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Assessing Truck Driver Exposure at the World Trade Center Disaster Site: Personal and Area Monitoring for Particulate Matter and Volatile Organic Compounds During October 2001 and April 2002

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The destruction of the World Trade Center (WTC) in New York City on September 11, 2001, created a 16-acre debris field composed of pulverized and burning material significantly impacting air quality. Site cleanup began almost immediately. Cleanup workers were potentially exposed to airborne contaminants, including particulate matter, volatile organic compounds, and asbestos, at elevated concentrations. This article presents the results of the exposure assessment of one important group of WTC workers, truck drivers, as well as area monitoring that was conducted directly on site during October 2001 and April 2002. In cooperation with a local labor union, 54 drivers (October) and 15 drivers (April) were recruited on site to wear two monitors during their 12-hour work shifts. In addition, drivers were administered a questionnaire asking for information ranging from "first day at the site" to respirator use. Area monitoring was conducted at four perimeter locations during October and three perimeter locations during April. During both months, monitoring was also conducted at one location in the middle of the rubble. Contaminants monitored for included total dust (TD), PM_{10}, $PM_{2.5}$, and volatile organic compounds. Particle samples were analyzed for mass, as well as elemental and organic carbon content. During October, the median personal exposure to TD was 346 $\mu g/m^3$. The maximum area concentration, 1742 $\mu g/m^3$, was found in middle of the debris. The maximum TD concentration found at the perimeter was 392 $\mu g/m^3$ implying a strong concentration gradient from the middle of debris outward. $PM_{2.5}/PM_{10}$ ratios ranged from 23% to 100% suggesting significant fire activity during some of the sampled shifts. During April, the median personal exposure to TD was 144 $\mu g/m^3$, and the highest area concentration, 195 $\mu g/m^3$, was found at the perimeter. During both months, volatile organic compounds concentrations were low.

Keywords area monitoring, personal monitoring, truck drivers, particles, volatile organic compounds, World Trade Center

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On September 11, 2001, the World Trade Center (WTC) in New York City was attacked and destroyed. Both towers and a number of surrounding skyscrapers collapsed or sustained significant structural damage. The area of destruction, covering 16 acres, was a mountain of pulverized and burning debris that has been estimated to exceed 1.8 million tons.(1) The inventory of materials that contributed to the debris matrix included concrete, metals, asbestos, plastics, foams, solvents, insulation materials, glass, and asphalt. The fire that was ignited from burning jet fuel and the compaction energy from the collapsing buildings, generated concern about high concentrations of combustion products and volatile air contaminants. The cleanup operation began within 3 weeks of the attack. It immediately became clear that assessing worker exposure at the site was necessary, as there was the potential for significant exposure to airborne contaminants that could result in acute and chronic health effects. An initial limited exposure assessment was conducted by the National Institute for Occupational Safety and Health (NIOSH) and focused on search and rescue personnel, heavy equipment operators, and iron workers.(2) A more extensive effort was conducted by the Occupational Safety and Health Administration (OSHA) throughout the entire cleanup period. OSHA personal monitoring focused on heavy equipment operators, dock builders, laborers, ironworkers, surveyors, carpenters, supervisors, and other unclassified personnel.(3)

This article describes the exposure assessment of one important group of workers—truck drivers—who were involved in the cleanup effort and whose exposure on site has not been previously described. Throughout the cleanup effort, truck drivers drove both flatbed and box trucks onto the debris to be loaded with the building rubble for transport to the Fresh Kills landfill on Staten Island. Specific activities related to hauling this debris presented a range of opportunities for exposure during the work shifts. Working with an International Brotherhood of Teamsters New York City local union, we obtained permission to access the disaster site and began work on site October 1, 2001. Personal and area monitoring were carried out during October 2001 and then again in April 2002 as the cleanup effort was coming to a close. Contaminants measured included particulate matter in three size fractions—(1) total dust (TD), (2) PM_{10} and $PM_{2.5}$, and (3) elemental and organic carbon (EC/OC); a limited suite of volatile organic compounds (VOC); and asbestos. All area monitoring was conducted directly within the boundaries of the disaster site. Presented in this article are results of the particle, EC/OC, and VOC monitoring. The asbestos results will be reported in a subsequent publication.

STUDY DESIGN

Study Population

Truck drivers accounted for a significant proportion of the WTC worker population, especially during the initial phase of the cleanup operation. During the first week of October 2001, we estimated that on average a minimum of 135 drivers were on site each day. This estimate was based on sign-in records for the local labor union that represented drivers who participated in this study; the estimate does not include truck drivers on site represented by other local labor unions. Between September 22 and October 5, 2001, it was estimated that 1350 construction workers were on site each day;[(4)] a similar estimate is not available for April 2002. Monitoring truck driver exposure, therefore, provides information about one important occupational group. Recruitment, with local union assistance, was conducted on site with the goal of monitoring as many drivers as possible. Drivers were asked by project staff if they would be willing to wear two air pollution monitors during their entire work shift and answer a very brief questionnaire about their activities while they were on site. If they were interested they were asked to sign an informed consent form before they were fitted with monitoring equipment. Fifty-four drivers were recruited on site in October 2001, and 15 were recruited in April 2002. The project had received approval from the Johns Hopkins Bloomberg School of Public Health Institutional Review Board.

Personal Monitoring

During October, the personal exposure of 54 truck drivers involved in hauling debris away from the rubble pile was assessed for asbestos and either TD, EC/OC, or VOCs. Drivers who were nonsmokers were selected to wear an EC/OC or VOC monitor. Each driver was given two monitors consisting of small portable pumps and battery packs worn on at the waist, and sampling cartridges worn on the shoulder within the breathing zone. Each monitor weighed a maximum of 1 kg. Cleanup was conducted on site 7 days a week, 24 hours a day, with two 12-hour work shifts per day, 6:00 a.m. to 6:00 p.m. or 6:00 p.m. to 6:00 a.m. Monitoring was conducted across a work shift on all days of the week during both day and night shifts. Drivers were asked to wear their monitors at all times. If they were planning to sleep in their trucks, they were told they could remove the pumps from their belts and place them on the seat beside them. In April, the personal exposure of the last 15 remaining truck drivers at the site was assessed for the same contaminants.

Time Activity

Before monitoring was initiated, a brief questionnaire was administered to each driver. Questions were designed to identify key factors affecting total exposure since starting work at the WTC including first day on site, number of days off since starting work at the site, number of hours on site per day, number of truck loads of debris hauled during a shift, use of windows for ventilation, and respirator use. Smoking activities were also documented.

Area Monitoring

During October, area monitoring was conducted at four locations around the perimeter of the disaster site on streets approximately representing the north, east, and south/southwest boundaries of the debris field. Figure 1 shows the monitoring locations. October locations (indicated by the stars), included the cross streets of Park Place and Greenwich (PG), Church and Dey (CD), Liberty and Greenwich (LG), and Albany and West (AW). Monitoring was also conducted directly in the debris pile on several days. By April, the boundaries of the site had consolidated. The debris pile had been significantly reduced in size and was confined by the basement slurry walls of the North and South Towers, referred to by the workers on site as the "pit." Therefore, during April, monitoring was conducted at a reduced number of locations (indicated by the dots) including the cross streets of Church and Dey, Barclay and Greenwich (BG), Liberty and West (LW) and directly in the pit. At each location, monitoring was conducted for all contaminants listed above. Each monitor consisted of a sampling cartridge and a portable pump powered by a battery pack. The sets of monitors were hung at head height either from scaffolding, which had been erected around the damaged buildings at the site perimeter, from perimeter chain link fencing, or placed on supports, such as tank cages in the debris pile.

MATERIALS AND METHODS

Sampling

Filter loading, pump calibration and flow check, and equipment maintenance and repair were conducted during October

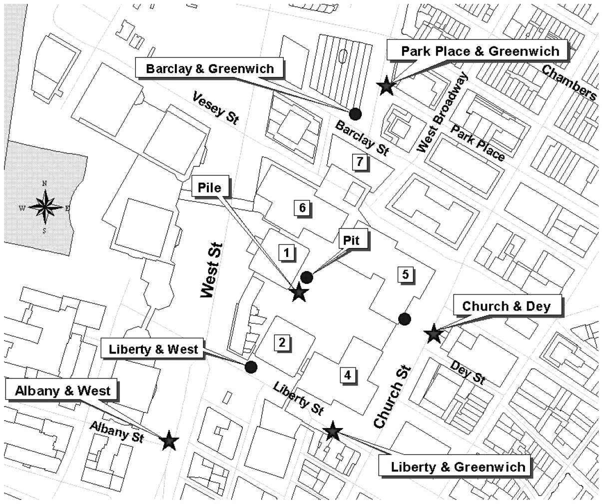

FIGURE 1. Area monitoring locations. October locations (indicated by the star) included the cross streets of Park Place and Greenwich (PG), Church and Dey (CD), Liberty and Greenwich (LG), Albany and West (AW), and directly in the debris pile. April locations (indicated by the dots) included the cross streets of Church and Dey, Barclay and Greenwich (BG), Liberty and West (LW) and directly in the pit. Numbers indicate the WTC buildings numbers 1–7.

in either temporary laboratory space or in a hotel room. During April, the same activities were accomplished in an on-site trailer.

Particulate Matter

TD samples were collected using 37-mm polystyrene filter cassettes (Pall Gelman Laboratory Ann Arbor, Mich.) loaded with either preweighed Teflon membrane filters (37-mm Telfo 2 μm pore, Pallflex Pall Corp., Ann Arbor, Mich.) or prefired quartz fiber filters (37-mm, Sunset Laboratory, Forest Grove, Ore.). All TD sampling cassettes were preloaded in the laboratory in a static air shelter and deployed according to NIOSH method 0500. TD sampling was conducted at a flow rate of approximately 2 L/min. PM_{10} and $PM_{2.5}$ samples were collected using SKC Personal Environmental Monitors, (PEM 761-203B; SKC Inc., Eighty Four, Pa.) loaded with pre-weighed Teflon membrane filters. Because a limited number of PEMs were available for use at the site, filter loading and unloading was conducted at the staging locations described above. The target flow rate for both PM_{10} and $PM_{2.5}$ PEMs was 4 L/min. After sampling, all 37-mm Teflon filters were stored in sealed 50-mm petri dishes. After sampling, all 37-mm prefired quartz filters were sealed in 50-mm petri dishes lined with aluminum foil that had been baked for 1 hour at 500°C and stored at 4°C.

Volatile Organic Compounds

VOC concentrations were measured using activated charcoal tubes (SKC Inc., Anasorb CSC) attached to low flow pumps. The target flow for VOC sampling was 0.2 L/min. After sampling, all charcoal tubes were capped at each end and stored at 4°C.

Pumps and Flow Measurements

Sampling pumps used for particle sampling were either SKC Universal pumps (model 223-PCXR4), BGI personal sampling pump (model 400S; BGI Inc., Waltham, Mass.) or ELF personal sampling pump (MSA Inc., Pittsburgh, Pa.). VOC sampling was conducted with SKC pocket pumps (Personal Pocket Pump 210 series). All sampling pumps were equipped with elapsed time counters. Before sampling, all flow rates were set to within ±2.5% of target flow with dummy filters in line using either a DryCal DC-2 calibrator (BIOS International, Inc., Pompton Plains, N.J.) or an Alltech Digital Flow Check HR Model 5700 (Alltech Associates, Inc., Deerfield, Ill.). At the end of sampling, all flows were measured through the sampled filter and the results recorded.

Quality Control and Quality Assurance

Approximately 10% additional samples for each analyte were collected as blank samples. All mass and carbon measurements were blank corrected using the appropriate average blank value. Method detection limits (MDL) were determined for each analyte as three times the standard deviation of sample blanks divided by the nominal collection volume. A very limited number of samples were collected as duplicates to assess precision

Deployment

Prior to deployment, all samplers were enclosed in protective resealable plastic bags. Immediately before monitoring commenced, samplers were removed from protective bags and uncapped. Pumps were turned on and the start time recorded. At the end of the sampling period, all pumps were turned off at the sampling location, the elapsed times recorded, and samplers were placed in resealable plastic bags.

SAMPLE ANALYSIS

Mass Analysis

Filters were weighed within 10 days of sampling in a room controlled for temperature and humidity (21°C ± 2°C; 40% ± 5%, respectively) using a Mettler T5 microbalance with precision of ±0.001 mg (Mettler-Toledo, Columbus, Ohio). For each mass measurement, filters were weighed twice with the average of the two measurements recorded as the mass value for that weighing. If the difference between the first and the second measurement was greater than 0.003 mg, the filter was reweighed and the two closest measurements were averaged.

Elemental and Organic Carbon Analysis

Carbon content of the TD was determined by analysis of TD samples collected on quartz fiber filters. Carbon analysis for the October samples was conducted at Rutgers University (New Brunswick, N.J.) using a modification of NIOSH method 5040. Carbon analysis for the April samples was conducted by Sunset Laboratory (Sunset Laboratory, Hillsborough, N.C.). Analytical results from an inter-laboratory comparison study in which both groups participated demonstrated good agreement between laboratory results as quantified by their average z-scores, which were within ±0.5.[5] For both sets of analyses, organic and elemental carbon were measured by thermal-optical transmittance in a Sunset Laboratory Carbon Analyzer,[6] with a maximum OC temperature of 820–870°C and a maximum EC temperature of 900–910°C.

Volatile Organic Compound Analysis

Samples were extracted and analyzed according to methods described by Chung et al.[7] In summary, samples were extracted in a glass vial with 1 mL of extraction solvent (including an extraction surrogate 4-bromofluorobenzene) made up of 2:1 v/v acetone (99.9+% capillary GC grade, Sigma-Aldrich, Milwaukee, Wisc.) and carbon disulfide (99.9+% low benzene, Sigma-Aldrich). The vials were placed in an ultrasonic bath with crushed ice for 30 min. The sample extracts were filtered using a syringe filter (Acrodisc CR 4 mm syringe filter; VWR, Corp., Bridgeport, N.J.). Ten μL internal standard (bromofluoromethane, 1,4-difluorobenzene, and chlorobenzene-d5) made up in 2:1 acetone:CS_2 (100 μg/mL) was added to 200 μL of extract then transferred to an amber auto sampler vial with a glass insert. Samples were analyzed by gas chromatograph mass spectroscopy (models GC-17A Ver3/MSQP-5000; Shimadzu Corp., Columbia, Md.) equipped with a capillary column (Rtx - 624, 60 m, 0.25 mm ID, 1.4 μm thickness; Restek Corp., Bellefonte, Pa.). For analysis, 1 μL sample solution was injected by autosamplers set in split mode (11:1) at 180°C with helium as the carrier gas. Oven temperature was programmed as follows: start at 40°C, hold for 4 min, ramp at 8°C/min to 210°C, hold for 2 min. Target compounds were detected by mass spectrometry in single ion monitoring mode. Sample analytes were quantified based on response factors derived from internal standards. Instrument tuning was accomplished for every analytical batch using the mass spectrum of perfluorotributylamine.

Statistical Analysis

Descriptive statistics are reported as the arithmetic mean and standard deviation, median, minimum, and maximum values for each sample type by location (area or personal) and month. One-way analysis of variance, and student's t-test were employed to assess the difference in mean concentrations by location and/or by month monitored using STATA (version 7, College Station, Texas). For each work shift monitored $PM_{2.5}/PM_{10}$, PM_{10}/TD, and EC/TD ratios were examined to assess the relative contribution of combustion products to the overall PM burden.

RESULTS

Sample Collection

A list of personal and area monitoring dates, approximate sample collection periods, work shifts, and monitoring locations are given in Table I. The frequency of monitoring during October 2001 depended on availability of the truck drivers and accessibility to the monitoring locations, personal safety, and equipment security. The most frequently monitored location in October was Church and Dey, with Albany and West monitored the least. Monitoring in the middle of the pile was halted after equipment was buried in the debris while sampling on October 27. During April, the site had become less hazardous and more controlled. As a result, the frequency of area monitoring at each location was more consistent. Permission to sample in the middle of the pit was granted on April 20th. During April, drivers refused to wear the personal monitoring equipment. We understood their refusal to wear the monitors to be the result of emotional and physical exhaustion related to working at the site. To approximate driver exposure, monitors were placed in the truck cab with sampling cartridges hung at head height from the rear view mirror or from a hook near the driver's head.

Quality Control

For October samples, estimated MDLs were 15 $\mu g/m^3$, 5 $\mu g/m^3$, and 5 $\mu g/m^3$ for TD, PM_{10}, and $PM_{2.5}$, respectively, and 3.23 $\mu gC/m^3$, and 12 $\mu gC/m^3$ for EC and OC respectively. During April, estimated MDLs were 12 $\mu g/m^3$, 3 $\mu g/m^3$, and 9 $\mu g/m^3$ for TD, PM_{10}, and $PM_{2.5}$, respectively, and 0.18 $\mu gC/m^3$ and 3 $\mu gC/m^3$ for EC and OC, respectively. The higher EC and OC MDLs determined from the October blank samples were likely a result of opportunistically using prefired quartz fiber filters that had not been recently purchased from the vendor and had an unknown storage history. For October and April, VOC MDLs ranged from 0.003 ppt to 0.6 ppt.

Quality Assurance

Percent precision estimates by month (±October%, ±April%) were TD(±2%, ±10%), PM_{10} (±4%, ±14%), $PM_{2.5}$ (±35%, ±35%), EC (±9%, ±41%), and OC (±11%, ±38%). VOC precision for both months was similar and ranged ±3–39%. A total of eight PM_{10} and eight $PM_{2.5}$ samples were collected with average flow rates outside of the target range. Due to the limited number of samples collected at the site, these nonstandard samples were not invalidated. To assess the impact of an incorrect flow rate on collection efficiency, we calculated the change to the cut point for each sample that was collected at a flow rate different from the flow rate specified for the PEM. The specified average flow for both PM_{10} and $PM_{2.5}$ was 4.0 ± 0.2 L/min with ±5% difference in the start to end flows. Flow rates greater than the specified rate shifted the 50% cut point below 2.5 μm or 10 μm, while flow rates less than 4.0 L/min shifted the 50% cut point above 2.5 μm or 10 μm. For the eight nonstandard PM_{10} samples, average flow rates

TABLE I. Area and Personal Sampling Collection Data

Sampling Start Date	Approximate Start Time	Approximate End Time	Work Shift	Locations Monitored
10/02/01	6:30 p.m.	7:00 a.m.	Night	Per
10/03/01	8:00 p.m.	7:00 a.m.	Night	Per
10/04/01	8:00 p.m.	7:00 a.m.	Night	Per
10/05/01	11:00 p.m.	7:00 a.m.	Night	CD, LG
10/05/01	7:00 a.m.	6:30 p.m.	Day	Per
10/06/01	11:00 p.m.	6:00 a.m.	Night	CD
10/06/01	7:00 a.m.	6:00 p.m.	Day	Per
10/18/01	7:00 a.m.	8:00 p.m.	Day	CD
10/18/01	9:00 p.m.	9:00 a.m.	Night	CD
10/19/01	6:30 p.m.	5:00 a.m.	Night	CD, Pile, Per
10/20/02	9:00 a.m.	5:00 p.m.	Day	AW, Per
10/21/01	10:00 p.m.	6:30 a.m.	Night	AW, CD, LG, PG
10/22/01	8:00 p.m.	7:30 a.m.	Night	LG, PG, Pile, Per
10/23/01	6:00 p.m.	12:00 a.m.	Night	Pile, Per
10/24/01	9:00 p.m.	8:00 a.m.	Night	CD, LG
10/26/01	6:30 a.m.	5:30 p.m.	Day	CD, LG, Pile, Per
10/28/01	8:00 a.m.	7:30 p.m.	Day	PG, LG
10/29/01	8:00 a.m.	6:30 p.m.	Day	AW, CD, LG, PG
10/30/01	10:00 a.m.	10:00 p.m.	Day	LG
4/13/02	8:00 a.m.	7:00 p.m.	Day	BG, CD, LW, Per
4/14/02	8:00 a.m.	7:30 p.m.	Day	BG, CD, LW,
4/15/02	8:30 a.m.	7:00 p.m.	Day	Per
4/15/02	7:00 p.m.	8:00 a.m.	Night	BG, CD, LW
4/16/02	6:00 p.m.	7:00 a.m.	Night	BG, CD, LW, Per
4/17/02	5:30 p.m.	7:30 a.m.	Night	BG, CD, LW, Per
4/18/02	7:01 p.m.	6:30 a.m.	Night	BG, CD, LW
4/19/02	9:00 a.m.	5:00 p.m.	Day	BG, CD, LW, Per
4/20/02	8:00 a.m.	12:00 p.m.	Day	BG, CD, LW, Pit , Per
4/21/02	8:00 a.m.	4:30 p.m.	Day	BG, CD, LW, Pit
4/22/02	7:00 a.m.	7:00 p.m.	Day	BG, CD, LW, Pit, Per
4/23/02	8:00 a.m.	7:00 p.m.	Day	BG, CD, LW, Pit

Notes: Locations include the cross streets of Albany and West (AW), Barclay and Greenwich (BG), Church and Dey (CD), Liberty and Greenwich (LG), Liberty and West (LW), Park and Greenwich (PG), and middle of the pile (Pile) and middle of the Pit (Pit).

ranged from 5.4 to 3.3 L/min with a corresponding change in cut point ranging from 9.02 to 11.52 μm, respectively. For the 8 nonstandard $PM_{2.5}$ samples, flow rates ranged from 2.9 to 4.6 L/min with a corresponding change in cut point ranging from 2.96 to 2.32 μm, respectively. For purposes of ascribing the relative contribution of particles in each size range to the total particle burden, the nonstandard samples were included under the designation of PM_{10} and $PM_{2.5}$, as appropriate.

EC and OC samples were collected on a single prefired quartz fiber filter, which are typically used because they can withstand the high temperatures of thermal-optical analysis. However, in addition to collecting particulate carbon with approximately 100% efficiency, some organic vapors also adsorb to the filter surfaces, which can result in artifacts of up to 30%–50% for samples collected under similar conditions.[8]. Therefore, the reported OC contribution to TD should be assessed conservatively.

October 2001

Table II gives summary statistics for airborne concentrations of particulate matter and for elemental and organic carbon associated with TD by location during the month of October. Perimeter concentrations for TD, PM_{10}, and $PM_{2.5}$ concentrations ranged from 43 to 331 $\mu g/m^3$, 41 to 392 $\mu g/m^3$, and 21 to 321 $\mu g/m^3$, respectively. Although concentration data from the debris pile were very limited, an estimation of the concentration difference between the middle of the pile and the perimeter can be made by comparison of PM_{10} values from three days (10/19/01, 10/22/01, and 10/26/01) when samples were collected in both perimeter and pile locations. For these days, PM_{10} in the middle of the pile was 1.7 to 4.2 times

TABLE II. Summary Statistics by Area Location During October 2001

	n	Mean (SD)	Median	Min	Max
Albany and West					
TD^{A}	4	83 (33)	80	48	124
$PM_{10}{}^{A}$	2	52^{B}	52	43	60
$PM_{2.5}{}^{A}$	3	36 (16)	33	21	53
EC^{C}	2	5.9^{B}	5.9	5.7	6.1
OC^{C}	2	36^{B}	36	34	38
Liberty and Greenwich					
TD^{A}	7	130 (59)	162	43	189
$PM_{10}{}^{A}$	9	100 (56)	82	41	210
$PM_{2.5}{}^{A}$	7	43 (15)	47	23	58
EC^{C}	6	5.3 (2.2)	5.3	$< MDL^{D,E}$	8.3
OC^{C}	6	30 (9)	30	18	38
Park Place and Greenwich					
TD^{A}	4	208 (142)	228	47	331
$PM_{10}{}^{A}$	4	148 (91)	146	41	259
$PM_{2.5}{}^{A}$	4	152 (95)	151	58	250
EC^{C}	3	14.5 (5.4)	16.4	8.4	18.6
OC^{C}	3	72 (26)	58	56	101
Church and Dey					
TD^{A}	6	146 (57)	152	69	229
$PM_{10}{}^{A}$	8	211 (109)	182	100	392
$PM_{2.5}{}^{A}$	10	116 (86)	98	36	321
EC^{C}	5	7.9 (3.3)	7.2	5.7	12.9
OC^{C}	5	48 (15)	45	31	72
Middle of the Pile					
TD^{A}	3	1401 (476)	1603	857	1742
$PM_{10}{}^{A}$	4	850 (516)	908	241	1345
$PM_{2.5}{}^{A}$	4	361 (343)	236	107	865

$^{A}\mu g/m^3$.
^{B}Standard deviation not applicable.
$^{C}\mu gC/m^3$.
^{D} < MDL = less than method detection limit.
^{E}One sample below MDL; the concentration for this sample was set to 0.5 MDL.

higher than PM_{10} at the perimeter. The relative contribution of $PM_{2.5}$ to PM_{10} and $PM_{2.5}$ to TD was highly variable and ranged from 23% to 100% and 16% to 86%, respectively. The personal exposure to TD was monitored over 27 work shifts, and 22 valid samples were collected. These are reported in Table III. Personal exposures ranged from 72 to 790 $\mu g/m^3$, falling in between the highest and lowest area TD concentrations.

No carbon data are available from the middle of the pile. For the work shifts monitored, EC concentrations ranged from < MDL to 18.6 $\mu gC/m^3$ (mean: 8.0 $\mu gC/m^3$). From matched carbon and TD samples by date and location, EC was found to account for 2% to 9% of total dust. OC concentrations ranged from 18 to 101 $\mu gC/m^3$ (mean: 47 $\mu gC/m^3$) contributing 26% to 58% to total dust. Personal exposure to EC and OC was monitored for eight nonsmoking drivers (Table III). EC exposures ranged from 5.5 to 11.9 $\mu g/m^3$ (mean: 7.8 $\mu gC/m^3$). OC ranged from 119 to 229 $\mu gC/m^3$ (mean: 165 $\mu gC/m^3$) and were on average 118 $\mu g\ C/m^3$ higher than concentrations found from area monitoring.

Results of monitoring for both personal and area VOCs are found in Table IV. For all compounds detected, concentrations were in the ppb range. The highest area concentration measured was for benzene at 17.8 ppb; the

TABLE III. Summary Statistics for October Personal Exposure

	n	Mean (SD)	Median	Min	Max
October 2001					
TD^{A}	22	344 (195)	346	72	790
EC^{B}	8	7.8 (2.3)	6.9	5.5	11.9
OC^{B}	8	165 (43)	164	119	229

$^{A}\mu g/m^3$.
$^{B}\mu gC/m^3$.

TABLE IV. Summary Statistics for Personal and Area VOCs for October 2001 and April 2002

	Area Monitors			Personal Monitors		
	n	n > MDL	Max Area (ppb)	n	n > MDL	Max Personal (ppb)
October 2001						
Methylene chloride	5	0	NA	12	6	1.44
MTBE	5	5	5.24	12	12	11.47
Chloroform	5	5	0.26	12	12	0.17
Carbon tetrachloride	5	5	0.18	12	12	0.19
Benzene	5	5	17.81	12	12	9.15
Trichloroethylene	5	1	1.23	12	2	0.78
Toluene	5	5	9.56	12	11	6.86
Tetrachloroethylene	5	5	0.78	12	12	0.42
Ethylbenzene	5	5	8.13	12	9	3.20
m,p-Xylene	5	5	1.52	12	12	13.77
o-Xylene	5	5	0.79	12	12	2.33
Styrene	5	5	1.33	12	11	0.81
1,2,4-Trimethylbenzene	5	5	1.66	12	12	6.44
1,4-Dichlorobenzene	5	3	0.13	12	12	1.76
April 2002						
Methylene chloride	34	2	2.10	5	0	Not applicable
MTBE	34	31	27.05	5	5	10.02
Chloroform	34	6	0.13	5	4	1.37
Carbon tetrachloride	34	34	0.47	5	5	0.17
Benzene	34	34	4.56	5	5	3.95
Trichloroethylene	34	7	2.22	5	1	1.01
Toluene	34	33	20.78	5	5	6.44
Tetrachloroethylene	34	34	1.30	5	5	0.70
Ethylbenzene	34	33	3.39	5	5	2.50
m,p-Xylene	34	34	8.73	5	5	3.63
o-Xylene	34	34	3.01	5	5	1.29
Styrene	34	33	0.57	5	5	0.38
1,2,4-Trimethylbenzene	34	34	2.88	5	5	1.64
1,4-Dichlorobenzene	34	24	1.10	5	5	1.49

highest personal exposure measured was 13.8 ppb for *m*, *p*-xylenes.

April 2002

Table V gives summary statistics for airborne concentrations of particulate matter and for elemental and organic carbon associated with TD by location during the month of April. TD concentrations ranged from 14 to 195 $\mu g/m^3$, PM_{10} from 13 to 144 $\mu g/m^3$, and $PM_{2.5}$ from 4 to 102 $\mu g/m^3$. The highest concentrations were found in the center of the main work area, which was the pit where debris removal activity was still being conducted. The contribution of $PM_{2.5}$ to PM_{10} and $PM_{2.5}$ to TD ranged from 9% to 97% and 7% to 85%, respectively. Concentrations in the pit in April were on average 8% of those found during the October monitoring in the middle of the debris pile. Median perimeter concentrations of TD, PM_{10}, and $PM_{2.5}$ were 59, 45, and 19 $\mu g/m^3$ representing a reduction from October of 60%, 63%, and 67% respectively. Figure 2A–D illustrates the distribution of particle concentrations in the middle of the site and at one perimeter location (Church and Dey), and the difference in concentrations at these sites between October and April.

Carbon concentrations were measured for all perimeter locations and in the pit. During April, EC ranged from <MDL to 7.9 $\mu gC/m^3$ and were on average 44% lower than those measured during October (2-tailed t-test $p = 0.006$). From matched carbon and TD samples by date and location, EC was found to account for 5% to 11% of total dust. OC concentrations ranged from 1 to 69 $\mu gC/m^3$(mean: 47 $\mu gC/m^3$) contributing 30% to 61% to total dust and were on average 43% lower than those measured in October (2-tailed t-test $p = 0.004$).

During April, personal exposure to EC and OC was monitored in the cabs of three nonsmoking drivers (Table VI).

TABLE V. Summary Statistics by Area Location During April 2002

	n	Mean (SD)	Median	Min	Max
Liberty and West					
TD^A	11	51 (33)	47	14	139
$PM_{10}{}^A$	11	46 (22)	41	22	97
$PM_{2.5}{}^A$	10	27 (12)	28	11	45
EC^B	8	4.2 (2.1)	3.7	2.1	7.7
OC^B	8	26 (13)	24	11	55
Barclay and Greenwich					
TD^A	11	71 (52)	73	17	194
$PM_{10}{}^A$	11	62 (39)	48	13	143
$PM_{2.5}{}^A$	8	25 (18)	16	4	54
EC^B	10	4.0 (2.6)	4.4	$<$ MDL^{C,D}	7.7
OC^B	10	18 (14)	14	1	38
Church and Dey					
TD^A	9	93 (50)	95	40	195
PM_{10}^A	11	68 (34)	72	23	144
$PM_{2.5}{}^A$	10	33 (28)	25	6	102
EC^B	10	4.5 (1.9)	4.5	0.8	7.8
OC^B	10	27 (15)	27	8	61
Middle of the Pit					
TD^A	4	106 (56)	105	46	168
$PM_{10}{}^A$	4	83 (34)	89	41	114
$PM_{2.5}{}^A$	4	42 (12)	44	26	55
EC^B	3	6.7 (1.0)	6.2	6.1	7.9
OC^B	3	40 (25)	26	25	69

^{A}ug/m^3.
^{B}ugC/m^3.
^{C} <MDL = less than method detection limit.
^{D}Two samples below MDL; the concentration for these samples was set to 0.5 MDL.

EC exposures ranged from 5.2 to 9.1 μg/m^3 and were on average similar to area concentrations. OC ranged from 110 to 189 μg/m^3. Mean personal OC was 134 μg/m^3 higher than area concentrations.

Results of monitoring for both personal and area VOCs are found in Table IV. Again, concentrations for all the VOC detected were very low. The highest area concentration measured during April was 27.05 ppb for methyl tertiary-butyl ether (MTBE); the high personal exposure was 10.02 ppb for MTBE.

TABLE VI. Summary Statistics for April Personal Exposures

	n	Mean (SD)	Median	Min	Max
April 2002					
TD^A	11	174 (90)	144	60	292
EC^B	3	6.5 (2.2)	5.2	5.2	9.1
OC^B	3	162 (45)	186	110	189

^{A}ug/m^3.
^{B}ugC/m^3.

ON-SITE ACTIVITIES

Drivers interviewed from October 1–29 reported working between 1–43 days out of a maximum possible of 49 (calculated from September 11 to October 29, 2001). Thirty-one percent of the drivers stated they were on site either on September 11th or the first days after. All drivers worked 12-hour work shifts. Because of the large number of trucks on site, 66% reported hauling four loads or less of debris per shift. More than half (52%) said that they spent less than half the time in their trucks when they were waiting for a load, and 61% said they had their window open more than half the time. When they were not in their trucks 70% said they were either standing near their truck, working on the pile, or walking within the site perimeter. A majority, 80%, reported using a respirator less than half the time. Sixty-five percent reported that they did not smoke. During October, the entire process to remove one load of debris from the disaster zone took on average 2 hours.

During April, the work shift was still 12 hours. Drivers interviewed between April 13–21, 2002, reported working 93–202 days out of a possible 223 (calculated from September 11, 2001–April 21, 2002). Of these 15 drivers who remained,

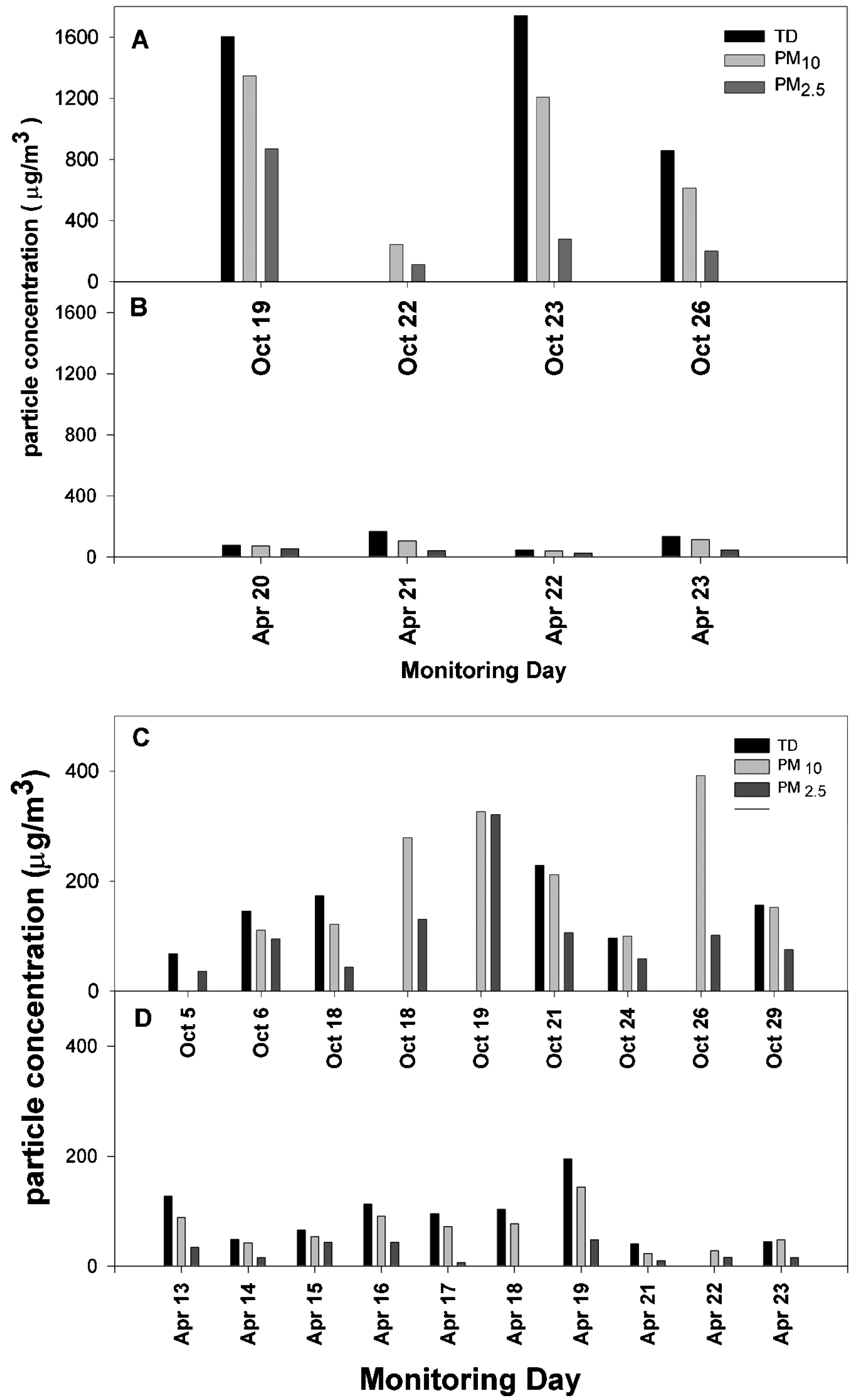

FIGURE 2. A and B: Distribution of particle concentrations at the middle of the site by month; C and D: Distribution of particle concentrations in the Church and Dey location of the site by month

6 (43%) had been there on September 11th or the first 3 days after. Seventy-three percent reported hauling 9–15 loads per shift. Sixty percent reported being in their truck all or most all the time indicating that the cab samples were a good representation of personal exposure during the April monitoring effort. Eighty-seven percent said they had their window down more than half the time. Eighty-seven percent reported using their respirators more than half the time. Sixty percent reported that they did not smoke. During April, the debris removal process took about 1 hour or less per load.

DISCUSSION

The World Trade Center disaster site presented a complex and dynamic exposure environment. The debris pile encompassed over a million tons of pulverized and burning material. The debris removal effort involved hundreds of construction workers and took several months. Over the entire cleanup period, which started during September 2001 and officially ended May 30, 2002, over 1.5 million worker hours were committed to removing the 1.8 million tons of debris. Debris removal was a 24-hour per day, 7-day per week activity, and over this time period, 108, 342 truckloads of debris were removed from the site.[1] From September 11 through the end of December 2001, airborne contamination at the site was due to debris removal activities that disturbed the rubble, resuspended dust that had already settled to the ground, and underground fires, which continued to burn until December 19 when they were officially declared extinguished. Around the beginning of 2002, the number of vehicles on site began to decrease, and the debris removal had moved into the substructure of the twin towers. By April 2002, the rubble pile had been reduced to a 3-story mound where the North Tower formerly stood. Although clear evidence of the disaster remained, the 16-acre area had become more similar to a normal construction site and the air quality had significantly improved.

The work described here focuses on the personal exposure of one important group of cleanup workers—truck drivers—who were not included in other personal monitoring efforts at the site. In addition, the data presented provide insight into exposure conditions directly within the disaster zone during important portions of the cleanup effort. Although limited in scope, both the area and personal particulate matter data sets are useful complements to those collected and reported by the governmental agencies. While the U.S. Environmental Protection Agency (USEPA) collected several months of particle data, their monitors were located a few to several blocks from the site boundaries and were, therefore, not reflective of worker exposures directly within the disaster zone. In addition, the USEPA specifically monitored for PM_{10} and $PM_{2.5}$, thereby missing an important part of the particle size distribution—the larger particles. Although OSHA collected numerous personal samples, none were for truck drivers. Of the personal samples, a total of 176 were for total dust. Monitoring was conducted specifically for the purpose of determining if permissible exposure limits were being exceeded. Only a subset of these OSHA data is available online and are not in a downloadable format.

Personal exposure to and area concentrations of particulate matter and volatile organic compounds were monitored to assess the extent of exposure at the disaster site. The elemental and organic carbon content of the TD was also examined to assess the potential contribution of combustion products to the particle mixture. During October, the highest PM concentrations were measured in the middle of the debris pile. PM concentrations at the perimeter were approximately 80% lower suggesting a steep concentration gradient from the center of the debris pile outward. By April, particle concentrations had dropped significantly at all locations. There was no difference in mean concentration for TD, PM_{10}, and $PM_{2.5}$ between the three perimeter locations (one-way ANOVA, $p = 0.14$, 0.27, 0.66, respectively). In addition, there was no difference in the mean concentration between the middle of the work area and the perimeter sites for all of the particle sizes measured (multiple pairway comparison using Bonferroni adjusted t-tests). Figure 3 illustrates the differences between PM_{10} concentrations at the perimeter and in the center of the debris pile or work pit during October and April.

The localized impact of the site on air quality is further reflected by concentrations of $PM_{2.5}$ collected at monitoring stations located within a few city blocks of the disaster site. At the beginning of October 2001, the New York State Department of Environmental Conservation (NYSDEC) installed additional continuous particle monitors in lower Manhattan. These new monitors were located at Chambers and West Streets (approximately 2 blocks northwest of the site), Spruce and Gold Streets (approximately 2 blocks northeast of the site), and at the base of FDR Drive (approximately 4 blocks south of the site). Data from these stations are available at the Aerometric Information Retrieval System (AIRS), a public database of national air quality data maintained by USEPA. Although the NYSDEC collected both PM_{10} and $PM_{2.5}$, currently only hourly $PM_{2.5}$ data are available through the AIRS data base. The ratio of mean $PM_{2.5}$ concentrations during matched sampling periods from the NYSDEC (16.9 $\mu g/m^3$) and perimeter sites from this study (90.8 $\mu g/m^3$) is 0.19, which is consistent with the trend toward lower PM concentrations at locations farther from the middle of the debris field. It is possible that the strong concentration gradient from the center of the debris pile outward was due to convective action resulting from the intense heat generated by the fires. A similar comparison was not possible in April as the monitors at the sites listed above had been removed.

Although the overall concentrations of PM at the site were significantly lower in April, the relative contributions of fine particles to the PM_{10}, and EC and OC to the TD were similar. Figure 4A, B gives the distribution of $PM_{2.5}/PM_{10}$ and EC/TD ratios by location and month. During October, the fires burned aggressively, but debris removal activity also resuspended an enormous amount of dust. The variable contribution of each size fraction during October was driven by daily differences in the intensity of the fires, the number of on-site construction vehicles, and the extent of settled dust disturbance due to debris removal activity. For example, during the memorial service held on October 28, all work was suspended for 24 hours, and dust and fire suppression was intensified. As illustrated in Figure 5, at the one location where monitoring was possible that day, the Park Place and Greenwich location, particle concentrations were reduced by approximately 80% from the preceding shift monitored. When work activity resumed and dust suppression became less intense, particle concentrations tripled.

By April 2002, with the fires officially out and the number of on-site construction vehicles reduced, it was expected that the

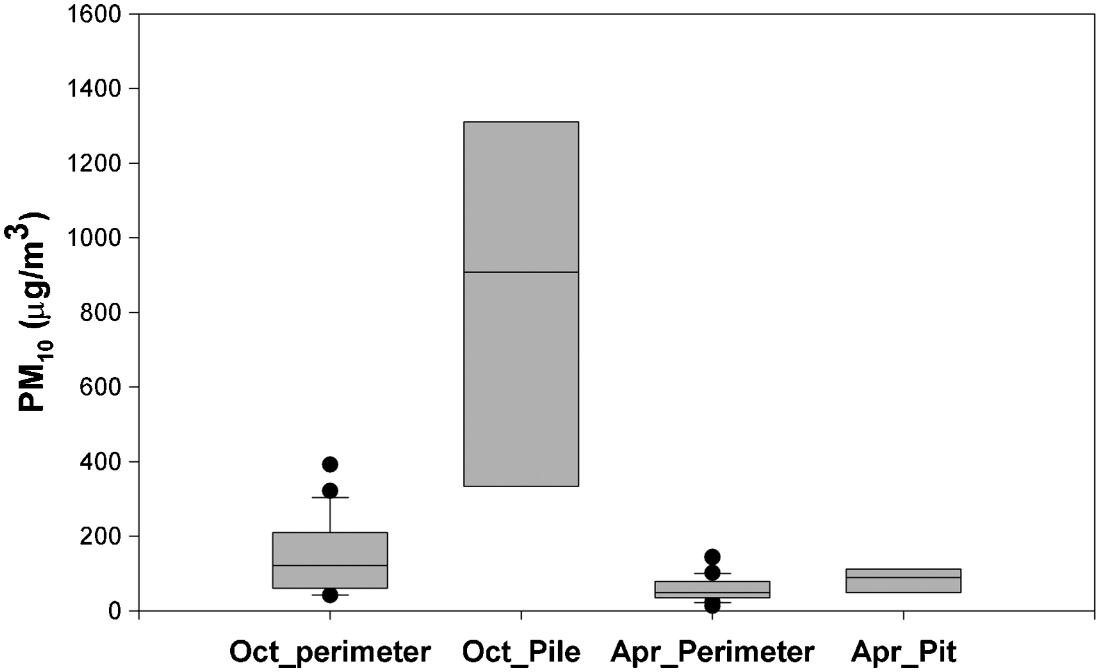

FIGURE 3. Differences in PM_{10} concentrations at the perimeter and the center of the site by month. Box plot description—lower and upper whiskers represent the 10th and 90th percentile; the box lower and upper boundaries signify the 25th and 75th percentile; the median is represented by the center line and outliers are designated by the dots.

relative contribution of $PM_{2.5}$ to PM_{10} and EC to TD would be reduced and be more consistent across all locations. However, this was not true at all locations. The wider distribution of $PM_{2.5}$ to PM_{10} (as well as EC to TD) at the southwest site (LW/AW) may be reflective of low-level localized fire activity, which we observed in the basement of 90 West Street. In addition, on average, the ratios of $PM_{2.5}$ to PM_{10} from the middle of the work pit were higher during April than October. Since the fire activity was not a factor in the work pit, this was mostly likely driven by a decrease in resuspended debris, better dust suppression at the site, and a greater relative contribution to the particle mixture of on-site construction vehicle emissions. In addition, normal traffic patterns had been re-established, including a major thoroughfare on the west side of the site.

PERSONAL EXPOSURE

During October, truck driver activities on site resulted in exposures to TD ranging from 72–790 μg/m^3. The October median personal exposure to TD was 346 μg/m^3, which dropped in April to 144 μg/m^3 (Figure 6). Over the same time period, the median EC and OC exposure concentrations were unchanged. Personal VOCs exposures were low in October and remained low in April.

Comparison of these TD exposure levels to those of truck drivers involved in standard driving jobs is not possible as no data for truck driver TD exposure exist. In fact, from a review of the literature, comparable data are not available. Review of the literature found no comparable data either because the location of the published occupational studies was different (i.e., noncomparable) or the size fraction of the sampling differed—making these data not useful for comparison. In addition, the composition of the dust was likely different from that found on typical construction sites.

To contextualize the contribution of EC and OC measured at the WTC worksite, personal exposure to EC during both October and April was compared with earlier studies in the scientific literature. Zaebst et al.[9] found that over typical 8-hour work shifts, long- and short-haul drivers were exposed to, on average, 5.1 μgC/m^3 and 5.4 μgC/m^3, respectively. This suggests that the primary source of exposure to EC for the WTC truck drivers was emission from their vehicles. OC exposures for our study population were substantially higher than those found by Zaebst. However, the differences in sampling and analytical methods make the OC results more difficult to compare (i.e., different flow rates used during sample collection and differences in the temperature profiles used for sample analysis).

Between the beginning of October and the end of December, conditions on site resulting from the fires, the number of construction vehicles, debris removal activities, and site operation were very similar. After the beginning of January 2002, site conditions change substantially. The fires were extinguished, the badly damaged buildings had been demolished, and the debris was well into the substructure. Therefore, for workers whose on-site activities and respirator use were similar to truck drivers, the median value measured in October, 346 μg/m^3, could be considered an estimate of daily exposure between

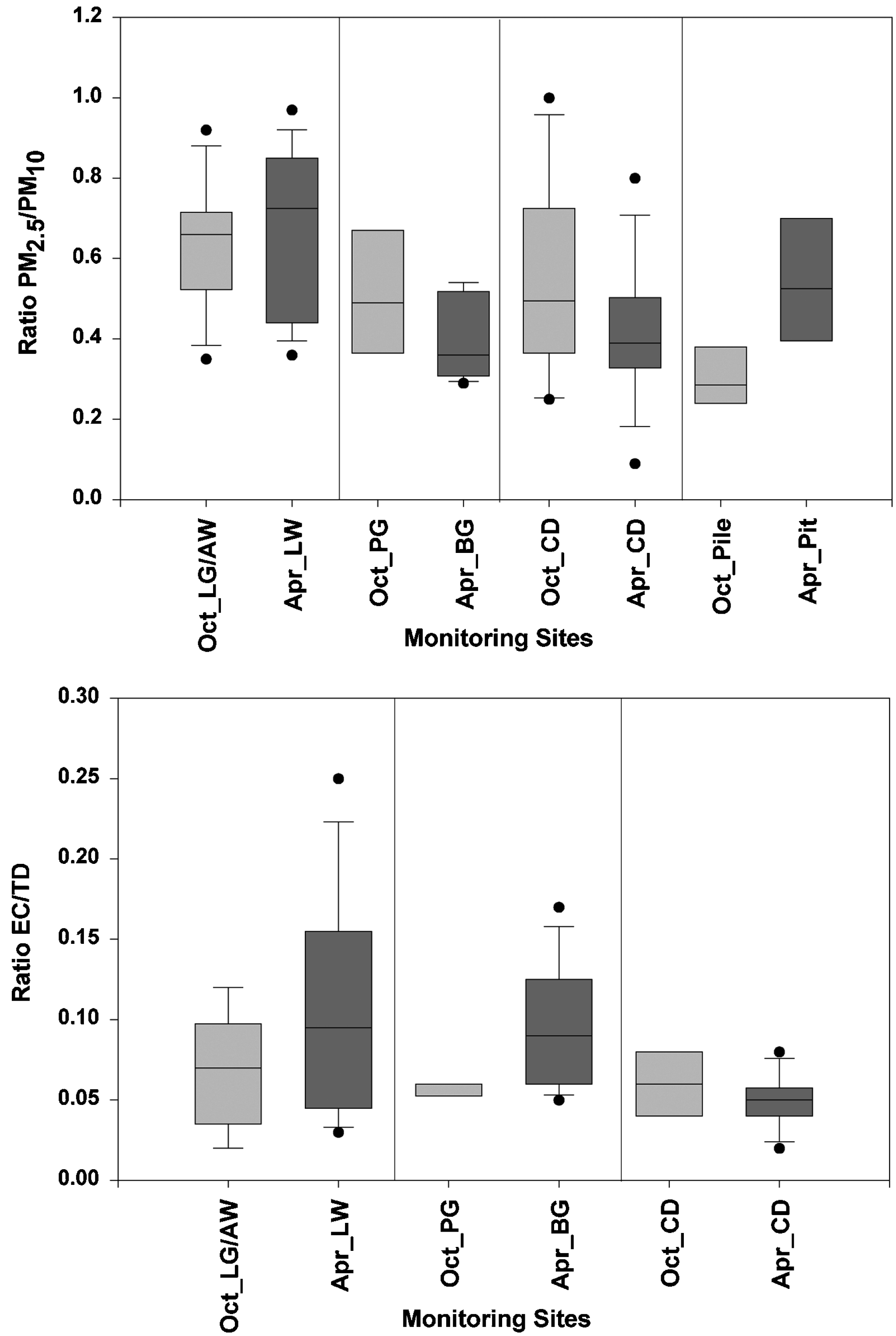

FIGURE 4. (A): Distribution of $PM_{2.5}/PM_{10}$ ratios by location and month. Box plot description—lower and upper whiskers represent the 10th and 90th percentile; the box lower and upper boundaries signify the 25th and 75th percentile; the median is represented by the center line and outliers are designated by the dots. (B): Distribution of EC/TD ratios by location and month. Box plot description—lower and upper whiskers represent the 10th and 90th percentile; the box lower and upper boundaries signify the 25th and 75th percentile; the median is represented by the center line and outliers are designated by the dots.

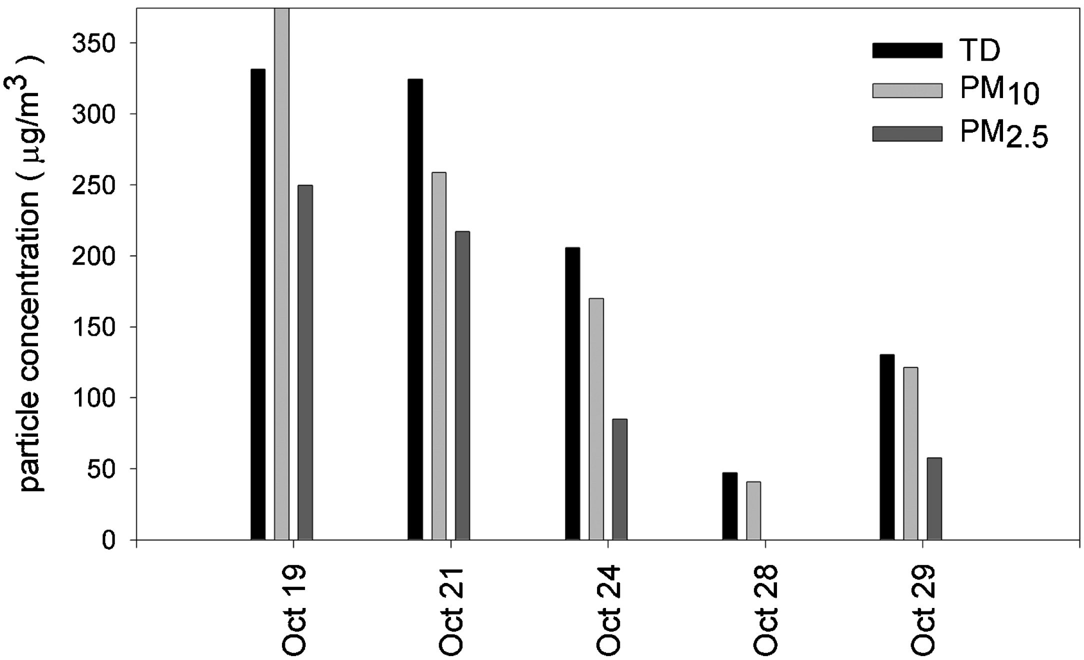

FIGURE 5. October TD, PM_{10}, and $PM_{2.5}$ concentrations at the Park Place and Greenwich location

the beginning of October and the end of December. If it is assumed that exposure from January to April decreased linearly by month, the median monthly decrease in exposure to TD was approximately 50 $\mu g/m^3$.

Composition information from settled dust samples collected shortly after the attack provides some insight into the exposure mixture. Analysis of whole settled dust samples by Lioy et al.[10] showed the dust to be a complex mixture composed

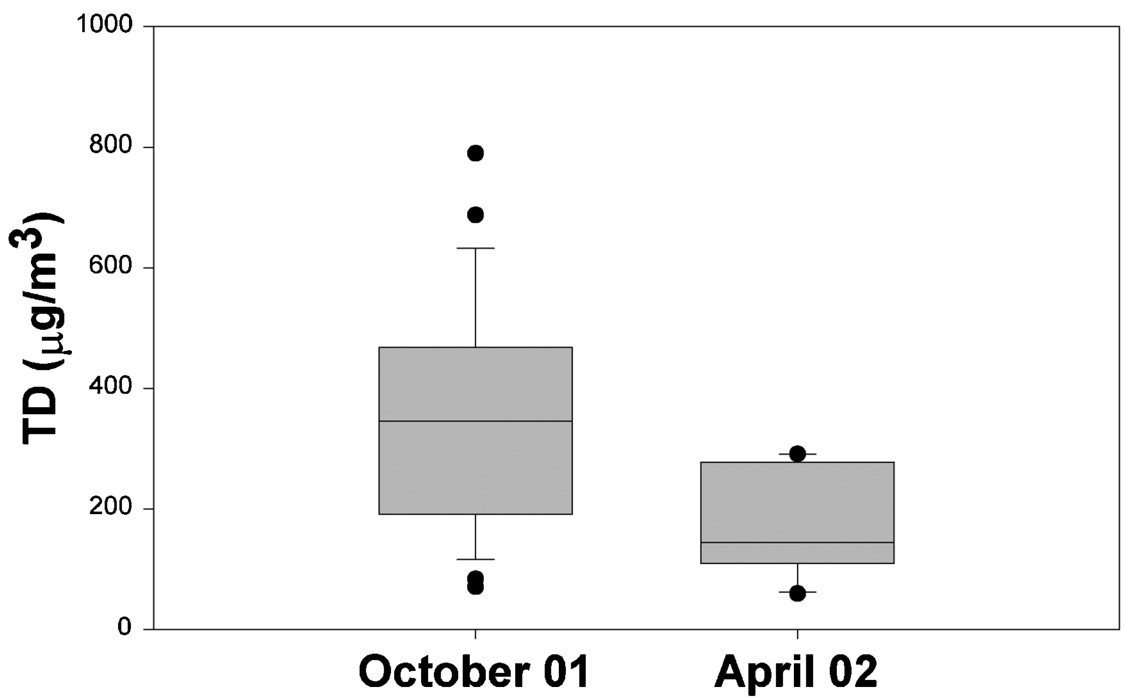

FIGURE 6. Distribution of personal exposure measurements to TD by month. Box plot description—lower and upper whiskers represent the 10th and 90th percentile; the box lower and upper boundaries signify the 25th and 75th percentile; the median is represented by the center line and outliers are designated by the dots.

of cement, charred wood fragments, paint particles, and glass fibers (mineral wool and fiberglass) and asbestos. As expected, the settled dust was dominated by larger particles. The pH of the dust ranged from 9.2–11.5. Additional analysis of these settled dust samples found evidence of polycyclic aromatic hydrocarbons at levels considered to be high relative to concentrations of PAHs measured in total suspended particulate matter collected in New Jersey City, N.J., from July 1998 to January 2001.[11] McGee et al.[12] analyzed the fine, coarse, and large fractions of the settled dust collected 1 and 2 days after the attacks. They found that, compositionally, the large fraction of the settled dust was dominated by calcium-based compounds specifically calcium sulfate (gypsum) and calcium carbonate (calcite). These compounds were indicated in the fine fraction of this dust as well. Given that our data show the fine fraction to account from 16% to 86% of the total dust during October and 7% to 85% during April, this compositional information for the fine fraction has significant implications from a health standpoint.

Respiratory health effects have been reported for some groups of WTC workers. In a study of 183 workers, who were actively involved in the cleanup effort during December 2001, Herbstman et al.[13] found that 52% reported nasal congestion, 43% reported sore throat, and 44% reported experiencing a hoarse throat while working at the site. Of the 119 workers who began working at the site with no previous history of lower respiratory symptoms, 34% developed a new cough, 24% reported new phlegm production, and 19% reported new wheeze. Levin et al.[14] report acute and longer-term respiratory symptoms in a subset of workers who participated in a program that provided medical screening to WTC workers and volunteers. Of the 1138 workers who were screened 9–14 months after the attacks, a majority reported lower-respiratory (60%) and upper-respiratory (74%) symptoms. Of this subgroup, 50% reported persistent upper respiratory symptoms after being absent from the site 7 to 63 weeks. Feldman et al.[15] report new or worsening symptoms of sore throat (54%), congestion (40%), hoarseness (34%) daily cough (53%) and wheeze (21%) for 319 firefighters who were at the WTC either the morning of the attack, 1–2 days after, or 3–7 days after.

Missing from this data set, as well as from all other data sets collected in response to the events of September 11, 2001, is information about exposures experienced when concentrations were highest—immediately after the attack and then during the first few days. Therefore, in terms of understanding future health effects for the cleanup worker population, it will be important to consider these unmeasured exposures for those who were present during this critical time period. In our sample, a third of workers reported being on site either the day of or the first days after the attacks. This represents a significant portion of our study population. If our sample is reflective of the entire cleanup work force, many workers also experienced similar exposures during the first few days. However, there is no reliable estimate of the total number of workers on site throughout the entire cleanup effort. Therefore, the absolute number of workers who were affected during the first few days, along with magnitude of their exposure cannot be estimated. Thus, the extent of the potential public health impact cannot be assessed.

CONCLUSIONS

The cleanup and recovery effort formally ran the end of September 2001 to May 30, 2002. It was expected that as the cleanup effort proceeded, air quality at the disaster site would improve. The intent of the monitoring effort described here was to help quantify that change and to provide a better understanding of airborne particulate matter and volatile organic compound concentrations at the site near the highest exposure period and then again near the lowest. An understanding of the dynamic nature of the particle mixture and the significant decrease in total particle concentrations over time may be important in helping to account for potential health effects related to these exposures.

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