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Estimation of Citywide Air Pollution in Beijing

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Abstract

There has been discrepancies between the daily air quality reports of the Beijing municipal government, observations recorded at the U.S. Embassy in Beijing, and Beijing residents' perceptions of air quality. This study estimates Beijing's daily area $PM_{2.5}$ mass concentration by means of a novel technique SPA (Single Point Areal Estimation) that uses data from the single $PM_{2.5}$ observation station of the U.S Embassy and the 18 PM_{10} observation stations of the Beijing Municipal Environmental Protection Bureau. The proposed technique accounts for empirical relationships between different types of observations, and generates best linear unbiased pollution estimates (in a statistical sense). The technique extends the daily $PM_{2.5}$ mass concentrations obtained at a single station (U.S. Embassy) to a citywide scale using physical relations between pollutant concentrations at the embassy $PM_{2.5}$ monitoring station and at the 18 official PM_{10} stations that are evenly distributed across the city. Insight about the technique's spatial estimation accuracy (uncertainty) is gained by means of theoretical considerations and numerical validations involving real data. The technique was used to study citywide $PM_{2.5}$ pollution during the 423-day period of interest (May 10, 2010 to December 6, 2011). Finally, a freely downloadable software library is provided that performs all relevant calculations of pollution estimation.

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Introduction

Beijing, the capital city of China, is an international metropolis with a population of over 19 million. As in many big cities worldwide, air pollution is a major concern for city residents. Particulate matter (PM) is the air pollutant that most commonly affects people's health, where PM_{10} and $PM_{2.5}$ are the two main PM pollutants, i.e., PM consisting of particles with aerodynamic diameters $\leq$10 μm and $\leq$2.5 μm, respectively [1,2]. The sources of PM10 consist of smoke, dirt and dust from factories, farming and roads, as well as mold, spores, and pollen. $PM_{2.5}$ is linked to toxic organic compounds, heavy metals (from smelting, processing, and others), burning of plant material, and forest fires.

$PM_{2.5}$ is a greater health threat than the PM_{10} particles. Laboratory studies have confirmed that the smaller the particle, the more likely it is to lodge in the lungs [3]. In situ studies have shown that these small particles can penetrate indoors, thus altering the home environment. The particles may cause an increase in cardiac and respiratory morbidity and mortality [4]. Indeed, significant increases in deaths from heart and lung disease occur during multi-day periods with high concentrations of fine particles [5]. More than 500,000 deaths per year have been reported worldwide due to $PM_{2.5}$ pollution [6].

In the case of Beijing, there is considerable discrepancy between air pollution levels in terms of PM_{10} records provided by the municipal government, $PM_{2.5}$ observations from individual unofficial stations, and perceptions among the local population. Rapid population growth, urbanization, and greater numbers of vehicles have inevitably caused a considerable increase in air pollution emissions throughout the city [7–12]. PM_{10} concentration is a mandatory air quality index that is routinely observed at several official PM_{10} monitoring stations and published daily by the Beijing Municipal Environmental Protection Bureau (BJ-EPB). The U.S. Embassy in Beijing has kept unofficial hourly $PM_{2.5}$ records since spring 2008, using a single monitoring station atop its building [13]. On the other hand, according to BJ-EPB the official stations monitoring Beijing's air quality are evenly distributed across the city in accordance with relevant scientific standards, whereas the U.S. Embassy data do not accurately represent the overall pollution level in the city [14]. As a result, in the last few years a serious disagreement has emerged between the daily air pollution assessments provided by the BJ-EPB [15], the U.S. Embassy, and those based on population's perceptions. For example, on October 23, 2011, a thick smog blanket over Beijing revealed a major discrepancy between the categorizations of "slightly polluted" air suggested by BJ-EPB data and "hazardous" air quality determined by U.S. Embassy monitoring [13,16].

PM_{10} and $PM_{2.5}$ concentrations are related, since most of the PM_{10} is contributed by $PM_{2.5}$ [17–19]. Therefore, evaluating the PM_{10}-$PM_{2.5}$ relationship can provides information on $PM_{2.5}$ concentrations in areas that are not monitored for it [20,21]. In this study, we proposed a technique to estimate daily averages of $PM_{2.5}$ concentrations in Beijing, by integrating daily $PM_{2.5}$ observations at the single U.S. Embassy station and their physical

correlations with PM_{10} data obtained at a spatially exhaustive monitoring network operated by BJ-EPB. The proposed technique, called SPA (Single Point Areal Estimation), takes advantage of the aforementioned physical link between $PM_{2.5}$ and PM_{10} concentrations to generate areal $PM_{2.5}$ pollution estimates over the entire city. In other words, the PM_{10} observations served as the key secondary information that can improve the estimation of Beijing's areal daily $PM_{2.5}$ concentration [22].

Materials and Methods

Materials

Daily PM_{10} concentration data were collected from May 10, 2010 to December 6, 2011 at the 18 authorized (BJ-EPB) observation stations, which are evenly distributed across the city. Daily $PM_{2.5}$ concentrations reported by the embassy monitoring station were also gathered for the same period. Days with long periods of missing $PM_{2.5}$ (hourly) data were discarded based on the following criterion: if during a day there were consecutive data gaps of more than 3 hours or the cumulative amount of missing data exceeded 12 hours, that day was not included in pollution estimation. The final result was a dataset covering a 423-day period. We also acquired information about the geographic locations of the U.S. Embassy and 18 BJ-EPB stations, as well as data on population density, main traffic routes, traffic flow volumes, daily mean wind direction and speed, and geomorphology. All data were stored in a Geographic Information System (GIS), and are represented in Figure 1.

The SPA Technique

We developed a technique, called Single Point Areal Estimation (SPA), which belongs to the category of biased areal estimation techniques [23]. SPA was used to extend the temporal $PM_{2.5}$ data recorded at a single (U.S. Embassy) monitoring station to areal-average $PM_{2.5}$ pollutant estimates, taking advantage of physical correlations between the $PM_{2.5}$ mass concentrations (U.S. Embassy station) and the PM_{10} data (18-station BJ-EPB network). This point-to-area transformation yields best linear unbiased estimates (BLUE) of $PM_{2.5}$ spatial averages over the entire city of Beijing. A formal derivation of the SPA technique is given in the following.

The objective of the SPA technique is to estimate citywide $PM_{2.5}$ pollution in the Beijing area. The estimate is based on $PM_{2.5}$ data from a single monitoring station at the U.S. Embassy in Beijing, and PM_{10} concentrations observations obtained at the official BJ-EPB monitoring network. Figure 2 outlines the SPA method.

The true average $PM_{2.5}$ concentration (X) over the entire area per time unit (e.g., daily) is calculated in theory by

$$X = \sum_{i=1}^{N} g_i x_i, \tag{1}$$

where x_i ($i = 1, \ldots, 18$) denotes $PM_{2.5}$ concentration at the i-th station (which, in the present study, was not available from the official surveillance network); N denotes the total number of observation stations (18 in this case); g_i denotes the weight (contribution) of the i-th observation station to $PM_{2.5}$ estimation so that $\sum_{i=1}^{N} g_i = 1$ (unbiased estimation). There is only one $PM_{2.5}$ monitoring station (U.S. Embassy). Accordingly, the areal $PM_{2.5}$ concentration for Beijing is estimated by

$$\hat{X} = w_0 x_0, \tag{2}$$

where x0 denotes hourly PM2.5 concentration at the single monitoring station, as reported by the embassy and made available via the web site Twitter.com; w0 denotes the weight assigned to the embassy PM2.5 observation. This weight is estimated by minimizing

$$w_0 = \text{argmin}[v\hat{X} = E(w_0 x_0 - X)^2], \tag{3}$$

where vX is the variance of the estimated area-averaged X (= PM2.5 concentration); and the E(·) denotes statistical mean.

At the same time, it is valid that

$$E\hat{X} = E(w_0 x_0), \tag{4}$$

i.e., the SPA technique generates an unbiased pollutant estimate that is also the best (in the minimum mean squared estimation error sense).

Derivation of the SPA Equations

The variance of $\hat{X}$is derived as

$$\begin{aligned} v\hat{X} = E(w_0 x_0 - X)^2 &= E[(w_0 x_0 - X) - E(w_0 x_0 - X)]^2 \\ &= C(w_0 x_0, w_0 x_0) - 2C(w_0 x_0, X) + C(X, X), \end{aligned} \tag{5}$$

where $C(\cdot)$ is the covariance between concentrations at any pair of points (the covariance provides a quantitative assessment of the spatial dependence between concentrations at these points).

The first term in Eq. (5) is

$$C(w_0 x_0, w_0 x_0) = {w_0}^2 C(x_0, x_0); \tag{6}$$

the second term is

$$2C(w_0 x_0, X) = 2w_0 C(x_0, \sum_{j=1}^{N} g_j x_j) = 2w_0 \sum_{j=1}^{N} g_j C(x_0, x_j), \tag{7}$$

and the third item is

$$\begin{aligned} C(X, X) &= E(\sum_{j=1}^{N} g_j x_j - E\sum_{j=1}^{N} g_j x_j)^2 \\ &= E[\sum_{j=1}^{N} g_j (x_j - E x_j)]^2 \\ &= \sum_{i=1}^{N} \sum_{j=1}^{N} g_i g_j C(x_i, x_j) \end{aligned} \tag{8}$$

By substituting Eqs. (6)–(8) into Eq. (5), we obtain

$$\begin{aligned} v\hat{X} = {w_0}^2 C(x_0, x_0) - 2w_0 \sum_{j=1}^{N} g_j C(x_0, x_j) \\ + \sum_{i=1}^{N} \sum_{j=1}^{N} g_i g_j C(x_i, x_j). \end{aligned} \tag{9}$$

Taking into consideration the unbiased condition of Eq. (4), the Lagrange parameter μ is introduced into Eq. (9) in the following manner:

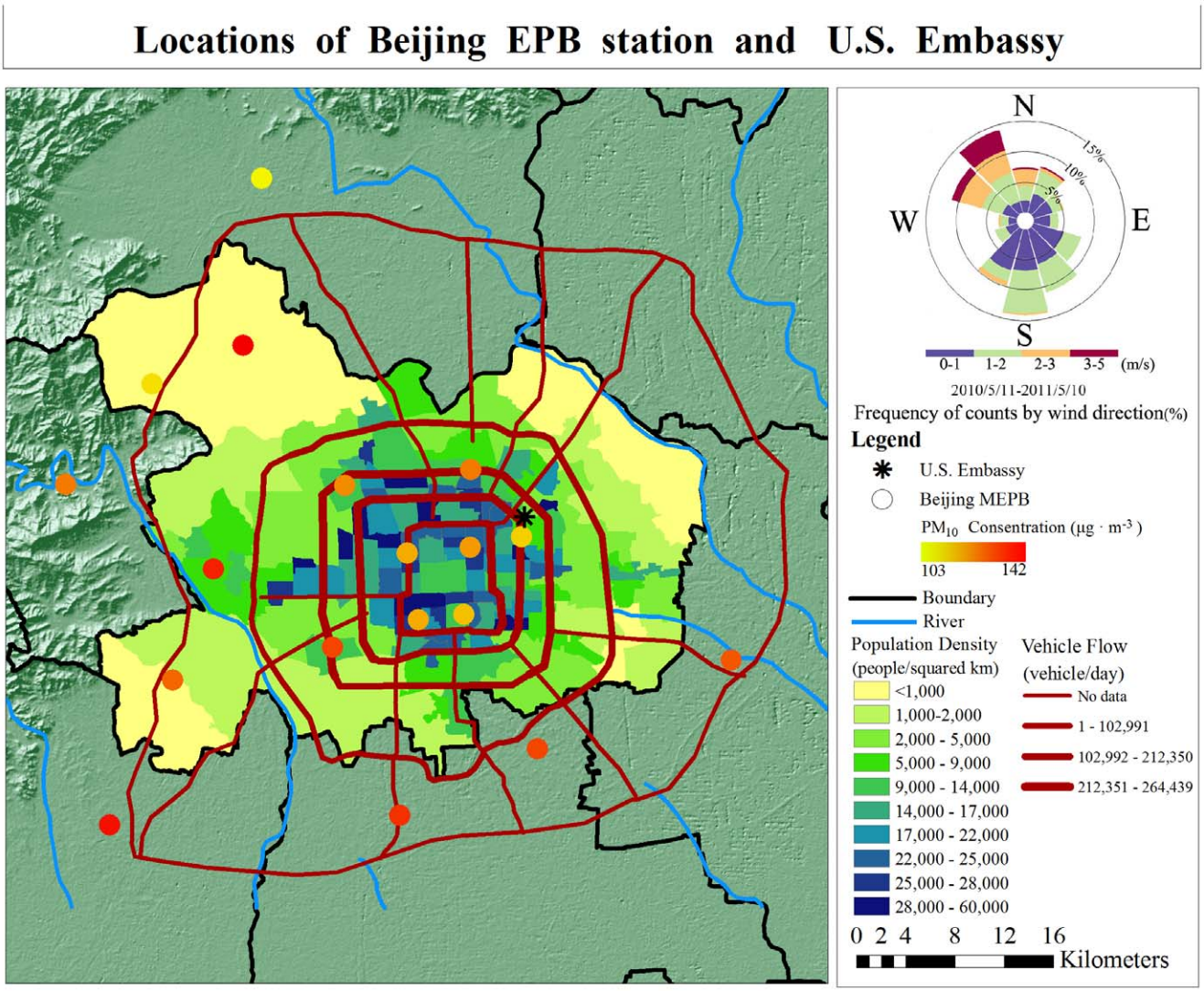

Figure 1. Location of BJ-EPB PM$_{10}$ monitoring stations and U.S Embassy PM$_{2.5}$ station (Beijing, China).
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$$v\hat{X} = w_0^2 C(x_0,x_0) - 2w_0 \sum_{i=1}^{N} g_i C(x_0,x_i) + \sum_{i=1}^{N}\sum_{j=1}^{N} g_i g_j C(x_i,x_j) + 2\mu\left(\sum_{i=1}^{N} g_i - 1\right) \quad (10)$$

Minimization of Eq. (10) with respect to the g_i's, w_0 and μ is a standard optimization problem, leading to the system of equations (to be solved with respect to g_i, $i=1,2,...,N$, w_0 and μ):

$$\begin{cases} \dfrac{\partial v\hat{X}}{\partial w_0} = w_0 C(x_0,x_0) - \sum_{j=1}^{N} g_j C(x_0,x_j) = 0 \\ \dfrac{\partial v\hat{X}}{\partial g_i} = -w_0 C(x_0,x_i) + g_i C(x_i,x_j) + \sum_{j\neq i}^{N} g_j C(x_i,x_j) + \mu = 0 \\ \dfrac{\partial v\hat{X}}{\partial \mu} = \sum_{i=1}^{N} g_i - 1 = 0 \end{cases} \quad (11)$$

This system of equations can be written in matrix notation as

$$\begin{bmatrix} C(x_0,x_0) & C(x_0,x_1) & C(x_0,x_2) & \cdots & C(x_0,x_N) & 0 \\ C(x_1,x_0) & C(x_1,x_1) & C(x_1,x_2) & \cdots & C(x_1,x_N) & 1 \\ C(x_2,x_0) & C(x_2,x_1) & C(x_2,x_2) & \cdots & C(x_2,x_N) & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \\ C(x_N,x_0) & C(x_N,x_1) & C(x_N,x_2) & \cdots & C(x_N,x_N) & 1 \\ 0 & 1 & 1 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} -w_0 \\ g_1 \\ g_2 \\ \vdots \\ g_N \\ \mu \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \quad (12)$$

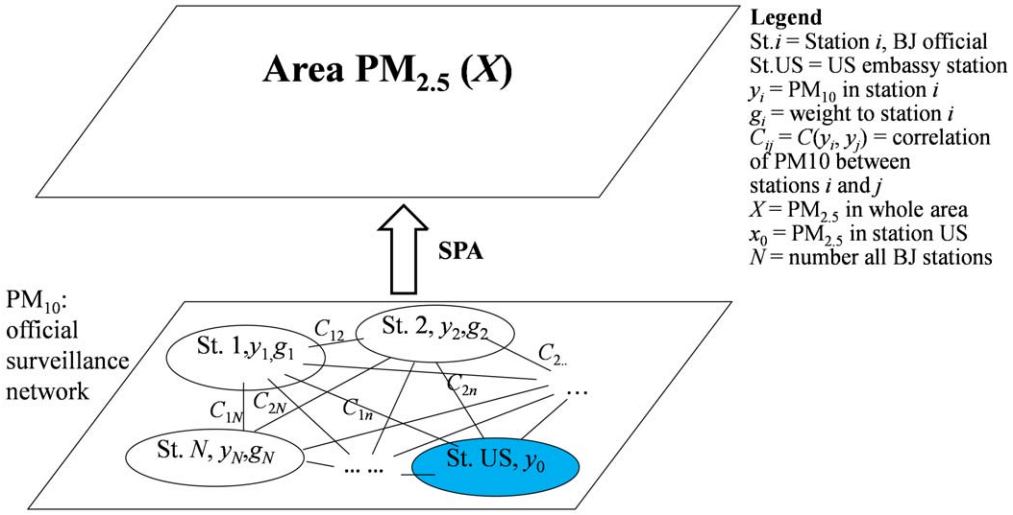

Figure 2. Relationship between stations and $PM_{2.5}$ areal concentration: y_i denotes PM_{10} concentration reported by station *i*, and *X* is areal $PM_{2.5}$ concentration for Beijing; St. US denotes the U.S. Embassy station at which daily $PM_{2.5}$ concentration x_0 is observed; *X* is estimated by x_0 using the SPA technique, based on observed $PM_{2.5}$ data at the embassy station, and their correlation with PM_{10} concentrations observed at the 18 (evenly distributed) stations operated by BJ-EPB.
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The solution of Eq. (12) yields w_0, g_i and μ, as appropriate.

Accuracy of the SPA Technique

A variety of studies have discussed the uncertainty sources affecting the accuracy of data-based air quality estimates [24,25]. Generally, there is an inverse relationship between uncertainty and accuracy – the higher the data uncertainty, the lower the accuracy of a model or technique. Usually the accuracy of a technique is measured in terms of its estimation error. The theoretical background of the **SPA** technique considers both horizontal correlations between samples, and vertical correlations between samples and area populations. It subsequently produces pollutant estimates that satisfy two key criteria – unbiasedness and minimum estimation error. Accordingly, **SPA** is a network-based estimation technique that is resistant to shifts [26] such as dust storms, which are addressed by statistical autocorrelation parameters in the model.

In this study, the horizontal (spatial) correlation between $PM_{2.5}$ concentrations is approximated by that between spatial PM_{10} concentrations. The estimation error of this approximation is small due to various reasons:

(i) The citywide $PM_{2.5}$ concentration estimated by SPA is defined as the weighted spatial $PM_{2.5}$ average from all 18 stations (for each station the weight was proportional to the associated Voronoi area). Note that spatial topology – which is a key determinant of horizontal (spatial) autocorrelation [27]– is identical for $PM_{2.5}$ and PM_{10} [28].

(ii) Both particulates vary in space and time, subject to the same weather conditions, providing a valuable determinant of horizontal correlation [29,30]. Vertical correlations between $PM_{2.5}$ and PM_{10} concentrations were calibrated in terms of the observed data.

(iii) Empirical evidence has shown that $PM_{2.5}$ and PM_{10} concentrations are highly correlated, with values as high as 0.85 and 0.97, respectively [31,32].

(iv) In the SPA technique, the correlation coefficients between $PM_{2.5}$ and PM_{10} are calibrated by the data so that they can correct for potential discrepancies (see section 2 in the *SI* text). Historical data have shown high correlations between the U.S. Embassy $PM_{2.5}$ concentrations and the 18 PM_{10} observation stations (Table 1). The maximum and minimum values of Pearson correlation efficient are 0.85 and 0.69, respectively.

Estimation precision was further assessed by a validation study using an exhaustive PM_{10} dataset in the study area. In particular, daily areal PM_{10} concentrations were estimated by the SPA technique based on records at each of the 18 PM_{10} stations. The actual daily areal PM_{10} concentration is the weighted spatial PM_{10} average from all 18 stations (for each station, the weight was proportional to the associated Voronoi area; see *Supporting material*). Subsequently, the areal PM_{10} concentration estimated by each of the 18 PM_{10} monitoring stations and SPA was compared to the actual concentration value, resulting in good agreement (Table 2

Table 1. Pearson correlation coefficient between the U.S. Embassy PM2.5 concentration and 18 Beijing EPB PM_{10} concentrations.

BJ-EPB Station	r	BJ-EPB Station	r
Aotizhongxin	0.81	Longquanzhen	0.82
Changpingzhen	0.72	Nongzhanguan	0.83
Dongsi	0.83	Tiantan	0.82
Fengtaihuanyuan	0.85	Tongzhouzhen	0.79
Gucheng	0.81	Wanliu	0.81
Guanyuan	0.83	Wanshouxigong	0.84
Haidingbeibuxinqu	0.69	Yizhuangkaifaqu	0.82
Huangcunzhen	0.80	Yungang	0.81
Liangxiang	0.82	Zhiwuyuan	0.77

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Table 2. Summary of R^2 values of the linear relationships between Beijing areal PM_{10} estimated on the basis of a single station using SPA and the true area.

BJ-EPB Station	R^2	BJ-EPB Station	R^2
Aotizhongxin	0.961	Longquanzhen	0.921
Changpingzhen	0.862	Nongzhanguan	0.966
Dongsi	0.969	Tiantan	0.941
Fengtaihuanyuan	0.961	Tongzhouzhen	0.867
Gucheng	0.933	Wanliu	0.947
Guanyuan	0.964	Wanshouxigong	0.971
Haidingbeibuxinqu	0.764	Yizhuangkaifaqu	0.888
Huangcunzhen	0.896	Yungang	0.925
Liangxiang	0.849	Zhiwuyuan	0.901

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and Figure S1 in SI text). This result supports the reliability of the SPA technique when used to estimate areal pollution concentration based on a single monitoring station. An SPA software is provided that can be used to perform the data calculations of this study (www.sssampling.org/SPA). Readers can apply the SPA software to their own data.

Results

Daily $PM_{2.5}$ mass concentrations observed at the embassy station ranged from 4 to 487 $\mu g/m^3$ for the 423-day period. The annual average concentration (December 7, 2010–December 6, 2011) was 98.85 $\mu g/m^3$, with high temporal variability. For the entire time series, the highest $PM_{2.5}$ concentrations (>300 $\mu g/m^3$) occurred during 10 days: December 7 and November 18–19, 2010, February 21–24, October 23 and December 5, 2011; see Figure 3.

During the same period, estimated citywide $PM_{2.5}$ daily pollution in Beijing ranged from 2.86 to 318.29 $\mu g/m^3$. The annual average pollution was 64.78 $\mu g/m^3$. The highest concentrations (>300 $\mu g/m^3$) occurred during two days, November 19, 2010 and February 21, 2011, as shown in Figure 3.

Discussion

It was found that the U.S. Embassy $PM_{2.5}$ observations exhibited approximately the same trend as citywide $PM_{2.5}$ areal concentrations estimated by the SPA technique, although the embassy's concentration values were clearly higher. The most important reason for this could be that the U.S. Embassy is at the city center, where population density and traffic volume are the highest in the city. The ratio between the embassy's $PM_{2.5}$ concentration and the estimated area-average concentration pollution varied with time. It is affected by the dynamic correlation between $PM_{2.5}$ and PM_{10}, caused by variation in local emission and atmospheric conditions between the embassy and the entire city.

Estimated area-average $PM_{2.5}$ concentrations varied on a daily and monthly basis. The lowest concentrations occurred during January and March 2011, owing to the large number of windy days (refer to Figure S2 in *SI* text for monthly wind speeds). Estimation uncertainty is high for March 2011, because of serious data gaps. The highest concentrations occurred during July and November 2010, and during February and July–September 2011. During November, formation of a temperature inversion layer was observed over Beijing, which is a meteorological condition that plays an important role in the accumulation of $PM_{2.5}$. The $PM_{2.5}$ mass concentration peak during February was most likely due to emissions from coal consumption for heating purposes [33,34]; this was the month with the lowest temperatures and slowest winds during 2011. July–September was the hottest period during a year. Long and intense solar irradiation during summer favors photochemical formation of aerosol particles [35,36], which benefits the synthesis of $PM_{2.5}$. This caused the high $PM_{2.5}$ levels observed during that season. As regards seasonal variation, winter and summer had higher $PM_{2.5}$ levels, with concentrations 68.74 $\mu g/m^3$ and 70.42 $\mu g/m^3$, respectively. Spring and fall concentrations were 63.59 $\mu g/m^3$ and 61.54 $\mu g/m^3$, respectively.

In sum, $PM_{2.5}$ pollution in Beijing remained relatively high during the study period (Figure 3). Daily and annual interim target-1 standards recommended by the World Health Organization (WHO) are 75 $\mu g/m^3$ and 35 $\mu g/m^3$, respectively [37]. As mentioned earlier, the annual (December 7, 2010–December 6, 2011) average concentration in Beijing was 64.78 $\mu g/m^3$. During that period, daily concentrations during 93 out of 259 days exceeded the WHO standard. Compared to the Beijing $PM_{2.5}$ levels of five years ago reported in previous studies [33,34], this level has dropped significantly. The situation may be attributed to

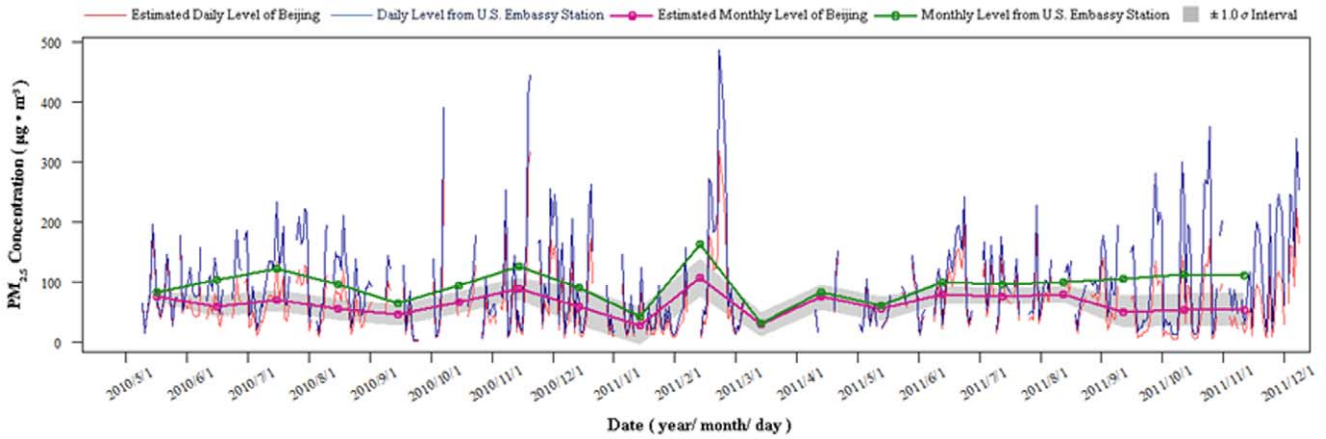

Figure 3. $PM_{2.5}$ concentration observed by a single station (U.S. Embassy), and estimated citywide $PM_{2.5}$ areal concentration (Beijing, China).
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a policy of prioritizing development of public transport, displacement of heavy industrial factories away from the city, and other efforts associated with the 2008 Beijing Olympics. Yet, the number of cars in the city has grown, from 2.6 million in 2005 to 5 million in 2010. Furthermore, air quality remains dependent on weather conditions, which means that considerable willingness and effort are needed to eliminate $PM_{2.5}$ sources, thereby clearing the sky over the city.

Conclusion

PM air pollution is a severe problem for Beijing city, as is demonstrated by both the official PM_{10} and the estimated $PM_{2.5}$ concentrations. The areal $PM_{2.5}$ concentration estimated by the proposed SPA technique was found to be a little lower than that observed at the U.S. Embassy monitoring station that is located at the city center and near a traffic junction. Validation results showed that the SPA technique is a useful tool in the estimation of areal PM2.5 concentration, even when only one PM2.5 observation station is available. Concerning the in situ implementation of SPA, (i) the key input to the technique is the correlation (covariance) between the $PM_{2.5}$ and PM_{10} stations calculated from historical data, (ii) the estimation weight of the PM2.5 station was obtained by solving a linear equation (equation (12)) and, subsequently, (iii) the areal PM2.5 concentration was calculated from equation (2). Concluding, given the prohibitive costs of measurement campaigns and monitoring networks, the proposed SPA technique can be an effective and accurate pollution estimation tool, especially in cases in which, due to limited monitoring stations or in remote areas or in the past, other sources of information need to be used.

Supporting Information

Details on data, estimation, the accuracy test, and a software of the method are available free of charge online at http://pubs.acs.org, or from www.sssampling.org/SPA.

Supporting Information

Table S1 Data description & model validation.
(DOC)

Table S2 Original data.
(XLS)

Author Contributions

Conceived and designed the experiments: JFW GC. Performed the experiments: MGH CDX YZ. Analyzed the data: JFW MGH CDX YZ. Contributed reagents/materials/analysis tools: MGH YZ GC. Wrote the paper: CDX JFW.

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