Ultrafine Particle Concentrations in Schoolrooms and Homes

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Abstract

Field monitoring of ultrafine particles and copollutants was undertaken at seven houses and six classrooms in the East Bay region near San Francisco, California. At each site, time-resolved measurements were made indoors and outdoors of particle number (PN) concentration in addition to nitric oxide, ozone, carbon dioxide and carbon monoxide. Data were also acquired through the use of questionnaires (houses), observation (classrooms), and temperature and proximity sensors. The information from each site were analyzed to characterize (1) indoor and outdoor PN concentrations; (2) key factors that influence indoor PN concentrations; and (3) the exposure of building occupants to indoor PN and its determinants.

During the observational monitoring periods, the time-average PN concentrations from the primary indoor monitor varied across the seven house sites from 3.7×10^3 particles per cm^3 to 28×10^3 particles per cm^3 with a mean of 14.5×10^3 particles per cm^3. The corresponding outdoor concentrations ranged from 5.5×10^3 to 23×10^3 particles per cm^3 (averaging 15×10^3 particles per cm^3). For five classroom sites (excluding one at which overnight outdoor data were incomplete), the time-average indoor concentrations ranged from 3.2×10^3 to 10.5×10^3 particles per cm^3 (averaging 6.9×10^3 particles per cm^3); the corresponding outdoor concentrations ranged from 9.7×10^3 to 16×10^3 particles per cm^3 (averaging 13×10^3 particles per cm^3).

Overall, the results inform the interplay among building factors, human occupancy, and pollutant dynamics as they influence concentrations of and exposures to ultrafine particles in the studied houses and classrooms. Particle levels in classrooms and in houses were much higher when occupied than when vacant. In houses, important contributions to PN levels were attributable to both outdoor particles and indoor emission sources such as cooking (both with natural gas and electricity) and natural gas furnace use. In schools, the dominant PN source was outdoor air and indoor levels were significantly influenced by time-varying ventilation conditions. Daily average PN exposures per person were much higher in houses than in schools.

Executive Summary

Background

Atmospheric ultrafine particles (UFP) are airborne solids or liquids whose individual diameters are smaller than 0.1 micrometers (100 nanometers). This class dominates the number concentration of airborne particles, but makes only a small contribution to mass concentrations. Chemically and physically, UFP are distinct from the currently regulated fine airborne particulate matter, $PM_{2.5}$. Although uncertain, evidence is sufficient to raise concerns about the potential for adverse health effects to result from exposure to UFP in the environment.

A pivotal element in evaluating health risks from air pollutants is to properly characterize exposure. Such characterization requires knowledge about the concentrations of pollutants in the spaces people occupy. Making enough measurements to directly characterize exposure poses great challenges; the effort to understand exposure is facilitated by studying the factors that influence it.

People spend most of their time indoors, and so characterizing conditions in buildings is essential if we are to properly understand exposure to UFP. For particles of outdoor origin, buildings offer some degree of protection. The extent of protection varies with building design and operation and has not been well characterized for UFP. In addition, there are important sources of UFP that can emit directly indoors, thereby substantially influencing exposures.

The main objective of this research is to increase the base of knowledge about the concentrations of UFP in California schoolrooms and residences. A second objective is to advance understanding of the factors that influence UFP levels in these microenvironments.

Methods

Field monitoring was conducted in seven houses and six classrooms in the East Bay area near San Francisco, California. The sites were selected to have features that might produce higher-than-average concentrations, but were not intended to be unusual or extreme. At each site, we conducted observational monitoring for several days under normal occupancy and use conditions. We also conducted manipulation experiments designed to characterize ventilation conditions, the indoor penetration and persistence of outdoor particles, and the emissions of particles from potential indoor sources. In all, monitoring at one site or another occurred during ten calendar months between November 2007 and December 2008. (No monitoring was conducted in January, May, July, or August 2008. A supplemental field investigation of emissions from continuous gas pilot lights was undertaken in February 2009.) The seven house sites were occupied, single-family residences built between 1904 and 1996 (average year built = 1945). The six classrooms were from four elementary schools in the urban East Bay.

The primary particle-measuring instruments employed were a set of water-based condensation particle counters (WCPC), which measure the number concentration of airborne particles with excellent time resolution. We monitored and recorded particle number concentrations at one-minute resolution in two indoor locations and also outside of each study site. The WCPC data were augmented with continuous measurements of several copollutants: ozone, nitric oxide, carbon monoxide, and carbon dioxide. We used occupant diaries (in houses) and direct observation (in schools) to record time-dependent information on occupancy, building configuration (e.g., opening of doors and windows), and source-related activities (e.g., cooking). Temperature and proximity sensors provided further information about source activities and building configuration during observational monitoring. Side-by-side sampling was conducted at each site to ensure comparability of indoor and outdoor pollutant concentration measurements.

In addition, the flow rates of the WCPCs were checked regularly at each field site and laboratory calibrations of copollutant monitors were conducted at approximately monthly intervals.

The data were analyzed and interpreted to achieve several goals. Time-averaged particle number concentrations were determined for entire periods of observation as well as for periods classified according to the occupancy status of individuals and of the houses and classrooms monitored. Ventilation conditions were characterized using the decay of carbon dioxide as a tracer gas. The contribution of outdoor particles to indoor PN levels was assessed at each site. Contributions of indoor emission sources to indoor particle levels were also evaluated. Indoor exposures to particle number concentrations were assessed for each of the 21 residents of the seven houses studied. We also evaluated exposures for the classroom teacher and for the average student in the six classrooms evaluated. These indoor exposures were apportioned to major source categories: penetration and persistence of particles from outdoor air, emissions from episodic indoor sources, and (at two house sites) continuous emissions from natural-gas pilot lights.

Results

A summary of the time-averaged particle number concentrations from observational monitoring is presented in Figure ES.1. For each site, data are presented for outdoor and indoor conditions. The indoor results presented here are based only on the primary indoor monitor, which was placed in a main living space of each house and in the classroom monitored in the case of schools. The overall average monitoring result for the full observational period is represented in the figure by a circle. Averages for parts of the observational monitoring period sorted according to occupancy condition are also presented. For houses, we present the average when all occupants are at home awake (square) and at home asleep (×). For classrooms, we present the average when one or more students are present (square). Note that the horizontal axis is presented on a logarithmic scale spanning a factor of 100. The concentration scale is in units of 1000 particles per cm^3, so a value of 10 on this scale represents 10,000 particles per cm^3. On this scale, the overall average indoor concentration in the seven houses ranged from 3.7 (H5) to 28 (H3), with a mean of 14.5. The corresponding outdoor concentrations ranged from 5.5 (H5) to 23 (H1), with a mean of 14.9. For five classroom sites (excluding S4, where we lack a complete record outdoors), the overall average indoor concentration ranged from 3.2 (S5) to 10.5 (S3) with a mean of 6.9, while the corresponding outdoor concentrations ranged from 9.7 (S5) to 16 (S1), with a mean of 13.2.

In houses, the average air-exchange rates varied from 0.1 per hour (H0) to 1.0 per hour (H3) with an overall average of 0.6 per hour, consistent with evidence for overall ventilation conditions for residences in California. In classrooms, air-exchange rates varied strongly with configuration. When all exterior doors were closed and the ventilation system (if any) was off, the average air-exchange rate varied from 0.3 per hour (S2 and S4) to 0.7 per hour (S5) with an overall average of 0.5 per hour. With one or more exterior doors open or with a mechanical ventilation system operating, the air-exchange rates varied from 1.9 per hour (S5) to 4.6 per hour (S3), with an average across all sites of 3.3 per hour. In houses, PN concentration showed little correlation with air-exchange rates. In schools, the higher air-exchange rate condition of the open or mechanically ventilated classroom correlated with higher indoor PN concentrations.

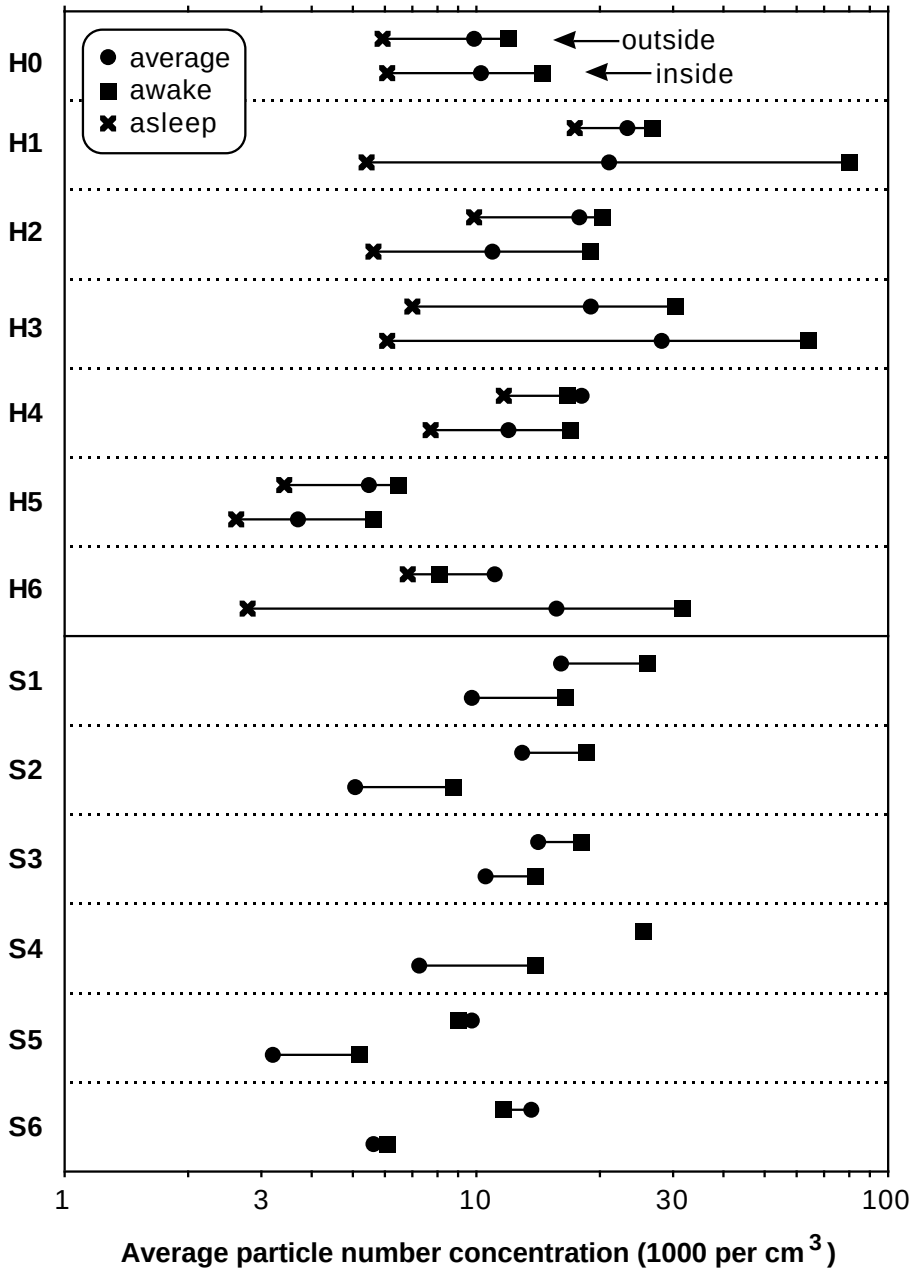

Figure ES.1. Average particle number concentrations determined during observational monitoring at seven house sites (H0-H6) and six school sites (S1-S6). For each site, results are reported for outdoor air (upper symbols) and for the primary indoor monitor (lower symbols). The circles represent the overall average for the full observational monitoring period. The squares represent the average for times when the space was occupied with people who were awake. In the case of houses, full occupancy by all residents was required. In the case of schools, the presence of at least one student was required. For houses, the "×" symbols represent average PN concentrations when all of the residents were at home asleep.

In houses, we observed a strong influence of occupant activities on indoor PN levels. In aggregate, for the seven houses monitored for a total of 26 days, we observed 59 emission events

that caused a sudden, usually large rise in the indoor PN level. In most cases, we could correlate the source with a particular activity. For example, in 43 cases showing a sudden particle rise, a single activity was indicated as occurring at the same time, based either on occupant diary information or temperature sensors deployed on suspected sources. For another 14 cases, two activities occurred simultaneously that each might have contributed to the particle concentration rise. Among the single-activity sources, the most common were use of a gas stove or oven (20 cases), use of a gas-fired furnace (9), use of an electric stove or oven (5), and use of a toaster or toaster oven (5).

In schools, episodic sources did not contribute much to indoor particle levels. Instead, the dominant source was outdoor air and indoor levels were influenced by time-varying outdoor levels as well as by time-varying ventilation conditions in the classrooms.

In houses and in classrooms, we evaluated the indoor proportion of outdoor particles. This important parameter (given the symbol f_1 in this report) quantifies the degree of protection afforded by being indoors against UFP pollution in outdoor air. It is a fraction whose theoretical bounds are 0 (implying complete protection) and 1 (implying no protection). For houses, we found that f_1 varied between 0.11 (H1) and 0.51 (H2) with a mean of 0.38. In classrooms, we determined f_1 values in relation to occupancy status and ventilation configuration. Overall, when students were present, the values of f_1 for the six classroom sites varied between 0.48 (S2) and 0.76 (S3) with a mean of 0.57. These results indicate that these indoor environments provide some, but far from complete protection against UFP in outdoor air.

Conclusions

Four main qualitative findings summarize the results of this study. First, particle levels in classrooms and in houses are much higher when occupied than when vacant. Second, the indoor proportion of outdoor particles (f_1) tends to be higher in classrooms than in homes. Third, indoor emission sources are important contributors to PN levels in houses, but not in classrooms. Fourth, daily average PN exposures per person are much higher in houses than in schools.

In summary, this project was undertaken with the goal of advancing information about ultrafine particles in schoolrooms and in homes in California. This effort is aligned with efforts of the California Air Resources Board to better understand air pollution exposures of California populations. As stated in the Strategic Plan for Research, 2001-2010, “Improved understanding of exposures helps assure that our regulatory activities focus on reducing those that represent the greatest health concerns.”

The study design involved detailed investigation, incorporating both observational monitoring and manipulation experiments, at seven houses and six classrooms. With such a small number of sites, we did not intend to collect data that are statistically representative of broader classes of California buildings. In addition, the study is limited to one geographic area in California. Overall, the limits of the study’s scope preclude drawing broad conclusions about ultrafine particles in houses and schools throughout California. On the other hand, the intensive monitoring generated rich sets of data that were mined for insights about not only what was observed but also the underlying causes. The study provides information and insight about the interplay among human occupancy, building characteristics, and pollutant dynamic behavior related to the occurrence of ultrafine particles in schoolrooms and homes and the associated exposures. The methods and findings provide an important foundation for future investigations of human exposure to ultrafine particles in California and elsewhere.