeneity between the mass concentrations measured. However, while $PM_{2.5}$ mass concentration CODs may be relatively low, recent studies of Los Angeles-area $PM_{2.5}$ individual chemical components yield widely varying CODs indicating homogenous (Wongphatarakul et al. 1998) to very heterogeneous spatial distributions (Krudysz et al. 2008), as also observed for trace elements in St. Louis (Kim et al. 2005). Similarly, concurrent observations of PM mass and number concentrations in four European cities using paired residential and city center sites yield homogeneous CODs for the mass measurements ($PM_{2.5}$ and PM_{10}, 0.02–0.10 COD range), but heterogeneous values for

particle number concentrations (0.07–0.53 range) (Lianou et al. 2007). In order to evaluate intra-community variability in total particle number concentrations, both the correlation coefficient and the COD for each individual site pair will be calculated. Both values together facilitate the determination of the magnitude of the observed variability and help to address how dense monitoring networks for UFP in urban "source" regions may need to be.

RESULTS AND DISCUSSION

Given the high temporal and spatial resolution of the data (e.g., 1 min particle number concentration, wind speed, wind direction, temperature, relative humidity, and other parameters collected at up to 13 sites simultaneously for approximately 10 months) it is not possible within the space available to provide a detailed description and interpretation of all observations. Therefore we present the following data primarily as hourly averages calculated by month. Consistent differences in observations between sites therefore stem from persistent differences in sources and meteorology and may be useful from a regulatory perspective. A limited discussion of the typical stable meteorological conditions at the sites provides an overview of study conditions. More specific discussion of site meteorological conditions is included in the interpretation of the number concentration data where appropriate.

Meteorology

In general, meteorological conditions during the study exhibited limited diurnal and seasonal variability. Table 2 shows the mean temperature and relative humidity at 3 selected sites—LA1 (the regional site, 32 km inland), LB1 (on the San Pedro Harbor), and LB8 (5 km inland from the Harbor). Temperature tends to peak mid-day, declining overnight and into the early morning, and relative humidity (RH) follows the opposite pattern. At LB1, cooler mean temperatures are observed in March (14.3°C) warming to 20.7°C in August before cooling again in November (16.9°C). The RH (70–85% range) is relatively stable and high, and variability in both the temperature and RH is muted due to the presence of the Harbor. Moving inland to LB8, the same seasonal pattern in temperature is observed, although it is up to ca. 2°C warmer on average and the RH is correspondingly slightly reduced (65–74% range). At LA1, mean temperatures are another ca. 1°C warmer than at LB8 and mean RH is also lower (51–64% range). As the sites move further inland, the moderating influence of the Harbor is reduced, variability increases and some urban heat island effect is observed. The conditions at LB1 and LB8 bound the observations made at the other sites in the Harbor area.

Wind speed and direction can significantly affect observations of ultrafine particle number concentrations. A general discussion of the wind patterns observed at the study sites during the field measurement campaign is included here. More specific information will be provided as necessary in the presentation of the UFP number concentration results that follow. (Selected wind roses for September 2007 are included in the supplemental figures for reference (Figures S3–S7).) At the regional site LA1, wind was most often from the SW (28%), WSW (15%), and S (12%) and typically light (predominantly < 2.0 m s^{-1}). Calms (16%) were observed overnight with wind speed increasing into the afternoon. Given this pattern, LA1 was usually downwind from the I-110, particularly during daylight hours. As the study progressed from March into the spring and summer, peak wind speeds increased slightly (mean wind speed in March ca. 1 m s^{-1} and ca. 1.6 m s^{-1} in July) and fewer calms were observed overnight. These observations are very consistent with previous measurements reported for this site (Moore et al. 2007). Occasionally during the fall, this consistent pattern was disrupted by Santa Ana wind conditions in the Los Angeles basin (dry persistent offshore winds driven by synoptic high pressure

TABLE 2
Temperature and Relative Humidity—monthly mean for select sites[a,b]

	LA1		LB1		LB8	
Month	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
March	16.7 ± 4.4	51 ± 25	14.3 ± 1.2	78 ± 6	15.5 ± 3.0	70 ± 12
April	16.2 ± 3.2	61 ± 19	14.3 ± 0.9	79 ± 4	15.9 ± 2.6	70 ± 11
May	17.7 ± 4.0	59 ± 19	15.5 ± 1.0	78 ± 4	17.3 ± 2.7	68 ± 10
June	19.6 ± 3.5	64 ± 14	17.2 ± 1.1	84 ± 3	19.0 ± 2.6	74 ± 10
July	22.6 ± 3.3	62 ± 14	19.6 ± 1.0	85 ± 3	22.0 ± 2.7	73 ± 10
August	23.5 ± 3.9	58 ± 15	20.7 ± 1.4	82 ± 6	22.9 ± 3.0	70 ± 11
September	21.7 ± 4.7	56 ± 16	18.8 ± 1.3	80 ± 5	21.0 ± 3.1	69 ± 12
October	20.3 ± 4.7	50 ± 23	18.1 ± 1.6	73 ± 6	18.9 ± 4.0	65 ± 14
November	16.9 ± 4.0	58 ± 26	15.6 ± 1.1	78 ± 3	15.9 ± 2.8	73 ± 10

[a]Based upon hourly mean data.
[b]Mean ± standard deviation.

systems over the southwestern United States). During these periods (e.g., October 19–26), SE and SSE components in the wind rose are observed, particularly from 8 pm through noon. In the afternoon, the SW component is again evident. Measured wind speeds at LA1 remain light and variable throughout the Santa Ana conditions.

Similar to the observations at LA1, wind patterns at the study sites near the Harbor tended to be relatively stable throughout the study period. Overall wind speeds tended to increase into the late summer. Calms were observed overnight, with fewer observed in the spring/summer months. Mean and peak wind speeds were often higher closer to the Harbor where there were fewer obstructions to the flow. Mean monthly wind speeds overall, however, remained relatively light (not more than a few m s^{-1}), although this may in part reflect the relatively low installation height of the anemometer. Some sites (e.g., W1, W2, LB4, LB5) exhibit a predominantly onshore/offshore (e.g., S/N) flow pattern with the onshore flow strongest in the morning followed by the offshore return flow in the afternoon. Many of the farther inland sites in Long Beach exhibit the same general pattern (e.g., LB2, LB3, LB6, LB7, LB8, LB9) but include the development of a strong WNW or NW wind in the early afternoon that persists into at least the early evening. Santa Ana wind conditions generally produced somewhat lighter winds overall and a significant overnight N component.

Total Particle Number Concentrations

The hourly average data are first presented for select individual sites by alternating month to highlight the differences/similarities between sources and observations at these sites. Comprehensive hourly data for each cluster showing alternating months follow. Alternating months only are shown to improve the clarity of the figures. A few examples are presented where specific impacts on total particle number concentrations are identified (e.g., weekday vs. weekend concentrations), followed by the monthly mean 24 h concentrations and selected correlation coefficient and COD results calculated across all site pairs. While not shown in each figure for clarity, the standard error of the mean for each hour at most of the sites was about 10%. The two exceptions are the harbor background sites (SP1, LB1) where the standard error was ca. 10–30% primarily due to lower mean concentrations. Geometric mean concentrations are not provided, but, where calculated, were typically 80–90% of the arithmetic mean.

At LA1 data considered to be typical of a Los Angeles urban background site were observed (Figure 2a). In the early spring and late fall months, a distinct early commute peak from light duty gasoline vehicles (LDGV) between 5–10 am is evident. As overnight temperatures and the mixing height increase into the late spring and summer, this peak almost vanishes (e.g., July), but a later peak in the early afternoon (12 noon–4 pm) slightly increases, despite the mixing height change. We interpret this peak to represent secondary production of particles, which is consistent with earlier summertime observations of changes in physical properties and chemical composition in the UFP reported for the same site (Moore et al. 2007; Ning et al. 2007). The evening peak in the data are consistent with secondary condensation of low vapor pressure compounds into the particle-phase growing sub-7 nm particles into the range observable by the CPC and a decreasing mixing height, both of which have also been observed previously in Los Angeles (Kuhn et al. 2005; Biswas et al. 2007). At several sites in the study area, however, the influence of HDDV traffic and the regular goods movement patterns are starkly evident and very different from the LA1 observations. At site LB9, only limited early morning commute peaks and no distinct secondary afternoon or evening peaks are observed (Figure 2b). Instead, particle number concentrations start to climb around 5 am, reach a plateau at 40,000–50,000 cm^{-3} from 10 am–4 pm and then start a slow decline into the evening. Peak concentrations decline somewhat in the summer months and the concentration gradient in the morning is less steep due to higher mixing heights and warmer overnight temperatures consistent with their impacts on site LA1 (discussed above). Limited measurements at a nearby intersection indicate up to 600–700 HDDVs per hour pass by during the day en route to the adjacent Intermodal Container Transfer Facility (ICTF) (Houston et al. 2008), and traffic can become considerably backed up, particularly in the afternoon. Therefore, this UFP concentration pattern is representative of HDDVs and goods movement from the Ports. A similar pattern was also observed at site W2 (Figure 2c) where concentrations are somewhat lower and limited data suggest this site experiences comparatively lighter HDDV traffic compared to the ICTF (Port of Los Angeles 2004; Houston et al. 2008).

Figures 3 and 4 show the hourly mean data for the San Pedro/Wilmington and West Long Beach clusters. In both clusters, the LA1 data are included for regional context. In March, site W3—near the Alameda and Anaheim intersection—shows a similar early morning peak as LA1 (Figure 3a). While the available traffic data are out-of-date, this would be consistent with the relatively large fraction of LDGV at this intersection compared to others (e.g., W2) in the Harbor area (Port of Los Angeles 2004). Site W2 shows relatively constant concentrations throughout, as it is immediately adjacent to traffic sources. Concentrations at both sites are not appreciably different from those observed at LA1. As the sampling campaign progresses (Figures 3b–3d), sites W2 and SP1 come on-line showing impacts from HDDV traffic (discussed previously) as well as the lower harbor background concentrations. Total particle number concentrations at site W3 in the mixed residential/industrial area remain comparable to or larger than site LA1, downwind of the I-110, although site W3 is much further away from freeways. The morning commute peak returns to site W3 as the fall progresses. Even site W1—at least a 1000 m from high traffic roadways—shows concentrations comparable to LA1 with observations roughly double those observed at the harbor background sites. Given W1's location across the channel from the

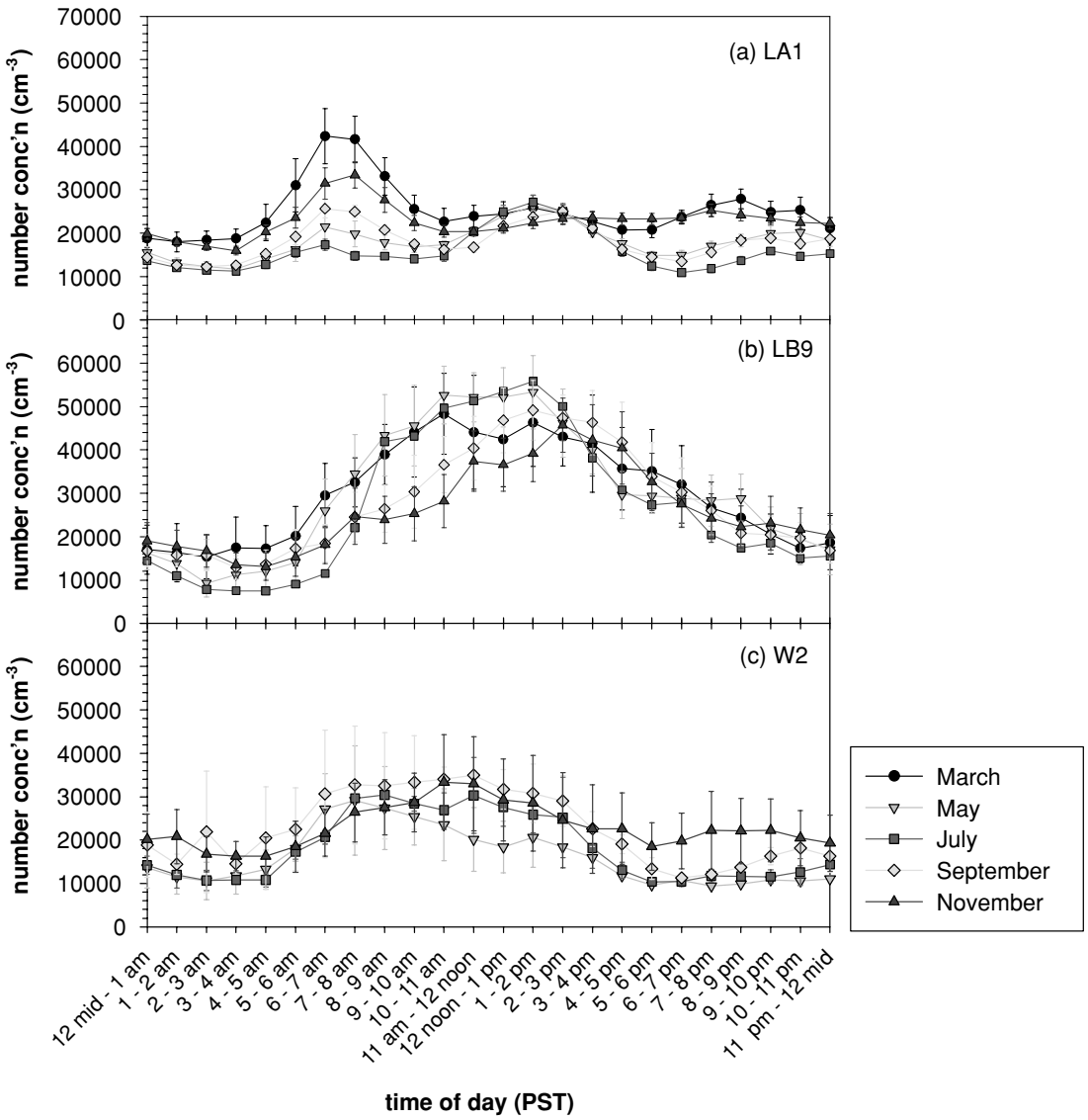

FIG. 2. Hourly average concentrations shown by alternating month (standard error of the mean shown) for site (a) LA1, (b) LB9, and (c) W2.

Ports, this suggests that Port-related activities are primarily responsible for the change in concentrations.

In the West Long Beach cluster (Figure 4a–e), total particle number concentrations at many of the sites are higher than at LA1, particularly in the afternoon. While this is expected at site LB5, immediately adjacent to the I-710, this is also true at LB2 due to the high LDGV and HDDV traffic volume (Houston et al. 2008; Port of Los Angeles 2004) and the other sites with the exceptions of the harbor background site, LB1, and LB6 where particle number concentrations are comparable. Of particular note is the persistent HDDV signal at LB9 during the day, apparent at many of the sites. The prevailing westerly winds that affect the West Long Beach cluster in the afternoon may well be responsible. While the morning commute signal remains evident at LB5 throughout the study period, it is stronger in the early spring and fall as observed at LA1. As the fall progresses, concentrations at LB1 increase and are no longer distinctly lower than observed at the other sites as shifting wind patterns cause LB1 to be consistently downwind of the PoLB.

The two harbor background sites—SP1 and LB1—generally yielded the lowest total particle number concentrations of the study sites as they were mostly upwind of the nearby UFP sources (Figure 5 includes monthly data not shown in Figures 3–4). Concentrations were generally comparable between the two, although in the fall, LB1 concentrations (as discussed above) became consistently higher than SP1's. SP1 total particle number concentrations were occasionally relatively elevated than LB1's during summer afternoons where the wind shifted and the site was downwind of downtown San Pedro (not shown). Overall concentrations increased in the cooler months but consistent

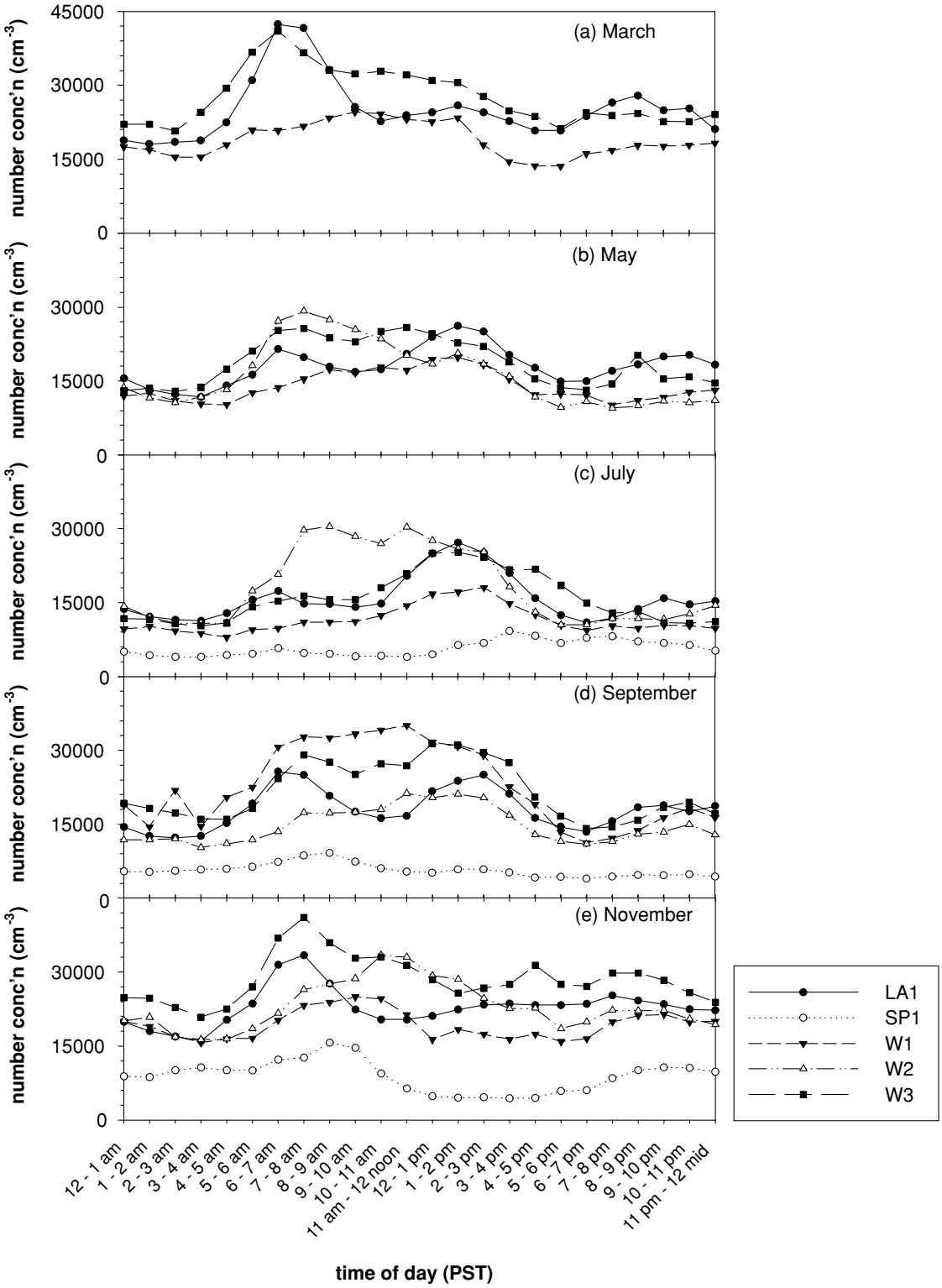

FIG. 3. San Pedro/Wilmington site cluster—hourly average concentrations shown by alternate month (a) March, (b) May, (c) July, (d) September, and (e) November. Site LA1 is shown for context.

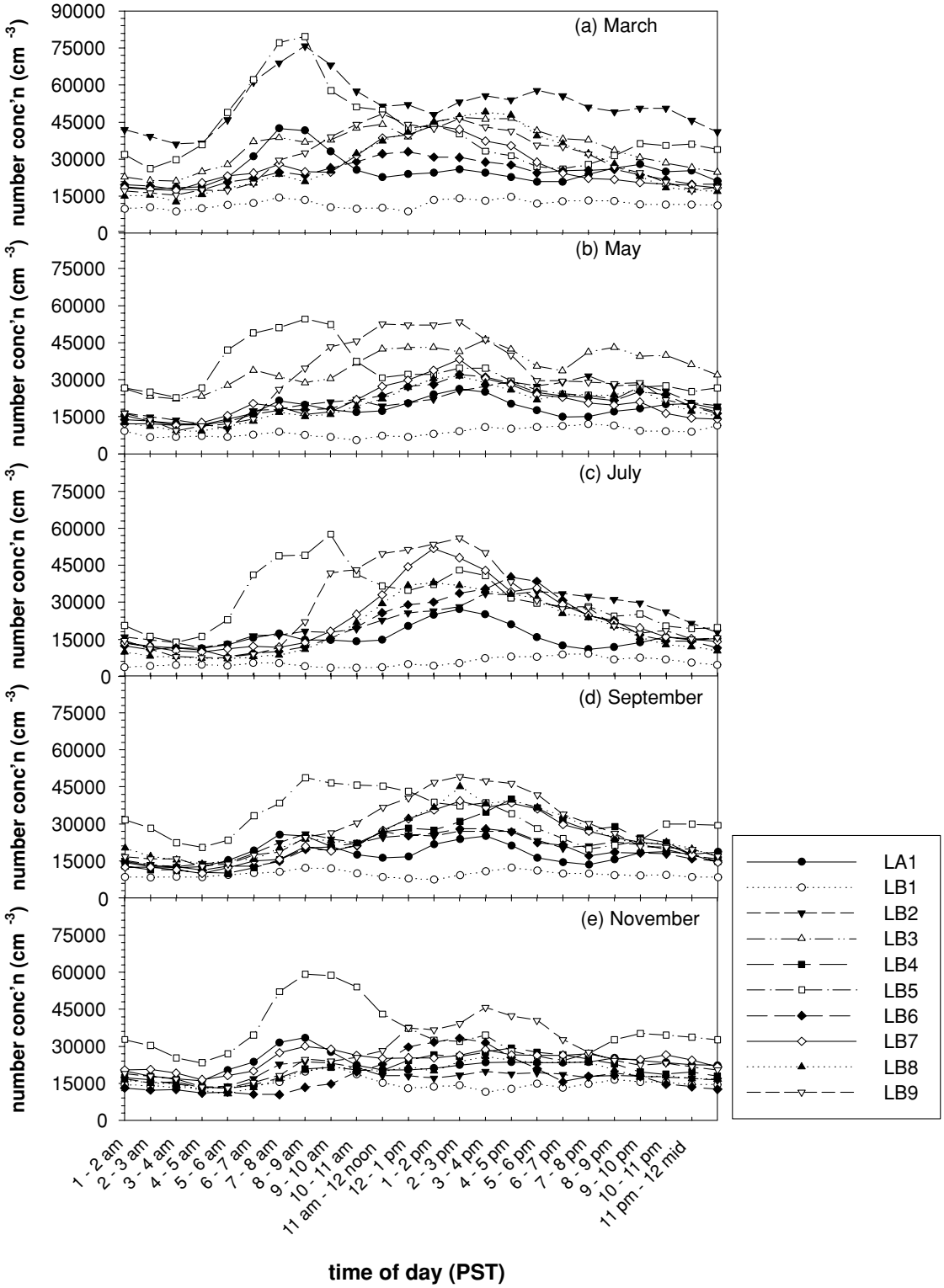

FIG. 4. West Long Beach site cluster—hourly average concentrations shown by alternate month (a) March, (b) May, (c) July, (d) September, and (e) November. Site LA1 is shown for context.

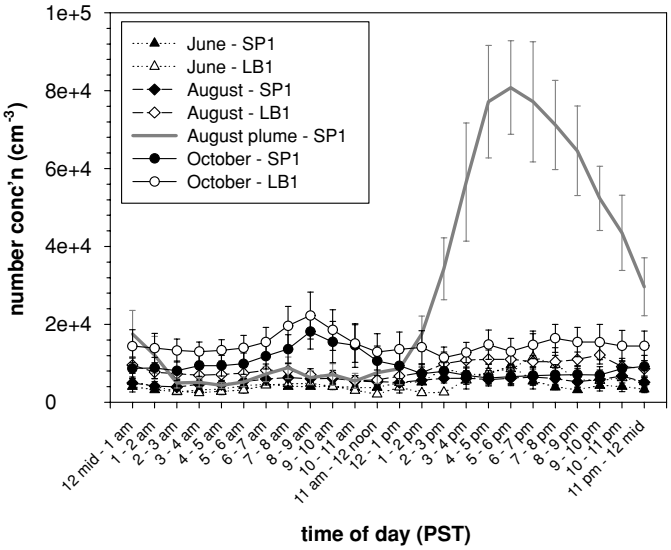

FIG. 5. Harbor background site comparison: hourly mean number concentration data at sites SP1 and LB1 shown for selected alternate months ("August–SP1" excludes August 5–13, which are included in the "August plume–SP1").

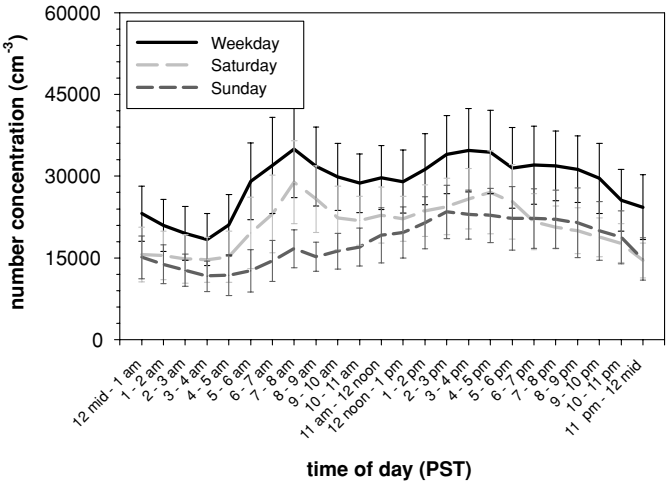

FIG. 6. Site LB2: Day-of-the-week diurnal concentration profile comparison calculated using all available monthly mean data.

diurnal patterns were infrequently observed. There was one distinct event, however, during early August where SP1 was strongly impacted each afternoon by a ship's plume. The bulk carrier Xiamen Sea was docked at Berth 47 while undergoing engine repairs intermittently through June–August. The ship's buoyant plume—even if present and upwind of the sampling site—was above our sampling site and no evidence for significant plume impacts from this source were observed prior to August 5. On August 5–13, highly elevated UFP concentration plumes were measured every afternoon, with hourly concentrations occasionally exceeding 140,000 cm^{-3}. Concurrent notes indicate the plume was from the ship. These observations suggest the potential for near-field impacts from strong sources such as ship plumes.

Day-of-the-week differences in PM mass concentrations have been routinely observed where motor vehicle traffic is the dominant source of PM (Motabelli et al. 2003; Aalto et al. 2005; among others). We observe similar differences in the number concentration at the selected study sites representative of the overall study (Figure 6, Table 3, Figures S8–S9). Saturday concentrations follow a similar pattern to the mean weekday concentrations, if somewhat lower in overall amount and Sunday's are lower yet. There is a larger relative reduction in total particle number concentration during the weekend at the sites near the Ports (70% and 60% on Saturday and Sunday, respectively, Table 3) than there is at LA1 near downtown Los Angeles (90 to 80%). This again indicates the importance of commercial traffic in the Port area. As observations in European cities show (Table 3), the amount of change depends very strongly on the measurement location, including the proximity to industry, roads and traffic. In the last few years, the Ports have begun to implement a program ("Pier Pass") to shift container movement via truck to off-peak hours (evenings and weekends). As more HDDV movement is shifted, these day-of-the-week patterns may well change.

Wind patterns can have a strong effect on total particle number observations as sources shift upwind of the fixed monitoring sites. Occasionally during this study, we encountered relatively extended periods with different meteorology—the warm, dry off-shore winds known as the Santa Anas (discussed previously). These occurred over approximately 20 of the 61 days in October and November 2007, including several large wildfires on October 20–21. Visibility was poor in the Los Angeles basin for several days following the start of the fires and elevated CO concentrations consistent with the impact of a fire plume were observed October 23–26 in northern Long Beach. We observe differences in total particle number concentration on these four fire days as well as on all of the twenty Santa Ana wind condition days. At site LB1 (Figure 7), for example, Santa Ana wind conditions—with or without the specific fire days—produce relatively elevated total particle number concentrations in the early morning (12 midnight–4 am) with a strong peak apparent from 6 am–12 noon. This peak appears to be consistent with traffic sources, although the sampled air travels over the Port of Long Beach during these periods. Fire-impacted concentrations are not noticeably different from the rest of the Santa Ana days indicating that these events did not strongly affect total particle number concentrations. As the study area was hundreds of km downwind from the fires, this is not surprising. While some sites show similar strong changes in total particle number concentrations during the Santa Ana wind conditions (e.g., LA1, LB5, LB7, B47), not all sites did (e.g., LB2, LB4) (see Figures S10–S11). Strong local UFP sources in close proximity to the monitoring station (e.g., LB9) appear to overwhelm additional signals, if any, associated with the wind shift.

The 24 h daily mean concentrations are as low as 5,000 cm^{-3} (SP1, LB1) to over 40,000 cm^{-3} (LB2, LB5) (Figure 8). These concentrations are similar to those observed elsewhere for

TABLE 3

Day of the week comparison between mean 24 h concentrations for selected Los Angeles basin sites (this study) and European cities (data from Aalto et al. 2005)

Day of week	Helsinki number concentration (#/cc)	Barcelona number concentration (#/cc)	Rome number concentration (#/cc)	Augsburg number concentration (#/cc)	Stockholm number concentration (#/cc)	LA1 number concentration (#/cc)	LB2 number concentration (#/cc)	LB9 number concentration (#/cc)
Weekday mean	12,540	42,348	46,009	10,821	11,196	21,340	28,689	33,820
Saturday	62%	81%	87%	88%	73%	87%	73%	69%
Sunday	55%	65%	74%	76%	72%	80%	62%	64%

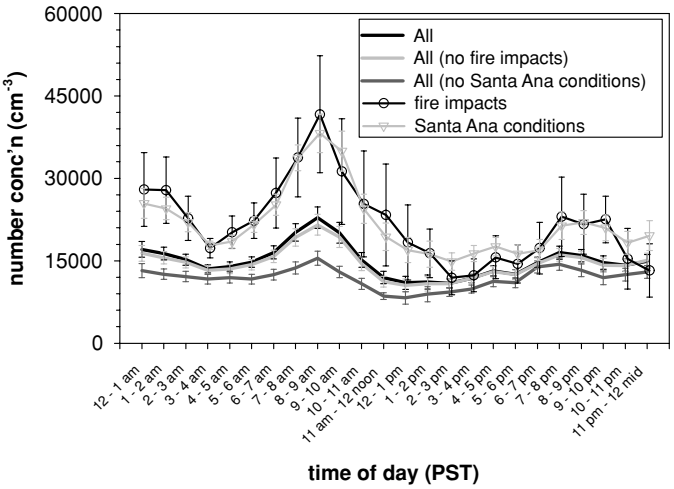

FIG. 7. Site LB1: October and November 2007 ("all") hourly mean number concentration data with fire impacted days and days with Santa Ana wind conditions separated out (standard error of the mean shown).

primarily urban locations (20,000–80,000 cm^{-3} (Buzorius et al. 1999), 13,000–26,000 cm^{-3} (Tuch et al. 2006), 12,500–20,300 cm^{-3} (Puustinen et al. 2007), 10,000–45,000 cm^{-3} (Aalto et al. 2005)). A distinct seasonal pattern, with relatively higher levels observed in the fall/winter, is also consistent with prior observations (Singh et al. 2006; Aalto et al. 2005; Harrison and Jones 2005; Buzorius et al. 1999). Many of the sites in Wilmington and West Long Beach have similar concentrations to those observed at LA1 near downtown Los Angeles. There are substantial differences, however, between sites only several hundred meters apart due to differences in proximity to traffic and other strong UFP sources. During 2002–2003, the CHS studied different cities within the Los Angeles air basin (Singh et al. 2006). Data from the CHS Long Beach site (farther inland than the Long Beach sites here and influenced by the I-405) are consistent with those obtained from this study (Figure 8). Note, however, that the inter-urban variability observed between cities in the Los Angeles basin appears to be less than the intra-urban variability observed between sites in this study. Clearly, this stems from study site locations chosen specifically because of their proximity to UFP sources. However, this observation confirms how relevant spatial scales and a detailed knowledge of likely sources are to understanding variability in total particle number concentrations between sites. It is also useful to be able to quantify the degree of variability between sites.

Figure 9 shows the overall hourly CODs and correlation coefficients calculated across all site pairs for all of the study data. (Additional correlation coefficient and COD data for all sites pairs at each site are shown in Figures S12–S25 and Table S1, supplemental data.) The hourly CODs for the entire study are shown together (Figure 9a) because the month-to-month variations were small. The median COD was approximately 0.30–0.35 for the entire study, and the range between the 1st and 3rd quartiles was mostly on the order of 0.20 units (mean CODs of approximately 0.05 were calculated from the December 2007 side-by-side testing for context). This suggests that overall the total particle number concentrations are moderately heterogeneous for the sites chosen. The correlation coefficients (Figure 9b) are shown to match the COD data, although somewhat more seasonal variability was observed with the correlation somewhat better during the summer than in the spring or fall. The median correlation coefficient varied from 0.30 to 0.56 and there is considerable scatter in the data for every hour with values spanning the entire range. The correlation between site pairs is modest, particularly considering the close proximity of these sites to each other. The diurnal patterns in the correlation coefficient and COD data vary (Figure 9). They do not exactly

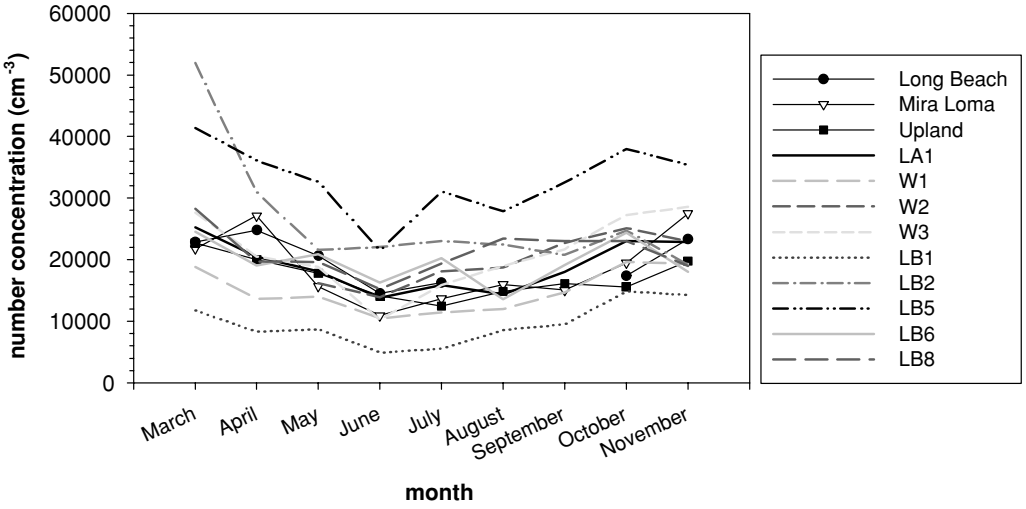

FIG. 8. 24 h daily mean number concentrations by month and selected sites including data from the 2002–2003 Children's Health Study in California (named locations, data from Singh et al. 2006).

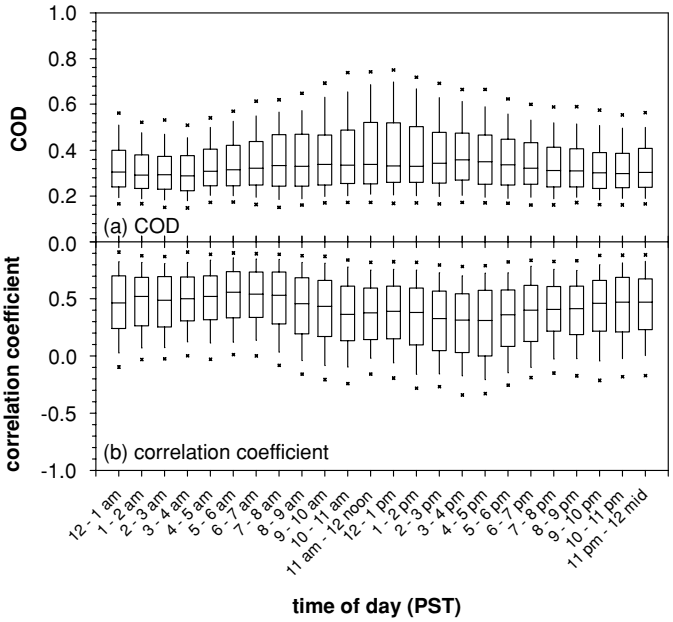

FIG. 9. Coefficients of Divergence (CODs, (a)) and the correlation coefficient (r, (b)) calculated for the entire study based upon all hourly mean number concentration data and using all site pairs. In both (a) and (b), the 1st quartile, median, and 3rd quartile are represented by the box. The whisker/cross represent the 10%/5%, and 90%/95% values.

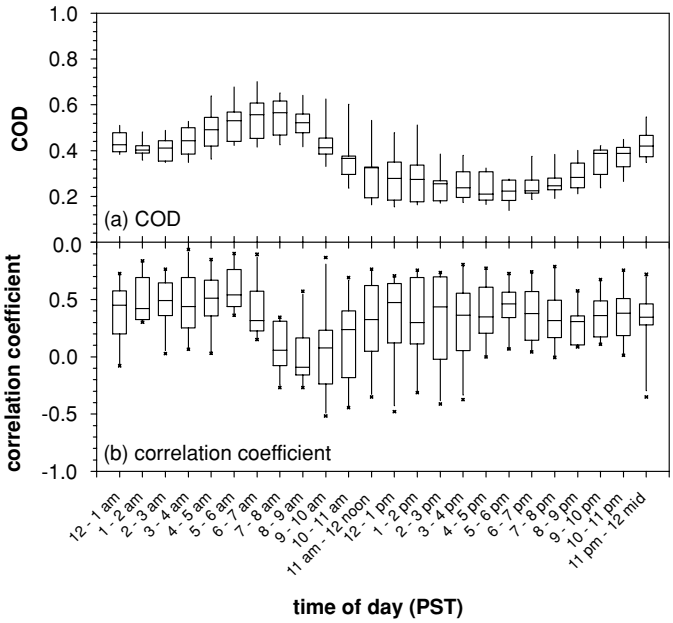

FIG. 10. Coefficients of Divergence (CODs, (a)) and correlation coefficient (r, (b)) calculated for the LB5-LB8 site pair only for all data. In both (a) and (b), the 1st quartile, median, and 3rd quartile are represented by the box. The whisker/cross represent the 10%/5%, and 90%/95% values.

mirror each other, although overall relatively higher correlation coefficients tend to be associated with relatively lower CODs. No fixed numerical relationship, however, between COD and r values is observed, in general, from site pair-to-site pair. Figure 9 indicates that meaningful variability occurs over the limited geographical area investigated (the LA1 site pairs are included in Figure 9, and do not yield appreciably different results when separated out (Figure S12), although the specific UFP sources/sinks were different than those in the Harbor area).

A representative sample of the diurnal variation for an individual site pair (LB5–LB8) provides COD results that vary from a median value of approximately 0.2–0.55 during the study in a consistent diurnal pattern, but the variability observed for any specific hour was relatively limited (Figure 10a). The consistent diurnal pattern in COD values for specific site pairs reflect the influence of particular sources (e.g., HDDV activity at W2) and their relative persistence throughout the study. The correlation coefficients for this site pair (Figure 10b) exhibit more scatter than the COD values and vary from −0.1 to 0.56. The relatively low/near homogeneous CODs calculated in the later afternoon for this site pair are associated with relatively high correlation coefficients. However, correlation coefficients of similar value (>0.4) are associated with median COD values that are clearly heterogeneous (approximately 0.4) in the late evening. In general, the maximum COD values (up to 0.88) were associated with site pairs including one of the harbor background locations (either LB1 or SP1, not shown) where the paired number concentration data exhibit the largest difference as has been noted by others (Pinto et al. 2004). Minimum COD values (<0.1) implying spatial homogeneity were associated with pairs located close together or with similar sources (the LB2–LB3 pair, Figure 11). The LB2–LB3 site pair yields the lowest overall CODs and highest correlation coefficients and they are the two sites in closest proximity to each other (approximately 200 m) and are impacted to the same degree by nearby UFP sources. The uniformly higher correlation coefficients and low CODs shown in Figure 11 were the exception in this data set, however. Only

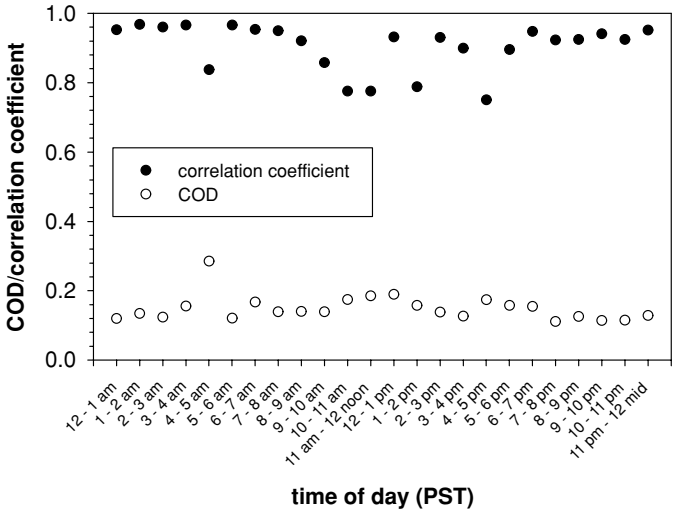

FIG. 11. Median Coefficients of Divergence (CODs) and correlation coefficient (r) calculated for the LB2–LB3 site pair only (March–May data).

for this site pair with virtually identical sources could the correlation coefficient or the COD alone express the variability between sites.

Daily mean number concentration data (Figure 8) averages over profound differences in hourly concentrations (Figures 2–8). Diurnal concentration patterns vary widely due to changes in sources, wind speed and direction, and other factors. These patterns affect the hourly variability expressed by the COD and correlation coefficient calculations between specific site pairs, although averaging over all pairs yields moderate heterogeneity and modest correlation both near the Ports and at the regional site 32 km inland subject to different UFP sources, with limited exception. There is no fixed relationship observed between site pairs for calculated COD and r values, although both methods are useful tools in assessing observed differences between sites. The correlation coefficients may well be modest due to the multiplicity of factors affecting concentrations even in this limited area. The pre-dominant UFP source is motor vehicles and similar (e.g., rail) emission sources. Different motor vehicle types (e.g., HDDV and LDGV) and traffic patterns strongly influence the observations. Without having detailed knowledge of all of these factors a priori, it is difficult to estimate either inter-urban (as in the CHS) or intra-community (as in this study) variability in total particle number concentrations. Site selection is critical and a sufficient number of sites located in proximity to strong sources are required to capture their effect on total particle number concentrations, observed intra-community variability, and, ultimately, exposure assessments. These results suggest that considering distance between sites alone without also considering the proximity of nearby UFP sources and sinks as well as wind patterns is inadequate.

CONCLUSIONS

Significant intra-community variability in total particle number concentrations was observed near the San Pedro Harbor. Extreme spatial heterogeneity, as characterized by the CODs, was driven by the inclusion of two harbor background sites with relatively low ambient concentrations of UFPs. Correlation between most site pairs was weak. Considerable differences in concentration were observed between sites in close proximity to each other due to multiple factors including proximity to sources, source strength, and traffic patterns. Diurnal patterns varied between sites, and a pattern associated with high HDDV fractions/goods movement was observed at several of the sites. The intra-community variability observed in this study was on the order of the inter-community variability observed during the Children's Health study conducted earlier in Los Angeles.

In view of these observations, the documented concern regarding the applicability of centrally located $PM_{2.5}$ mass concentration measurements in estimating exposure to UFPs expressed in the Introduction is warranted. Although the cost of commercially available CPCs has been reduced in recent years, the routine deployment of dense CPC networks measuring particle number concentrations remains prohibitively expensive. Therefore for the foreseeable future, data such as presented here will not be regularly available. The potential importance of exposure to UFPs to adverse health effects suggests that it would be useful to develop models capable of simulating ambient UFP concentrations for typical meteorological conditions and knowledge of local UFP sources and sinks including aerosol processes. While this is also a more expensive option than using $PM_{2.5}$ mass concentration data, there is a growing number of data sets—such as reported here—available for model validation.

REFERENCES

Aalto, P., Hameri, K., Paatero, P., Kulmala, M., Bellander, T., Berglind, N., Bouso, L., Castano-Vinyals, G., Sunyer, J., Cattani, G., Marconi, A., Cyrsys, J., von Klot, S., Peters, A., Zetzsche, K., Lanki, T., Pekkanen, J., Nyberg, F., Sjovall, B., and Forastiere, F. (2005). Aerosol Particle Number Concentration Measurements in Five European Cities Using TSI-3022 Condensation Particle Counter Over a Three-Year Period During Health Effects of Air Pollution on Susceptible Populations, *J. Air & Waste Manage. Assoc.* 55:1064–1076.

Arhami, M., Sillanpaa, M., Hu, S., Olson, M. R., Schauer, J. J., and Sioutas, C. (2008). Size-Segregated Inorganic and Organic Components of PM in the Communities of the Los Angeles Harbor, *Aerosol Sci. Technol.* 43(2):145–160.

Biswas, S., Ntziachristos, L., Moore, K. F., and Sioutas, C. (2007). Particle Volatility in the Vicinity of a Freeway with Heavy-Duty Diesel Traffic, *Atmos. Environ.* 41:3479–3493.

Buzorius, G., Hameri, K., Pekkanen, J., and Kulmala, M. (1999). Spatial Variation of Aerosol Number Concentration in Helsinki City, *Atmos. Environ.* 33:553–565.

Cyrys, J., Heinrich, J. et al (1998). Spatial Variability of Acidic Aerosol, Sulfate and PM10 in Erfurt, Eastern Germany, *J. Exposure Anal. Environ. Epidemiol.* 8(4):447–464.

Delfino, R. J., Sioutas, C., and Malik, S. (2005). Potential Role of Ultrafine Particles in Associations Between Airborne Particle Mass and Cardiovascular Health, *Environ. Health Perspect.* 113(8):934–946.

Donaldson, K., Li, X. Y., and MacNee, W. M. (1998). Ultrafine (Nanometer) Particle Mediated Lung Injury, *J. Aerosol Sci.* 29(5/6):553–560.

Donaldson, K., Brown, D., Clouter, A., Duffin, R., MacNee, W., Renwick, L., Tran, L., and Stone, V. (2002). The Pulmonary Toxicology of Ultrafine Particles, *J. Aerosol Medicine*, 15(2):213–220.

Fine, P. M., Shen, S., and Sioutas, C. (2004). Inferring the Sources of Fine and Ultrafine Particulate Matter at Downwind Receptor Sites in the Los Angeles Basin Using Multiple Continuous Measurements. *Aerosol. Sci. Technol.* 38(S1):182–195.

Freiman, M. T., Hirshel, N., and Broday, D. M. (2006). Urban-Scale Variability of Ambient Particulate Matter Attributes, *Atmos. Environ.* 40:5670–5684.

Gong, K. W., Zhao, W., Li, N., Barajas, B., Kleinman, M. T., Sioutas, C., Horvath, S., Lusis, A. J., Nel, A. E., and Araujo, J. A. (2007). Air-Pollutant Chemicals and Oxidized Lipids Exhibit Genome-Wide Synergistic Effects on Endothelial Cells, *Genome Biology*, 8:R149 doi:10.1186/gb-2007-8-7-4149.

Harrison, R. M., and Jones, A. M. (2005). Multisite Study of Particle Number Concentrations in Urban air, *Environ. Sci. Technol.* 39:6063–6070.

Hinds, W. C. (1999). *Aerosol Technology*, 2nd edition. John Wiley and Sons, New York.

Hricko, A. (2008). Global Trade Comes Home–Community Impacts on Goods Movement, *Environ. Health Perspect.* 116(2):A78–A81.

Jacobson, M. Z., and Seinfeld, J. H. (2004). Evolution of Nanoparticle Size and Mixing State Near the Point of Emission. *Atmos. Environment.* 38(13):1839–1850.

Kim, S., Shen, S., and Sioutas, C. (2002). Size Distribution and Diurnal and Seasonal Trends of Ultrafine Particles in Source and Receptor

Sites of the Los Angeles Basin, *J. Air & Waste Manage. Assoc.* 52:297–307.

Kleeman, M. J., Hughes, L. S., Allen, J. O., and Cass, G. R. (1999). Source Contributions to the Size and Composition Distribution of Atmospheric Particles: Southern California in September 1996, *Environ. Sci. Technol.* 33:4331–4341.

Krudysz, M. A., Froines, J. F., Fine, P. M., and Sioutas, C. (2008a). Intra-Community Spatial Variation of Size-Fractionated PM Mass, OC, EC and Trace Elements in the Long Beach, CA area, *Atmos. Environ.* 42:5374–5389.

Krudysz, M. A., Froines, J. R., Moore, K. F., Geller, M. D., and Sioutas, C. (2009). Intra-Community Spatial Variability in Particle Size Distributions in the Los Angeles Harbor-Area. *Atmos. Chem. Phys.* 9:1–15.

Kulmala, M., Vehkamaki, H., Petaja, T., Dal Maso, M., Lauri, A., Kerminen, V. M., Birmili, W., and McMurry. P. H. (2004). Formation and Growth Rates of Ultrafine Atmospheric Particles: A Review of Observations, *J. Aerosol Sci.* 35:143–176.

Li, N., Sioutas, C., Froines, J. R., Cho, A., Misra, C., and Nel, A. (2003). Ultrafine Particulate Pollutants Induce Oxidative Stress and Mitochondrial Damage, *Environ. Health Perspect.* 111(4):455–460.

Lianou, M., Chalbot, M.-C., Kotronarou, A., Kavouras, I. G., Karakatsani, A., Katsouyanni, K., Puustinnen, A., Hameri, K., Vallius, M., Pekkanen, J., Medings, C., Harrison, R. M., Thomas, S., Ayres, J. G., ten Brink, H., Kos, G., Meliefste, K., de Hartog, J. J., and Hoek, G. (2007). Dependence of Home Outdoor Particulate Mass and Number Concentrations on Residential and Traffic Features in Urban Areas, *J. Air & Waste Manage. Assoc.* 57:1507–1517.

Minguillon, M.-C., Arhami, M., Schauer, J. J., and Sioutas, C. (2008). Seasonal and Spatial Variations of Sources of Fine and Quasi-Ultrafine Particulate Matter in Neighborhoods Near the Los Angeles-Long Beach Harbor, *Atmos. Environ.* 42(32):7317–7328.

Moore, K. F., Ning, Z., Ntziachristos, L., and Sioutas, C. (2007). Daily Variation in Summer Urban Ultrafine Particle Properties—Physical Characterization and Volatility, *Atmos. Environ.* 41(38):8633- 8646.

Motabelli, N., Tran, H., Croes, B. E., and Larsen, L. C. (2003). Day-of-Week Patterns of Particulate Matter and its Chemical Components at Select Sites in California, *J. Air & Waste Manage. Assoc.* 53:876–888.

Nel, A. (2005). Air Pollution-Related Illness: Effects of Particles. *Science*, 308:804–806.

Ning, Z., Geller, M., Moore, K. F., Sheesley, R., Schauer, J. J., and Sioutas, C. (2007). Daily Variation in Summer Urban Ultrafine Aerosols and Inference of their Sources, *Environ. Sci. Technol.* 41(17):6000–6006.

Pekkanen, J., Timonen, K. L., Ruuskanen, J., Reponen, A., and Mirme, A. (1997). Effects of Ultrafine and Fine Particles in Urban Air on Peak Expiratory Flow Among Children with Asthmatic Symptoms, *Environ. Res.* 74(1):24–33.

Petaja, T., Kerminen, V.-M., Dal Maso, M., Junninen, H., Koponen, I. K., Hussein, T., Aalto, P. P., Andronopoulos, S., Robin, D., Hameri, K., Bartzis, J. G., and Kulmala, M. (2007). Sub-Micron Atmospheric Aerosols in the Surroundings of Marseille and Athens: Physical Characterization and New Particle Formation, *Atmos. Chem. Phys.* 7:2705–2720.

Pinto, J. P., Lefohn, A. S., and Shadwick, D. S. (2004). Spatial Variability of PM2.5 in Urban Areas in the United States, *J. Air & Waste Manage. Assoc.* 54:440–449.

Pope, C. A., and Dockery, D. W. (2006). Health Effects of Fine Particulate Air Pollution: Lines that Connect, *J. Air & Waste Manage. Assoc.* 56:709–742.

Port of Long Beach Inventory of Air Emissions for Calendar Year 2005. Starwood Consulting Group, LLC. September 2007.

Port of Los Angeles Inventory of Air Emissions for Calendar Year 2005. Starwood Consulting Group, LLC. September 2007.

Port of Los Angeles Baseline Transportation Study. Meyer, Mohaddes Associations, Inc. April 2004.

Puustinen, A., Hameri, K., Pekkanen, J., Kulmala, M., de Hartog, J., Meliefste, K., ten Brink, H., Kos, G., Katsouyanni, K., Karakatsani, A., Kotronarou, A., Kavouras, I., Meddings, C., Thomas, S., Harrison, R. M., Ayres, J. G., van der Zee, S., and Hoek, G. (2007). Spatial Variation of Particle Number and Mass Over Four European Cities, *Atmos. Environ.* 41:6622–6636.

Sardar, S. B., Fine, P. M., Yoon, H., and Sioutas, C. (2004). Associations Between Particle Number and Gaseous Co-Pollutant Concentrations in the Los Angeles Basin, *J. Air & Waste Manage. Assoc.* 54:992–1005.

Schauer, J. J., Kleeman, M. J., Cass, G. R., and Simoneit, B. R. T. (2001). Measurements of Emissions From Air Pollution Sources. 3. C1-c29 Organic Compounds from Fireplace Combustion of Wood, *Environ. Sci. Technol.* 35:1716 –1728.

Shi, J. P., Evans, D. E., Khan, A. A., and Harrison, R. M. (2001). Source and Concentration of Nanoparticles (<10 nm Diameter) in the Urban Atmosphere, *Atmos. Environ.* 35:1193–1202.

Singh, M., Phuleria, H. C., Bowers, K., and Sioutas, C. (2006). Seasonal and Spatial Trends in Particle Number Concentrations and Size Distributions at the Children's Health Study Sites in Southern California, *J. Exposure Anal. Environ. Epidemiol.* 16(1):3–18.

Sioutas, C., Delfino, R. J., and Singh, M. (2005). Exposure Assessment for Atmospheric Ultrafine Particles (UFPs) and Implications in Epidemiological Research, *Environ. Health Perspect.* 113(8):947–955.

Tuch, T. M., Herbarth, O., Franck, U., Peters, A., Wehner, B., Wiedensohler, A., and Heintzenberg, J. (2006). Weak Correlation of Ultrafine Aerosol Particle Concentrations < 800 nm Between Two Sites in One City, *J. Exposure Science and Environmental Epidemiology*, 16:486–490.

Turner, J. R., and Allen, D. T. (2008). Transport of Atmospheric Fine Particulate Matter: Part 2–Findings from Recent Field Programs on the Intraurban Variability in Fine Particulate Matter, *J. Air & Waste Manage. Assoc.*:58 196–215.

Wehner, B., and Wiedensohler, A. (2003). Long Term Measurements of Submicrometer Urban Aerosols: Statistical Analysis for Correlations with Meteorological Conditions and Trace Gases, *Atmos. Chem. Phys.* 3:867–879.

Westerdahl, D., Fruin, S., Sax, T., Fine, P. M., and Sioutas, C. (2005). Mobile Platform Measurements of Ultrafine Particles and Associated Pollutant Concentrations on Freeways and Residential Streets in Los Angeles, *Atmos. Environ.* 39(20):3597–3610.

Wilson, J. G., Kingham, S., Pearce, J., and Sturman, A. (2005). A Review of Intraurban Variations in Particulate Air Pollution: Implications for Epidemiological Research, *Atmos. Environ.* 39:6444–6462.

Wilson, J. G., and Zawar-Reza, P. (2006). Intraurban-Scale Dispersion Modeling of Particulate Matter Concentrations: Applications for Exposure Estimates in Cohort Studies, *Atmos. Environ.* 40:1053–1063.

Wongphatarakul, V., Friedlander, S. K., and Pinto, J. P. (1998). A Comparative Study of PM2.5 Ambient Aerosol Chemical Databases, *Environ. Sci. Technol.* 32:3926–3934.

Xia, T., Kovochich, M. J., Brant, J., Hotze, M., Sempf, J., Oberley, T., Yeh, J., Sioutas, C., Wiesner, M. R., and Nel, A. E. (2006). Comparisons of the Abilities of Ambient and Commercial Nanoparticles to Induce Cellular Toxicity According to an Oxidative Stress Paradigm, *Nano Letters* 6(8):1794–1807.

Xia, T., Korge, P., Weiss, J. N., Li, N., Venkatesen, M. I., and Sioutas, C. (2004). Quinones and Aromatic Chemical Compounds in Particulate Matter Induce Mitochondrial Dysfunction: Implications for Ultrafine Particle Toxicity, *Environ. Health Perspect.* 112(14):1347–1358.

Zhang, K. M., Wexler, A. S., Zhu, Y. F., Hinds, W. C., and Sioutas, C. (2004). Evolution of Particle Number Distribution Near Roadways. Part II. The "Road-to-Ambient" Process, *Atmos. Environment.* 38(38):6655–6665.

Zhu, Y., Hinds, W. C., Kim, S., Shen, S., and Sioutas, C. (2002a). Study on Ultrafine Particle and Other Vehicular Pollutants Near a Major Highway with Heavy Duty Diesel Traffic, *Atmos. Environ.* 36:4323–4335.

Zhu, Y., Hinds, W. C., Kim, S., and Sioutas, C. (2002b). Concentrations and Size Distribution of Ultrafine Particles Near a Major Highway, *J. Air & Waste Manage. Assoc.* 52:1032–1042.

Zhu, Y., Hinds, W. C., Shen, S., and Sioutas, C. (2005). Seasonal Trends of Concentration and Size Distributions of Ultrafine Particles Near Major Highways in Los Angeles, *Aerosol Sci. Technol.* 38(S1):5–13.

Zhu, Y., Kuhn, T., Mayo, P., and Hinds, W. C. (2006). Comparison of Daytime and Nighttime Concentration Profiles and Size Distributions of Ultrafine Particles Near a Major Highway, *Environ. Sci. Technol.* 40:2531–2536