

# UCLA

## UCLA Previously Published Works

### Title

Concentration, size distribution, and dry deposition rate of particle-associated metals in the Los Angeles region

### Permalink

<https://escholarship.org/uc/item/3s93s8nf>

### Journal

Atmospheric Environment, 40(40)

### ISSN

1352-2310

### Authors

Lim, Jeong-Hee H  
Sabin, L D  
Schiff, K C  
[et al.](#)

### Publication Date

2006-12-01

### Supplemental Material

<https://escholarship.org/uc/item/3s93s8nf#supplemental>

Peer reviewed



1 **Abstract**

2 Daily averaged atmospheric concentrations and dry deposition fluxes of particulate  
3 metals were measured seasonally at six urban sites and one non-urban coastal site in the Los  
4 Angeles region using a conventional total suspended particulate matter (TSP) filter, surrogate  
5 surface deposition plates, and a Noll Rotary Impactor (NRI), which provides information about  
6 particle size distribution in four size ranges above 6 microns. With the exception of the non-  
7 urban site, particulate metal concentrations and deposition fluxes were remarkably uniform  
8 spatially and temporally. At all sites there were significant metal concentrations on particles  
9 greater than 10 microns, a commonly used upper limit for many air quality monitoring studies,  
10 and these large particles were estimated to be responsible for most of the deposited mass of  
11 metals. Annual averaged values of deposition rates measured with a surrogate surface were in  
12 good agreement with values estimated using theoretical deposition velocities in conjunction with  
13 measured size- segregated particle concentrations. Image analysis of particles deposited on NRI  
14 stage A, which collects all particles greater than 6  $\mu\text{m}$ , indicated nighttime metal concentrations  
15 and deposition at the non-urban coastal site was higher than in the day time due to offshore  
16 advection of urban air associated with the diurnal land breeze. Measured enrichment of crustal  
17 and metals was correlated, indicating efficient mixing of natural and anthropogenic material from  
18 different sources, hypothesized to be the result of cyclical resuspension and deposition of dust by  
19 moving vehicles and wind.

20 *Keywords:* NRI; Dry Deposition Velocity; Resuspension; Image Analysis; Enrichment Factor

21

22

23

1    **1.    Introduction**

2            Atmospheric deposition has long been recognized as a potentially significant non-point  
3 source of contaminants and nutrients to water bodies (Davis et al., 2001; Van Metre and Mahler,  
4 2003). Recent studies have identified the importance of atmospheric deposition for organic  
5 compounds such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls  
6 (PCBs) (Simcik et al., 1998; Franz et al., 1998), metals (Zufall et al., 1998; Shahin et al., 2000;  
7 Yi et al., 2001), and nitrogen (Paerl, 1995; Scudlark et al., 1998). Typically, the dry deposition  
8 flux has been calculated indirectly from measured particle concentrations and a modeled dry  
9 deposition velocity (Holsen and Noll, 1992; Caffrey et al., 1998; Stolzenbach et al., 2001).  
10 Several studies, however, have been conducted to measure dry deposition directly and to  
11 characterize the deposited material using artificial collectors (Paode et al., 1999; Tai et al., 1999;  
12 Shahin et al., 2000). Many of these studies concluded that dry deposition was primarily the result  
13 of deposition of relatively large particles, greater than 10 microns in size, that were present in the  
14 atmosphere.

15            The air quality in the Los Angeles metropolitan area ranks among the worst in the United  
16 States. Particles in the ambient air of greater Los Angeles are known to contain concentrations of  
17 toxic constituents, as well as potentially eutrophying nutrients (Young et al., 1976; Arey et al.,  
18 1989). Although the Los Angeles basin has been extensively studied with regard to priority air  
19 pollutants and, to a lesser extent, acid rain and fog (e.g. Russell et al., 1993) and metals (Cass  
20 and McRea, 1986; Lyons et al., 1993), little information currently exists for assessing the relative  
21 contribution to runoff from atmospheric deposition of toxic contaminants and nutrients compared  
22 to other, better-characterized sources. Stolzenbach et al. (2001) used a regional air quality model  
23 to estimate that atmospheric deposition accounted for between 13 % and 99% of the total mass

1 loading of metals to Santa Monica Bay. They also determined that dry deposition of large  
2 particles accounted for more than 80% of the total for most metals studied. These results are  
3 consistent with earlier studies of deposition in the Los Angeles region (Kaplan and Lu, 1993;  
4 Eaganhouse and Venkatesan, 1993; Lankey et al., 1998), but were limited by the absence of  
5 confirming measurement of contaminant concentrations on large particles and atmospheric  
6 deposition.

7 The objective of this study was to make measurements of metal concentrations on  
8 particles and dry deposition in the Los Angeles region. This paper describes the methodologies  
9 used to make these measurements and reports results relating to the size distribution of particles  
10 contributing to deposition and to measured and calculated deposition fluxes. A companion paper  
11 (Sabin et al., 2006) discusses the relative importance of atmospheric deposition to storm water  
12 runoff in the Los Angeles region.

## 13 2. METHODOLOGY

### 14 2.1. Sampling sites

15 Sampling took place over a 24-hour period during each of four seasons at six urban sites  
16 (Fig. 1) from August 2002 through June 2003. These included three sites in the Los Angeles  
17 River watershed (LA1, LA2, LA3), one in the Dominguez Channel watershed (DC), one in the  
18 Ballona Creek watershed (BC), and one in the lower Santa Ana River watershed (SA). Two sites,  
19 LA1 and LA2, were located at existing air monitoring stations operated by the South Coast Air  
20 Quality Management District (SCAQMD). Both BC and SA were located on rooftops, while  
21 LA3 was located within the grounds of a water reclamation facility, and DC was located on the  
22 grounds of a university. We also sampled at one non-urban coastal site at Malibu Lagoon State  
23 Beach within the Malibu Creek watershed (MA). Specific site selection criteria for all sites

1 incorporated the recommendations of the National Atmospheric Deposition Program (NADP,  
2 2000).

### 3 2.2. Instrumentation

4 Atmospheric concentrations and coarse particle size distributions of metals were  
5 measured over a 24-hour period using a Noll Rotary Impactor (NRI), which consisted of a multi-  
6 stage rotary impactor that operates by simultaneously rotating four rectangular collector stages of  
7 different widths through the air. This instrument has been used successfully to measure air  
8 concentrations on coarse particle size fractions in other studies and is described elsewhere (Lin et  
9 al., 1994; Yang et al., 1999). The instrument was operated at 320 rpm, producing cut diameters  
10 of 6 $\mu$ m (stage A), 11  $\mu$ m (stage B), 20  $\mu$ m (stage C), and 29  $\mu$ m (stage D). Mylar strips, sized  
11 according to the desired cut point, were coated with a thin layer of Apezion L grease (M&I  
12 Materials Ltd., UK) and mounted onto each of the four collector stages. To prevent saturation of  
13 the strip surfaces, strips on stage A were changed at 2-hour intervals during the day and 4-hour  
14 intervals at night during the 24-hour collection period. Stage B strips were changed every 4  
15 hours during the day and every 8 hours at night. Stage C and D were not changed during the 24-  
16 hour collection period.

17 Dry deposition fluxes were measured over a 24-hour period using surrogate surfaces.  
18 Surrogate surfaces for this study were comprised of a circular PVC deposition plate, 33 cm in  
19 diameter, with a sharp edge ( $< 10^\circ$  angle), covered with a Mylar® sheet coated with a thin  
20 (average thickness of 10  $\mu$ m based on total volume applied) layer of Apezion L grease. During  
21 sampling, the plate was mounted onto a tripod at a height of 2 m.

22 Total suspended particulate matter (TSP) were collected over a 24-hour period on a 2.0  
23  $\mu$ m pore Teflon filter (Pall Life Science, R2PJ037) with a diameter of 37 mm. A metered flow

1 rate of  $16 \text{ l min}^{-1}$  was maintained during all sampling intervals. For this configuration particles  
2 with a diameter of  $54 \mu\text{m}$  will be collected with a 50 percent collection efficiency (Hinds, 1999),  
3 which is consistent with image analyses of the NRI Mylar strips. TSP measurements were not  
4 obtained during the summer 2002 and a portion of the fall 2002 sampling events.

5 Meteorological data, including wind speed and direction, temperature, relative humidity  
6 and barometric pressure, were also measured during each sampling period using a portable  
7 meteorological station (PortLog, Rain Wise, Inc.). All the samples were collected during dry  
8 period.

### 9 2.3. Sample preparation and analysis

10 Prior to sampling, Mylar to be mounted on the NRI or deposition plates was cut to the  
11 desired size (e.g. strips or sheets), wiped with methanol and soaked in 10% nitric acid followed  
12 by methanol for 5 minutes each, then rinsed with distilled water, and allowed to air dry. Mylar  
13 strips/sheets were coated with a thin layer of Apeizon L grease and mounted onto collector stages  
14 of the NRI and deposition plates, and stored in clean, airtight containers for transport to the field.  
15 After sampling, all Mylar strips from the NRI were placed in a clean Petri dish prior to analysis  
16 and Mylar sheets from deposition plates were removed, folded (greased side inward), and placed  
17 inside a clean glass jar.

18 For TSP sampling a clean Teflon® filter was loaded into the TSP sample holder, and the  
19 sample holder was stored in a clean plastic bag for transport to the field. After sampling, the filter  
20 was stored in a clean Petri dish prior to analysis and the entire Petri dish was rinsed to collect any  
21 particles lost from the filter during transport.

1 For chemical analysis, the Mylar strips and Teflon filters and rinse water were placed into  
2 clean 15 ml plastic centrifuge tubes and 10 ml of 5% Optima Grade nitric acid was added to the  
3 tubes and capped tightly. The samples were acid-digested at 65° C under sonication for a  
4 minimum of 24 hours.

5 Mylar sheets were cut into 10 smaller pieces and rinsed three successive times with 15 ml  
6 of n-hexane. The rinses were combined into a 50 ml centrifuge tube. The Mylar® pieces were  
7 then rinsed with 5% Optima Grade nitric acid and the acid and hexane rinses were combined.  
8 The hexane was evaporated in a 50° C water bath and the remaining sample was acid digested at  
9 65° C under sonication for a minimum of 24 hours.

10 All acid-digested samples were transferred to a centrifuge tube and analyzed for metals  
11 per EPA Method 200.8 using inductively coupled plasma-mass spectroscopy (ICP-MS). Method  
12 detection limits were 0.5ng for Pb and 1.0 ng for the remaining metals. Crustal elements had  
13 higher detection limits (10 ng for Al and 50 ng for Fe).

14 Laboratory blanks were analyzed with each batch of 15 or fewer samples and were all  
15 non-detectable. Field blanks were collected during every sampling period for each type of media  
16 (Mylar strips, including duplicate blank Mylar strips for each stage of the NRI, Mylar sheets, and  
17 Teflon filters) and analyzed with the samples. All samples were corrected for levels measured in  
18 their respective field blank.

19 Concentrations of metals were calculated for each NRI stage using the measured metal  
20 mass and the known NRI rotation speed (Noll et al., 1985). For most sampling sites, only a 24-  
21 hour total concentration was obtained by compositing all of the strips for each stage.  
22 Concentrations for each size range between NRI cutoffs were obtained as the difference of the  
23 high and low range NRI concentrations. The metal concentration for particles smaller than 6 µm



1 was calculated by subtracting the NRI stage A ( $> 6 \mu\text{m}$ ) concentrations from the measured TSP  
2 concentration. An example of the size dependent concentration values resulting from this  
3 analysis is shown in Fig. 2a.

#### 4 2.4. Deposition velocity and flux calculation

5 The dry deposition flux ( $F$ ) of a particle associated metal is directly proportional to the  
6 airborne metal concentration ( $C$ ) and a size - dependent deposition velocity ( $V_d$ ) at some  
7 reference height  $z_r$  above the surface:

$$8 \quad F = V_d C \quad (1)$$

9 Size-dependent deposition rates were calculated using established theoretical expressions  
10 for the deposition velocity  $V_d$ . For particles with a gravitational settling velocity  $V_g$ , which are  
11 assumed to adhere to the surface upon contact without resuspension, the deposition velocity is  
12 determined by the transport properties in the atmosphere (Seinfeld and Pandis, 1998):

$$13 \quad V_d = \frac{1}{r_a + r_b + r_a r_b V_g} + V_g \quad (2)$$

14 where  $r_a$  is the resistance due to turbulent transport through the overlying atmosphere to the  
15 molecular sub-layer and  $r_b$  is the resistance of the molecular scale diffusive transport at the  
16 boundary where deposition is occurring. In this study the effects of atmospheric stability were  
17 neglected and the aerodynamic resistance given by (McRae et al., 1982):

$$18 \quad r_a = \frac{0.74}{C_d u_r} \quad (3)$$

19 where  $u_r$  is the velocity at height  $z_r$  and  $C_d$  is a drag coefficient given by:

1 
$$C_d = \left[ \frac{k}{\ln(z_r / z_0)} \right]^2 \quad (4)$$

2 in which  $k$  is the Von Karman constant (0.41) and  $z_0$  is the aerodynamic surface roughness height.

3 For particles the resistance  $r_b$  is given by (McRae et al., 1982):

4 
$$r_b = \frac{2Sc^{2/3}}{kC_d^{1/2}u_r} \quad (5)$$

5 In this expression, transport of particles by Brownian diffusion is represented by the Schmidt  
 6 number, which is defined as  $Sc = v/D_p$ , where  $v$  is the kinematic viscosity of air and  $D_p$  is the  
 7 Brownian diffusion coefficient calculated as a function of the particle diameter  $d_p$  using the  
 8 Stokes-Einstein relationship:

9 
$$D_p = \frac{k_B T}{6\pi d_p \mu} \quad (6)$$

10 in which  $k_B$  is the Stefan-Boltzman constant,  $T$  is the absolute temperature, and  $\mu$  is the dynamic  
 11 viscosity of air. The gravitational settling velocity ( $V_g$ ) is given by:

12 
$$V_g = \frac{(\rho_p - \rho_a)gd_p^2C_c}{18\mu} \quad (7)$$

13 in which  $\rho_p$  and  $\rho_a$  is density of particle and air, respectively,  $g$  is the gravitational acceleration  
 14 and  $C_c$  is the Cunningham slip correction factor (Finlayson-Pitts and Pitts, 2000).

15 The above equations were used to calculate the deposition velocity for each metal as a  
 16 function of particle size at each of the sampling sites using site-specific values of air temperature  
 17 and wind velocity, measured at  $z_r = 2$  m. The estimated aerodynamic roughness height  $z_0$  at all

1 measurements sites was set equal to 1.0 meter on the basis of values obtained from the South  
 2 Coast Air Quality Management District, which ranged from 0.08 m at the Malibu site to 0.66 to  
 3 1.4 meters at the other more urban sites. A size independent particle density  $\rho_p = 1800 \text{ kg m}^{-3}$   
 4 was assumed. Calculated deposition velocities were then used to obtain a size-dependent  
 5 deposition mass flux for each metal at each site and season. For each size range the flux was  
 6 defined as the average of the fluxes computed from Eq. (1) using the deposition velocity  
 7 associated with the low and high values of particle size and the measured metal concentration  
 8 associated with that range. For the largest size range (greater than  $29 \mu\text{m}$ ) a maximum particle  
 9 size of  $60 \mu\text{m}$  was assumed based on the results of image analysis of the NRI stages (see below).  
 10 An example of the size dependent deposition flux values resulting from this analysis is shown in  
 11 Fig. 2b. Total deposition fluxes were computed as the sum of the fluxes from all size ranges.

## 12 2.5. Image analysis of NRI Mylar strips

13 Particle size distributions were determined from the photographs of Mylar strips from  
 14 Stage A taken from the NRI sampler. Images were viewed using an optical microscope (LW  
 15 Scientific) set at a magnification of 100x. Because the particles were observed to be relatively  
 16 uniformly distributed on the Mylar strip, only one image was analyzed for each strip. For each  
 17 image the distribution of the equivalent projected area diameter  $d_{PA}$  was determined. Values of  
 18  $d_{PA}$  were converted to an aerodynamic particle diameter  $d_p$  using

$$19 \quad d_p = \frac{1}{S_v} \left( \frac{\rho_p}{\rho_0 S_D} \right)^{\frac{1}{2}} d_{PA} \quad (8)$$

20 where  $S_D$  is a dynamic shape factor set equal to 1.41 (Davies, 1979),  $\rho_p$  is the particle density,  
 21  $\rho_0$  is a unit particle density of  $1000 \text{ kg m}^{-3}$ , and  $\overline{S_v}$  is the volume averaged shape factor. Shape

1 factor values have been reported with a range from 1.61 (Lin et al., 1994; Tai et al, 1999) to 1.89  
2 (Noll et al., 1988) for urban area, and 1.16 (Fang, 1989) for a non-urban area. For this study a  
3 value of 1.61 for was used for the urban sites and 1.16 for the non-urban sites. Particle  
4 atmospheric mass concentrations and deposition fluxes for the four NRI size ranges (6-11 $\mu\text{m}$ , 11-  
5 20 $\mu\text{m}$ , 20-29 $\mu\text{m}$ , and above 29 $\mu\text{m}$ ) were determined using the known NRI rotation speed and  
6 collection efficiency (Noll et al., 1985),  $d_p$  and  $\rho_p$  to calculate particle mass, and Eq. 7 to  
7 calculate particle settling velocity. It was not possible to compare these results with measured  
8 elemental concentrations on the NRI strips because of the presence of material such as  
9 hydrocarbons that were not analyzed chemically.

### 10 **3. Results and Discussion**

11 Measured and calculated values of concentration and deposition rate for five metals with  
12 significant anthropogenic sources (Cr, Cu, Pb, Ni and Zn) are presented in this section. In all  
13 cases where averages were calculated, measured values below the detection limit were replaced  
14 by half the detection limit.

#### 15 3.1. Particle Metal Concentration

16 Averages of metal concentrations based on TSP samples were similar to those measured  
17 in other studies in California (Table 1). These averages were not true annual values, as TSP  
18 measurements were not obtained during the summer 2002 and half of the fall 2002 sampling  
19 events. Seasonal variations in metal concentrations and the size distribution of metal mass as  
20 determined from TSP and NRI samples are shown in Fig. 3. These data indicate the majority of  
21 the metal mass was associated with particles smaller than 6  $\mu\text{m}$ . However, as discussed below,  
22 the mass of larger particles was sufficient to constitute the major portion of the deposition flux.

1 Sabin et al. (2006) analyzed a full year of data from Stage A of the NRI, representing the  
2 concentration of metals on particles larger than 6  $\mu\text{m}$  for chromium, copper, lead, nickel and  
3 zinc. They found there was little statistical difference between the annual mean concentrations at  
4 the six urban sites, but the concentrations were significantly lower at the one non-urban site in  
5 comparison with the urban sites. In addition, they found no significant seasonal differences in  
6 metal concentrations or significant correlations between metal concentrations and wind speed,  
7 temperature and relative humidity, with the exception of nickel, which was correlated with wind  
8 speed. However, antecedent rainfall did affect metal concentrations with the lowest values  
9 consistently observed within five days after a rain event.

### 10 3.2. Measured Metal Deposition Flux and Velocity

11 Annual averages of measured dry deposition mass fluxes of metals at all sites were  
12 similar to those obtained in studies of other urban locations (Table 2). As was the case for the  
13 measured concentrations, the annual dry deposition mass fluxes were similar between urban  
14 sites, but significantly lower at the non-urban site. Seasonal values of metal deposition fluxes  
15 (Fig. 4) were also similar. The general level of precision for the deposition plate measurements  
16 was reflected in relative standard deviation (RSD) for field duplicates; average RSDs for the five  
17 metals were 47% (chromium), 42% (copper), 79% (nickel), 41% (lead), and 58% (zinc). These  
18 values are consistent with other studies of metal deposition in urban areas using the same  
19 measurement techniques (e.g. Tasdemir and Kural, 2005), and reflect an acceptable level of  
20 precision for field duplicates because differences of less than a factor of two between fluxes  
21 measured during different sampling events were not considered significant in this study.

22 The flux-averaged deposition velocities, calculated as the measured total deposition flux  
23 divided by the total concentration, for the full suite of metals analyzed range from 0.34  $\text{cm sec}^{-1}$

1 (Sn) to  $1.5 \text{ cm sec}^{-1}$  (Zn, Sr). These values compare well with those obtained in urban  
2 environments by Yi et al. (2001).

3 For each sampling event, the measured deposition fluxes of the complete set of metals  
4 analyzed were generally well-predicted by the deposition rates calculated using the equations in  
5 section 2.4 for all seasons except spring, for which the calculated fluxes were high at some sites  
6 (Figure 5). The differences between the measured and calculated deposition fluxes were likely  
7 the result of limitations of the theoretical expressions for deposition and variability in the  
8 deposition measurements. Clearly, the plates do not fully represent the larger scale roughness of  
9 the land surface implied in the values of  $z_o$  used in the calculations. To reduce the impact of  
10 measurement error, annual average deposition fluxes for each method were compared (Table 3).  
11 The annual average measured and calculated fluxes were within 20% for chromium, copper, lead  
12 and zinc, and within 60% for nickel, indicating reasonable agreement.

### 13 3.3 Uncertainty in the deposition velocity calculations

14 The equations used to calculate particle deposition velocity in this study reflect the  
15 current state of knowledge of these processes and assumptions about important parameters. For  
16 the particle size range of interest, the most important factor in determining the deposition rate is  
17 the gravitational settling velocity of the particles. The error in the computed deposition rate,  
18 which is directly proportional to the difference between the actual particle density and the  
19 assumed value of  $1800 \text{ kg m}^{-3}$ , is likely to be no more than 10-20%. The effect of atmospheric  
20 stability on the deposition rate was neglected in computing the aerodynamic resistance (Eq. 3).  
21 This factor, which can be relatively significant for dry deposition of vapor constituents (McRae  
22 et al., 1982), has no significant effect on the computed deposition for particles larger than about 1  
23  $\mu\text{m}$ . The use of a constant value of  $z_o$  is justified because of the relative insensitivity of the result

1 to this parameter value.

2           There are a number of issues related to the computation of the drag coefficient given by  
3 Eq. (4). First, Eq. (4) is based on the logarithmic velocity profile, which for rough surfaces is  
4 known to be valid only for  $z > 50z_0$  (Brutsaert, 1982), a criteria that was not met by the  
5 measurement height (2 meters) and estimated roughness height (~1 meter) used in this study.  
6 For  $z < z_0$ , the actual velocity will be greater than that predicted by the logarithmic law, so the  
7 use of the logarithmic law will tend to overestimate the value of the drag coefficient. Second, this  
8 expression does not include a displacement height  $z_d$ , which would modify the argument of the  
9 logarithm to be  $(z_r - z_d)/z_0$ . The displacement height is commonly used for surfaces with canopy  
10 type roughness and is thought to be on the order of 2/3 of the canopy height (Brutsaert, 1982).  
11 Addition of this factor would increase the computed drag coefficient and deposition rate. These  
12 two factors have opposite effects on the computed deposition rates, but only affect the  
13 aerodynamic and surface resistances, which are far less important than the settling rate for  
14 particles larger than 1  $\mu\text{m}$ .

15           The expression used to calculate the boundary resistance (Eq. 5) is relatively well-  
16 established for vapor transport, and is similar, but not identical to, other formulations applied to  
17 diffusive particle deposition (e.g. Giorgi, 1986). However, for the particle size range considered  
18 in this study, deposition by diffusion is much smaller than deposition by gravitational settling.

19           The boundary resistance formulation (Eq. 5) also neglects the effect of inertial particle  
20 deposition. This process, which is thought to be potentially most important for particles in the  
21 size range 1-10  $\mu\text{m}$ , has proven to be one of the most difficult to predict theoretically.  
22 Expressions developed for inertial transport through a viscous sublayer on surfaces with  
23 relatively uniform roughness (Slinn, 1977) are not likely to be valid for the highly irregular and

1 canopy-like surface of a watershed. These expressions have the additional drawback that the  
2 associated transport resistance is proportional to the square of the measured velocity, thus  
3 amplifying the velocity profile uncertainties discussed above. Expressions for particle deposition  
4 by impaction in canopies more typical of natural surfaces indicate that this process is only  
5 significant compared to gravitational settling if the presence of very fine (1- 10  $\mu\text{m}$ ) vegetative  
6 “hairs” is postulated (Davidson and Friedlander, 1978; Giorgi, 1986). While this assumption may  
7 be valid for relatively densely vegetated surfaces, it is less likely to be so for a typical urbanized  
8 surface where many of the collecting surfaces are sufficiently large that significant inertial  
9 deposition does not occur. Finally, experimental studies have documented a high fraction of loss  
10 to “bounce off” of particles contacting a surface by inertial deposition (Wu et al., 1992). For  
11 these reasons, we believe it was justified to omit explicit inclusion of deposition by inertial  
12 deposition. To the extent that inertial deposition is important, the estimates presented here should  
13 be considered lower bounds on actual deposition rates.

#### 14 3.4 Diurnal Variations in Concentration and Flux

15 With the exception of the NRI samples obtained during the summer at LA1, for which the  
16 strips were not composited before chemical analysis, the image analysis of NRI strips provides  
17 the only estimates of variability in particle mass concentrations on an hourly time scales as well  
18 as the only estimates of total particle mass concentration and total particle deposition flux. Metal  
19 concentrations measured at LA1 varied an order of magnitude between day and night (Fig. 6).  
20 The diurnal variation of total particle mass concentration at the urban sites and flux at an urban  
21 site and the non-urban site are contrasted in Fig. 7 and the results of analysis of all of the urban  
22 sites in Table 4. Although the total particulate concentration at the urban sites does not vary  
23 greatly from day to night, both deposition and the number of large particles was greater during



1 the day, suggesting an anthropogenic source, although increased wind velocities during the day  
2 could also be a contributing factor. In contrast, at the non-urban site both particle concentration  
3 and deposition were greatest at night. The pattern of variation at the non-urban site indicates that  
4 larger particles were largely absent during the day but present at night, probably associated with  
5 advection of urban air during the early evening when a seaward wind flow typically occurs  
6 associated with cooling of the air over the land. The occurrence of such an event was clearly  
7 indicated in the wind and temperature data collected at the site. The average seaward wind speed  
8 during the night was  $2.7 \text{ mi hr}^{-1}$  for duration of 9.8 hrs.

### 9 3.4 Comparison with Crustal and Dust Composition

10 The anthropogenic contribution to the mass concentration or flux of a given metal can be  
11 assessed by examining the ratio of a concentration or flux of a potentially anthropogenic metal to  
12 the concentration or flux of a non-anthropogenic (crustal) element measured in the same sample.  
13 In this context “anthropogenic” refers to the source of the metal and not the mode of  
14 resuspension, which may be affected by human activities for all metals. The enrichment factor  
15 for a given metal is defined as this ratio divided by the same ratio in crustal material (Wedepohl,  
16 1995). In this study, iron was used as reference element for determining metal enrichment,  
17 because of its higher correlation to other metals compared to aluminum (Schiff and Weisberg,  
18 1999). Enrichment factors (Table 5) were high in our measurements and in the ARB and MATES  
19 II samples. Pearson correlation analysis found high correlation between pairs of crustal elements  
20 ( $r > 0.95$  for Al, Fe, Si, and Mg) and the anthropogenic metals ( $0.5 < r < 0.83$  for Cr, Ni, Pb, and  
21 Zn). These high correlations suggest an efficient process resulting in the mixing of crustal and  
22 anthropogenic material originating from different sources. It is well-known that dust resuspended  
23 from road surfaces by moving vehicles and from other surfaces by wind is a major source of

1 contaminants to the atmosphere (Watson and Chow, 2000). Data on paved road dust samples in  
2 the Los Angeles area (SCAQMD, 2003) indicate road dust is also enriched in non-anthropogenic  
3 metals, but the relative enrichment factors for different metals are not definitive in terms of  
4 identifying road dust as the source of the metals.

#### 5 **4. Conclusions**

6 The results of this study indicate metals in the atmosphere above Los Angeles are  
7 associated with a wide range of particle sizes, but that atmospheric deposition is dominated by  
8 particles larger than 10  $\mu\text{m}$ . With the exception of a non-urban site located directly on the  
9 coastline, the spatial uniformity of measured concentration and deposition at six sites within the  
10 inland urban area is consistent with earlier modeling results (Lu et al., 2003) and evokes a picture  
11 of particles being relatively well-mixed in the atmosphere over the air basin. This picture is not  
12 consistent with the dominance of larger sizes, which should deposit close to sources, unless there  
13 is substantial resuspension from both road and non-road surfaces. The likelihood of significant  
14 resuspension is suggested by the elemental profile in measured particle concentrations and  
15 deposition fluxes.

16 This study supports the use of surrogate surfaces of relatively simple design based on the  
17 assumption that gravitational settling is the main mode of deposition for the particles of interest  
18 in this study. Annual average deposition mass fluxes measured by these plates were in substantial  
19 agreement with values estimated using theoretical expressions for deposition velocity as a  
20 function of particle size. The plates are an attractive method for measuring the long-term  
21 deposition fluxes of contaminants given the relative difficulty of obtaining size-dependent  
22 particle concentrations.

#### 23 **Acknowledgements**

1 We would like to acknowledge the assistance of Tom Parsons and Tom Mack  
2 (SCAQMD), Bruce Moore (Orange County Public Facilities and Resources Department), Marco  
3 Guardi (California State University Dominguez Hills), Dariush Vosooghi (Tillman Water  
4 Reclamation Plant), and Christine Savitski (Adamson House) who provided access to their  
5 facilities for our sampling events. We wish also to acknowledge the valuable contributions of the  
6 following Southern California Coastal Water Research Project personnel and UCLA students  
7 who assisted in sample collection: Liesl Tiefenthaler, David Tsukada, Nicholas Tourneur, An  
8 Kaliman, and Yonas Zemuy. This project was funded in part by the Santa Monica Bay  
9 Restoration Project, the Regional Water Quality Control Board, the Los Angeles County  
10 Department of Public Works, the State Water Resources Control Board, the City of Los Angeles,  
11 and the U.S. Environmental Protection Agency Great Waters Program.

## 12 **References**

- 13  
14 Air Resource Board (ARB) (2002) "California Emission Inventory".  
15 <http://www.arb.ca.gov/ei/speciate/speciate.htm>.  
16  
17 Arey, J.R., Atkinson, R, Zielinska, B. and McElroy, P. (1989) "Diurnal concentrations of volatile  
18 polycyclic aromatic hydrocarbons and nitroarenes during a photochemical air pollution episode  
19 in Glendora." *Environmental Science and Technology* 23: 321-327.  
20  
21 Brutsaert, W.H. (1982) "Evaporation into the Atmosphere." Reidel.  
22  
23 Carrery, P.F., Ondov, J.M., Zufall, M.J. and Davidson, C.I. (1998) "Determination of size-  
24 dependent dry particle deposition velocities with multiple intrinsic elemental tracers."  
25 *Environmental Science and Technology* 32: 1615-1622.  
26  
27 Cass, G.R. and McRea, G.J. (1986) "Emission and air quality relationships for atmospheric trace  
28 metals." *Toxic metals in the atmosphere* edited by J.O. Nriagu and C.I. Davidson , Wiley, New  
29 York: 145-171.  
30  
31 Davidson, C.I. and Friedlander, S.K. (1978) "Filtration model for aerosol dry deposition-  
32 application to trace-metal deposition from the atmosphere." *Journal of Geophysical Research*  
33 83(C5): 2343-2352.  
34  
35

- 1 Davies, C.N. (1979) "Particle fluid interaction." *J. Aerosol Sci.* 10: 477-513.
- 2
- 3 Davis, A.P., Shokouhian, M. and Ni, S. (2001) "Loading estimates of lead, copper, cadmium, and  
4 zinc in urban runoff from specific sources." *Chemosphere* 44: 997-1009.
- 5
- 6 Eganhouse, R.P. and Venkatesan, M.I. (1993) "Chemical Oceanography and Geochemistry."  
7 Ecology of the Southern California Bight, edited by M.D.Dailey, D.J.Reish, and J.W.Anderson,  
8 Univ. of Calif. Press, Berkeley, CA.
- 9
- 10 Fang, K.Y. (1989) "Measurement and modeling of atmospheric coarse particle to a flat plate,  
11 Ph.D. thesis. Illinois Institute of Technology."
- 12
- 13 Finlayson-Pitts, B.J. and Pitts, J.N. (2000) "Chemistry of the upper and lower atmosphere."  
14 Academic Press, San Diego, CA.
- 15
- 16 Franz, T.P., Elsenreich, S.J. and Holsen, T.M. (1998) "Dry deposition of particulate  
17 polychlorinated biphenyls and polycyclic aromatic hydrocarbons to Lake Michigan."  
18 *Environmental Science and Technology* 32: 3681-3688
- 19
- 20 Giorgi, F. (1986) "A particle dry deposition parameterization scheme for use in tracer transport  
21 models." *Journal of Geophysical Research* 91(D9): 9794-9806.
- 22
- 23 Hinds, W.C. (1999) "Aerosol Technology (properties, behavior, and measurement of air borne  
24 particles)". Wiley-Interscience publication, New York.
- 25
- 26 Holsen, T.M. and Noll, K.E. (1992) "Dry deposition of atmospheric particles: application of  
27 current models to ambient data." *Environmental Science and Technology* 26: 1807-1815.
- 28
- 29 Kaplan, I. and Lu, S.T. (1993) "Contribution of atmospheric contaminants to the Southern  
30 California Bight Water Column." Report to the Southern California Coastal Water Research  
31 Project.
- 32
- 33 Lankey, R.L., Davidson, C.I. and McMichael, F. (1998) "Mass balance for Lead in the California  
34 South Coast Air Basin: an update." *Environmental Research A* 78: 86-93.
- 35
- 36 Lin, J.M., Noll, K.E. and Holsen, T.M (1994) "Dry deposition velocities as a function of particle  
37 size in the ambient atmosphere." *Aerosol Science and Technology* 20: 239-252.
- 38
- 39 Lu, R., Turco, R.P., Stolzenbach, K.D., Friedlander, S., Xiong, C., Schiff, K., Tiefenthaler, L  
40 (2003) "Dry deposition of airborne trace metals on the Los Angeles Basin and adjacent coastal  
41 waters." *Journal of Geophysical Research* 108(D2): 4074.
- 42
- 43 Lyons, J.M., Venkataraman, C., Main, H.H. and Friedlander, S.K. (1993) "Size distributions of  
44 trace metals in the Los Angeles atmosphere." *Atmospheric Environment* 27B (2): 237-249.
- 45
- 46 McRae, G.J., Goodin, W.R. and Seinfeld, J.H. (1982) "Development of a second generation

1 mathematical model for urban air pollution, I, Model formulation." *Atmospheric Environment*  
2 16(4): 679-696.  
3  
4 National Atmospheric Deposition Program (NADP). (2000) "Instruction Manual NADP/NTN  
5 Site Selection and Installation." <http://nadp.sws.uiuc.edu/lib/manuals/siteinst.pdf>.  
6  
7 Noll, K.E., Pontius, A., Frey, R. and Gould, M. (1985) "Comparison of atmospheric coarse  
8 particles at an urban and non-urban site." *Atmospheric Environment* 19(11): 1931-1943.  
9  
10 Noll, K. E., Fang, K.Y. and Watkins, L.A. (1988) "Characterization of the deposition of particles  
11 from the atmosphere to a flat plate." *Atmospheric Environment* 22: 1461-1468.  
12  
13 Paerl, H.W. (1995) "Coastal eutrophication in relation to atmospheric nitrogen deposition:  
14 current perspectives." *Ophelia* 41: 237-259.  
15  
16 Paode, R.D., Shahin, U.M., Sivadechathep, J., Holsen, T.M. and Frank, W.J. (1999) "Source  
17 apportionment of dry deposited and airborne coarse particles collected in the Chicago area."  
18 *Aerosol Science and Technology* 31: 473-486.  
19  
20 Russell, A.G., Winner, D.A., Harley R.A. Mccue, K.F. and Cass, G.R. (1993) "Mathematical  
21 modeling and control of dry deposition flux of nitrogen-containing air pollutants."  
22 *Environmental Science and Technology* 27: 2772-2782.  
23  
24 Sabin, L.D., Lim, J.H., Schiff, K. and Stolzenbach, K.D. (2006) "Atmospheric dry deposition of  
25 trace metals in the Los Angeles coastal region." *Environmental Toxicology and Chemistry* 25(9).  
26 (in press)  
27  
28 Schiff, K.C. and Weisberg, S.B. (1999) "Iron as a reference element for determining trace metal  
29 enrichment in Southern California coastal shelf sediments." *Marine Environmental Research* 48:  
30 161-176.  
31  
32 Scudlark, J.R., Russell, K.M., Galloway, J.N., Church, T.M. and Keene, W.C (1998) "Organic  
33 nitrogen in precipitation at the Mid Atlantic US coast-methods evaluation and preliminary  
34 measurements." *Atmospheric Environment* 32: 1719-1728.  
35  
36 Seinfeld, J.H. and Pandis, S.N. (1998) "Atmospheric Chemistry and Physics: From Air Pollution  
37 to Climate Change, John Wiley, New York."  
38  
39 Shahin, U.M., Yi, S.M., Paode, R.D. and Holsen, T.M (2000) "Long-term elemental dry  
40 deposition fluxes measured around lake Michigan with an automated dry deposition sampler."  
41 *Environmental Science and Technology* 34: 1887-1892.  
42  
43 Simcik, M.F., Franz, T.P., Zhang, H. and Eisenreich, S.J. (1998) "Gas-particle partitioning of  
44 PCBs and PAHs in the Chicago urban and adjacent coastal atmosphere: state of equilibrium."  
45 *Environmental Science and Technology* 32: 251-257.  
46

1 Slinn, W.G.N. (1977) "Some approximations for wet and dry removal of particles and gases from  
2 atmosphere." *Water air and soil pollution* 7(4): 513-543.  
3  
4 South Coast Air Quality Management District (SCAQMD). (2003)  
5 <http://www.aqmd.gov/aqmp/AQMD03AQMP.htm>.  
6  
7 Stolzenbach, K.D., Lu, R., Xiong, C., Friedlander, S., Turco, R., Schiff, K., Tiefenthaler, L  
8 (2001) "Measuring and Modeling of Atmospheric Deposition on Santa Monica Bay and the  
9 Santa Monica Bay Watershed." Report to the Santa Monica Bay Restoration Project.  
10  
11 Tai, H.S., Lin, J.J. and Noll, K.E. (1999) "Characterization of atmospheric dry deposited particles  
12 at urban and non-urban locations." *Journal of Aerosol Science* 30(8): 1057-1068.  
13  
14 Tasdemir, Y. and Kural, C. (2005) "Atmospheric dry deposition fluxes of trace elements  
15 measured in Bursa, Turkey." *Environmental Pollution* 138(3): 462-472.  
16  
17 USEPA. (2000) "Understanding and Accounting for Method Variability in Whole Effluent  
18 Toxicity Applications under the NPDES Program." <http://www.epa.gov/OST/WET/wetstudy.htm>.  
19  
20 Van Metre, P.C. and Mahler, B.J. (2003) "The contribution of particles washed from rooftops to  
21 contaminant loading to urban streams." *Chemosphere* 52: 1727-1741.  
22  
23 Watson, J.G. and Chow, J.C. (2000) "Reconciling Urban Fugitive Dust Emissions Inventory and  
24 Ambient Source Contribution Estimates: Summary of Current Knowledge and Needed  
25 Research." Desert Research Institute DRI Document No. 6110.4F.  
26  
27 Wedepohl, K.H. (1995) "The composition of the continental crust." *Geochimica et*  
28 *Cosmochimica Acta* 59: 1217-1232.  
29  
30 Wu, Y.L., Davidson, C.I., Dolske, D.A. and Sherwood, S.I. (1992) "Dry Deposition of  
31 Atmospheric Contaminants: the Relative Importance of Aerodynamic, Boundary Layer, and  
32 Surface Resistances." *Aerosol Science and Technology* 16: 65-81.  
33  
34 Yang, H.H., Chiang, C.F., Lee, W.J., Hwang, K.P. and Wu, E.M.Y. (1999) "Size distribution and  
35 dry deposition of road dust PAHs." *Environmental International* 25(5): 585-597.  
36  
37 Yi, S.M., Shahin, U., Sivadechathep, J., Sofuoglu, S.C. and Holsen, T.M. (2001) "Overall  
38 elemental dry deposition velocities measured around Lake Michigan." *Atmospheric Environment*  
39 35: 1133-1140.  
40  
41 Young, D.R., McDermott, D.J. and Heesen, T.C. (1976) "Aerial fallout of DDT in Southern  
42 California." *Bulletin of Environmental Contamination and Toxicology* 16: 604-611.  
43  
44 Zufall, M.J., Davidson, C.I., Caffrey, P.F. and Ondov, J.M. (1998) "Airborne concentrations and  
45 dry deposition fluxes of particulate species to surrogate surfaces deployed in Southern Lake  
46 Michigan." *Environmental Science and Technology* 32: 1623-1628.

1 **Figure Captions**

2 Figure 1 Location of sampling sites and boundaries of associated watershed (BC – Ballona  
3 Creek; DC – Dominguez Channel; LA – Los Angeles River; MA – Malibu Creek; SA – Santa  
4 Ana River).

5  
6 Figure 2 (a) Size-dependent concentration ( $\text{ng m}^{-3}$ ) of zinc measured in air at DC during summer,  
7 and (b) resulting calculated deposition flux ( $\mu\text{g m}^{-2} \text{day}^{-1}$ ) of zinc.

8  
9 Figure 3 Size-dependent concentration of metals measured by NRI and TSP samplers: left -- bar  
10 height indicates TSP total concentration and light shading is fraction with particle size greater  
11 than  $6 \mu\text{m}$  based on NRI stage A; right -- bar height indicates NRI stage A concentration and  
12 shading indicates breakdown by particle sized based on other NRI stages (solid  $6\text{-}11 \mu\text{m}$ ; grey  
13  $11\text{-}20 \mu\text{m}$ ; striped  $20\text{-}29 \mu\text{m}$ ; white  $> 29 \mu\text{m}$ ). For each season the order of sites is LA1, LA3,  
14 SA, LA2, BC, DC, MA except for Fall in the left figures in which there are no data for the first  
15 three sites.

16  
17 Figure 4 Seasonal metal fluxes measured using deposition plates. For each season the order of  
18 sites is LA1, LA3, SA, LA2, BC, DC, and MA. Note that not all sites are represented  
19 in each season.

20  
21 Figure 5 Comparison between measured and calculated deposition fluxes at different seasons for  
22 the complete set of metals for which an analysis was performed: a) summer; b) fall; c) winter; d)  
23 spring, and different sampling sites: – LA1, ■ LA2, ▲ LA3, × BC, ✱ DC, ● SA, + MA.  
24 The data points shown are not differentiated by which metal is represented.

25  
26 Figure 6 Diurnal variation of metal concentration measured on NRI stage A at LA1 between  
27 12:30 pm on 8/1/2002 and 12:30 pm on 8/2/2002.

28  
29 Figure 7 Diurnal pattern of particle mass concentration with particle size analyzed by image  
30 analysis; a) urban site (SA), b) non-urban site (MA) between 13:00 pm on 6/23/2003 and 13:00  
31 pm on 6/24/2003.

32  
33  
34  
35  
36  
37  
38  
39  
40  
41

1 Table 1 Summary of average metal concentrations  $\pm$  standard deviation ( $\text{ng m}^{-3}$ ) on TSP samples  
 2 measured in the Los Angeles region.

3

	Chromium	Copper	Lead	Nickel	Zinc
LA1	5.1 $\pm$ 2	71 $\pm$ 20	15 $\pm$ 3	15 $\pm$ 2	84 $\pm$ 20
LA2	3.6 $\pm$ 0.2	30 $\pm$ 30	14 $\pm$ 2	4.4 $\pm$ 0.8	54 $\pm$ 20
LA3	1.5 $\pm$ 0.7	24 $\pm$ 20	5.6 $\pm$ 6	11 $\pm$ 8	31 $\pm$ 6
BC	5.7 $\pm$ 3	90 $\pm$ 50	17 $\pm$ 10	5.5 $\pm$ 1.2	97 $\pm$ 40
DC	6.5 $\pm$ 3	43 $\pm$ 20	15 $\pm$ 5	10 $\pm$ 6	69 $\pm$ 20
SA	6.0 $\pm$ 4	52 $\pm$ 30	14 $\pm$ 10	12 $\pm$ 8	150 $\pm$ 110
All Urban Sites	4.9 $\pm$ 3	52 $\pm$ 40	14 $\pm$ 7	9.2 $\pm$ 6	84 $\pm$ 60
Non-urban MA	1.3 $\pm$ 1.8	6.8 $\pm$ 6	2.2 $\pm$ 1.7	3.3 $\pm$ 2	12 $\pm$ 8
ARB <sup>a</sup> (2002)	5.5 $\pm$ 7	34 $\pm$ 30	11 $\pm$ 9	4.5 $\pm$ 4	58 $\pm$ 7
Mates II <sup>b</sup> (1998~1999)	4.9 $\pm$ 5	39 $\pm$ 30	25 $\pm$ 30	8.7 $\pm$ 9	110 $\pm$ 110

4 <sup>a</sup>Air Resource Board annual toxic summary-statewide data  
 5 (<http://www.arb.ca.gov/adam/toxics/sitesubstance.html>)

6 <sup>b</sup>Multiple Air Toxics Exposure Study in the South Coast Air Basin (MATES II):  
 7 <http://www.aqmd.gov/matesiidf/matestoc.htm>

8

9

10

11

12

13

14

15

16

17

18

19

20



1 Table 2 Summary of average measured metal deposition fluxes  $\pm$  standard deviation ( $\mu\text{g m}^{-2} \text{ day}^{-1}$ ) in the Los Angeles region  
 2  
 3

	Chromium	Copper	Lead	Nickel	Zinc
LA1	6.0 $\pm$ 5	21 $\pm$ 20	15 $\pm$ 10	14 $\pm$ 13	130 $\pm$ 110
LA2	2.3 $\pm$ 3	30 $\pm$ 22	31 $\pm$ 32	5.0 $\pm$ 5	160 $\pm$ 180
LA3	9.0 $\pm$ 7	16 $\pm$ 20	32 $\pm$ 50	6.0 $\pm$ 10	110 $\pm$ 150
BC	2.7 $\pm$ 1.5	18 $\pm$ 3	20 $\pm$ 20	1.7 $\pm$ 2	77 $\pm$ 30
DC	3.3 $\pm$ 1.3	12 $\pm$ 5	11 $\pm$ 7	2.3 $\pm$ 3	74 $\pm$ 40
SA	4.3 $\pm$ 0.6	30 $\pm$ 20	10 $\pm$ 4	0.01 $\pm$ 0	180 $\pm$ 90
All Urban Sites	4.6 $\pm$ 4	21 $\pm$ 20	19 $\pm$ 20	5.2 $\pm$ 8	120 $\pm$ 100
Non-urban MA	0.01 $\pm$ 0.0	0.5 $\pm$ 0.7	0.3 $\pm$ 0.4	3.5 $\pm$ 5	8.0 $\pm$ 10
Chicago	5.7 $\pm$ 6	63 $\pm$ 50	38 $\pm$ 30		120 $\pm$ 110
Yi et al., 2001					
South Haven	0.7 $\pm$ 0.8	31 $\pm$ 40	23 $\pm$ 60		51 $\pm$ 50
Sleeping Bear Dunes	1.6 $\pm$ 4	79 $\pm$ 20	35 $\pm$ 80		68 $\pm$ 80

1 Table 3 Comparison of annual average of calculated and measured deposition fluxes  
 2 ( $\mu\text{g m}^{-2} \text{day}^{-1}$ )

Metal	Calculated Flux	Measured Flux
Chromium	5.4	4.8
Copper	26	21
Lead	16	19
Nickel	6.3	9.4
Zinc	130	120

4  
5  
6  
7  
8  
9  
10

11 Table 4 Total particle mass concentration and deposition flux  $\pm$  standard deviation determined by  
 12 microscopic image analysis

	Day *	Night *
<u>Concentration(<math>\mu\text{g m}^{-3}</math>)</u>		
Urban	4.2 $\pm$ 2	3.5 $\pm$ 1
Non-urban	1.4 $\pm$ 0.3	4.9 $\pm$ 0.5
<u>Deposition Flux (<math>\text{mg m}^{-2} \text{day}^{-1}</math>)</u>		
Urban	26 $\pm$ 17	18 $\pm$ 5
Non-urban	9.2 $\pm$ 7	31 $\pm$ 2

14 \* Day time period: 7am to 5pm; night time period: 5pm to 7 am

15  
16  
17  
18  
19  
20

1 Table 5 Comparison of enrichment factors in air and dust samples

2

Metal	This Study <sup>a</sup>	ARB <sup>b</sup>	MATES II <sup>c</sup>	Paved Road Dust <sup>d</sup>	Unpaved Road Dust <sup>d</sup>
Chromium	1.0	1.2	1.0	0.1	0.1
Copper	52	38	39	4.7	5.2
Lead	22	20	43	6.7	7.3
Nickel	4.0	2.2	3.9	0.2	0.5
Zinc	31	25	41	12	4.8

3 <sup>a</sup> Mean values of both urban and non-urban TSP measurements

4 <sup>b</sup> Air Resource Board annual toxic summary-2002 statewide data

5 <sup>c</sup> Multiple Air Toxics Exposure Study in the South Coast Air Basin (MATES-II, 1998 ~1999)

6 <sup>d</sup> Data source: Emission Inventory compiled by SCAQMD, 1998

7

8

9

10

11

12

13

14

15