United States
Environmental Protection
Agency

Environmental Monitoring Systems
Laboratory
Las Vegas NV 89114

Research and Development

EPA-600/S4-81-012 Apr. 1981

EPA

Project Summary

Optimum Meteorological and Air Pollution Sampling Network Selection in Cities: Volume III. Objective Variational Analysis Model

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This report is the third in a series of reports on the development and application of a procedure to establish an optimum sampling network (OSN) for ambient air quality in urban areas. In the first report, the theoretical aspects and the model algorithms for the procedure and an optimum network for St. Louis were presented (EPA-600/4-78-030). The results of the comparison of the wind field obtained from the optimum network in St. Louis and that obtained from all available data were described in the second report (EPA-600/4-79-069). This report discusses the development and application to St. Louis of the Objective Variational Analysis Model which is used to provide the air pollution distribution.

The OSN technique provides an objective method to develop a sampling network for air pollution and meteorological parameters that will yield a representative distribution of those parameters within the domain of the network. Though the technique has been used to develop an entire network, probably the greatest utilization of the technique can be in improving an existing network in a given urban area. Most urban areas already have a sampling network and would not want to undertake the economic burden to establish a new network.

This Project Summary was developed by EPA's Environmental Monitoring Systems Laboratory, Las Vegas, NV, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The research was motivated by the realization that the cost of implementing an air sampling network within budgetary constraints of a control agency may result in fewer stations than desirable, but the stations must be adequate for the task in the present and future. Conventional networks are often designed to monitor specific sources or concentration characteristics of a subsection of an urban area. With separate source distributions for each pollutant, a good site for one pollutant may not be a good site for another. As sources are added or deleted, the monitoring requirements change. As stations are moved, valuable time histories of pollutants are lost.

Objective

This study takes the approach that knowledge of the wind distribution about the urban area should give a principal guidance for design of a network for air quality monitors. Distribution of pollutants is controlled primarily by the source distribution and the meteorological conditions. Sources and source distributions change as the urban area changes, but the wind characteristics are not a function of the source and should remain relatively unaffected by source changes. Thus, by having a sampling network that will accurately depict the distribution of winds about the urban area, the distribution of pollutants should follow from a knowledge of the source distribution.

The approach involves six steps. Though, in the initial case, the technique was employed in St. Louis, Missouri, the algorithms are generalized and can be applied to any urban region. The six steps are:

(1) A three-dimensional hydrodynamic model was developed to generate simulated wind fields for the urban area under a variety of initial meteorological conditions.

(2) A statistical model was chosen from a class of statistical model forms, relating wind to geographic location and topography and giving a reasonable approximation to the simulated results for any of the initial conditions.

(3) A site-selection methodology (backward elimination) was developed, and an optimum set of sites for monitoring winds was selected using the methodology and the statistical model.

(4) An OSN was developed for St. Louis, and wind and air quality monitoring stations were established at the indicated sites.

(5) Wind fields were created by fitting statistical models (based on the class of forms determined in step 2) to the observed data, and the predicted data were compared to observed data.

(6) An objective variational analysis model was developed and tested for estimating the pollution distribution for an area by combining the emissions inventory, the observed pollutant concentrations, and the estimated wind fields.

With minor modifications resulting from practical and economic constraints, the first four steps above have been completed for the St. Louis area as described in the first report (Vol. I). Results of the comparison of the wind field obtained from the OSN to that obtained from all available data were described in the second report (Vol. II). Volume III discusses the development and application of the Objective Variational Analysis Model (OVAM) to St. Louis for the pollutant carbon monoxide (CO).

The Model

The OVAM obtains an analysis of air quality in an area by solving a Euler-Lagrange equation that minimizes the weighted error variance between the analysis and observations and between the analysis and the solution from the mass continuity equation (the analysis being assumed to be in a steady-state). In this manner, the source inventory serves as another set of observations, allowing the analysis to have a greater order of variability than is possible using the observations alone.

Methodology

The OVAM was adapted for field data and applied to the CO concentrations obtained from the OSN for St. Louis for selected days in the August 1975 and February 1976 periods of intensive study by the Regional Air Pollution Study (RAPS) program. Measurements of CO concentrations and winds at the 19-station OSN and CO emissions inventory were used to estimate the concentrations in a 20-km square area centered about the city. Seven additional nonnetwork stations were available for verification. Four cases, totaling 26 hours, were selected for study. Cases were chosen on the basis of wind speed and of the pollutant concentration magnitudes. Initialization of the OVAM was accomplished by utilizing the CO data from the 19-station OSN and an objective analysis model (the Barnes method). The OVAM, essentially, adjusted the initial field to conform simultaneously with the observations, the transport associated with the wind distribution, and the emissions inventory.

Methodologies to incorporate point sources were developed. Studies of the sensitivity of the analysis to various user-defined parameters were conducted. Afterwards, the model was applied to the case studies and an error analysis was applied. Finally, tests were made to determine whether all 19 stations in the OSN needed to monitor CO. The results of these studies are described below.

The principal parameters in the OVAM were the weights which placed emphasis on an observation (if the grid point was near an observation point) or the continuity equation (if the grid point was not near an observation point); the radius of influence which defined how rapidly the value of the weight related to the observation decreased away from a grid point associated with an observation; and the depth of volume over which the OVAM determines an analysis. The OVAM analysis was particularly sensitive to the ratio of the weights for the observations and the continuity equation, but was insensitive to the radius of influence of the observations. For the OVAM, the grid spacing (1 km) was a practical lower limit to the radius of influence since it was half the resolvable spatial scale in the model. However, other RAPS studies have shown observed CO concentrations to often be highly variable on a scale of about 1 km, suggesting that a smaller radius of influence should be utilized. The OVAM analyses became smoother and less sensitive to the emissions as the depth of the volume in the model increased. Increasing the volume depth, and therefore the volume, allowed for a greater dilution of the emissions. A practical upper limit to the volume depth might be the atmospheric mixing height. The choice of the volume depth was also important because point sources that failed to rise above the volume depth were treated as area sources.

Results and Discussion

Results of the application of the OVAM to the 12 August 1975 case, a daytime period with low wind speeds and small CO concentrations, showed strong dependence upon the distribution of sources and winds. Upwind of the stronger area sources, the concentrations tended to decrease; downwind, they increased. Large percentage changes between the initial CO distribution and the results from the OVAM analysis were found in the vicinity of principal sources. Since concentrations were on the order of 0.5 ppm, which is near the practical lower limit for CO measurements, the percent changes were relatively meaningless except to help identify the ongoing processes.

For the 27 February 1976 case, a nighttime period with large wind speeds and CO concentrations, the CO emissions decreased by an order of magnitude, whereas the concentrations remained large. The OVAM produced analyses hat varied little from the initial distributions. The principal adjustments to the initial distribution were due to the boundary conditions and the winds because the magnitude of the sources was small.

In order to determine whether all 19 stations in the OSN were required to monitor CO, two, four, and six observations were randomly deleted from the OSN to gain insight into the effect on the CO analysis. The error variance which the OVAM attempts to minimize decreased by 20 to 30 percent of its initial value regardless of the number of stations deleted. However, large percent changes of concentration occurred, depending upon the location of the deleted data. In most daytime cases, the largest changes occurred when observations upwind or downwind of the principal source areas were deleted, and when the deleted observations were not near other observations which were near principal sources. Concentration changes were primarily controlled by changes in the initial distribution that resulted from the deleted observations.

When stations were deleted in regions with small or no emissions (the outlying regions of the city) and far from stations influenced by large sources, the impact was significant in those regions but relatively insignificant in the large emissions' areas. The impact of the deleted stations in the outlying region was primarily due to the initial values being different from the observations, suggesting that if initial conditions can be treated properly in the outlying regions, some of the stations in this region would not be required as CO monitors. Thirteen of the 19 stations were in such regions; possibly as many as half of these need not monitor CO, though they all must monitor the winds. However, further investigation is required on the initialization methodology before conclusive statements can be made.

The OVAM generally predicted the trends well but often failed to accurately predict the absolute magnitudes of CO concentrations at nonnetwork stations. In addition to model errors, the discrepancies arose because:

(1) The CO concentrations are often very source-oriented and sources were smoothed to a 1-km square area by the inventory (the problem effects all CO data), whereas the observations are point observations not necessarily representative of an area, and

(2) The OVAM values used for comparisons were at grid points up to 0.7 km from an observation, and plumes downwind of principal sources developed with strong gradients which may have a slight influence at the grid point which actually affects the station, or vice-versa.

These are shortcomings faced by modelers and analysts every day.

The OVAM relied upon the initial conditions generated by another objective analysis procedure to determine the initial concentration field. The initialization technique extended the influence of an observation over too large an area. For example, the OVAM analysis for 1300 and 1400 CST 12 August, when one of the stations did not report, showed large concentrations in a narrow plume over and downwind of that station. At 1500 and 1600 CST, when that station reported a *very* large CO concentration, the plume extended over almost half the southern region of the grid because the initialization technique produced an initial field where the observation at that station dominated the southern area. The OVAM results were considerably different from the observations at many of the other OSN stations as well as nonnetwork stations. As part of a test, that station was deleted at 1500 and 1600 CST and a new set of initial conditions was developed. These OVAM results compared more favorably with both the OSN and nonnetwork observations at those hours and were consistent with the analyses at 1300 and 1400 CST. Though part of the problem in this case resulted from the data mixture, the difference in the area influenced by the large sources around the particular station of interest with and without the observation at the station was completely dependent on the initialization technique.

Conclusions

Except for some improvements needed for the OVAM, the essential ingredients for the OSN technique have been developed and tested, and the test results have been shown to be reasonable. The OSN technique provides an objective method to develop a sampling network for air pollution and meteorological parameters that will yield a representative distribution of those parameters within the domain of the network. Though the technique has been used to develop an entire network, probably the greatest utilization of the technique can be in improving an existing network in a given urban area. Most urban areas already have a sampling network and would not want to undertake the economic burden to establish a new network.

The site-selection algorithm of the OSN technique can be altered so as to maintain certain sites as part of the improved network (stations in the existing network). The algorithm would then establish the minimum number and disposition of stations to be added to the existing network in order to determine a reasonable analysis of the wind field. The OVAM is, of course, independent of the network design; but since the wind field is an input to the OVAM, an accurate description of the wind field is necessary. Given the emissions inventory, then the air pollution distribution can be determined using the OVAM.

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The complete report, entitled "Optimum Meteorological and Air Pollution Sampling Network Selection in Cities: Volume III. Objective Variational Analysis Model," (Order No. PB 81-172 256; Cost: $8.00, subject to change) will be available only from:
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☆ U.S GOVERNMENT PRINTING OFFICE: 1981-757-012/7082

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