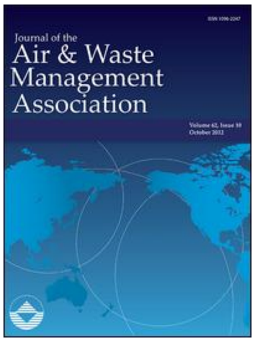

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Site Representativeness of Urban Air Monitoring Stations

Chang-Chuan Chan
National Taiwan University, College of Public Health, Institute of Occupational Medicine and Industrial Hygiene, Taipei, Taiwan

Jing-Shiang Hwang
Institute of Statistical Science, Academia Sinica, Taipei, Taiwan

ABSTRACT

This paper describes a statistic to quantify spatial representativeness for the air measurements of an urban fixed-site ambient air monitoring station. The application of such a statistic of representativeness has also been successfully demonstrated by two data sets collected at the Gu-Ting monitoring station in Taipei. By measuring NO_2 at 22 sites simultaneously around the Gu-Ting station, the statistic has characterized different degrees of spatial representativeness for nitrogen dioxide (NO_2) at various areas and microenvironments surrounding this fixed-site monitoring station. By measuring ambient air concentrations at six sites sequentially around the Gu-Ting station, the statistic has also characterized different degrees of representativeness for particulates less than 10 μm in size—(PM_{10}), carbon monoxide (CO), sulfur dioxide (SO_2), ozone (O_3), NO_2, nitrogen oxides (NO_x), nitrogen monoxide (NO), total hydrocarbons (THC), and nonmethane hydrocarbons (NMHC)—at an open area surrounding this fixed-site monitoring station. This statistical method identifies the Gu-Ting station is well representative of outdoor concentrations of all nine air pollutants for a period of three weeks at the areas within a 700 m radius around this station. The indoor NO_2 concentrations, however, are not represented by the measurements at the fixed-site monitoring station.

IMPLICATIONS

Determining deterioration and improvement of air quality increasingly relies on data reported from fixed-site monitoring stations worldwide. The statistic developed in this paper can be used to optimize the application of these measurements by checking their spatial representativeness for a predetermined sampling period in these monitoring stations. It will be helpful to include the representativeness statistic in the monitoring data in order to make legitimate comparisons between air quality data collected at different locations in different countries. This representativeness statistic will be useful for epidemiological studies in better defining exposure groups from fixed-site air quality monitoring data.

INTRODUCTION

Currently, ambient air quality is routinely measured by a network of fixed-site monitoring stations in most countries. Such monitoring of air pollution is performed for a wide variety of purposes, ranging from air quality assessment to public health study. The spatial representativeness of monitoring stations provides a basis for classifying such uses. The United States Environmental Protection Agency (U.S. EPA) defined five categories of spatial scales—micro, middle, neighborhood, urban, and regional scales—in its guidelines for siting State and Local Air Monitoring Stations and National Air Monitoring Stations.[1] For example, monitoring nitrogen dioxide (NO_2) on a middle scale is assumed to cover the area from about 100 to 500 meters around a monitoring station, and is assumed to characterize public exposure in populated areas. It is imperative that ambient concentrations of air pollutants within these designated areas be well represented by fixed-site monitoring, because compliance with National Ambient Quality Standards (NAAQS) still depends exclusively on outdoor measurements in most countries. The issue of representativeness, however, has been overlooked in the past. The lack of a quantitative method to describe the concept of representativeness results in inconsistent comparisons for monitoring data among different sites. Furthermore, studies have shown that ambient measurements alone can bias human exposure, because most people spend much time indoors, and concentrations of air pollutants sometimes can be higher inside buildings than outside.[2-5] Therefore, concentrations of air pollutants in various indoor microenvironments surrounding the fixed-site station also must be estimated in order to assess human exposure correctly from the fixed-site monitoring data. Conceptually, site representativeness is determined by spatial variation in measurements around monitoring sites over a period of time. Statistically, the representativeness with its spatial and temporal attributes becomes a four-dimensional problem. Because air measurements are always reported as time-averaged concentrations, we can treat the issue of site representativeness as a problem of time-dependent spatial representativeness.

Therefore, the complicated four-dimensional issue of site representativeness can be simplified as a three-dimensional problem. In this paper, we propose a simple statistical method to describe the degree of site representativeness of an urban fixed-site air monitoring station. We will first introduce a new statistic of spatial representativeness to quantify the degree of representativeness in the areas surrounding the monitoring station. We will then use two data sets collected from different sampling approaches to demonstrate how to apply our method to characterize the spatial representativeness of PM_{10}, CO, SO_2, O_3, NO_2, NO_x, NO, THC, and NMHC for one monitoring station in Taipei.

STATISTICAL METHOD

We propose a simple statistic to assess site representativeness in a quantitative way by estimating the differences in measurements between the fixed-site monitoring station and all available sampling sites in a designated sampling plan around the station. Let Y_{tj} be the time-matched differences in measurements for the t^{th} sampling execution at the j^{th} site in one predetermined space around the fixed-site monitoring station in such a sampling plan. Within a specified evaluation period, there can be T times of sampling execution, and for each t = 1, 2, ..., T, there can be J_t sampling sites in the sampling scheme. As the averaged differences in measurements,

$$\bar{Y}=\frac{1}{n}\sum_{t=1}^{T}\sum_{j=1}^{J_t}Y_{tj}$$

$$\text{where } n=\sum_{t=1}^{T}J_t$$

is closer to zero, the measurements in the fixed-site monitoring station become more representative of the concentrations of air pollutants in the designated space. Conventionally, $\bar{Y}$'s closeness to zero is usually tested by the ratio between $\bar{Y}$ and its standard deviation

$$\sqrt{SS_Y/n}$$

$$\text{where } SS_Y=\sum_{t=1}^{T}\sum_{j=1}^{J_t}Y_{tj}^2$$

assuming that Y_{ij} is normally distributed with a mean value of zero. Therefore, such statistical testing is subject to the limitation of data characteristics. Since

$$SS_Y=SS_{\bar{Y}}+n\bar{Y}^2$$

$$\text{where } SS_{\bar{Y}}=\sum_{t=1}^{T}\sum_{j=1}^{J_t}(Y_{ij}-\bar{Y})^2$$

we propose a statistic $R_n = SS_{\bar{Y}}/SS_Y$

to estimate the degree of $\bar{Y}$'s closeness to zero. The R_n statistic is, therefore, defined as a term to measure the representativeness of a fixed-site monitoring station. The form of R_n is similar to the coefficient of determination in regression equations, except that no models are used in the calculation of R_n. Apparently, the values of R_n are always located between 0 and 1 as implied in the equation. Therefore, the monitoring station's representativeness becomes greater as R_n is closer to 1.

Conventionally, the 100(1 - α)% Highest Probability Density (HPD) interval can be used to describe the uncertainty of a statistic, which is similar to traditional confidence intervals.[6] The lower (L) and upper (U) bounds of the HPD interval can be obtained from integrating the density function of R_n, $f_{R_n}(v)$. Accordingly, the 100(1 - α)% HPD interval (L,U) can be obtained by solving the equation: $\int_L^U f_{R_n}(v)dv=1-\alpha$ with the constraints of $f_{R_n}(v_I) \geq f_{R_n}(v_2)$ for all $v_I \in$ (L,U) and $v_2 \notin$ (L,U). Without any assumption about the distributions of Y_{tj}, the R_n's distribution usually is either unknown or unavailable. In such cases, the bootstrap method can be adopted to compute the HPD credible intervals, which has been successfully applied to various data sets without distribution assumption.[7]

The bootstrap method is basically a procedure to generate a bootstrap sample set, $Y=(y_1^*,...,y_n^*)$, by randomly sampling Y_{tj} for n times with replacement. After several bootstrap replications, B independent bootstrap data sets, $Y^{*1}, Y^{*2},...,Y^{*B}$, can be obtained. Therefore, the representativeness can also be calculated from the bootstrap data sets by the equation:

$$R_n^*(b)=\frac{SS_{\bar{Y}^{*b}}}{SS_{Y^{*b}}} \text{ for } b=1,2,...,B.$$

Furthermore, a bootstrap 100(1 - α)% HPD credible interval for R_n can be computed by the following steps. First, B sets of generated $R_n^*(b)$ are orderly list as $(r_1,r_2,...,r_B)$. Second, a rounded integer of B x 100 x (1 - α), m, is calculated. Third, the credible interval is increasingly expanded from the middle of the interval, i.e., $L_B = U_B = r_k$ where r_k may be median or mode of $(r_1, r_2,..., r_B)$. Let r_U and r_L be the nearest values next to U_B and L_B but not within the interval. If $(r_U - L_B) \leq (U_B - r_L)$, then U_B is replaced with r_U. Otherwise, L_B is replaced with r_L. A bootstrap 100(1 - α)% HPD credible interval (L_B, U_B) can be obtained by repeating the above expansion procedure for m times.

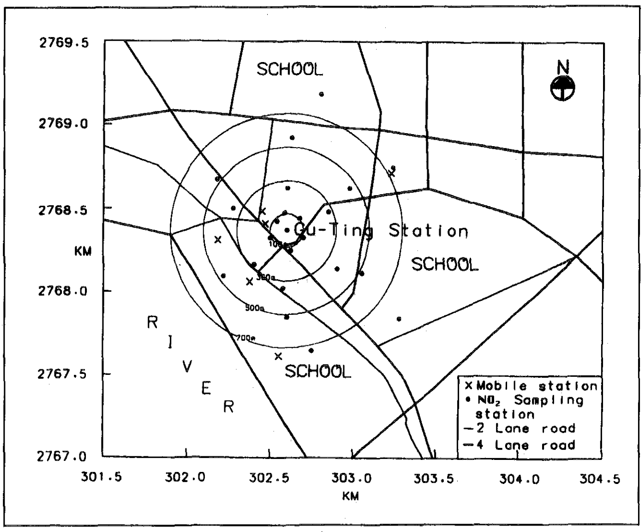

Figure 1. The 22 NO_2 sampling sites and six mobile stations around the Gu-Ting station.

DATA DESCRIPTION

The Gu-Ting air monitoring station was selected to evaluate spatial representativeness. This station is one of twelve Taiwan EPA operated fixed-site air monitoring stations in the Taipei basin. The Gu-Ting station is located on the campus of an elementary school in downtown Taipei, and was originally designed to monitor the ambient air quality within a distance of 500 m radius. The radius hourly concentrations of PM_{10}, CO, SO_2, O_3, NO_2, NO_x, NO, THC, and NMHC are continuously measured in the station. The height of the sampling probe is about 20 m above the ground at the station.

Data Set 1 consists of three consecutive three-day averaged NO_2 measurements at 22 sampling sites around the Gu-Ting monitoring station, which were simultaneously collected with the measurements at the station from May 18-27, 1993. In order to collect empirical NO_2 concentration data from the space surrounding the Gu-Ting station, the area around the station was further stratified into four zones at distances of 100 m, 300 m, 500 m, and 700 m away from the station. Next, six sampling sites were placed at intervals of 60 degrees on each circumference. In total, there were 22 sites in the final sampling scheme, because two pre-selected sites are in a river. As indicated in Figure 1, eight sites were close to traffic routes with more than two lanes, while another 14 sites were in small aisles. The aisles are narrow roads in residential areas where no vehicular traffic is allowed. At each site there were three sampling locations, one outdoors 20 m in height, one indoors 20 m in height, and one outdoors 3 m in height. Palmes tubes were used to measure three-day integrated NO_2 concentrations at all sampling locations simultaneously.[8] Due to the detection limits of Palmes tubes, three days is the minimum averaging time for reliable NO_2 measurements. The sampling was repeated three consecutive times. The results of 20 duplicate pairs of Palmes tubes showed a relative mean difference of 4%. Co-located Palmes tubes in the Gu-Ting station indicated that the Palmes tubes consistently measured 20% higher NO_2 concentrations than the chemilluminent method used in the fixed-site monitoring station. Therefore, the Palmes tubes data discussed in this paper have been corrected by a factor of 1.2.

Data Set 2 was collected by a mobile monitoring station, which sequentially monitored hourly concentrations at six different locations surrounding the Gu-Ting station. The six locations were all located in open space near main traffic roads, about 180-750 m away from the Gu-Ting station. The hourly concentrations of PM_{10}, CO, SO_2, O_3, NO_2, NO_x, NO, THC, and NMHC were continuously measured at each location for three days. The collection of such sequential data took place from February 18 to March 8 in 1994. Therefore, the sequential data set consisted of about 450 hourly-matched data points between these locations and the Gu-Ting station.

RESULTS AND DISCUSSION

The three-day averaged NO_2 concentrations measured at 22 sampling sites around the Gu-Ting station are summarized in Table 1. The NO_2 concentrations were significantly different between indoor and outdoor sampling locations. On average, the NO_2 concentrations indoors were about 3 to 6 ppb lower than those outdoors. For outdoor measurements, the NO_2 concentrations, however, were about the same for sampling heights at 3 m and 20 m. There was also no significant difference in ambient NO_2 concentrations for different areas surrounding the monitoring station within a radius of 100 m to 700 m, and for areas at four different directions surrounding the station. By contrast, the ambient NO_2 concentrations were significantly different for the measurements at aisles and near main roads. On average, the ambient NO_2 concentrations at aisles were about 3 to 5 ppb lower than those near the main roads.

Table 1. Three sets of three-day averaged NO_2 concentrations at 22 sampling sites surrounding the Gu-Ting monitoring station (unit: ppb).

Site	*1st 3-day mean (sd)*	*2nd 3-day mean (sd)*	*3rd 3-day mean (sd)*
By location			
20 m high outdoor	31.70 (4.42)	35.72 (5.60)	40.38(4.98)
20 m high indoors	31.71 (7.99)	29.22 (4.97)	35.22 (5.57)
3 m high outdoors	34.72 (8.02)	33.31 (2.62)	39.04 (4.41)
By distance (outdoors)			
within 100m	34.46 (5.73)	35.59 (3.21)	40.90 (5.49)
within 300m	35.28 (6.16)	34.45 (3.85)	40.74 (4.40)
within 500m	33.99 (6.42)	35.46 (4.85)	40.48 (4.24)
within 700m	33.05 (6.38)	34.46 (4.73)	39.80 (4.73)
By direction (outdoors)			
north	34.17 (6.38)	35.65 (5.31)	38.50 (5.09)
south	31.93 (6.35)	33.79 (3.97)	41.03 (4.12)
east	34.79 (6.35)	35.90 (5.70)	39.53 (3.24)
west	34.74 (4.73)	37.31 (2.85)	41.13 (3.72)
By traffic (outdoors)			
near small aisles	31.23 (5.57)	33.61 (4.89)	38.96 (4.63)
near main roads	36.17 (6.66)	37.43 (3.10)	41.35 (4.68)

The results shown in Table 2 are calculated R_n and bootstrap 95% HPD credible intervals (L_B, U_B) for nine-day-averaged NO_2 measurements at the Gu-Ting station from May 18-27, 1993. The representativeness at indoor sampling locations was found to be significantly lower than those at outdoor locations for the entire areas within the Gu-Ting station's 700 m radius. For 20 m indoor locations, the R_n value was 0.57, with bootstrap 95% HPD credible interval (0.39, 0.77). For both 3 m and 20 m outdoor locations, the R_n value was 0.89 with bootstrap 95% HPD credible interval (0.74, 1.00). Lower representativeness for NO_2 measurements indoors is understandable because NO_2 concentrations

Table 2. Spatial representativeness R_n, and related HPD credible interval (L_B and U_B) for nine-day NO_2 concentrations measured at 22 sites surrounding the Gu-Ting station.

Site	R_n	L_B	U_B
By location			
20 m high outdoor	0.89	0.75	1.00
20 m high indoors	0.57	0.40	0.78
3 m high outdoors	0.89	0.73	1.00
By distance (outdoors)			
within 100m	0.98	0.77	1.00
within 300m	0.99	0.88	1.00
within 500m	0.96	0.86	1.00
within 700m	0.89	0.78	0.97
By direction (outdoors)			
north	0.92	0.76	1.00
south	0.86	0.74	0.99
east	0.96	0.75	1.00
west	1.00	0.85	1.00
By traffic (outdoors)			
near small aisles	0.74	0.58	0.88
near main roads	0.98	0.86	1.00

indoors are influenced by factors other than outdoor sources, such as indoor emissions and housing ventilation conditions. The similarity in the spatial representativeness for outdoor locations at 3 m and 20 m high indicates that ambient NO_2 concentrations are vertically homogeneous up to at least 20 m in the areas around the Gu-Ting station.

The areas surrounding the Gu-Ting station were further divided into four zones by their distances away from the station, in order to investigate the degree of representativeness for different areas. For the ambient NO_2 concentrations, the degree of representativeness does not decrease until the radius becomes 700 m. For areas within 100 to 500 m, the R_n values were 0.96-0.99 with bootstrap 95% HPD credible intervals (0.77, 1.00). By contrast, the R_n value became 0.89 with bootstrap 95% HPD credible interval (0.78, 0.97) for areas within 700 m.

The areas within 700 m radius were further divided into four zones in order to investigate the degree of representativeness in four different directions. The lowest representativeness was found in the south direction. The R_n value became 0.86 with bootstrap 95% HPD credible interval (0.74, 0.99) for areas in the south. It is reasonable to have a lower degree of representativeness for the station in this direction, because this area neighbors a river where the traffic is less crowded.

A significant contrast in the representativeness of NO_2 measurements was found at sampling locations between small aisles and main traffic routes. For locations at small aisles, the R_n value was only 0.74 with bootstrap 95% HPD credible interval (0.58, 0.88). For sampling locations near main roads, the R_n value was 0.98 with bootstrap 95% HPD credible interval (0.86, 1.00). Apparently, the Gu-Ting station was strongly influenced by emissions from mobile sources, because it had a higher degree of representativeness for NO_2 measurements near main traffic routes.

Hourly measurements of PM_{10}, CO, SO_2, O_3, NO_2, NO_x, NO, THC, and NMHC at and around the Gu-Ting station are shown in Figure 2. Hourly concentrations during the monitoring period were about 0.2 to 32.4 ppb for SO_2, 5.4 to 160.2 $\mu g/m^3$ for PM_{10}, 0.1 to 43.3 ppb for O_3, 9.6 to 75.2 ppb for NO_2, 0.1 to 4.3 ppm for CO, 0.7 to 5.4 ppm for THC, and 0.1 to 1.4 ppm for NMHC. The spatial representativeness, R_n, and credible intervals (L_B, U_B) of these pollutants are shown in Table 3. All pollutants seemed to have high degrees of representativeness since their R_ns were all above 0.75 and their credible intervals (L_B, U_B) ranged between 0.69 and 1.00. There was also good agreement in the spatial representativeness of NO_2 calculated by Data Set 1 and Data Set 2. The R_n of NO_2 was 0.98 for measurements near main roads in Data Set 1, and 0.97 in Data Set 2. Such results indicate that the measurements at the Gu-Ting station are well representative of the ambient air concentrations at open spaces near main traffic routes around the station.

The curves in Figure 2 also show a good agreement in the trends of hourly concentrations measured at and around the Gu-Ting station for SO_2, O_3, NO_2, and PM_{10}. By contrast, agreement was not good for the trends of hourly concentrations of CO, THC, NMHC and NO_x. Such a contrast can also be illustrated by the comparisons in correlation coefficients (Corr.) between measurements at different locations shown in Table 3. Just as the R_n is the spatial representativeness of the monitoring station, the correlation coefficient can be treated as "temporal representativeness." The correlation coefficients between measurements at the Gu-Ting station and measurements around the Gu-Ting

Table 3. Spatial representativeness, R_n, and related HPD credible interval (L_B and U_B) for hourly concentrations of nine air pollutants measured by mobile stations at six sites surrounding the Gu-Ting station.

	SO_2	CO	O_3	PM_{10}	NO_x	NO	NO_2	THC	NHMC
R_n	0.99	0.89	0.75	0.96	0.92	0.96	0.97	1.00	0.96
L_B	0.97	0.83	0.69	0.91	0.84	0.90	0.94	0.98	0.91
U_B	1.00	0.95	0.81	0.99	0.97	1.00	1.00	1.00	1.00
Corr.	0.70	0.45	0.72	0.67	0.48	0.73	0.73	0.27	0.31

Note: Corr.: correlation coefficients for air measurements between fixed-site and mobile stations.

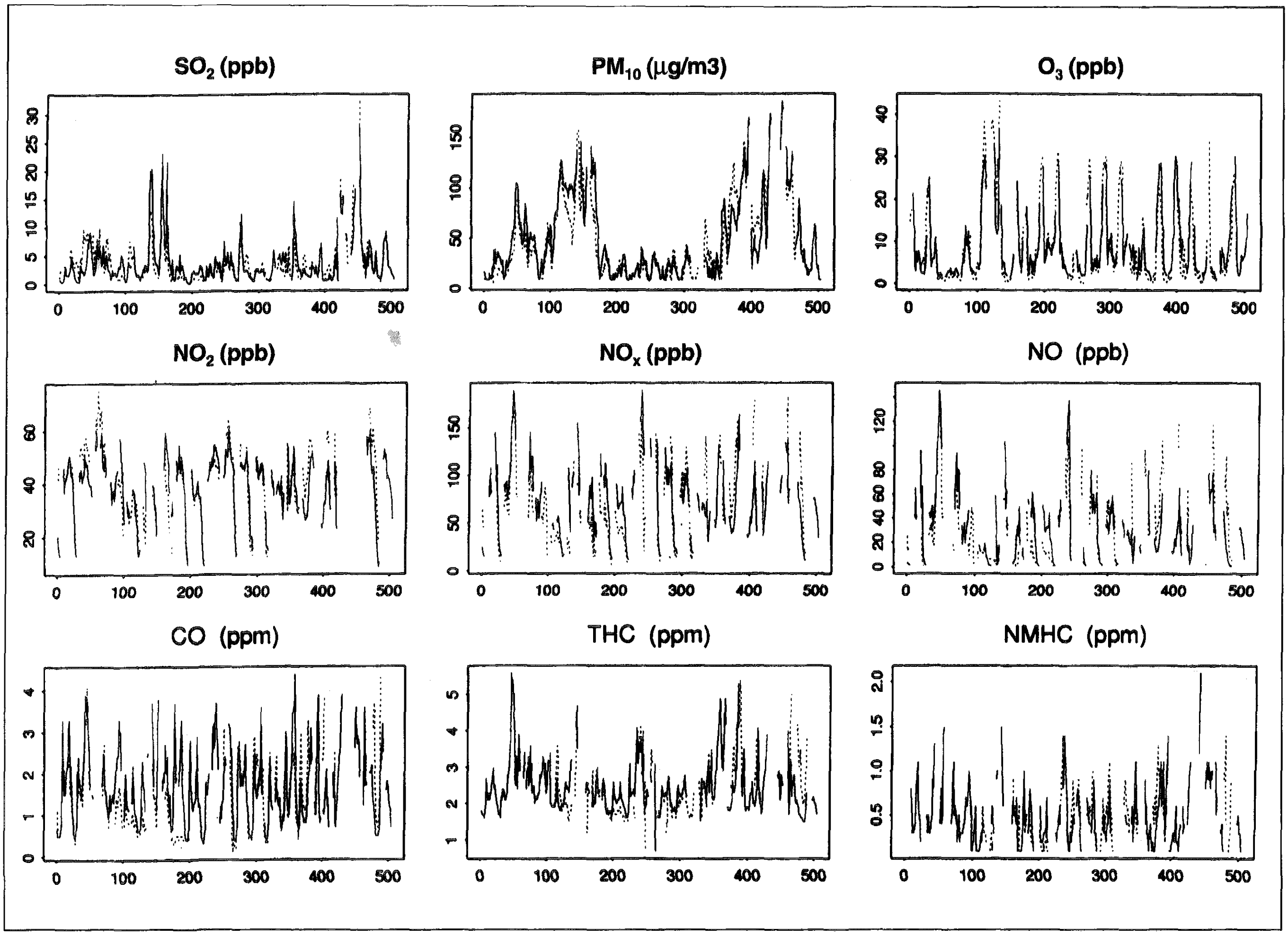

Figure 2. Hourly concentrations of nine air pollutants at the Gu-Ting station and the mobile station during the period February 17, 1994 to March, 9 1994. (Solid line = Gu Ting station; dotted line = mobile station)

station were about 0.67 to 0.73 for SO_2, O_3, NO_2, and PM_{10}, but only about 0.27 to 0.48 for CO, THC, NMHC, and NO_x. Because CO, THC, NMHC, and NO_x are all direct emissions from various mobile sources, their simultaneous measurements at two different locations were influenced by emission sources at individual locations during the monitoring periods. Therefore, a lower correlation in measurements over time between two different locations for these pollutants was expected. By contrast, the concentrations of SO_2, O_3, NO_2, and PM_{10} were less influenced by direct emissions from local sources. Instead, they are either formed by chemical reactions or contributed by various sources in larger areas surrounding the station. Accordingly, higher correlation in the measurements over time between the two different locations for these pollutants is expected. Comparing the results of R_n and Corr., the Gu-Ting station's spatial representativeness was generally higher than its temporal representativeness for most air pollutants, and was particularly higher for CO, THC, NMHC, and NO_x.

Due to the limitations of sampling durations, we could only calculate the Gu-Ting monitoring station's representativeness for a period of 21 days. The station's representativeness over one year is likely to be different from the results presented here, due to climatic changes. In order to estimate site representativeness by our statistic, we need to obtain a data set by randomly sampling throughout the year to get independent measurements covering the full range of variability. We are also aware that several sophisticated spatial and multivariate statistical techniques are currently available to analyze environmental monitoring data, such as spatial process and kriging methods.[9,10] By using these sophisticated methods, we can establish comprehensive and clear time-space correlation structures for the air measurements of all available air monitoring data surrounding the fixed-site station. It is likely that site representativeness may also be derived from these approaches. However, our results indicate that the representativeness statistic seems to meet very well the requirements of estimating a fixed-site station's representativeness for predetermined duration. The simplicity of calculating the representativeness statistic is also an advantage of our method.

CONCLUSIONS

This paper describes the development and application of a new statistic to express the spatial representativeness of air measurements at an urban fixed-site station in Taipei. The monitoring station was found to be representative of ambient air concentrations near main traffic roads, but unrepresentative of indoor concentrations in the areas surrounding the station. The spatial representativeness was also found to be higher than the temporal representativeness for this monitoring station. One obvious policy implication of the representativeness statistic is that data collected at the monitoring station should be modified by the degree of representativeness, before assessing whether the national ambient air quality standards have been attained in the areas surrounding the station. Additionally, this statistic can be further developed to estimate distributions of air concentrations in various microenvironments surrounding the station by including known empirical characteristics of microenvironments, such as location, scale, and pollutant penetration parameters. Lastly, this statistic can also be helpful in characterizing personal exposure levels for future epidemiological studies of the health effects of air pollution.

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About the Authors

Dr. Chang-Chuan Chan (corresponding author) is Associate Professor at the Institute of Occupational Medicine and Industrial Hygiene, National Taiwan University, Rm. 1447, No. 1, Jen-Ai Rd., 1st Sec., Rm 1447, Taipei, Taiwan (e-mail: ccchan@ntumc1.mc.ntu.edu.tw). Jing-Shiang Hwang is Assistant Research Fellow at the Institute of Statistical Science, Academia Sinica, Taipei, Taiwan.