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Development of an approach to correcting MicroPEM baseline drift

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ABSTRACT

Background: Fine particulate matter ($PM_{2.5}$) is associated with various adverse health outcomes. The MicroPEM (RTI, NC), a miniaturized real-time portable particulate sensor with an integrated filter for collecting particles, has been widely used for personal $PM_{2.5}$ exposure assessment. Five-day deployments were targeted on a total of 142 deployments (personal or residential) to obtain real-time $PM_{2.5}$ levels from children living in New York City and Baltimore. Among these 142 deployments, 79 applied high-efficiency particulate air (HEPA) filters in the field at the beginning and end of each deployment to adjust the zero level of the nephelometer. However, unacceptable baseline drift was observed in a large fraction (> 40%) of acquisitions in this study even after HEPA correction. This drift issue has been observed in several other studies as well. The purpose of the present study is to develop an algorithm to correct the baseline drift in MicroPEM based on central site ambient data during inactive time periods.

Method: A running baseline & gravimetric correction (RBGC) method was developed based on the comparison of MicroPEM readings during inactive periods to ambient $PM_{2.5}$ levels provided by fixed monitoring sites and the gravimetric weight of $PM_{2.5}$ collected on the MicroPEM filters. The results after RBGC correction were compared with those using HEPA approach and gravimetric correction alone. Seven pairs of duplicate acquisitions were used to validate the RBGC method.

Results: The percentages of acquisitions with baseline drift problems were 42%, 53% and 10% for raw, HEPA corrected, and RBGC corrected data, respectively. Pearson correlation analysis of duplicates showed an increase in the coefficient of determination from 0.75 for raw data to 0.97 after RBGC correction. In addition, the slope of the regression line increased from 0.60 for raw data to 1.00 after RBGC correction.

Conclusions: The RBGC approach corrected the baseline drift issue associated with MicroPEM data. The algorithm developed has the potential for use with data generated from other types of PM sensors that contain a filter for weighing as well. In addition, this approach can be applied in many other regions, given widely available ambient PM data from monitoring networks, especially in urban areas.

1. Introduction

Airborne particulate matter with an aerodynamic diameter below 2.5 µm ($PM_{2.5}$) have been shown to have health risks associated with their toxic components and their ability to lodge deeply in the lung (Laden et al., 2006; Chen et al., 2013; Hänninen et al., 2014). Personal exposure is believed to be the gold-standard method for characterizing exposure (Jantunen et al., 2002). Several real-time personal nephelometer sensors have been developed in recent years. Among them, the MicroPEM, a miniaturized $PM_{2.5}$ personal exposure monitor (RTI International, Research Triangle Park, NC, USA), has been widely used (Jack et al., 2015; Vesper et al., 2015; Wang et al., 2017). The MicroPEM includes a two-stage impactor with a $PM_{2.5}$ cut point, a light scattering nephelometer for real-time measurement, temperature and relative humidity sensors, a Teflon filter for integrative gravimetric measurement of $PM_{2.5}$, and a 3-axis accelerometer for the activity record (RTI, 2012).

Compared with some other personal sensors, the MicroPEM stands out due to its responsive range, portability, and agreement with standard units used by the US Environmental Protection Agency (EPA) (Steinle et al., 2013; EPA, 2014). In addition, PM collected on MicroPEM filters allows the nephelometer data for each deployment to be calibrated to the average optical properties of aerosol monitored, and also enables later lab analyses such as black carbon, metals, polycyclic aromatic hydrocarbons, etc. However, the MicroPEM also has its limitations. According to a report from the EPA (EPA, 2014) as well as our on-going studies in New York and China, baseline drift of the real-time $PM_{2.5}$ data has been observed in MicroPEM data on regular basis.

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Baseline drift (or, zero offset) is not only a problem for MicroPEM nephelometers but also an unresolved issue for other nephelometer sensors, all of which measure particle concentration based on the intensity of laser light reflected by particles (Wheeler et al., 2011; Ryswyk et al., 2013).

High-efficiency particulate air (HEPA) filter zeroing has been used for correcting baseline drift (Wallace et al., 2011; EPA, 2014; Sloan et al., 2016). Following the MicroPEM protocol, HEPA correction is typically conducted at the beginning and/or end of deployment. Researchers have found that for a deployment of more than one day, this approach can be insufficient to correct the drift and a daily HEPA correction has been suggested (Wallace et al., 2011; EPA, 2014). However, it is impractical to have the daily correction in large epidemiological studies, given the demand of extra labor/travel time. To the best of our knowledge, no other efficient method for correcting baseline drift has been reported.

In this study, we aim to develop a reliable method to adjust the baseline while tying real-time data to the mass-weighted average optical properties of the particulate matter collected. We used widely available PM data from established monitoring networks, e.g., EPA Airnow and World Air Quality Index (AQICN), to adjust the baseline during the periods of low activity when there are little to no local particle sources. The premise of this use is that the baseline of personal or indoor PM level generally followed a similar trend to that of ambient data during periods of low activity; typically this was the case as shown in Fig. S1. Thus we hypothesized that the baseline of a MicroPEM was proportional to the ambient level during periods of low activity. The gravimetric correction based on the PM mass collected onto MicroPEM filters was also included in this method. Given that baseline drift is a common issue for nephelometer PM sensors, the developed algorithm has the potential for use in correcting data from other types of nephelometers.

2. Materials and methods

2.1. Data acquisition and sample collection

Residential and personal $PM_{2.5}$ levels were investigated in the Environmental Monitoring and Biological Airway Response Study (EMBARS) conducted in New York City (NYC), New York and Baltimore, Maryland (USA). The aim of this validation project is to determine the association between biological response of the airway gene-expression markers and continuous/integrated measures of second hand smoke (SHS) exposures for non-smoking adults and children, based in part on analysis of the Teflon filter by optical methods (Lawless et al., 2004; Yan et al., 2011). In this study, MicroPEMs were used to characterize $PM_{2.5}$ exposure.

MicroPEMs were set to log data at 10-second intervals. Subsequently, the original data were reduced to one-minute or one-hour averages for different usages. To extend sampling run time and reduce noise, MicroPEMs ran at a flow rate of 0.4 L/min, with the internal flow measurements calibrated to a TSI Flowmeter 4140 (TSI Incorporated, MN, USA) at setup and then measured externally by the TSI flow meter in the field before and after each deployment. Each MicroPEM's baseline was set to zero under HEPA filtered air period (Pall Corporation, NY, USA) in the laboratory at setup. In a large fraction of deployments, a HEPA filter was attached to the MicroPEMs inlet in the field for ≥ 5 min at the beginning and the end of each deployment. A Mettler Toledo UMX2 microbalance was used to pre- and post-weigh Teflon filters in a room-sized environmental chamber at RTI that was maintained at 35% RH and 21 °C. All filters are equilibrated in the chamber for a minimum of 24 h before pre and post weighing. Filters were weighed twice in the same day and the difference between the two weighings must be less than 1 μg to be accepted as a valid measurement.

In both NYC and Baltimore, a total of 106 personal acquisitions, including one duplicate measurement, were collected over a sampling period of 4.01 ± 1.45 days. NYC residential sampling was performed in 24 homes, with 6 of these homes having valid duplicates. The average residential sampling period was 4.86 ± 0.49 days. Baltimore residential levels were not measured by MicroPEM and thus not included in this study.

2.2. Approach for HEPA baseline correction and gravimetric correction

The HEPA baseline correction method was applied to those deployments having both valid start and end HEPA data. Real-time $PM_{2.5}$ data were corrected by the following equation:

$$c\,[PM_{2.5}]_i^{HEPA} = c\,[PM_{2.5}]_i - \ HEPA_{Start} + \frac{HEPA_{Start} - HEPA_{End}}{K-1} * (i-1) \tag{1}$$

where $c\,[PM_{2.5}]_i$ and $c\,[PM_{2.5}]_i^{HEPA}$ are the real-time $PM_{2.5}$ concentrations of minute i before and after HEPA correction; $HEPA_{Start}$ and $HEPA_{End}$ are the HEPA correction values for start and end HEPA corrections; K is total sampling time in minutes.

After the HEPA correction, $PM_{2.5}$ concentrations are then gravimetrically corrected (GC). The GC ratio (r_{GC}) is the ratio of gravimetric mass to the accumulated weight calculated based on HEPA corrected nephelometer data. The following equation is used to calculate r_{GC}:

$$r_{GC} = \frac{m_{post} - m_{pre} - m_{fieldblank}}{\sum (c\,[PM_{2.5}]_i^{HEPA} * mv)} \tag{2}$$

Where mv (acronym for minute volume) is the average of the volume (in m^3) of air per minute passing through a microPEM, and m_{pre} and m_{post} are filter mass weighed before and after the deployment (in μg). The $m_{fieldblank}$ is the average weight change of field blank filters (FBF), which had been installed in MicroPEMs and brought to and from the field but not used for active sampling. The weight change of each FBF was calculated as the difference of the FBF weights measured before and after deployment. The median FBF was used to correct the possible filter weight changes positive or negative due to transport, storage, and handling. Adjusted $PM_{2.5}$ concentrations after HEPA correction would be corrected using r_{GC}:

$$c\,[PM_{2.5}]_i^{*} = c\,[PM_{2.5}]_i^{HEPA} * r_{GC} \tag{3}$$

2.3. Running baseline & gravimetric correction (RBGC)

In our study, we found that MicroPEM deployments after HEPA correction could still have a large portion of the nephelometer data (> 40%) with large negative $PM_{2.5}$ levels, indicating that the baseline was not stable and thus making the simple subtraction of interpolated HEPA values inadequate. In order to correct this issue, we developed another protocol combining both running baseline and gravimetric corrections, as shown in Eq. (4). Fig. S2 conceptually shows how the correction was made: 1) the original data with issues (typically negative drifts) were adjusted to presumed baseline based on fixed site data (explained in detail in the next paragraph) and 2) the total mass on the filter calculated from adjusted real-time data (step 1) was set equal to gravimetric mass of particles on the filters.

$$\sum_1^N ((BL + r_c*(c[PM_{2.5}]_i - c[PM_{2.5}]_{LowPM}))*mv) = GM \tag{4}$$

where $c[PM_{2.5}]_i$ is the raw $PM_{2.5}$ concentration at minute i as measured by the MicroPEM; N is the total sampling time (in minutes); BL is the baseline $PM_{2.5}$ concentration (using Eqs. 5, 6, and 7); mv is the minute volume; GM is the gravimetric mass of particles collected on the MicroPEM filter during the total deployment; $c[PM_{2.5}]_{LowPM}$ is the $PM_{2.5}$ concentration from MicroPEM in a selected two-hour period when BL was chosen; and r_c is the correction ratio used to adjust the concentrations (see Eq. (8) below). The approach for the selection of the