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Urban Air Pollution Monitoring and Correlation Properties between Fixed-Site Stations

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ABSTRACT

The rich regional air-monitoring network of the Emilia-Romagna region of Italy has been used to quantify the spatial variability of the main pollutants within urban environments and to analyze the correlations between stations. The spatial variability of the concentrations of the majority of pollutants within the city was very high, making it difficult to differentiate and characterize the urban environments and to apply legal limits with uniform criteria. On the other hand, the correlations between the fixed-site monitoring stations were high enough for their data to be retained generally very appropriately for controlling temporal trends. Starting from the high correlation level, a procedure was proposed and tested to derive pollution levels, using short-term measurements, such as passive samplers and mobile-station data. The importance of long-term statistics in urban air pollution mapping was emphasized. Treatment of missing data in time series and quality assurance were indicated as possible fields for applications for the correlation properties.

INTRODUCTION

Air pollution monitoring involves assessing pollutant behavior in both space and time. A good monitoring program, therefore, should seek to optimize both spatial and temporal coverage, within available resource constraints. Continuously operating automatic analyzers are the most important information source on air pollution levels. Political environmental action and compliance with legal limits are based substantially on fixed-site monitoring networks. Furthermore, in epidemiologic studies, population exposure usually has been characterized with one city average concentration derived from automatic stations. Several studies have been performed on differences in the concentration of atmospheric pollutants within urban environments.[1–4] Recent epidemiologic studies also have attempted to relate the spatial variation in air pollution concentration within cities to health.[5–7] However, systematic assessments of spatial variability and correlation properties are very scanty, especially in Italian urban environments where urban characteristics are very typical and the importance of the canyon effect probably is enhanced. Furthermore, owing to its meteorological features and its high levels of industrialization and urbanization, a very rich regional monitoring network, especially inside the urban areas, was implemented in Emilia-Romagna, Italy. This makes this region an important study area for evaluating the relationships between monitoring sites in urban environments and their utility for environmental monitoring programs and epidemiologic studies. In this perspective, the spatial variability of air pollution within urban areas was analyzed and the correlation properties between measuring stations were calculated. The reliability of statistical regressions between different sites also was verified, and their utility for optimizing the use of short time measurements and for urban pollution mapping was investigated.

IMPLICATIONS

Following new European Union directives, the Regional Agency for Prevention and Environment of Emilia-Romagna currently is engaged in reorganizing the regional network of fixed-site monitoring stations for air quality control. This study supports this program by analyzing the information content of the existing monitoring sites within the urban environments to understand their utility for environmental and health policies. The agency also will take advantage of this study in assigning financing resources to the different experimental devices for air-quality control (fixed-site monitoring stations, mobile stations, passive samplers).

MATERIALS AND METHODS

For the present analyses, the data from the fixed-site monitoring stations within the 10 urban environments of Emilia-Romagna are used. In the case of Bologna, the chief town of the region, the monitoring stations located

in the metropolitan area (i.e., the municipalities that surround and are very close to the city) were considered. Emilia-Romagna is a fairly large region (~200 × 100 km) in the northeast of Italy (Figure 1). The meteorology of the area, flat for the most part and surrounded by mountains (Alps and Appennines), is characterized by low ventilation (annual mean wind intensity in the urban areas ranging from 1.2 to 2.5 m/sec) and, generally speaking, small values of atmospheric dispersion coefficients. The total population of the region is ~4,000,000; the population of the 10 cities considered by the study is ~1,600,000. The area is one of the most industrialized in Europe. The economic activities are directly responsible for a part of the emissions but, first and foremost, produce high traffic levels and traffic-related pollution (Table 1). The cities have very similar economic and topographic characteristics and are all located in the flat area.

Table 1. Summary of the annual mean, median, maximum, and minimum values of pollution concentrations among all the fixed-site monitoring stations located in the urban areas of the region.

	CO (mg/m^3)	NO ($\mu g/m^3$)	NO_2 ($\mu g/m^3$)	O_3 ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)	TSP ($\mu g/m^3$)	C_6H_6 ($\mu g/m^3$)
Median	1.15	45.7	50	39.8	51.9	68.1	4.2
Mean	1.15	48.3	51.5	39.4	54.5	66.5	4.5
Max	2.08	106.4	79.2	52.1	76.9	106.6	6.6
Min	0.31	18.3	29.4	22.2	35.2	27.7	2.6
Num[a]	45	43	43	15	12	27	8

[a]Number of pairs of measuring stations from which the statistics were calculated.

Data from the regional monitoring network from the year 2000 were used and came from a total of 46 stations located in the urban areas of the regional territory. The monitoring stations are of different types (36 are "traffic" stations, eight are "background," and two are "industrial"). The number of monitoring stations for each pollutant were 45 for carbon monoxide (CO), 43 for nitrogen monoxide (NO) and nitrogen dioxide (NO_2), 15 for ozone (O_3), eight for benzene (C_6H_6), 27 for total suspended particulates (TSP), and 12 for particulate matter (PM) with aerodynamic diameter less than 10 μm (PM_{10}). NO is monitored and included in this analysis owing to its importance with respect to the atmospheric chemistry. CO, NO, NO_2, TSP, and O_3 are the pollutants subject to the longest and most spatially detailed monitoring activity. Fewer in number and of more recent installation are the monitoring stations for benzene and PM_{10}. The data are regularly subjected to fairly conservative quality control, both during data collection and at the end of each year. Only the monitoring stations with a sampling efficiency of more than 75% have been considered in this analysis. The main part of PM_{10} instruments is Adam, but there are also three instruments of different types (Teom, Adm9000, MP101M). The sampling efficiency for PM_{10} resulted lower than the other pollutants, and a less strict criterion was adopted in the analysis (numerousness of data >65%). The SO_2 data were excluded from the analysis because measuring network for SO_2 was set up in the 1980s when diesel engines and oil-fired heating systems produced far more emissions and much higher typical concentration values (nearly 1 order of magnitude greater). Currently, the typical values of this pollutant are often below the measurement threshold value.

Figure 1. The Emilia-Romagna region, shown in the square on the map.

The significance of the differences between cities was analyzed on the annual scale. The goal was to compare the levels of pollution in the cities to verify if appreciable differences between the urban environments were detectable by the air-monitoring network. We chose the Kruskal-Wallis test (see Appendix), which is a nonparametric alternative to the analysis of variance (ANOVA) test[8] and does not need the assumption of distributive normality. The test evaluates whether the median values of the station means within each city differ across the region.

The relationships between temporal trends of different measuring stations were analyzed in terms of the Pearson correlation coefficient. This approach tests the linear correlation between two variables. Preliminary analyses with scatter plots showed that the hypothesis of linear dependence of the concentrations measured in different sites was generally a very good assumption, though the

dispersion of the data near the regression line was very different, depending on pollutant and station pair.

A procedure to derive pollution mean levels using short time measurements integrated by data collected by a fixed-site monitoring station was defined and tested. Short time measurement was simulated using pairs of fixed-site stations and, in particular, using observations of 2 months to estimate the regression function between the two sites. The selected months are January and July, periods with typical high and low values for the primary pollutants. Only for O_3 are the temporal trends inverted, January being a month with typical low values, July with high values. A study[9] conducted by our agency on 5-yr time series showed that the highest values of monthly mean concentrations divided by the minimum values are ~3 for CO, 8 for NO, 2 for NO_2, 8 for O_3, 4 for TSP, 2 for PM_{10}, and 3 for benzene. The linear regression function derived for each pollutant and each pair of stations then was used to estimate the daily concentration of one site for the entire year using the data collected in the other site. By comparing estimates and real values, we were able to evaluate the performances of the procedure with respect to determination of daily, monthly, and annual means. CO, NO, and NO_2 were the pollutants selected to verify the procedure because they are the most intensively monitored pollutants (~3 or 4 for each city). The procedure was applied to all the pairs of stations located in the individual urban areas, using each station as both the dependent and the independent variable. The performances of the procedure were analyzed in terms of standard deviations of the differences between real and estimated values and in terms of variation coefficients.

RESULTS

Air Pollution Spatial Variability

Table 1 gives an overview of the variability of pollution levels inside the regional urban environments with respect to the annual means. On an urban scale, the annual mean concentrations of the main traffic-related pollutants (CO, NO, NO_2, benzene) vary up to 5 times between one site and another. TSP also showed a marked spatial variability. The spatial variability for PM_{10} was lower, but there were only three pairs of PM_{10} stations in the same city. Quite variable among different measuring sites were the O_3 concentrations, with much higher values in the background sites. Figure 2 reports the annual mean concentrations of NO_2 for all stations grouped for each city. The graph illustrates the wide spatial variability within each urban area. This variability was greater than the variability between the mean concentrations of each urban area. A Kruskal Wallis test was conducted only for CO, NO, and NO_2 because these are monitored by a sufficient number of stations. The test showed a nonsignificance of the differences for both NO (P value = 0.50) and NO_2 (P value = 0.50). Only for CO did the test show a value at the limit of significance (P value = 0.02). This is because of the monitoring stations located in the urban area of Bologna having mean distances with respect to the traffic flow larger than for the other cities of the region. In conclusion, the differences between the pollution levels of each city, generally speaking, must be stochastically ascribed to the great in-city variability. In other words, Table 1 could be considered as an overview on the air pollution spatial variability not only on the regional but also on the urban scale.

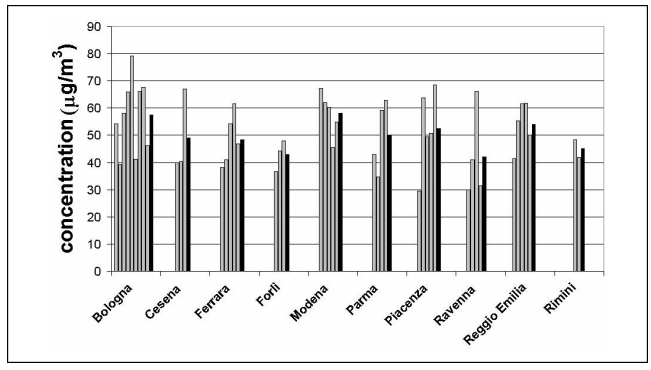

Figure 2. Annual means of NO_2 and CO grouped for city. Black bars are the means of all the stations of each urban environment.

Correlation between Measuring Stations on an Urban Scale

Table 2 summarizes the results of the correlation coefficient analysis. This table is presented with the idea that the correlation properties, like the pollution levels, could be synthesized as they were derived from a unique urban environment. A preliminary comment on correlation coefficients regards the influence of the experimental errors. A relative error of 10% in the pollution data reduces the correlation coefficient by ~9%.[10] This shows that the adopted approach is the estimate of the "at-least" correlation value.

The analysis showed generally high correlation values between the daily data of different measuring sites for the primary traffic-related pollutants. Although not illustrative of the temporal trends of all the pollutants, stations, and time windows, Figure 3 exemplifies the generally strong relationship between concentrations measured by stations of different type and characterized by different pollution levels. CO has the median of all the correlation coefficients equal to 0.82, NO = 0.89, NO_2 = 0.78. The correlation levels relative to O_3 are very high: median of correlations on daily data equal to 0.96 and all pairs with $r > 0.94$. Benzene is monitored in automatic mode in more than one site only in the city of Bologna (three stations). The data are thus too few to derive general conclusions. However, the daily correlations are all greater than 0.81, with a maximum of 0.91. Starting

Table 2. Synthetic table of the correlation analysis among all the fixed-site monitoring stations of urban areas of the region. The correlation coefficients were calculated from the daily data of all the pairs of measuring stations located in the same cities.

	CO	NO	NO_2	O_3	PM_{10}	TSP	C_6H_6
Median	0.82	0.89	0.79	0.96	0.89	0.85	0.84
Mean	0.81	0.87	0.77	0.96	0.89	0.79	0.85
Max	0.97	0.98	0.93	0.97	0.89	0.91	0.91
Min	0.58	0.61	0.52	0.94	0.89	0.49	0.81
Num[a]	82	99	90	6	2	11	4

[a]Number of pairs of measuring stations from which the statistics were calculated.

from the analysis of the data and in virtue of the close analogy between emission factors of benzene and CO and NO, it is therefore reasonable to hypothesize that there should exist a good correlation for this pollutant. The TSP correlations turned out quite different depending on the monitoring pair of stations, with the median value equal to 0.85. PM_{10} is usually monitored only by one station. There are only two cities with more than one station: the correlations are both equal to 0.89.

The correlations calculated from the daily values were always higher than those calculated from the hourly ones. The mean operation smoothes out the small micrometeorological and traffic differences at a very local scale, the measurement errors, and the short-time effect of the nonsystematic time lag of the hourly peaks in the measuring stations. The hourly correlations were ~10% lower than the daily ones. The correlations among the stations between annual means and 95th percentiles also were analyzed, to study the relationship between number of peaks and long-term averages. The correlation was greater than 0.9 for all the pollutants considered in the study.

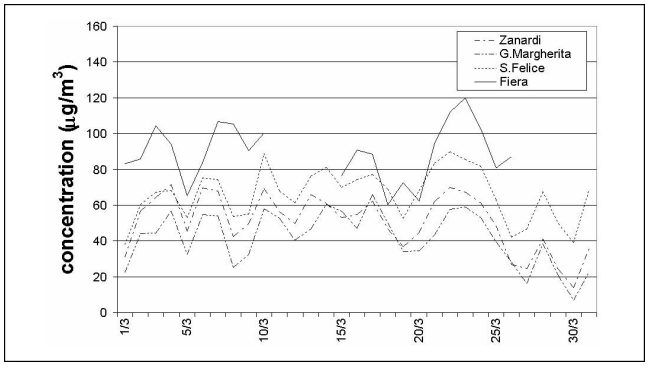

Figure 3. Example of temporal trends of pollution measured by different stations. NO_2 concentrations recorded by four stations in the urban area of Bologna (the chief city of the region) during March 2000. G. Margherita is a background station. The other stations (Zanardi, S. Felice, and Fiera) are all traffic stations located in areas with different characteristics.

Performance Analysis of the Regression between Different Sites

Table 3 shows the results of the performance of the regression procedure between different sites to estimate pollution levels in a site with short time measurements. The reported values of the standard deviation should be compared with the mean pollution levels reported in Table 1. Figure 4 reports the comparison between variation coefficients derived from the estimates of different time averages (daily, monthly, annual). The analysis of the standard deviations between real and estimated values and of the variation coefficients showed that the greater the interest in long-term mean values, the more reliable was the procedure: only a few estimates of annual means were substantially different with respect to the real values, and the annual variation coefficients were between 9 and 15, depending on the pollutant.

CONCLUSIONS

Knowledge of the in-city distribution of pollutants represents one of the more ambitious and highly important goals in environmental and epidemiologic research. The large spatial variability of the main traffic-related pollutants implies the impossibility of obtaining from the data of the fixed-site stations a complete picture of the atmospheric pollution in the urban areas and the mean population exposure. This is because the range of the experimental data is poorly representative. Especially in urban environments that have deep street canyons, high traffic densities, and very low ventilation, like those of Emilia-Romagna, the street canyon effect could be enhanced. The street canyon itself is also probably the typical spatial scale of the pollution in an urban environment and probably an important issue for epidemiologic surveys. The comparison between different cities is also heavily interfered with by the intra-urban spatial variability of air pollution, which could be greater with respect to the variability of the means of each city. European Union directives[11] should give priority to the implementation of background monitoring sites that would be more useful to compare the pollution levels of different cities and to survey mean population exposure; heavily polluted areas could be suitably monitored with other monitoring methods. It also

Table 3. Summary of the annual monthly and daily standard deviation of the differences between real and estimated concentrations among all the fixed-site monitoring stations located in the urban areas of the region.

	CO	NO	NO_2
Annual	0.18	5.7	4.9
Monthly	0.33	14.4	9.7
Daily	0.38	26.2	12.6

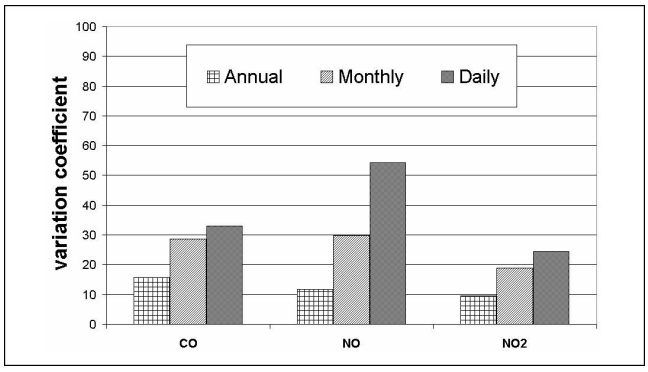

Figure 4. Synthetic view of the performances of the procedure for deriving annual, monthly, and daily means from two months of measurements. The reported values are the variation coefficients.

could be useful to consider the hypothesis of testing different types of environmental measurement for epidemiologic studies, especially to compare different cities. For example, following the meteorological measuring method in urban areas,[12–16] pollution also could be measured above the mean urban building height to collect data more representative of larger spatial scales. To be sure, these data would be further from the real population exposure with respect to the ground-level data, but they might be more useful as a proxy variable of the mean population exposure.

A notable exception, with respect to the spatial variability, might be PM_{10}. Several studies[17] found PM with aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) and PM_{10} concentrations to be uniformly distributed within an urban environment, but two recent studies reported high spatial variability within a city for both $PM_{2.5}$ and PM_{10} in Canada and California.[18,19] In this study, a low spatial variability was found, but general conclusions were not allowed because of the low number of PM_{10} stations. Further investigation should be made into the spatial variability of PM, especially in Italian urban environments, where diesel emissions in conjunction with the canyon effect could cause small-scale effects.

Analysis of the correlation level between the temporal trends of the measuring sites highlighted the strong relationship between the concentrations measured by different stations. This result, on the other hand, is supported by the observation of the peculiarity of the urban environment. The city could be considered to be affected by an almost unique pollution source: traffic. In addition, although the meteorological variables (especially of the dispersion properties) have very different values depending on the topography of the different sites within the urban area, they have very similar temporal trends. The atmospheric pollution concentrations derived from one or more measuring stations might be unrepresentative of the mean pollution level of the city and of the population exposure, but the temporal trend even derived from only one site is probably a good representation of the temporal trends of all the sites inside the urban environment and, hence, of the mean concentration of the city. It is thus possible to evaluate with reasonable accuracy the association between the trend of environmental and health data in differential terms, but it is difficult to evaluate eventual thresholds and to quantify the pollution concentration related to the health effects. Very high spatial detail analysis would be useful only for long-term atmospheric pollution assessment. The exact determination of where (in which point of the city) and when a pollution peak will occur is not only very difficult to obtain but also not very important from a health point of view. Furthermore, the good correlations between annual mean and 95th percentile for all the pollutants enhance the importance of the long-term means for characterizing the critical areas: there is a correspondence between annual means and the probability of acute events.

A complete monitoring program, therefore, should not be based on fixed-site stations alone. In this work, a simple statistical procedure to integrate fixed-site station data and short-term measurements was tested. The procedure is only one example of a more general class of procedures of data collection and treatment. The hypothesized procedure would, in a more general way, consist of measuring campaigns in different points of the city (with passive samplers or mobile stations) in two or more periods of the year, in estimating the regression function with respect to a fixed-site station and lastly the trend of concentration for the entire year. The study shows that, starting from the analyzed data, this approach could be very useful, especially in deriving the annual mean concentrations at an urban scale at high spatial definition and, hence, for urban air pollution mapping. In practice, the combined use of passive samplers and automatic analyzers in a hybrid monitoring program can offer a versatile and cost-effective approach to experimental urban air pollution monitoring, and financial resources should be suitably distributed between long- and short-term measurements. Currently, this approach is probably the most promising, although remote sensing and nonexperimental methods, such as use of models, are gaining importance in monitoring urban air pollution.[20]

The procedure was applied and verified using data from only three pollutants, because of the high number of monitoring stations. However, the reliability of the procedure is qualitatively related to the correlation levels between the sites, and the procedure probably could be used for many other pollutants that have correlation levels very similar to CO, NO, and NO_2. Finally, the high correlation levels found between different sites also could be used for data quality control. If two monitoring stations are well correlated, it is possible to highlight the

potentially incorrect measurements by analysis of the standardized residuals with respect to the regression line between the stations. This procedure seems very effective and quick, especially for analysis of quite long-term series (annual). It could provide the basis for an automatic system for identification of possible anomalous data.

APPENDIX

Consider the 10 cities included in the study as 10 random samples X_1, X_2,. . . X_{10} of size n_1, n_2,. . . , n_{10} where n_i is the number of monitoring station of each city. Form the combined sample of $N = n_1 + n_2 +. . . n_{10}$ annual means that in this study is equal to 45 for CO and 43 for NO and NO_2; order them and assign them the ranks 1,2,. . . N. Let R_{ij} denote the rank of X_{ij} $i = 1,. . . , 10$; $j = 1,2,. . . , n_i$. Let $R_i = \Sigma R_{ij}$ and $\bar{R}_i = R_i/n_{ij}$ denote the sum and mean, respectively, of the ranks in sample i. The sum of all N ranks is $N(N + 1)/2$, and under H_0 (null hypothesis), the expected value of each rank, as well as the expected value of the mean rank for each sample, is $(N + 1)/2$. Consider the statistic

$$H = \frac{12}{N(N+1)} \sum_{i=1}^{10} n_i \left(\bar{R}_i - \frac{N+1}{2} \right)^2$$

where $N(N + 1)/12$ is the variance of the ranks of the N annual means.

Hence, H is related to the differences between the ranks of each group and the mean rank. P values related to H express the probabilities that the differences of the ranks distributions in each group are random. Extensive tables for the probability levels of H are given in Iman et al.[21]

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