United States
Environmental Protection
Agency

Environmental Sciences Research
Laboratory
Research Triangle Park NC 27711

Research and Development

EPA-600/S7-81-102 Aug. 1981

EPA

Project Summary

ENAMAP-1 Long-Term SO_2 and Sulfate Pollution Model: Further Application of Eastern North America

C. M. Bhumralkar, R. L. Mancuso, D. E. Wolf, K. C. Nitz, W. B. Johnson, and T. L. Clark

Under contract to the U.S. Environmental Protection Agency (EPA), SRI International (SRI) developed and evaluated an Eastern North American Model of Air Pollution (ENAMAP) (Bhumralkar et al., 1980). The ENAMAP-1* model, which is a modified version of the SRI-developed European Model of Air Pollution (EURMAP) † was specifically designed to study long-term transboundary air pollution processes over eastern North America. The model can be used to calculate monthly, seasonal, and annual values of sulfur concentrations and depositions and to quantify interregional exchanges of airborne sulfur between various selected Canadian and EPA regions. ENAMAP-1 has been shown to be highly suitable for application to assess the long-term transboundary sulfur pollution problem in eastern North America, because of its realistic treatment of precipitation scavenging and wet deposition, and its consideration of both SO_2 and $SO_4^=$ emissions over a very large region.

*SRI is currently developing an improved version of ENAMAP-1 which will be designated ENAMAP-2. This will include, among other things, effects of complex terrain and emissions released at higher elevations.

†EURMAP-1 was developed by SRI under the sponsorship of the Environmental Agency (Umweltbundesamt) of the Federal Republic of Germany (FRG). For a detailed description of this model, see Johnson et al. (1978).

This report describes the results of a study funded by EPA with the objectives of applying the ENAMAP-1 model to further test the model and to study the variability of the model's seasonal calculations of sulfur concentrations and depositions due to year-to-year changes in the wind and precipitation patterns. Section 2 of this report reviews the basic structure of the ENAMAP-1 model with respect to model grid boundaries and other variables. Section 3 presents a review of the data bases, including the air-quality, emission, and meteorological data used with ENAMAP-1. The original report discusses the monthly and annual results obtained from ENAMAP-1 using weather data for the four years 1975, 1976, 1977, and 1978 and sulfur emissions data for 1977. Although the original report discusses seasonal and annual variations in SO_2 and $SO_4^=$ concentration and deposition patterns, as well as seasonal variations in concentration and deposition contributions from large emission regions to the same receptor regions, only the annual and seasonal variations in the $SO_4^=$ concentrations patterns are discussed in this report.

This Project Summary was developed by EPA's Environmental Sciences Research Laboratory, Research Triangle Park, NC, to announce key find-

ings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction and Review of the ENAMAP-1 Model

ENAMAP-1 is a practical air pollution model designed to have minimum computational requirements for use in making long-term calculations economically, while at the same time offering acceptable realism in simulating the most important processes involved in the transboundary air pollution problem. The ENAMAP-1 model can be used to calculate monthly, seasonal, and annual SO_2 and $SO_4^=$ air concentrations; SO_2 and $SO_4^=$ dry and wet deposition patterns; and interregional exchanges resulting from the SO_2 and $SO_4^=$ emissions over eastern North America. The model uses long sequences of historical meteorological data as input, retaining all the original temporal and spatial detail inherent in the data (Bhumralkar et al. (1980)).

In the ENAMAP-1 model, discrete puffs of SO_2 and $SO_4^=$ are assumed to be emitted at equal time increments from cells of an emission grid. This type of treatment provides a realistic representation of area sources. For a point source, it assumes that the pollutant expands initially to fill uniformly the volume of the cell from the point within the cell where the source is actually located. [In this application, seasonal emission data were conveniently available on an 80- by 80-km Universal Transverse Mercator (UTM) grid.] For each of the emission cells, the average annual or seasonal emissions are divided into discrete emission puffs released at 12-hour intervals and tracked at 3-hour time steps, until either they move outside the region of analysis or their mass drops to an insignificant level (10 tons of SO_2 *and* 1 ton of $SO_4^=$). The individual puffs are transported according to a transport wind field that is derived objectively from the available upper-air wind observations.

Since diffusion on the regional scale is not as significant as the transport and removal processes, very simple treatments of vertical and horizontal diffusion have been used. Upon release, each puff is assumed to undergo instantaneous vertical diffusion to give a uniform concentration in the layer between the surface and the top of the mixing height. Horizontal diffusion is treated by allowing the area of the puff to increase linearly with time on the basis of Fickian diffusion, assuming a horizontal eddy diffusivity of 36 km^2h^{-1}. During the transport of the puff, the model assumes that the pollutant concentration within a puff is always uniform.

The amount of pollutant mass that is removed from a puff during each 3-hour time step is dependent on the specified dry and wet deposition rates that are used; these amounts are deposited within the appropriate 70- and 70-km cells of the receptor grid. At each time step, a fraction of the SO_2 is transformed to $SO_4^=$ at the specified transformation rate. Figure 1 shows the eastern sector of the North American continent over which the ENAMAP-1 model has been applied. This sector covers the region between 30°N and 50°N latitudes and 65°W and 105°W longitudes. Figure 1(a) shows the EPA regions and subregions used in this study; southern portions of Quebec and Ontario provinces of Canada are also included. Figure 1(b) shows the model receptor grid; each receptor-cell is 70 by 70km. The pollutant depositions are accumulated and concentrations are averaged in these receptor cells. The values for the basic model elements that have been used are listed in Table 1. These values are based on reviews of recent field, laboratory, and theoretical studies and on evaluation studies (Mancuso et al. [1978]).

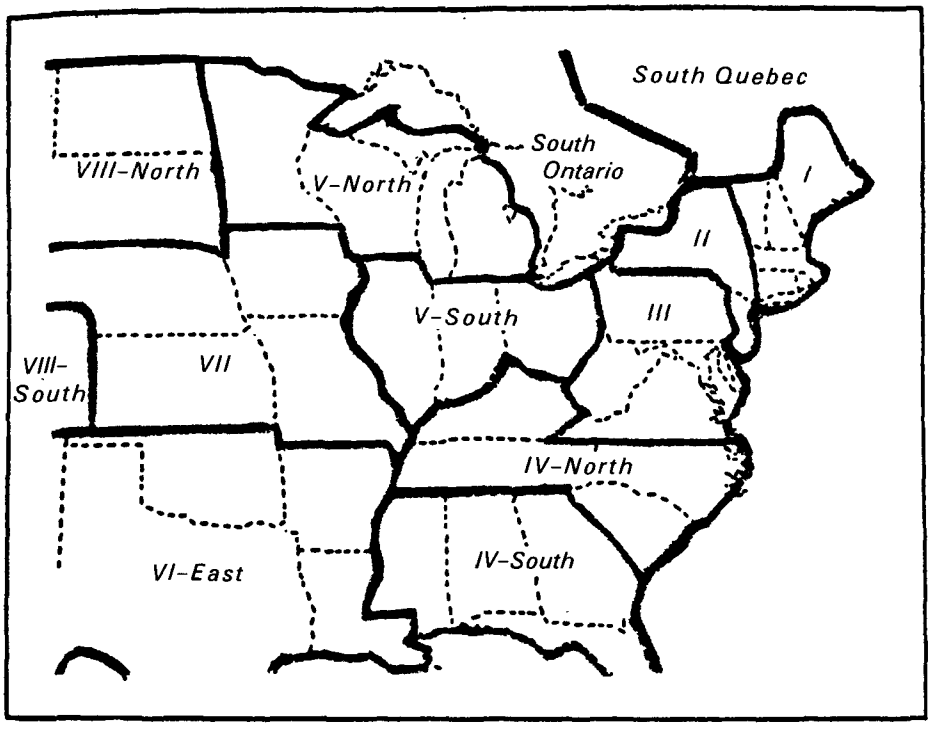
In this study, the basic model was run for the months of January, April, July and October of the years 1975, 1976, and 1978 and January, April, August, and October of 1977 using the meteorological data for each of the appropriate months. The emission data of 1977 were assumed to apply for all four years, mainly because no data base of similar quality and resolution was available for the other years. The particular months were selected in order to examine the seasonal variations in the results. [In 1977, August rather than July was chosen as representative of the summer because of the availability of a greater amount of Sulfate Regional Experiment (SURE) air quality data.] For each of the four months of each of the years, fields of SO_2 and $SO_4^=$ concentrations, dry depositions, and wet depositions resulting from the SO_2 emissions were calculated, stored, and displayed graphically. Interregional exchange tables were also generated.

Annual depositions for each of the years were estimated by assuming that the results for each of the four months were representative of seasonal values, totalling the four monthly deposition values, and multiplying by three. Similarly, estimates of annual average concentrations were obtained by averaging values for the four months of that year.

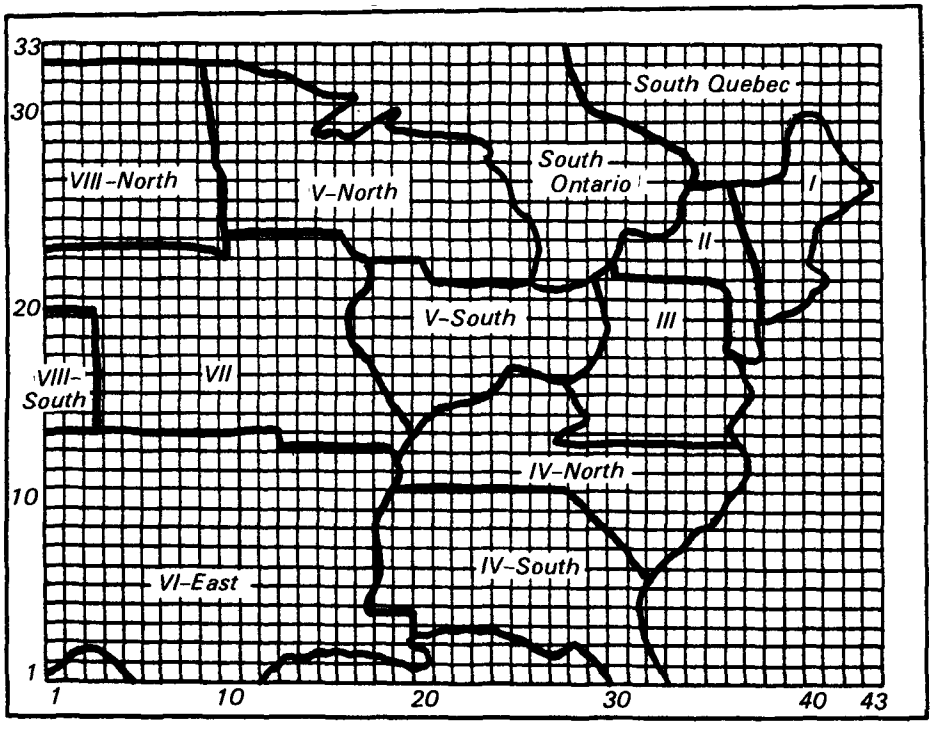
Table 1. *Element Values Used in the ENAMAP-1 Application to Eastern North America*

Element	*Values*
Emission rate	*Data provided by SURE and NEDS*
Transport windspeed (V) (ms^{-1}) and direction	*Derived by integrating winds over boundary layer using upper-air wind data*
Mixing height (km)	
$h = h_o - \zeta\Lambda$*	$h_o = 1.3$ $\zeta = 0.15$
SO_2 deposition rates (hr^{-1})	
Dry	*0.037*
Wet	*0.28R†*
$SO_4^=$ deposition rates (hr^{-1})	
Dry	*0.007*
Wet	*0.07R†*
$SO_2/SO_4^=$ transformation rate (hr^{-1})	*0.01*

Λ = +1 in winter, -1 in summer, and 0 in spring and fall.
†R is the precipitation rate in mm hr^{-1}.



(a) EPA Regions Used in This Study



(b) Emission Grid and Model Domain

Figure 1. *Eastern North American modeling domain and emission/receptor regions used in this study.*

Review of the Data Bases

The ENAMAP-1 model uses three types of data—meteorological (winds and precipitation), emission (SO_2 and $SO_4^=$), and air quality (SO_2 and $SO_4^=$ concentration measurements). The main purpose of this study was to determine the effects of seasonal variations in meteorological patterns on the ENAMAP-1 calculations. Therefore, actual meteorological data for the years 1975 through 1978 have been used, with the emission data for the year 1977, permitting a direct determination of the effects of weather on the results. However, the calculated results are thus strictly correct only for the year 1977, and the comparisons with the air quality data are most valid for that year. A detailed description of the data bases is given by Bhumralkar et al. (1980); a brief review is given below.

Meteorological Data

Historical meteorological data for this study (upper-air wind data for the United States and precipitation data for the United States and Canada) were obtained from the National Climatic Center (NCC) in Asheville, North Carolina. The basic analyses were made with a computer program that generated both transport winds and precipitation amounts at 3-hourly intervals for the 70- by 70-km ENAMAP-1 receptor grid. The upper-air wind data set consisted of the 12-hourly observations from about 50 sites in the U.S. The precipitation data set included hourly data from about 2,000 U.S. stations and six-hourly data from nearly 200 U.S. and Canadian sites; the analyzed values were expressed as rainfall rates in mm/hr and were used directly in the wet deposition calculations.

Emission Data

Emission data have been collected for a number of years and maintained by the National Emissions Data Systems (NEDS) of the EPA. The NEDS data cover the entire U.S. portion of the ENAMAP-1 study area and provide relatively high spatial resolutions. Specialized emission data also have been compiled for the SURE program. These data are complete for sources existing in July 1977 and effectively represent emissions for the 1977 time period. This SURE emission data base is essentially a refinement of the NEDS data base; that is, the NEDS data were updated and screened for errors and inconsistencies, especially with respect to electric power plants.

The 1977 seasonal emission data base that was used in this study was based, wherever possible, on the specialized emission data of the SURE program. The SURE data, which are arranged on an 80- by 80-km UTM grid, cover almost the entire area considered in this study except for Texas and the Great Plains states. For this westernmost portion of the ENAMAP-1 domain, gridded emission data were supplied by NEDS.

Air Quality Data

Two sets of air quality data were used for ENAMAP-1 model validation: Electric Power Research Institute - Sulfate Regional Experiment (EPRI-SURE) and the EPA Storage and Retrieval of Aerometric Data (SAROAD). The former set contained hourly averaged SO_2 and daily averaged $SO_4^=$ concentrations for 9 sites in the northeastern quadrant of the United States for the August 1977 to October 1978 period. For August and October 1977 and January, April, July, and October 1978, the same type of data were available for an additional 45 sites in the same region. These 54 rural monitoring sites were free from local effects. The latter set of data contained daily averaged SO_2 concentrations from many more sites. Data from sites thought to be influenced by local sources were ignored. This data set contained daily averaged $SO_4^=$ concentrations from about 70 monitoring sites. However, the typical frequency of monitoring was three days per month, which meant that the monthly averaged $SO_4^=$ concentration at each site was rather poor.

These air quality data were used to determine monthly averages for 140 by 140-km grid squares (2 by 2 receptor grid cells of 70-km dimensions). These averages were compared to those computed by the model.

Annual and Seasonal Variations in $SO_4^=$ Concentration Patterns

The calculated and measured $SO_4^=$ concentrations ($\mu g/m^3$) patterns for January 1975 - 1978; July 1975 and 1976; August 1977; and July 1978 are depicted in Figures 2-9, respectively. August 1977 was chosen as a modeling period since intensive SURE air quality data were available for that month. Monthly-averaged wind fields accompany the concentration analyses. The concentrations depicted in the figures represent a spatial average of monthly averaged concentrations across 140 by 140 km grid squares.

January 1975 - The calculated $SO_4^=$ concentration pattern for January 1975 [Figure 2(a)] is a very interesting one. A strip of higher $SO_4^=$ concentrations (>8 $\mu g/m^3$) extends across the Northeast and upper Midwest, strongly reflecting the anticyclonic pattern of the wind field. This $SO_4^=$ field shows relatively low values in the central Illinois-Indiana-Ohio area, as did the SO_2 field; however, the low $SO_4^=$ concentrations also extend across Illinois into the western Kentucky-Tennessee area.

Comparison of the calculated and measured $SO_4^=$ concentrations for January 1975 [Figure 2(b)] is difficult because of the lack of an extensive monitoring network. However, where there are data, the comparison is generally very good. For example, the strip of high calculated values mentioned above, which extends across the southern tips of the Great Lakes and across Pennsylvania, appears to be depicted by the measured data. The measured data show relatively low values in the southeastern and northeastern United States, in agreement with the calculated results. A few measured values in the western part of the domain are relatively high and inconsistent with the calculated values; however, these measurements are probably associated with local sources.

January 1976 - The calculated $SO_4^=$ concentration pattern for this period [Figure 3(a)] shows a center of high values (>8 $\mu g/m^3$) over the northeastern United States, while west of the Mississippi, the concentrations become quite low (<2 $\mu g/m^3$). The high values in the northeast of the United States indicate that there was a transport of the pollutant into this area, although this is not distinctly shown by the mean wind pattern of Figure 3(c). The calculated $SO_4^=$ concentrations for January 1976 [Figure 3(a)] and 1975 [Figure 2(a)] show definite differences. The $SO_4^=$ concentrations in New England were relatively low in January 1975, apparently because of stronger transport winds over this area. Also, the January 1976 pattern does not show as much variability in $SO_4^=$ concentrations as were produced in the Southeast during January 1975 in association with the anticyclonic circulation.

The $SO_4^=$ monitoring sites in January 1976 were again sparse. The available data [Figure 3(b)] appear to be generally consistent with the calculated concentrations. A large value (15 $\mu g/m^3$) in southern Michigan and a large value (11 $\mu g/m^3$) in North Carolina are inconsistent with the calculated results.

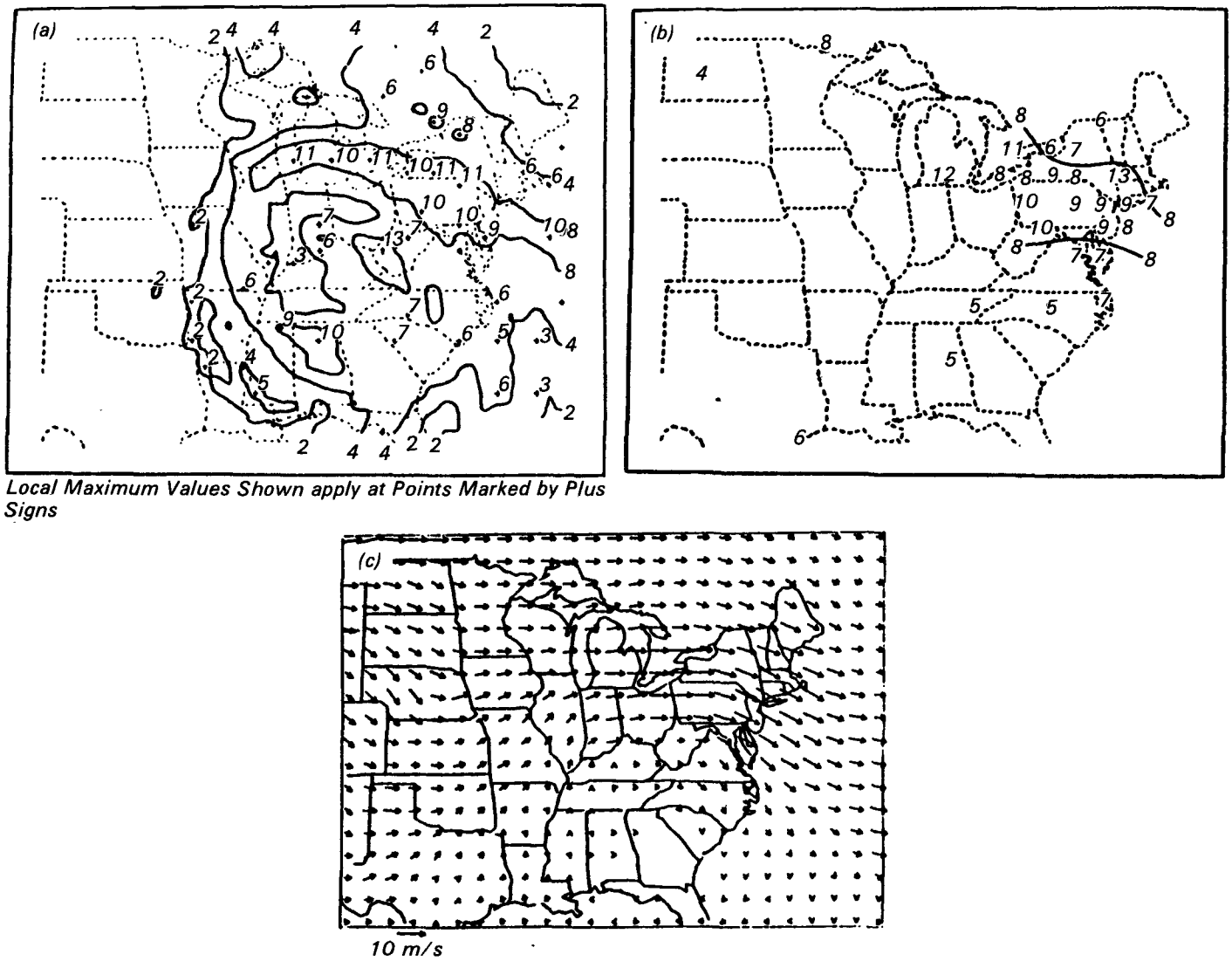
January 1977 - The calculated SO_4 concentrations for January 1977 [Figure 4(a)] show that the higher $SO_4^=$ concentrations (>8 $\mu g/m^3$) are centered over the northeastern United States as in 1976; however the "8" isoline extends farther west, apparently because of differences in the transporting winds that are not evident from the monthly mean fields. The high $SO_4^=$ concentrations off the East Coast in 1975, 1976, and 1977 are a reflection of a prevailing wind blowing from northwest to southeast.

The number of available measured $SO_4^=$ concentrations for January 1977 [Figure 4(b)] provide a more desirable coverage. The measured data show high values in the northeastern United States that are consistent with the calculated values (based on 1977 emission data). However, some high measured values (up to 10 $\mu g/m^3$) that have been recorded west of the Mississippi are probably unrepresentative data.

January 1978 - The calculated $SO_4^=$ concentration pattern for January 1978 [Figure 5(a)] is very similar to that for January 1977 [Figure 4(a)]. However, the 8 $\mu g/m^3$ isoline does not extend off the coast into the Atlantic apparently because the wind did not blow sulfur pollution off the coast as frequently during this January period as it did in 1977. The available measured data for this period [Figure 4(b)], which are again quite spotty, appear to be reasonably consistent with the calculations, with the exception of some high values, such as in Colorado.

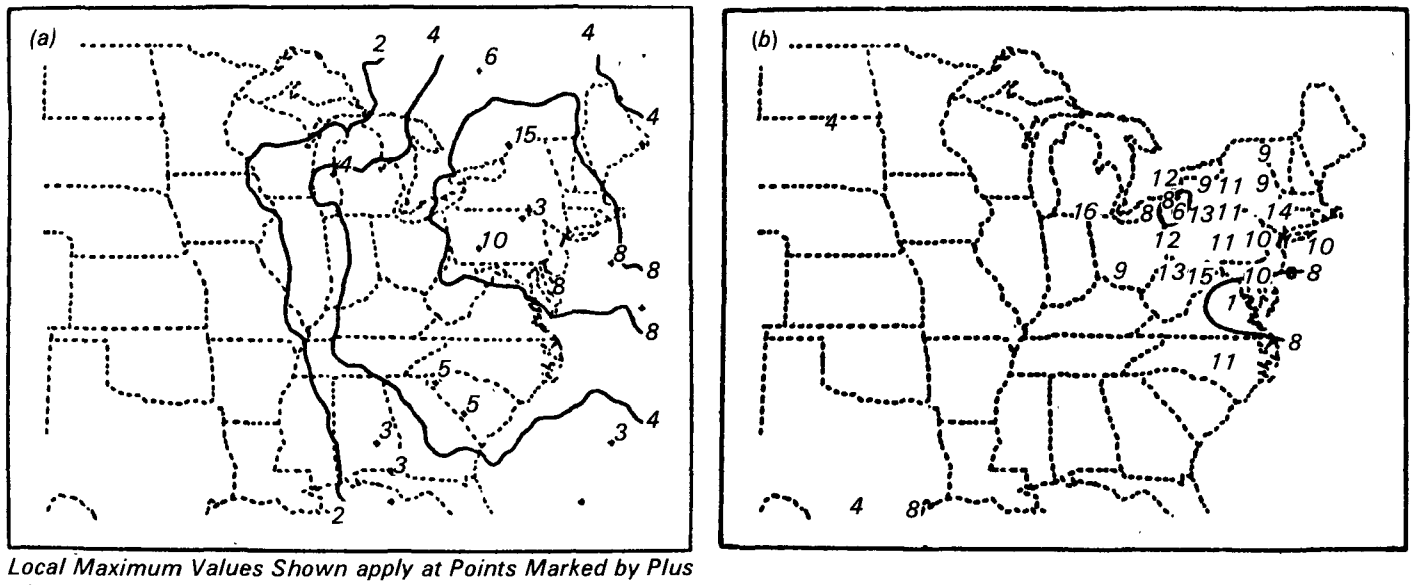
July 1975 - The calculated $SO_4^=$ concentration pattern [Figure 6(a)] for July 1975 is a symmetrical one produced by the light winds (or variable wind direction) during the month. Comparison of the calculated and measured $SO_4^=$ concentrations for July 1975 [Figure 6(b)] is difficult because of the scarcity of measured data. However, the high measured values over the New England area are not in good agreement with the calculated values.

July 1976 - The calculated $SO_4^=$ concentration pattern [Figure 7(a)] shows that the center of high values (>8 $\mu g/m^3$) is displaced to the southeast, lying principally over the Virginia area with a strip of relatively high values extending southwestward into Georgia.



Local Maximum Values Shown apply at Points Marked by Plus Signs

Figure 2. *$SO_4^=$ concentrations ($\mu g/m^3$) for January 1975. (a) calculated, (b) measured, (c) mean monthly transport winds.*



Local Maximum Values Shown apply at Points Marked by Plus Signs

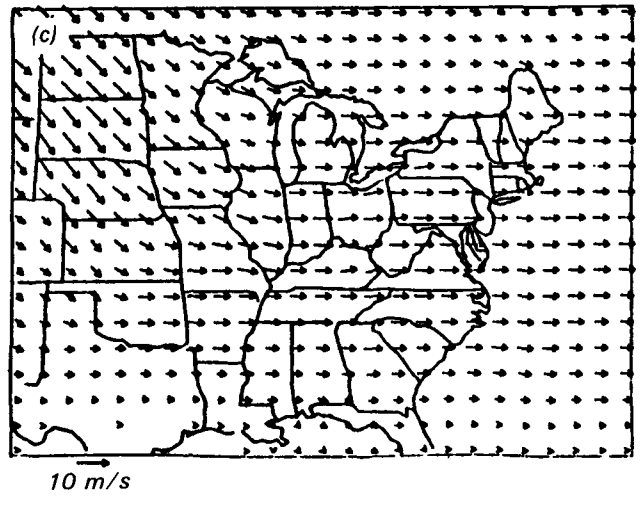
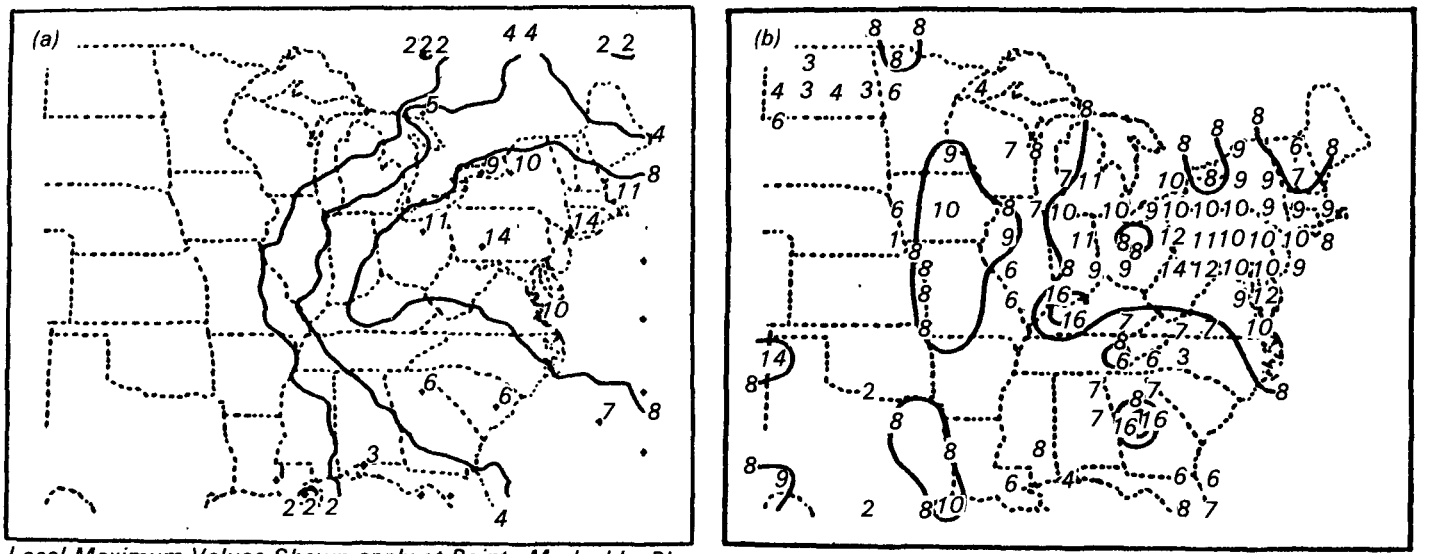


Figure 3. *$SO_4^=$ concentrations ($\mu g/m^3$) for January 1976. (a) calculated, (b) measured, (c) mean monthly transport winds.*



Local Maximum Values Shown apply at Points Marked by Plus Signs

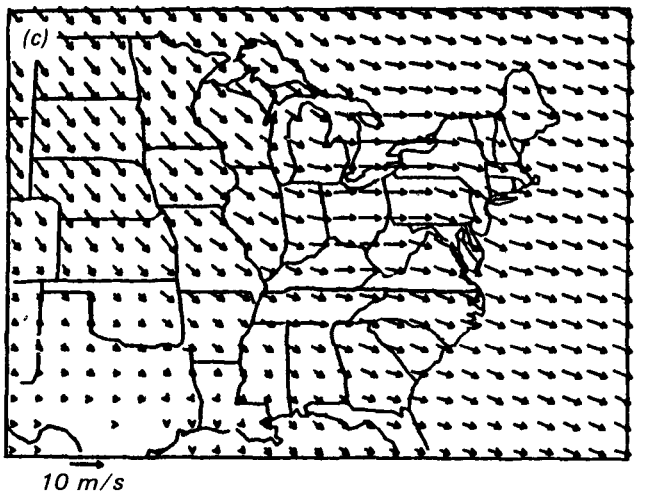
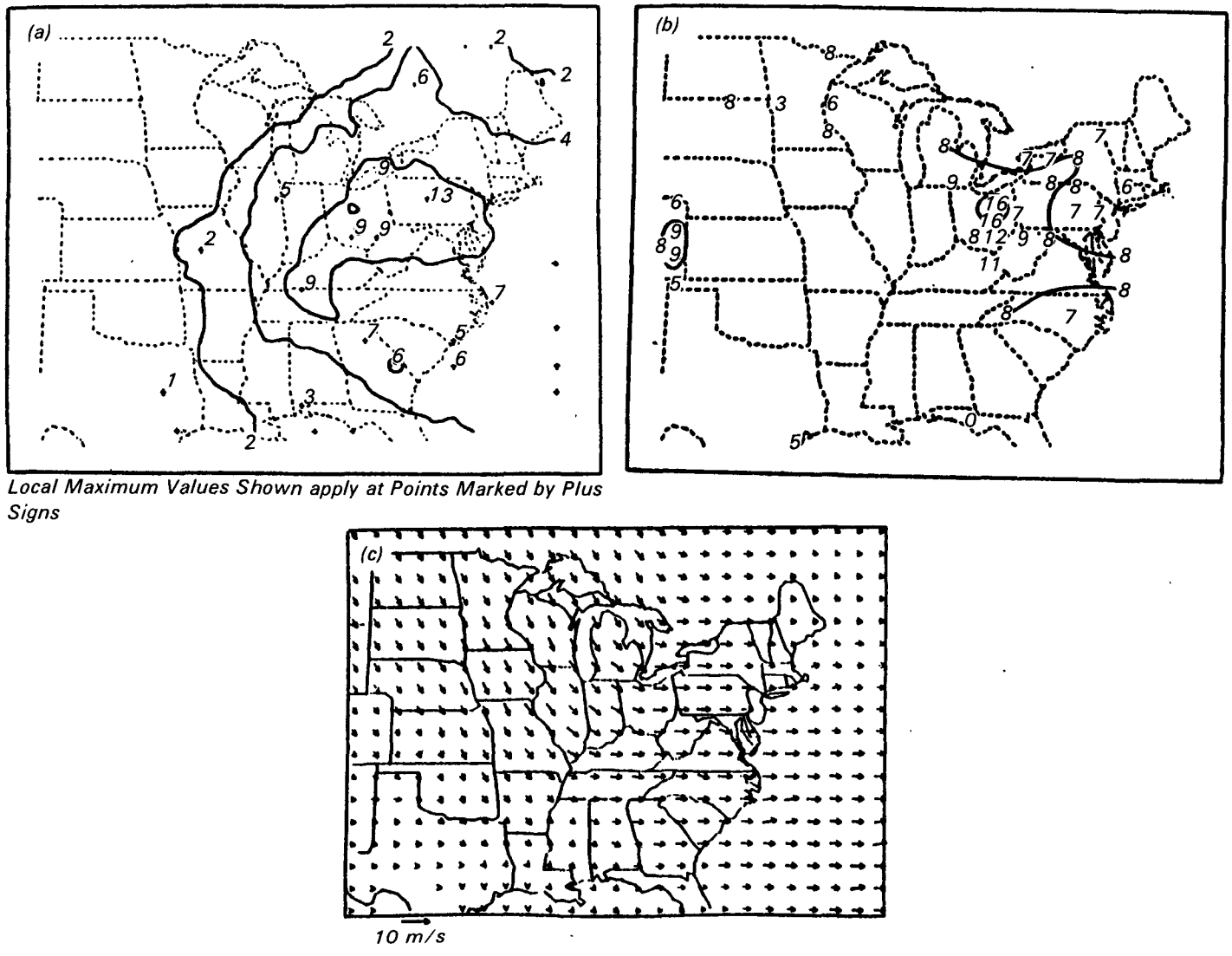
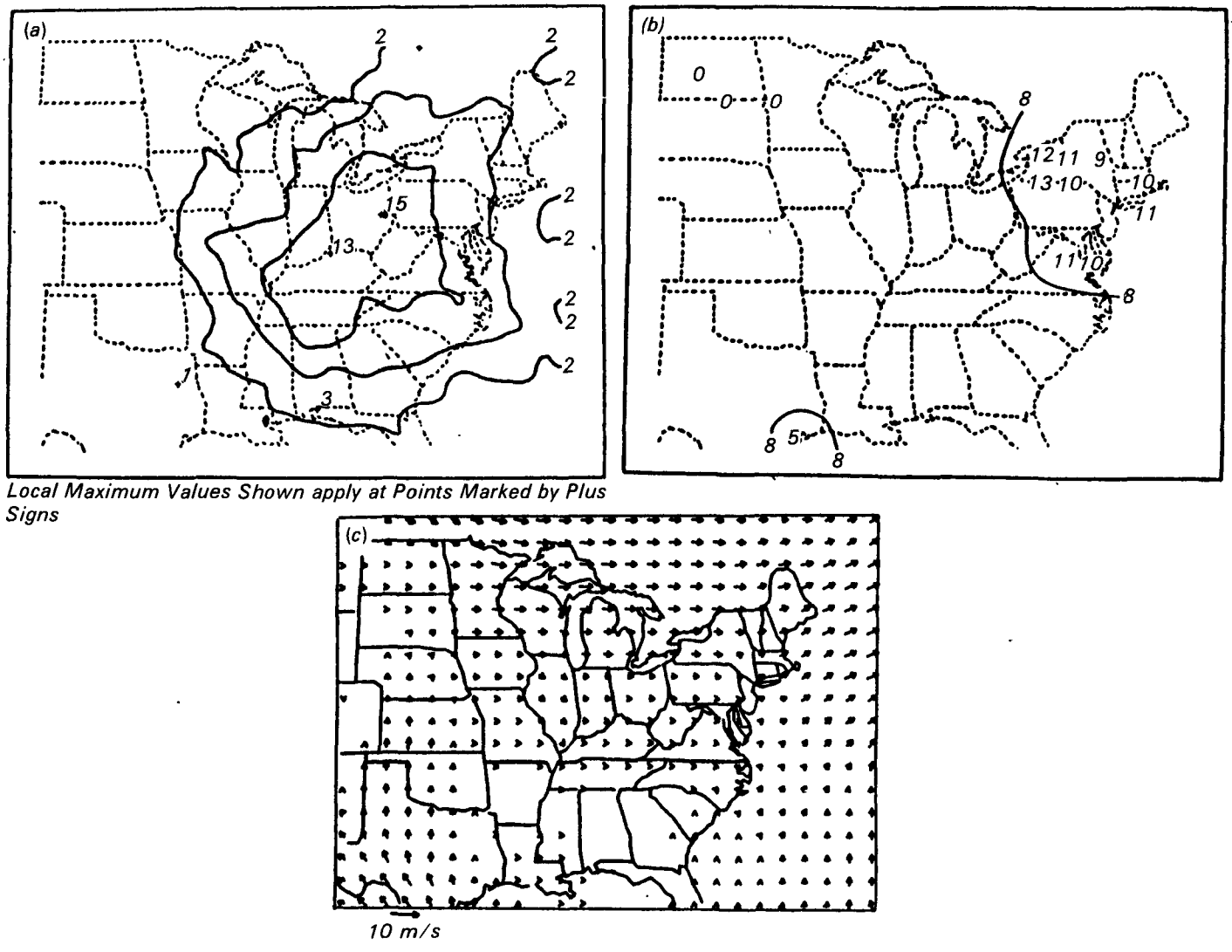


Figure 4. *$SO_4^=$ concentrations ($\mu g/m^3$) for January 1977. (a) calculated, (b) measured, (c) mean monthly transport winds.*



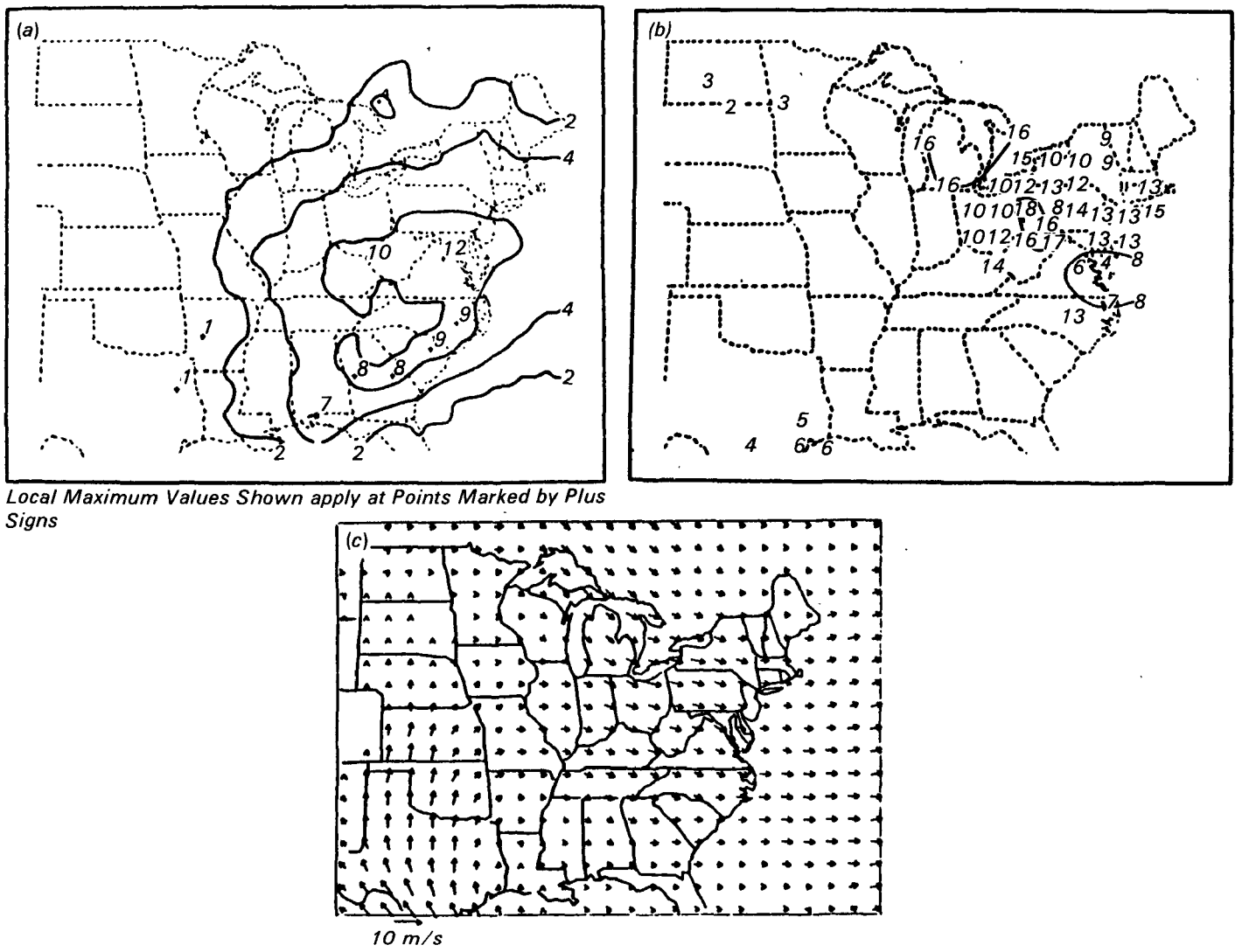
Local Maximum Values Shown apply at Points Marked by Plus Signs

Figure 5. *$SO_4^=$ concentrations ($\mu g/m^3$) for January 1978. (a) calculated, (b) measured, (c) mean monthly transport winds.*



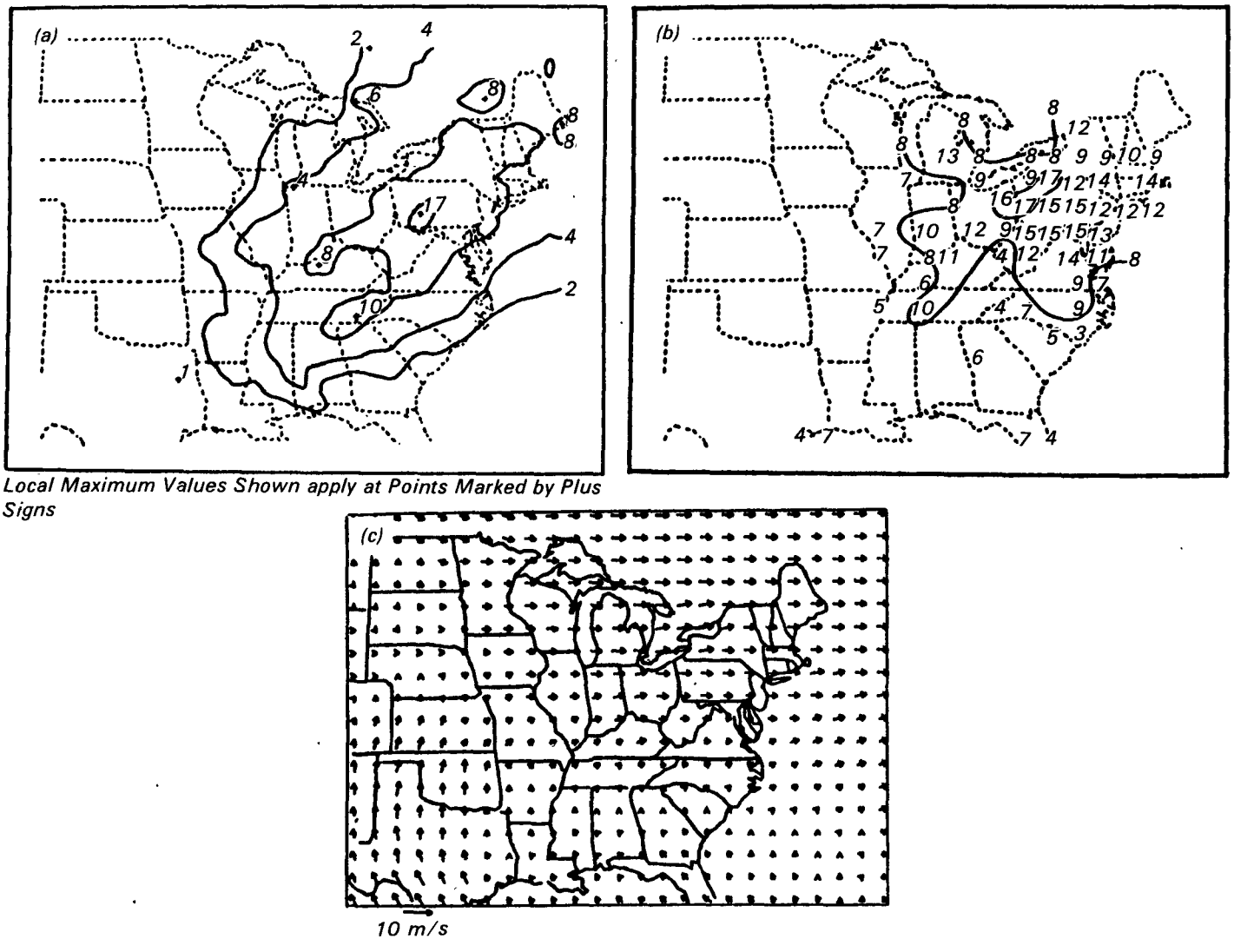
Local Maximum Values Shown apply at Points Marked by Plus Signs

Figure 6. *$SO_4^=$ concentrations ($\mu g/m^3$) for July 1975. (a) calculated, (b) measured, (c) mean monthly transport winds.*



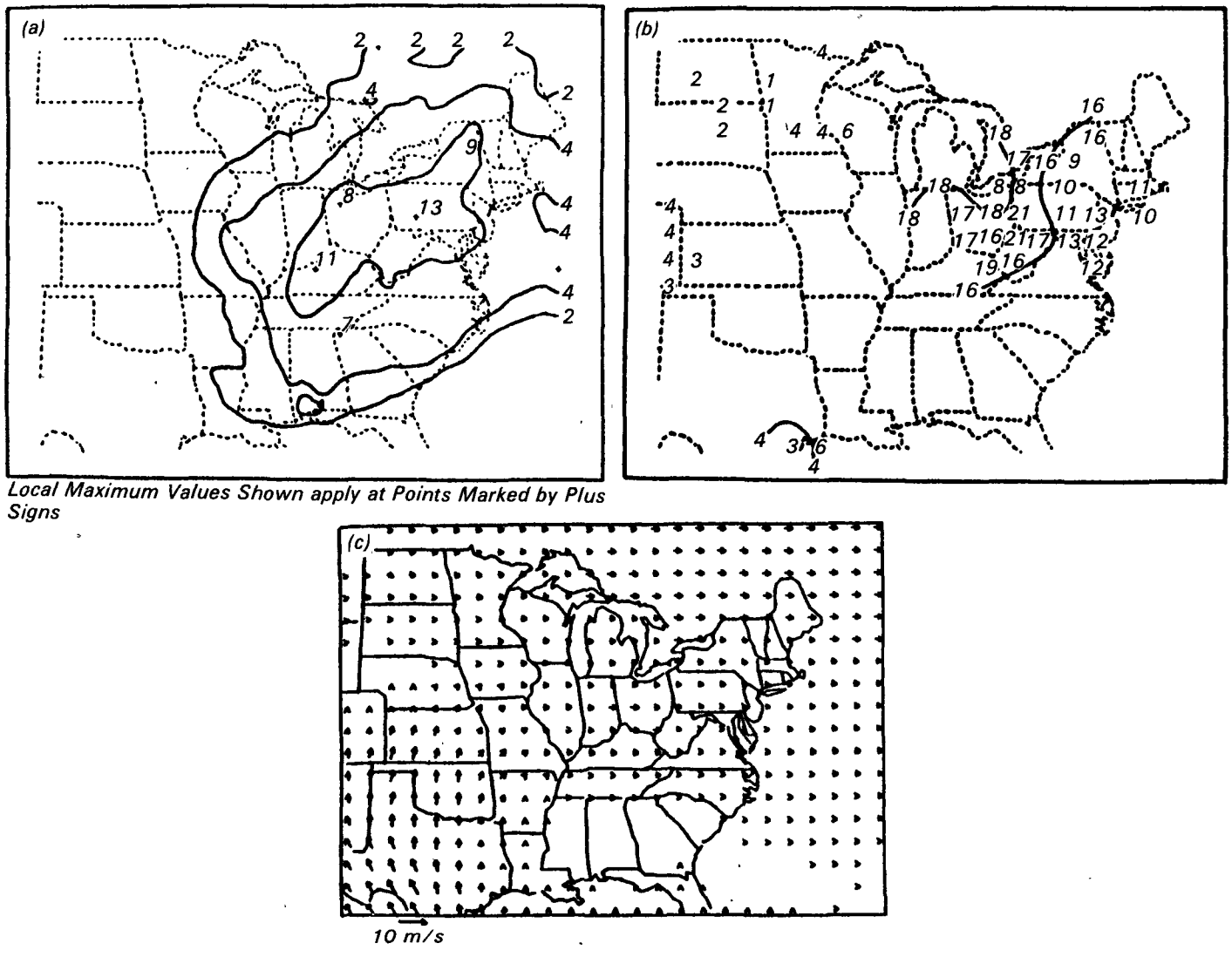
Local Maximum Values Shown apply at Points Marked by Plus Signs

Figure 7. *$SO_4^=$ concentrations ($\mu g/m^3$) for July 1976. (a) calculated, (b) measured, (c) mean monthly transport winds.*



Local Maximum Values Shown apply at Points Marked by Plus Signs

Figure 8. *$SO_4^=$ concentrations ($\mu g/m^3$) for August 1977. (a) calculated, (b) measured, (c) mean monthly transport winds.*



Local Maximum Values Shown apply at Points Marked by Plus Signs

Figure 9. *$SO_4^=$ concentrations ($\mu g/m^3$) for July 1978. (a) calculated, (b) measured, (c) mean monthly transport winds.*

This can be attributed to the stronger winds [Figure 7(c)], which would have moved the emissions in this direction. The measured $SO_4^=$ concentrations for January 1976 [Figure 7(b)] are also incomplete, but do not appear to show the same southeast displacement as the calculated values. In the measured data, the major $SO_4^=$ pollution appears to be located over the highly SO_2-emitting Pittsburgh area. Also, as was noted for July 1975, the relatively high measurement of $SO_4^=$ values suggests either that the calculated values are slightly low or that the $SO_4^=$ measurements are somewhat biased by local $SO_4^=$ sources.

August 1977 - The calculated $SO_4^=$ concentrations for August 1977 [Figure 8(a)] show a distinct southwest-to-northeast elongation of the concentration isolines. ENAMAP-1 appears to have performed quite well in calculating these $SO_4^=$ concentrations for this summer period, since they compare very favorably with the measured values [Figure 8(b)]. The higher $SO_4^=$ concentrations (>8 $\mu g/m^3$) occur over the northeastern United States in both the calculated and measured fields, with peak values (17 $\mu g/m^3$) occurring near the Pittsburgh area. A region of low concentrations is indicated in both the calculated and measured fields over eastern Kentucky, although the measured concentrations are somewhat lower than the calculated.

July 1978 - The calculated $SO_4^=$ concentration pattern for July 1978 [Figure 9(a)] is similar to that for 1977 [Figure 8(a)]. The available measured data for this period [Figure 9(b)] show a pattern that is reasonably consistent with the calculated one. However, the measured $SO_4^=$ values appear to be significantly higher than the calculated, possibly because of an increase in the sulfur emission in 1978 that was not accounted for in the model calculations.

Conclusions

In this study, the SRI-developed ENAMAP-1 model was applied to determine the significance of seasonal and yearly variations in meteorological patterns on the ENAMAP-1 model calculations. To achieve this, the sulfur emission data for 1977 were used with meteorological data for four different years: 1975, 1976, 1977, and 1978. Model calculations were made for the monthly and annual SO_2 and $SO_4^=$ concentrations, depositions, and regional exchanges. The calculated results were generally consistent with the air quality measurements, although discrepancies may have been caused by the use of 1977 emissions for all four years and by use of certain measurements that were unrepresentative of average values within receptor cells. The yearly variations in the meteorological data were found:

- To produce changes in the SO_2 $SO_4^=$ concentrations and depositions that were consistent with the changes in transport winds and precipitation amounts.
- To be most noticeable in the monthly $SO_4^=$ concentrations and $SO_4^=$ wet depositions; the latter being sensitive to yearly variations in both the boundary layer wind and precipitation amounts.
- To have little effect on the monthly SO_2 concentrations, which principally depict the high emission areas.
- To have little effect on the annual fields, since the results for a given year were derived by averaging the results for January, April, July, and October of that year.

As noted in this study and its predecessor (Bhumralkar et al., [1980]), there are some differences between the calculated and measured results, particularly in regard to seasonal and latitudinal variation. These differences appear to be partially caused by the imperfect simulation of mixing height and the vertical growth of puffs. Also, the neglect of terrain influences is noticeable in the Appalachian region. An improved version of the model (called ENAMAP-2) is being developed with a view to mitigate these limitations.

References

Bhumralkar, C.M., R.L. Mancuso, D.E. Wolf, R.A. Thuillier, K.C. Nitz, and W.B. Johnson, 1980: "Adaptation and Application of a Long-Term Air Pollution Model ENAMAP-1 to Eastern North America," *Final Report*, Contract 68-02-2959, SRI International, Menlo Park, California.

Johnson, W.B., D.E. Wolf, and R.L. Mancuso, 1978: "Long Term Regional Patterns and Transfrontier Exchanges of Airborne Sulfur Pollution in Europe," *Atmos Environ.*, Vol. 12, pp. 511-527.

Mancuso, R.L., C.M. Bhumralkar, D.E. Wolf, and W.B. Johnson, 1978: "Evaluation and Sensitivity Analyses of the European Regional Model of Air Pollution (EURMAP-19," Progress Report, Contract LUP-411 515/IIIA315, /SRI International, Menlo Park, California.

Perhac, R.M., 1978: "Sulfate Regional Experiment in the Northeastern United States: The SURE Program," *Atmos. Environ.*, Vol. 12, pp. 641-647.

C. M. Bhumralkar, R. L. Mancuso, D. E. Wolf, K. C. Nitz, and W. B. Johnson are with SRI International, Menlo Park, CA 94025; ***T. L. Clark*** *is the EPA author and also the EPA Project Officer (see below).*

The complete report, entitled "ENAMAP-1 Long-Term SO_2 and Sulfate Pollution Model: Further Application of Eastern North America," (Order No. PB 81-213 217; Cost: $12.50, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

The EPA Project Officer can be contacted at:

Environmental Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

☆ U S GOVERNMENT PRINTING OFFICE, 1981 — 757-012/7342

cy Cincinnati OH 45268

Environmental
Protection
Agency
EPA-335