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Side-by-Side Comparison of Particle Count and Mass Concentration Measurements in a Residence

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Abstract

Particulate matter (PM) is a contaminant of concern in many indoor environments, including residential and commercial buildings. Health guidelines for exposure to particles are in units of mass concentrations. Relative to time-integrated mass measurements collected on filters, real-time particle counters are less time-consuming to operate. Studies found reasonable correlation between these two measurement techniques, but agreement may vary in different sampling environments, and depends on the instruments used. We performed a side-by-side comparison of particle counts and mass concentrations estimated by three types of real-time instruments: MetOne BT-637 optical particle counter (OPC), TSI DustTrak aerosol monitor, and TSI aerodynamic particle sizer (APS) spectrometer. In addition to these real-time instruments, time-integrated particle mass was also collected using PM2.5 and PM10 Personal Environmental Monitors (PEMs) manufactured by SKC. Sampling was conducted for two consecutive days in an occupied single-family house in Berkeley, California. Concentration profiles had similar trends, with DustTraks reporting higher particle mass concentrations, partially explained by the density value assumed in the calibration. We made assumptions for particle size and density to calculate the PM2.5 and PM10 mass concentrations for the MetOne and APS, and compared with the filter-based measurements. Despite uncertainties and assumptions, there was generally good agreement for the different methods.

1. Background

Two on-going projects, both funded by the California Energy Commission, are evaluating various aspects of indoor environmental quality in buildings. The Energy and Indoor Environmental Quality (IEQ) Retrofits in Low-income Apartment project is evaluating the reduction in energy use and the IEQ improvement associated with retrofits in low-income apartments. The Healthy Zero Energy Buildings (HZEB) Program is conducting field studies in retail stores where air contaminant concentrations will be measured (Chan et al., 2011). Real-time particle counters are used in both of these studies to assess exposure. Health guidelines are expressed in mass concentrations. Based on studies that have compared the performance of real-time instruments with mass-based methods for determining particle mass concentrations, reasonable correlation is expected (Wallace et al., 2011; Yanosky et al., 2002), but agreement may vary in different sampling environments. Mass-based methods that can monitor particle mass concentrations in real time exist (Hauck et al., 2004), but the cost of such instruments can be prohibitive for studies that require multiple instruments to perform simultaneous measurements at many locations.

Light-scattering optical particle counters, such as the MetOne instruments and DustTraks considered in this comparison, require assumptions about the aerodynamic diameters and density of the particles in order to estimate the mass concentrations from the measured scattering signals. The MetOne OPCs considered here report the number of particle counts in six size bins: 0.3–0.5 μm, 0.5–0.7 μm, 0.7–1 μm, 1–2 μm, 2–5 μm, and >5 μm. The DustTrak uses an internal calibration factor and reports the size-aggregated PM2.5 mass concentrations, starting from 0.1 μm. Manufacturer calibration was performed using the respirable fraction of Arizona Test Dust, which has a bulk density of 2.6 g/cm^3. Typical outdoor ambient particles are found to have an average density of 1.65 g/cm^3 (Tittarelli et al., 2008), but this may not be representative of indoor particles. The APS particle instrument uses a time-of-flight technique to measure particles in the size range from 0.5 to 20 μm. It provides a more reliable measure of the particle size distribution, but an assumed particle density is still needed to estimate a mass concentration. Other factors may also contribute to the differences between real-time and filter-based measurements beyond the assumption of particle density. These may include changes in relative humidity, gas-to-particle phase change, and volatilization or condensation of chemical components. The effects of these processes would require more detail measurement technique to evaluate than the approach used here. The experiment preformed aims to evaluate the level of agreement between the real-time optical instruments and the filter-based measurements.

2. Methods

The side-by-side comparison was conducted in an occupied single-family detached house in Berkeley, California. Sampling started on May 17, 2011 at 11:00 and ended on May 19 at 16:30. Two MetOne OPCs, three DustTraks, and one APS were operated continuously during this time period. All instruments were placed in closed proximity on a table approximately 1 m above the floor inside a small bedroom. The bedroom windows were

closed during the experiment, while the bedroom door was left open for most of the time. Cooking was likely the dominant source of particles generated indoors.

Two MetOne OPCs were operated to take five-minute samples. Particle mass concentrations, M (μg/m^3), were estimated from the particle count measurements, N (#/m^3), as follows:

$$M = \sum_i \frac{\pi}{6} \rho \overline{d_i}^3 N_i \qquad \text{Equation (1)}$$

where ρ = 1.65 μg/cm^3 is the particle density, $\overline{d_i}$ (μm) is the equivalent particle diameter for each size bin i and N_i is the particle count concentration. PM2.5 is estimated from the four smallest size bins: 0.3–0.5 μm, 0.5–0.7 μm, 0.7–1 μm, and 1–2 μm. Within each size bin, the equivalent particle diameter is calculated according to Equation (2). This equivalent particle diameter gives the same total volume of particles assuming that the number of particles are uniformly distributed within the size bin i that is bounded by the lower and upper diameters, $d_{i,a}$ and $d_{i,b}$.

$$\overline{d_i}^3 N_i = \int_{d_{i,a}}^{d_{i,b}} \frac{N_i}{\left(d_{i,b} - d_{i,a}\right)} x^3 dx$$

$$\overline{d_i} = \left[\frac{\left(d_{i,b}^{\,4} - d_{i,a}^{\,4}\right)}{4\left(d_{i,b} - d_{i,a}\right)} \right]^{1/3} \qquad \text{Equation (2)}$$

Using this method, the $\overline{d_i}$ for the six size bins are 0.41, 0.61, 0.86, 1.6, 3.7, and 7.8 μm. The largest equivalent particle diameter is computed assuming that the upper limit for the size bin is 10 μm. PM10 is estimated from the sum of all size bins. Our assumption is that there were very few particles larger than 10 μm that were counted by the MetOne OPCs in the >5 μm size bin. This assumption will be evaluated by considering the APS data, which include particle counts up to 20 μm.

The DustTraks were programmed to take two-minute samples. Mass concentrations were calculated using the manufacturer default calibration factor of one. Auto Zero, used to minimize zero drift, was performed once every 24 hours to minimize the effect of zero drift.

Particle mass concentrations were computed similarly from the APS data as described in Equations (1) and (2). The APS was operated to take 1-minute samples and measured particles from 0.5 to 20 μm at 52-channel resolution. We used the APS data to calculate the equivalent particle diameter that would correspond to each of the six channels measured by the MetOne OPCs, as follows:

$$\overline{d_i^*} = \left[\sum_j f_j \frac{\left(d_{j,b}{}^4 - d_{j,a}{}^4 \right)}{4\left(d_{j,b} - d_{j,a} \right)} \right]^{1/3} \qquad \text{Equation (3)}$$

where $d_{j,a}$ and $d_{j,b}$ are the lower and upper diameters of the APS size bin j, and f_j is the fraction of the particles counted by the APS within a size bin. For example, the APS measured particle counts in these size bins: 0.523–0.542 μm, 0.542–0.583 μm, 0.583–0.626 μm, 0.626–0.723 μm, and so on. These four smallest size bins measured by the APS correspond roughly to the 0.5–0.7 μm size bin measured by the MetOne. In this example, j = 4 and f_j is the fraction of particles counted in each of the four size bins relative to the total particle counts from all four size bins. Equation (3) gives an alternative estimate of the equivalent particle diameters for the MetOne measurements.

The time-integrated PM mass concentrations were measured using a sampler called the Personal Environmental Monitor (PEM, manufactured by SKC). The PEMs used in our experiments have a cut-point of either 2.5 μm or 10 μm to collect particles that are less than the respective diameters. Particle mass was collected for approximately 24 hours at the designed flow rate of 10 lpm. The actual flow rate was controlled within 5% of the designed flow, and was measured using a DryCal flow calibrator both at the start and end of sampling. A duplicated set of PM2.5 and PM10 samples were collected on each day. Particle mass was collected onto a Teflon filter, which was weighed in a temperature and relative humidity controlled chamber pre- and post-sampling.

Two lab blanks and two field blanks were collected for this side-by-side comparison. The filter blanks were loaded into a clean PEM following the same handling procedures as the sample filters. The PEMs containing the field blanks were taken out of the carrying sleeve whenever we handled the PEMs used for sampling. The four filter blanks differed by 0.35 to 2.7 μg between the pre- and post-weighing, with an average difference of 1.2 μg. For a 24-hour sample at 10 lpm, the total air sample volume is 14.4 m^3, which gives a sampling uncertainty of ±0.083 μg/m^3. This level of sampling uncertainty, ~0.1 μg/m^3, is similar to what was observed from our past experience working with PEMs[1].

3. Results

3.1. Concentration Time Series

The concentration time series measured by the three types of real-time instruments agree well with one another on both sampling days. The highest PM2.5 concentrations were measured on Day 2 (May 18th) at 18:00 during cooking. Figure 1 (top panel) shows the PM2.5 mass concentrations measured by the three DustTraks, and the sum of the size bins corresponding to <2.5 μm from the MetOne OPCs and APS. Figure 1 (bottom panel) shows the PM10 particle mass concentrations calculated using all size bins measured by

[1] On-going project where PEMs samples were collected from childcare facilities in California. Samples were analyzed gravimetrically using the same procedure used here.

the MetOne OPCs and the APS. The MetOne OPCs measured the highest PM10 concentrations during the first half hour of the sampling period. The high PM10 counts quickly decayed within the second half of the hour. Particle source was likely from our proximity to the instruments during the initial setup. For this reason, we exclude this initial hour of sampling on Day 1 when we estimated PM10 mass concentrations from the MetOne OPCs. The APS started monitoring about an hour later than the other instruments, so we do not have to make this adjustment. PM2.5 concentrations were also not affected.

The DustTraks report particle mass concentrations in the increment of 1 $\mu g/m^3$. Therefore, the time series data appeared to be step functions at low concentrations (Figure 1). Both the MetOne OPCs and the APS report particle counts from which the mass concentrations were computed using Equations (1) and (2). The sensitivity of the APS is 0.001 particles/cm^3. At a sample flow rate of 1 lpm and one-minute sampling time, this corresponds to a minimum count of one particle per sample. Particle counts were very much higher than one per sample for particles <5 μm. However, for particles >5 μm, particle counts equaled one or zero at more than half the time during sampling. This contributes to the uncertainty in the PM10 mass concentration estimates.

Figure 1 shows that agreement between the two MetOne OPCs was not as close as the three DustTraks. The DustTraks precision seems to be associated with the concentration range and increases for more typical concentrations as those found in Day 2. The mean root mean square deviation (RMSD) of the units with respect to the mean value was 0.8 $\mu g/m^3$. The MetOne OPCs have an overall measurement precision of ±10%, but the counting precision is poor for 0.3 μm particles. The MetOne OPCs count only 50%±20% of 0.3 μm particles. This counting efficiency improves to 100%±10% for 0.45 μm particles[2]. Compared with the APS, the estimated PM2.5 mass concentrations from the MetOne OPCs measurements were lower. The reverse is true for PM10, where the estimated mass concentrations from the OPCs were higher than the APS.

[2] Information on counting efficiency was obtained through personal communication with the MetOne OPCs manufacturer.

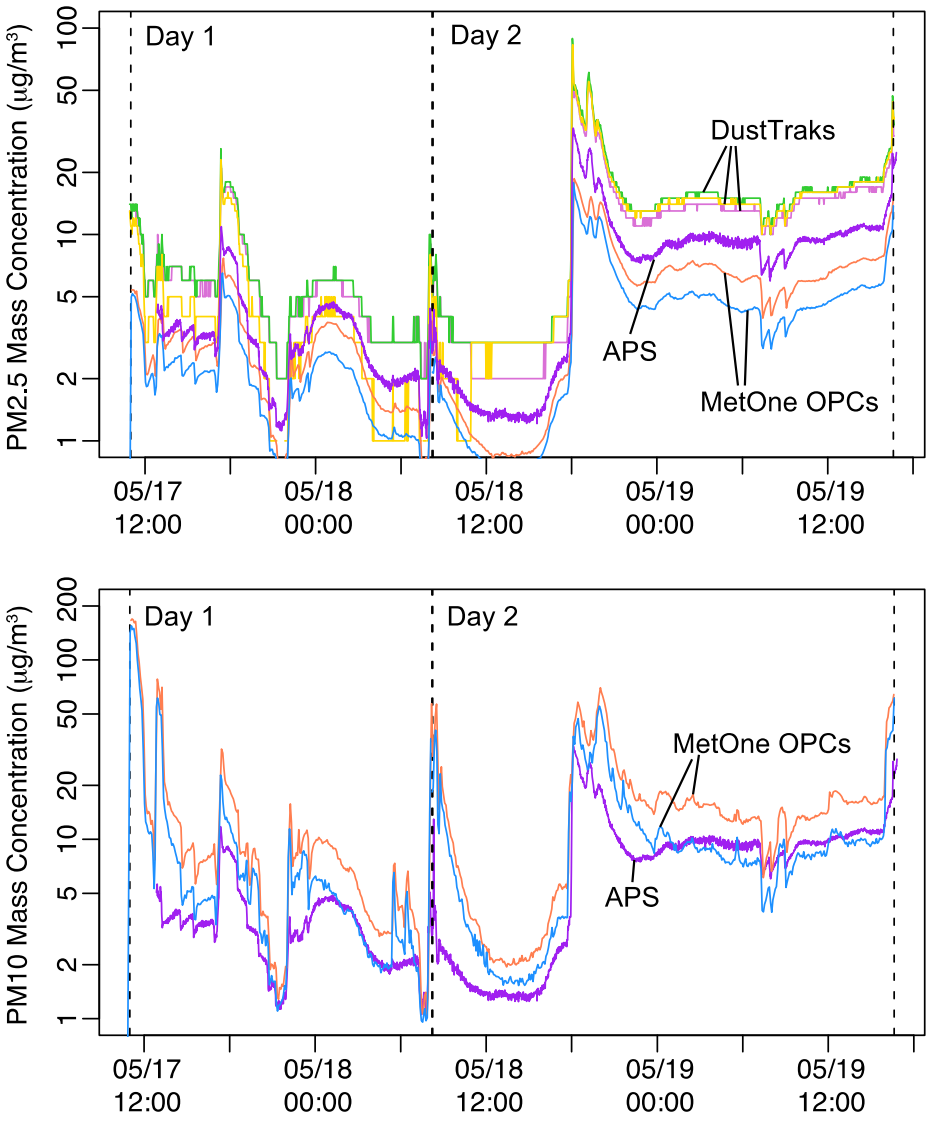

Figure 1. PM2.5 (top panel) and PM10 (bottom panel) mass concentrations estimated from three types of real-time instruments.

3.2. Time-Integrated Concentration

Table 1 shows the time averaged PM2.5 and PM10 mass concentrations sampled by the PEMs. There is good agreement between the duplicates collected on each day. The difference in particle mass concentration is about 8% on Day 1 and 5% on Day 2. The agreement is better on Day 2 when more mass of particles were collected onto the filters. These results suggest that about 25% to 40% of the particle mass collected by the PM10 samplers were in the 2.5–10 µm size range.

Table 1. PM2.5 and PM10 time-integrated mass concentrations measured by PEMs.

	Day 1 5/17 11:00 to 5/18 08:11		Day 2 5/18 08:15 to 5/19 16:37	
	PM2.5 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)	PM2.5 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)
PEM #1	3.1	5.0	5.6	7.2
PEM #2	2.8	4.6	5.3	6.9

Table 2 shows the time-integrated particle mass concentrations estimated using the real-time instruments for the two sampling days. The DustTraks only measured PM2.5, so PM10 values are left blank. As expected, the mass concentrations reported by the DustTraks are higher than the filter-based method because of the internal calibration factor used by the instruments. The DustTrak measurements were on average a factor of 1.8 higher than the filter-based method on Day 1, and a factor of 2.4 higher on Day 2. This discrepancy between the DustTraks and the PEMs can be partially attributable to the difference between the default particle density of 2.6 g/cm^3 and the typical density of 1.65 g/cm^3 of ambient particles. The ratio between the two densities is $2.6 \div 1.65 = 1.6$. Other studies have reported that DustTraks tend to overestimate PM2.5 concentrations by factors ranging between 1.94 and 2.57 (Ramachandran et al., 2000; Wallace et al., 2011; Yanosky et al., 2002). If the mass concentrations are corrected with the factor of 2.5 as found in test conditions similar to those of an occupied residence (Wallace et al. 2011), the DustTraks and the PEMs agree well, especially on Day 2.

Table 2. Time-integrated PM2.5 and PM10 mass concentrations estimated from three types of real-time instruments.

	Day 1		Day 2	
	PM2.5 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)	PM2.5 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)
DustTrak #1	5.9	–	12.5	–
DustTrak #2	6.1	–	14.1	–
DustTrak #3	4.2	–	13.4	–
MetOne OPC #1	2.7	9.7	5.6	16.2
MetOne OPC #2	2.0	6.7	4.3	11.0
APS #1	3.3	3.4	8.0	8.2

For PM2.5, the agreement between the MetOne OPCs, APS, and PEMs is reasonably good. Our method of estimating particle mass concentrations has significant limitations because of the assumptions made, such as particle density and mean particle diameter within a size bin. However, the difference between the time-integrated particle mass concentrations calculated from the MetOne measurements were within 20% of the PEMs. For the APS, the difference with the PEMs is also about 10% on Day 1, and about 50% on Day 2.

The MetOne OPCs measured particle counts that significantly overestimated PM10 mass concentrations relative to the PEMs. Discrepancies may be explained by factors such as loss of volatile species from the filters. On Day 2, particle mass concentrations increased

suddenly by 10-fold following cooking activities (see Figure 1). Concentrations remain relatively high for a few hours in the evening. It is possible that the particles emitted from cooking composed of volatile species that were partially lost from the filters by the time they were analyzed gravimetrically.

3.3. Particle Size Distribution

From the APS data, which is more size resolved compared to the MetOne OPCs, the equivalent particle diameter can be determined for each size bin of the MetOne OPCs using Equation (3). Table 3 compares the two methods of estimating the equivalent particle diameters. With the exception of the 2–5 μm particles, the two methods of estimating equivalent particle diameter give very similar results. APS measured particles between 2.1 to 5.4 μm in 12 size bins. Based on these data, the mean particle diameter is 2.8 μm. This is smaller than the particle diameter of 3.7 μm estimated using Equation (2). The reason for this is that particles measured by the APS in the 2–5 μm size range were dominated by particles that are towards the smaller end of the spectrum.

Table 3. Volume-weighted mean diameter estimated for each particle size bin.

MetOne OPCs		APS	
Particle Size Bin (μm)	Equivalent Particle Diameter (μm) from Equation (2)	Particle Size Bin (μm)	Equivalent Particle Diameter (μm) from Equation (3)
0.3–0.5	0.41	–	–
0.5–0.7	0.61	0.523–0.723	0.62
0.7–1.0	0.86	0.723–1.037	0.87
1.0–2.0	1.6	1.037–2.129	1.4
2.0–5.0	3.7	2.129–5.425	2.8
>5.0	7.8	5.425–19.81	7.5

The above analysis was performed using the total particle counts collected in the different size bins over two sampling days. This size distribution of the particle counts and the corresponding volume is shown in Figure 2. The size and volume distribution of particles was not constant throughout this time period, so our approach is primitive in assuming that there is one equivalent particle diameter that can be applied at all times. Nonetheless, Figure 3 shows our assumption that particles >10 μm are negligible is reasonable when computing particle mass concentrations from MetOne OPCs data.

The agreement between PEMs and the MetOne instruments for PM10 was improved by using the equivalent particle diameter derived from the APS data, as shown in Table 3. The PM10 concentration estimates would change from 9.7 and 6.7 $\mu g/m^3$ on Day 1 to 6.2 and 4.5 $\mu g/m^3$, and from 16.2 and 11.0 $\mu g/m^3$ on Day 2 to 10.5 and 7.5 $\mu g/m^3$. These estimates are within 30% of the PM10 concentrations measured by the PEMs.

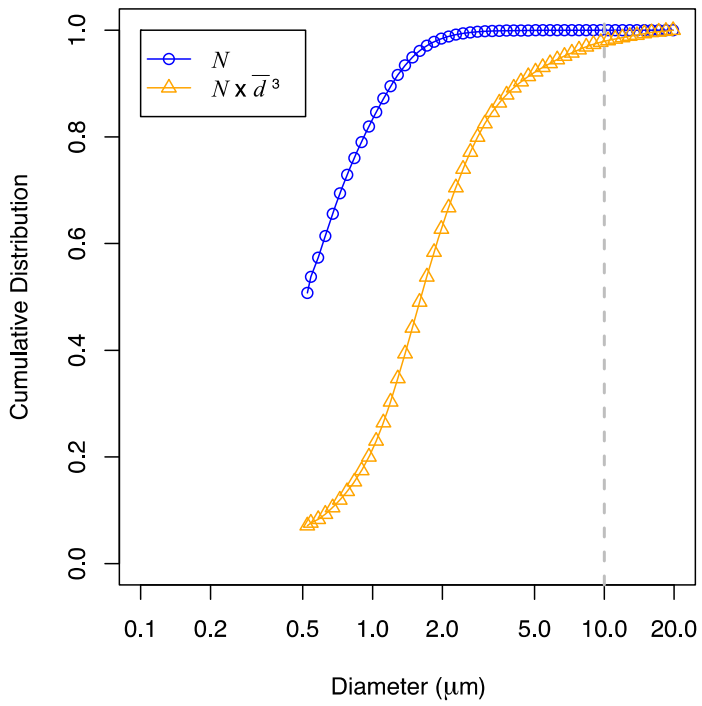

Figure 2. Cumulative distribution of particle counts, *N*, and the corresponding volume, $N \times \overline{d}^3$, measured by APS.

4. Summary

We measured particle counts and mass concentrations side-by-side using three types of real-time instruments in an occupied residence in Berkeley, California. Instruments included three TSI DustTraks, two MetOne OPCs, and a TSI APS. Because the three types of instruments all have different operation principles, they are not expected to agree perfectly with one another. However, analysis of the concentration time series show that they tend to trend with one another over the two sampling days.

In addition to the real-time measurements, we also collected time-integrated filter samples of PM2.5 and PM10. Two duplicated sets of PM2.5 and PM10 were collected on each of the sampling day. Lab and field filter blanks show that our handling procedure gives particle mass concentrations that are accurate to ±0.1 μg/m^3 for 24-hour sample at 10 lpm. The DustTraks reported higher particle mass concentrations, which can mostly be explained by the difference in density of the calibration particles and more typical values found in ambient air. Loss of volatile species from the filters by the time they were weighed gravimetrically also explained the discrepancies found when compared with the real-time measurements. We made assumptions about the mean particle diameters and density, and computed the PM2.5 and PM10 mass concentrations from the real-time particle count measurements. The agreement between the different methods is reasonably good, considering the assumptions made in our calculations and measurement uncertainties.

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