Final Report

TRENDS IN SULFUR DIOXIDE EMISSIONS FROM THE ELECTRIC UTILITY INDUSTRY AND AMBIENT SULFUR DIOXIDE CONCENTRATIONS IN THE NORTH-EASTERN UNITED STATES, 1975 TO 1982

SYSAPP 85/011

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Prepared for

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PREFACE

This report describes work performed under the first phase of what was originally perceived to be a multi-year study, and as such should be viewed as a report of work in progress. The intention of this phase was to assemble and evaluate data bases for statistical analyses of relationships among acid rain precursors, including ambient sulfur dioxide concentrations and sulfur dioxide emissions, and to investigate the evidence for trends in these precursors. We found that there were no extant sulfur dioxide data bases, either ambient or emissions, with enough time resolution for statistical analyses. We therefore developed the necessary data base with the approval of the EPA project officer. This major effort consumed most of the first-year project resources. Some statistical analyses were also performed, which were of a survey and exploratory nature, as we assumed that detailed statistical analyses would follow in the second year. Trends in sulfur dioxide emissions and air quality were found, and in some instances strong correlations between sulfur dioxide emissions and ambient concentrations were seen. This report should be viewed as an interim progress report in a longer-term study; the preliminary findings suggest several hypotheses for further study.

1 INTRODUCTION

Since the mid-1970s, there has been growing concern about the harmful effects of the deposition of acidic substances. The primary acid-forming substances of concern are sulfur and nitrogen oxides, which are associated with both natural and anthropogenic sources. Acidic deposition is postulated to adversely affect aquatic ecosystems, forests and crops, and even building materials. Hundreds of lakes in the Adirondacks in upstate New York have been declared "dead," devoid of many of their former species of fish; these effects are postulated to be the result of high-level, long-term emissions of sulfur dioxide (SO_2) from the heavily industrialized upper Midwest states. Other plausible postulates involve the "acidifying effects" of ground cover and soils in the region, changes in fish-stocking practices, or some combination of causes. Uncertainties abound, obscuring judgments about the effectiveness of mitigating actions, or even the need for action.

Some advocate control or regulation of harmful emissions, and call for reductions in emissions of sulfur dioxide principally from the electric power industry, the dominant source of SO_2 emissions. A key issue in the debate over forced SO_2 emissions reductions is the extent to which acidic deposition and precursors of acidic deposition, e.g., ambient SO_2, will be reduced as a result of reductions in emissions. For example, will a 50 percent decrease in SO_2 emissions result in a 50 percent decrease in ambient SO_2 and sulfate concentrations and a 50 percent decrease in acidic deposition, or only a 25 percent decrease? Considerable effort is being expended in sophisticated mathematical model development and in the design of field measurement programs to attempt to answer this and related questions.

In this report we consider still another alternative to modeling and design-specific field programs. As a result of the economic recession in the late 1970s, actual sulfur dioxide emissions were reduced. Data from the late 1970s and early 1980s, then, can be used to examine the results of actual decreases in SO_2 emissions. The purpose of this study is to examine recent trends in sulfur dioxide emissions and acid deposition precursors, specifically ambient SO_2, and to assess the degree of correlation between the two. This work is seen as the first step in a two-step process, in which the second step would be to examine the association between reductions in SO_2 emissions and/or ambient SO_2 and sulfate concentrations and sulfate deposition.

In this report we address the first step, reporting on our examination of trends in (1) sulfur dioxide emissions from electric power plants, and (2) ambient SO_2 concentrations from 1975 to 1982. The region of study is the heavily industrialized northeastern United States, extending to Wisconsin and Illinois on the west and to Tennessee and North Carolina in the south. Twenty-one states plus the District of Columbia (hereafter referred to as 22 states for simplicity) are included in the study. In Section 2 we discuss the development of the ambient sulfur dioxide data base, and in Section 3 we discuss the development of the power plant sulfur dioxide emissions data base. Correlations between these SO_2 emissions and ambient concentrations at local, state, and regional levels are examined in Section 4. Finally, Section 5 presents our conclusions and recommendations for further study.

2 AMBIENT SULFUR DIOXIDE TRENDS

AMBIENT SULFUR DIOXIDE DATA BASE

The National Aerometric Data Branch of EPA maintains the National Aerometric Data Base (NADB) of ambient air quality monitoring data, known as SAROAD (Storage and Retrieval of Air Quality Data). Data are submitted to the NADB by federal, state, and local government agencies responsible for criteria pollutant monitors.

Ambient SO_2 is measured either by a continuous ("instantaneous") monitoring instrument or by a 24-hour bubbler (integrated) device. Continuous monitors record a value every hour for a possible total of 8760 hourly measurements in a year; bubblers record one measurement per 24-hour period (midnight to midnight), and sampling is performed once every six days. Prior to 1978 many SO_2 monitors were 24-hour bubblers. In 1978 the EPA required that all SO_2 bubblers be modified with a temperature control device to rectify a sampling problem: when temperatures reached a certain degree, not all of the SO_2 was collected; therefore, SO_2 levels tended to be underestimated (Neligan, 1978). Subsequently, many SO_2 bubblers were retired and replaced with continuous monitors. Because the bubbler instrument modification would complicate the interpretation of trends, the bubbler data are not used in this study.

We received from NADB the hourly data for all SO_2 monitoring stations for the 22 states, 1975 to 1982, for this study. Each monitoring site is identified by a unique 12-character SAROAD code that indicates the state, the area within the state (city or county), the site within the area, the managing agency, and the project classification (e.g., point source surveillance vs. background monitoring); these codes are defined in EPA's

AEROS Manual of Codes (EPA, 1983). In many instances, the controlling agency or the project classification for a site changed although the site remained in the same physical location; therefore, for many monitoring stations, there are multiple SAROAD codes. We define "site" as a given physical location; thus one site may have two or more SAROAD codes. The 22-state NADB tapes contained raw data for 1783 SAROAD codes from 1117 actual monitoring sites.

From the hourly SO_2 monitoring data we calculated the following monthly summary statistics for each site:

Number of hourly measurements

Arithmetic mean concentration

Number of valid days (in which there are at least 75 percent of the hours between 9:00 a.m. and 9:00 p.m.)

Average daily maximum hourly concentration (calculated only from valid days)

Information on the number of SO_2 monitors and the amount of data available at the monitors is given by state in Table 1. The number of monitors in each states ranges from 6 (District of Columbia) and 7 (North Carolina and Vermont) to 121 (Indiana); the median number of monitors per state is 40. Generally, those states with relatively high SO_2 emissions have a greater number of ambient SO_2 monitors. The last five columns in Table 1 show that much data is missing at most of the monitors. Only a small percentage of the montiors have substantial long-term data; the percentage of monitors with greater than 50 percent of each year's hours for seven or eight years ranges from 0 percent (District of Columbia, Maine, Maryland, New Hampshire, North Carolina) to a high of only 37 percent in Tennessee. The middle columns in Table 1 show that the number of monitors is relatively constant for each state, from year to year, though some states such as Maine and Indiana add monitors to their networks each year.

TABLE 1. Number of monitors and amount of monitoring data available in the BAROAD ambient sulfur dioxide data base

	Total number of monitors	Number of monitors with any data in each year								No. of monitors with at least 50% data for the given number of years				
		1975	1976	1977	1978	1979	1980	1981	1982	0	1-2	3-4	5-6	7-8
Connecticut	24	21	16	15	15	12	11	9	9	5	7	2	3	7
Delaware	15	13	12	12	8	10	9	8	8	2	4	3	0	6
District of Columbia	6	4	5	5	3	3	3	3	2	1	1	3	1	0
Illinois	82	41	47	53	48	46	37	40	38	10	27	18	13	14
Indiana	121	19	35	42	45	65	71	79	102	21	36	38	15	11
Kentucky	73	40	40	48	43	54	45	42	29	7	20	16	9	21
Maine	60	6	3	5	9	16	28	35	40	21	27	9	3	0
Maryland	31	19	23	23	19	13	10	10	10	9	9	7	6	0
Massachusetts	84	24	16	17	19	49	21	19	40	33	33	7	7	4
Michigan	41	30	31	29	31	30	29	20	16	2	10	4	15	10
New Hampshire	21	5	7	9	9	8	7	9	12	4	9	6	2	0
New Jersey	38	23	24	23	24	26	31	32	27	3	12	3	4	16
New York	100	70	52	50	45	47	52	44	44	31	16	16	22	15
North Carolina	7	1	1	1	2	3	5	5	5	0	4	2	1	0
Ohio	86	34	42	41	44	47	46	52	52	12	30	21	14	9
Pennsylvania	78	49	42	35	42	42	51	39	48	15	25	17	12	9
Rhode Island	8	3	2	2	4	4	3	4	4	4	1	1	1	1
Tennessee	98	40	77	84	57	55	54	53	62	20	21	6	15	36
Vermont	7	4	4	4	3	4	5	4	4	2	1	1	2	1
Virginia	25	13	13	14	17	14	15	15	15	2	6	5	6	6
West Virginia	10	4	4	4	4	4	6	2	6	1	6	1	1	1
Wisconsin	102	23	16	33	50	54	31	41	47	36	44	14	4	4

All monitoring site locations are provided in the SAROAD site file, which we received from NADB. From this file we extracted latitude and longitude for all SO_2 monitoring stations in the 22 northeastern states. Figure 1 presents the 22-state SO_2 monitor locations. From the map one can see that SO_2 monitors are located predominantly in heavily populated urban areas; for example, there are heavy concentrations of monitors in and around New York City and Chicago.

Figures A1 through A22 show the location of, and amount of data from, SO_2 monitors in all 22 states, ordered alphabetically. The maps show latitude and longitude and county borders. Each SO_2 monitoring site is indicated with a circle on the map; the diameter of the circle corresponds to the amount of data available over the eight-year period under study, specifically on the number of months of at least 50 percent of the possible hours. For those sites marked with an "X" inside the circle, 50 percent of the available data for at least six out of the eight years are available. Four percent of the SO_2 monitoring sites are not shown on the maps because their latitudes and longitudes are not in the SAROAD site file. The maps show that SO_2 monitoring sites are primarily located in clusters in urban areas. In Tennessee (Figure A18) and Kentucky (Figure A6), however, the Tennessee Valley Authority (TVA) operates clusters of monitors in the vicinity of large power plants.

MONTHLY MEAN AND AVERAGE DAILY MAXIMUM CONCENTRATIONS

Trends in monthly mean and average daily maximum SO_2 concentration were calculated for each of the 22 states. The monthly averages are based on averages across all reporting sites for each state; because the monitoring sites tend to be clustered in urban areas, monthly average values usually reflect concentration levels of those urban monitors rather than those of background or rural monitors. Although the absolute levels of the concentrations within a state may reflect higher urban concentrations, the

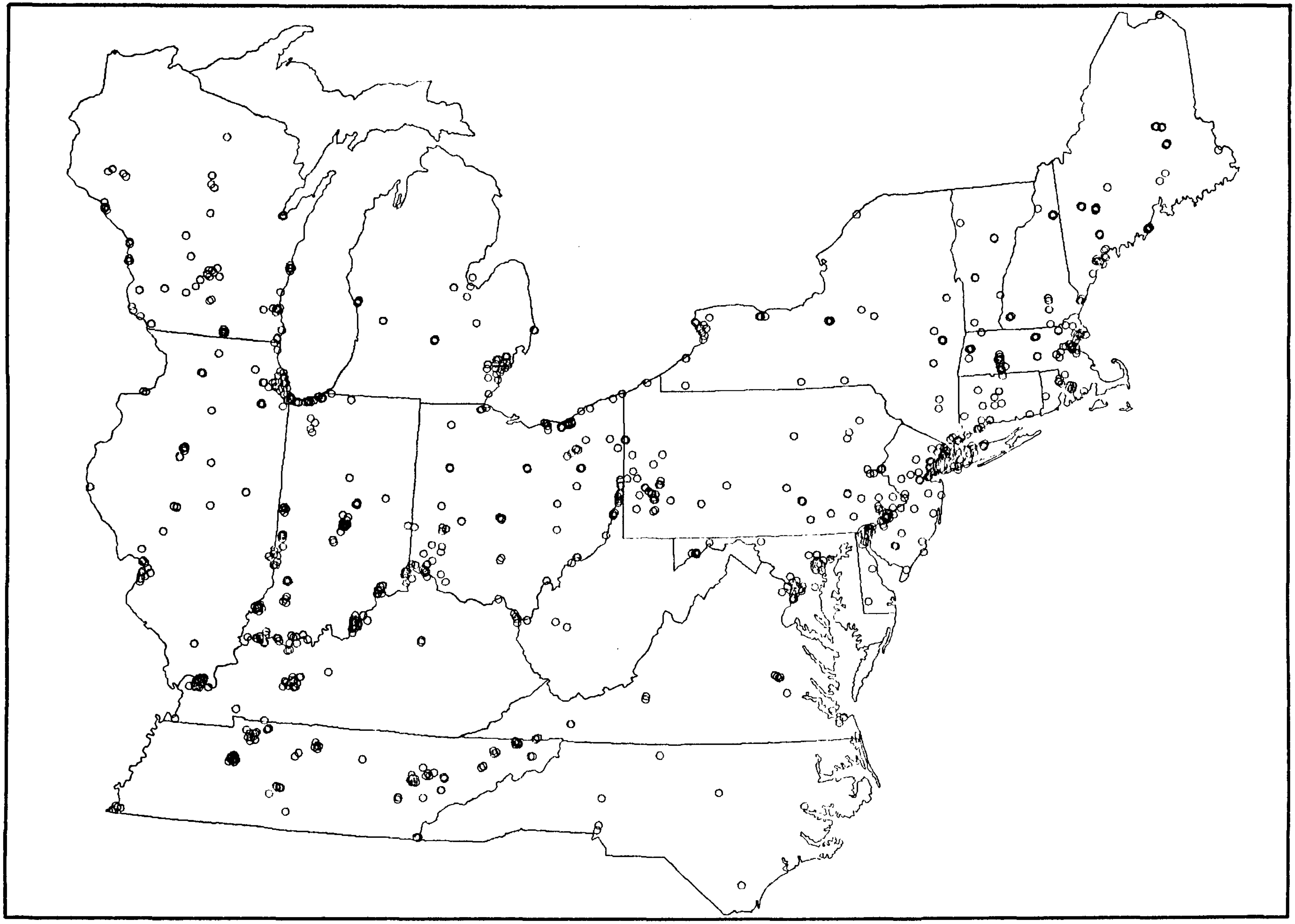

Figure 1. SO_2 Monitoring Stations in the Northeastern United States

relative levels (i.e., the increases and decreases observed) may be more representative of all areas in the state.

Figures B1 through B22 present trends in monthly average SO_2 concentrations for the 22 northeastern states from 1975 to 1982. Three methods used to calculate the monthly averages are plotted. When monthly averages are calculated by averaging across all individual site monthly averages, each site is weighted equally (thin line). When the sites are weighted according to the number of hours in the monthly site mean, each hourly observation in the month is weighted equally (thick dashed line). The thick black line indicates monthly averages calculated by averaging across individual site monthly averages, but only for those sites with at least 40 percent of the total possible hours in the month (the cutoff value of 40 percent was chosen according to the results of the data completeness study by Thrall et al., 1984). The bottom of each plot shows the number of monitoring sites available for calculating each monthly mean. There the thin line indicates the total number of sites with at least one hourly observation in the month, while the thick line indicates the number of sites with at least 40 percent of the data available for the month.

The seasonal nature of monthly average SO_2 concentrations can be seen in Figures B1 to B22: SO_2 concentrations for these urban-representative averages are highest in the winter when (1) the SO_2 emissions from low-elevation, sulfur-containing fuel heating sources are highest, (2) the air is relatively stagnant, and (3) mixing volumes are small; and lowest in the hot summer months when emissions from low-elevation sources are less and there is greater mixing. Some of the plots also display a secondary "peak" in the summer season, with an amplitude that is about 10 percent of the winter peak (cf. Figures B4, B13, and B18). The plots reveal that the three averaging methods result in remarkably similar trends; the few exceptions, such as New Hampshire in 1980 (Figure B11) or Rhode Island in 1976 (Figure B17) occur when there are only a few sites and one site has an erratic pattern of monthly means resulting from a limited number of hourly observations in a month. The three averaging methods result in similar trends because the majority of monitors report data for at least

40 percent of the total possible hours in each month, as can be seen at the bottom of each plot. Finally, more than half of the plots show evidence of a downward trend. Only one plot (for Maryland) indicates an upward trend in monthly average SO_2 concentrations over the period.

Trends in average daily maximum SO_2 concentration for each of the 22 northeastern states are shown in Figures C1 through C22. The three averaging methods shown in Figures B1 to B22 are also used here, with the same assignment of plotting line to averaging method, except that the 40 percent cutoff applies to the number of valid days rather than hours. A day is considered valid if at least 75 percent of the hours between 9:00 a.m. and 9:00 p.m. have valid observations. The general patterns and seasonal cycles for average daily maximums are similar to those observed in monthly averages. Massachusetts (Figure C9) has an unusually large average daily maximum in December of 1977, which most likely is caused by one site with an extremely high (possibly invalid) value. This deviation is possible because the raw SAROAD SO_2 data were not subjected to large-scale checking; rather, they were taken at face value.

3 POWER PLANT SULFUR DIOXIDE EMISSION TRENDS

DATA SOURCES

Power Plant Fuel Consumption

Data pertaining to monthly power plant consumption of fuels are available from the Energy Information Administration (EIA) on Form EIA-759 (also called by its original name, FPC Form 4), the Power Plant Report. The monthly electricity generation, consumption of fossil fuels, and fuel stocks data for each power plant in the United States have been computerized by the Department of Energy (DOE). We received a tape from DOE containing one file for each year, 1975 to 1982. We merged the files and sorted them by plant codes and by fuel source for further analysis. For the 22 northeastern states, there are approximately 31,000 records in the file.

Fuel Quality

Fuel quality data are available on federal Form 423, the Cost and Quality of Fuels Report. Each record in the file contains information on one fuel delivery, so there may be multiple records for a given fuel type at a plant in a given month; in addition, many plants consume more than one kind of fuel. Included in this computerized data base are Btu content, percent sulfur content by weight, and percent ash content by weight. We received from DOE a data tape with separate files for each year, 1975 to 1982. These files were sorted by plant code and merged into one file containing approximately 70,000 records for coal and oil deliveries.

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Cost and Quality of Fuels Reports are required only for plants with a generating capacity of at least 25 MW. All power plants, however, are required to file the monthly Power Plant Reports. For those small plants with less than 25 MW generating capacity, we substituted average sulfur content of oil and coal for each state in each year; these values were also used for larger plants for which data were missing from the Cost and Quality of Fuels file. For a given state and year, average sulfur content was calculated as the weighted average sulfur content of all deliveries for that state in that year separately for coal and oil; the weights used were the tons of coal or barrels of oil delivered. The weighted average sulfur contents of delivered coal and oil for the 22 states in each year are listed in Tables 2a and 2b, respectively. Qualitatively, one observes a downward trend in median percent sulfur (by weight) in coal (from approximately 2.03 percent in 1975 to approximately 1.7 percent in 1981 and 1982). The reverse trend is observed for the median weight percent oil sulfur content (1.18 percent in 1975 to approximately 1.3 percent in 1982).

Power Plant Flue Gas Desulfurization Systems

Flue gas desulfurization (FGD) systems, also known as scrubbers, have been installed at many large power plants in the northeast. A computer data base containing information about all existing and planned FGD systems is maintained on EPA's Univac computer by PEDCo Environmental, Inc. of Cincinnati, Ohio (PEDCo, 1982). This data base, known as FGDIS (for FGD Information System), provided a list of all scrubbers in operation in the 22 states between 1975 and 1982; the power plants with scrubbers are listed in Table 3.

Power Plant Location

Power plant location information (latitude and longitude) was extracted from the stack file of E. H. Pechan & Associates of Springfield, Virginia;

TABLE 2a. Weighted average sulfur content of coal delivered to electric power plants in 22 northeastern states, 1975 - 1982. (Units are tons sulfur per 100 tons coal)

	1975	1976	1977	1978	1979	1980	1981	1982
Connecticut	1.94	2.06	2.01	1.91	1.92	1.79	1.67	1.66
Delaware	2.07	2.02	1.96	1.75	1.80	1.60	1.33	1.23
District of Columbia	0.70	2.06	2.01	1.91	1.92	1.79	1.67	1.66
Illinois	2.29	2.28	2.10	1.98	1.86	1.78	1.71	1.93
Indiana	2.71	2.57	2.54	2.52	2.64	2.56	2.43	2.36
Kentucky	3.23	3.19	2.89	2.61	2.74	2.45	2.44	2.48
Maine	1.94	2.06	2.01	1.91	1.92	1.79	1.67	1.66
Maryland	1.55	1.47	1.47	1.48	1.41	1.60	1.69	1.60
Massachusetts	0.80	2.06	2.01	1.91	2.57	1.13	1.24	1.24
Michigan	2.39	2.13	2.05	1.79	1.58	1.26	1.20	1.34
New Hampshire	2.39	2.17	2.28	2.12	2.51	2.49	2.46	2.35
New Jersey	1.82	1.59	1.71	1.64	1.68	1.62	1.44	1.43
New York	1.87	1.83	1.76	1.68	1.78	1.80	1.82	1.80
North Carolina	1.05	1.01	1.03	1.06	0.92	0.94	0.91	0.89
Ohio	2.95	2.89	2.78	2.63	2.58	2.44	2.46	2.47
Pennsylvania	2.03	2.13	2.11	2.06	2.03	2.07	2.02	2.02
Rhode Island	1.94	2.06	2.01	1.91	1.92	1.79	1.67	1.66
Tennessee	2.86	2.78	3.01	2.41	2.24	2.21	2.27	2.00
Vermont	0.97	2.06	1.49	1.91	1.51	1.79	0.57	0.58
Virginia	0.82	0.84	0.95	0.95	0.84	0.86	0.89	0.87
West Virginia	2.04	1.86	1.88	1.81	1.87	1.75	1.77	1.86
Wisconsin	2.26	2.14	2.22	2.12	2.01	1.81	1.48	1.52

TABLE 2b. Weighted average sulfur content of oil delivered to electric power plants in 22 northeastern states, 1975 - 1982. (Units are tons sulfur per 1000 barrels oil)

	1975	1976	1977	1978	1979	1980	1981	1982
Connecticut	0.71	0.62	0.60	0.64	0.73	0.73	0.81	1.32
Delaware	1.44	1.55	1.56	1.54	1.67	1.67	1.97	1.94
District of Columbia	1.52	1.53	1.66	1.26	1.35	1.34	1.40	1.30
Illinois	0.89	0.82	0.88	0.86	0.98	1.10	1.09	1.12
Indiana	0.33	0.47	0.50	0.55	0.47	0.44	0.41	0.58
Kentucky	0.50	0.64	0.42	0.31	0.58	0.54	0.53	0.50
Maine	3.51	3.39	3.70	2.45	2.34	2.20	1.73	1.98
Maryland	1.85	2.11	2.12	2.08	2.13	2.09	1.65	1.85
Massachusetts	1.19	1.69	1.69	2.60	2.81	2.79	2.97	3.00
Michigan	1.18	1.14	1.20	1.14	1.08	1.10	1.16	1.17
New Hampshire	3.00	3.03	2.96	2.83	3.01	3.20	3.15	3.12
New Jersey	0.55	0.61	0.70	0.75	0.78	0.75	0.87	0.96
New York	1.77	1.72	1.83	1.81	2.11	2.06	2.22	2.10
North Carolina	0.53	0.30	0.33	1.01	0.34	0.35	0.35	0.33
Ohio	0.87	0.56	0.91	0.88	1.36	0.84	0.85	0.74
Pennsylvania	0.67	0.71	0.81	0.89	1.08	1.07	1.04	1.07
Rhode Island	1.31	1.57	1.56	1.46	1.49	1.55	1.91	1.76
Tennessee	0.99	1.02	1.03	1.03	0.85	0.81	0.81	0.73
Vermont	0.17	0.16	0.43	1.32	0.48	0.59	0.42	0.37
Virginia	2.61	2.53	2.50	2.58	2.35	2.16	1.94	1.79
West Virginia	0.16	0.15	0.35	0.44	0.57	0.43	0.32	0.44
Wisconsin	1.27	0.60	0.55	0.53	0.73	0.66	0.50	0.55

TABLE 3. Electric power plants with flue gas desulfurization systems operating between 1975 and 1982, 22 northeastern states.

Company Plant Name	No.	Gross MW	Net MW	Esc MW	Init. Start Date	Cmrcl. Start Date	Design SO2 Rem. Eff. %
Central Illinois Light							
Duck Creek	1	416	378	416	7607	7808	85.30
Central Illinois Public Serv							
Newton	1	617	575	617	7909	7910	89.50
Commonwealth Edison							
Powerton	51	450	400	450	8004	8106	75.50
Delmarva Power & Light							
Delaware City	1	60		60	8005	8005	90.00
Delaware City	2	60		60	8005	8005	90.00
Delaware City	3	60		60	8005	8005	90.00
Detroit Edison							
St. Clair	6a	325	154	163	7506	7509	90.00
Duquesne Light							
Elrama	1-4	510	487	510	7510	7510	83.00
Hoosier Energy							
Merom	2	490	460	441	8112	8202	90.00
Indianapolis Power & Light							
Petersburg	3	532	515	532	7712	7712	85.00
Kentucky Utilities							
Green River	1-3	65	59	65	7509	7606	98.00
Louisville Gas & Electric							
Cane Run	4	188	175	188	7608	7708	85.00
Cane Run	5	200	192	200	7712	7807	85.00
Cane Run	6	299	277	299	7904	7904	95.00
Mill Creek	1	358	334	358	8012	8104	85.00
Mill Creek	2	350	325	350	8112	8204	85.00
Mill Creek	3	427	420	427	7808	7903	85.00
Monongahela Power							
Pleasants	1	626	580	626	7812	8012	90.00
Pleasants	2	626	580	626	8010	8012	90.00

Continued

TABLE 3. Concluded.

Company Plant Name	No.	Gross MW	Net MW	Esc MW	Init. Start Date	Cmrcl. Start Date	Design SO2 Rem. Eff. %
Northern Indiana Pub Service							
Dean H. Mitchell	11	116	94	115	7607	7706	90.00
Pennsylvania Power							
Bruce Mansfield	1	917	780	917	7512	7606	92.10
Bruce Mansfield	2	917	780	917	7707	7710	92.10
Bruce Mansfield	3	917	800	917	8006	8010	92.20
Philadelphia Electric							
Eddystone	1a	120	120	120	7509	7509	90.00
Southern Illinois Power							
Marion	4	184	161	184	7904	7906	89.40
Southern Indiana Gas & Elec							
A.B. Brown	1	265	250	265	7903	7904	85.00
Springfield Water, Light & Pwr							
Dallman	3	205	192	205	8010	8101	95.00

Source: PEDCo Environmental, Inc., Flue Gas Desulfurization Information System Data Base the data base was developed with guidance from, and the participation of, the Utility Air Regulatory Group, the Utility Data Institute, and the U.S. EPA. The file contains information, including latitude and longitude, on 1951 stacks of 779 power plants across the United States. Latitude and longitude are missing for about 10 percent of the plants in the file; we manually located all plants for which location parameters were missing if their annual average sulfur dioxide emissions were more than 10,000 tons.

EMISSION ESTIMATES

Monthly sulfur dioxide emissions were estimated for all electrical power plants in the 22 northeastern states for the years 1975 to 1982. At each plant, monthly emissions were estimated from fuel consumption data and sulfur content of fuel data as follows:

$$Q_{SO_2} = C \times \frac{S}{100} \times (1 - \frac{A}{100}) \times 2 \quad ,$$

where

Q_{SO_2} = tons of SO_2 emitted;
C = tons of fuel consumed to generate electricity;
S = sulfur content of the fuel, percent;
A = ash retention, percent; and
2 = multiplier, since 1 ton of sulfur burned produces 2 tons of SO_2.

For each plant, SO_2 emissions were calculated separately for each type of fuel consumed (coal and/or oil) and then summed to estimate total plant emissions for the month. The sulfur content of each fuel for each plant was calculated not for each month, but for each year, since there are many plant-months with no fuel deliveries. An annual weighted average sulfur content is a reasonable approximation because there is little variability in sulfur content from one delivery to another within a given plant

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(Burton et al., 1982). This assumption should not lead to any bias in the calculated emissions. Ash retention for each fuel type is given by EPA (AP-42 Emission Factors, 1983); these values are listed in Table 4. We assumed that all fuels were burned in the same year in which they were delivered. Errors in emission estimates from lags in fuel consumption should be small since the trends in annual median coal and oil sulfur content were observed to be small (cf. Tables 2a and 2b).

Electric power plants with FGDs have reduced SO_2 emissions. For these plants, the following additional calculations were made:

$$Q'_{SO_2} = Q_{SO_2} \times \frac{TG - SG \times E/100}{TG} ,$$

where

Q'_{SO_2} = reduced monthly SO_2 emissions;
TG = total plant generating capacity;
SG = generating capacity of the unit with a scrubber; and
E = scrubber designed efficiency, percent.

Total plant emissions were thus reduced by the percentage of emissions scrubbed. Monthly emission estimates were reduced beginning with the month in which the FGD system started commercial (as opposed to initial testing) operations, as listed in Table 3. For these calculations we assumed that the scrubber, once in operation, was always operating at its designed efficiency. This assumption will, on the average, lead to an underestimation of emissions because it is more likely that scrubber efficiencies will be somewhat lower than design values; however, the overall downward bias in emission estimates is believed to be small.

TABLE 4. Ash retention for fuels consumed by electric power plants

Fuel Type	Ash Retention (Percent)
Bituminous coal	2.3
Subbituminous coal	12.3
Anthracite coal	0.0
All fuel oils	0.0

Source: EPA AP-42 Emission Factors, Supplement 13, 1983.

SUMMARIES OF EMISSION ESTIMATES

Total annual electric power plant SO_2 emissions for each year, 1975-1982, are given for each state in Table 5. The state with the highest emission levels in all years is Ohio, by a wide margin (30 to 48 percent for the 1975-1982 period); Illinois, Indiana, Kentucky, and Pennsylvania also have consistently high emissions. Average annual 1975-1982 SO_2 emission totals for each power plant are shown on the map of the 22 states in Figure 2. The diameter of the circle marking each plant is proportional to average annual plant emissions: the largest circles indicate plants with more than 100,000 tons emitted each year, while the smallest circles indicate small plants with less than 10,000 tons emitted each year. In the plot one can readily see the high concentration of the largest emitters of SO_2 in the Ohio River Valley, and on or near other bodies of water, e.g., Lakes Michigan and Erie.

COMPARISONS WITH OTHER EMISSION ESTIMATES

In two recent studies annual sulfur dioxide emissions from power plants were estimated. E. H. Pechan & Associates (EHPA, 1982) estimated annual emissions from 1976 through 1980; their totals by state are given in Table 6. Gschwandtner and Gschwandtner (1983) estimated total annual emissions of SO_2 and nitrogen dioxide (NO_2) for every five years since 1900 and also for 1978; their estimates of SO_2 emissions by state from the electric utility industry for those years which overlap our study are given in Table 7.

The data files used as a basis for the EHPA emission estimates are the same files used as the basis for the estimates in this study. Although similar calculations were performed, the state totals in Table 5 are generally about 1 to 5 percent higher than the EHPA state totals shown in Table 6. There are two reasons why our estimates are higher than those of EHPA. First, we estimated SO_2 emissions for all power plants reporting fuel consumption on the monthly Power Plant Report, while EHPA omitted

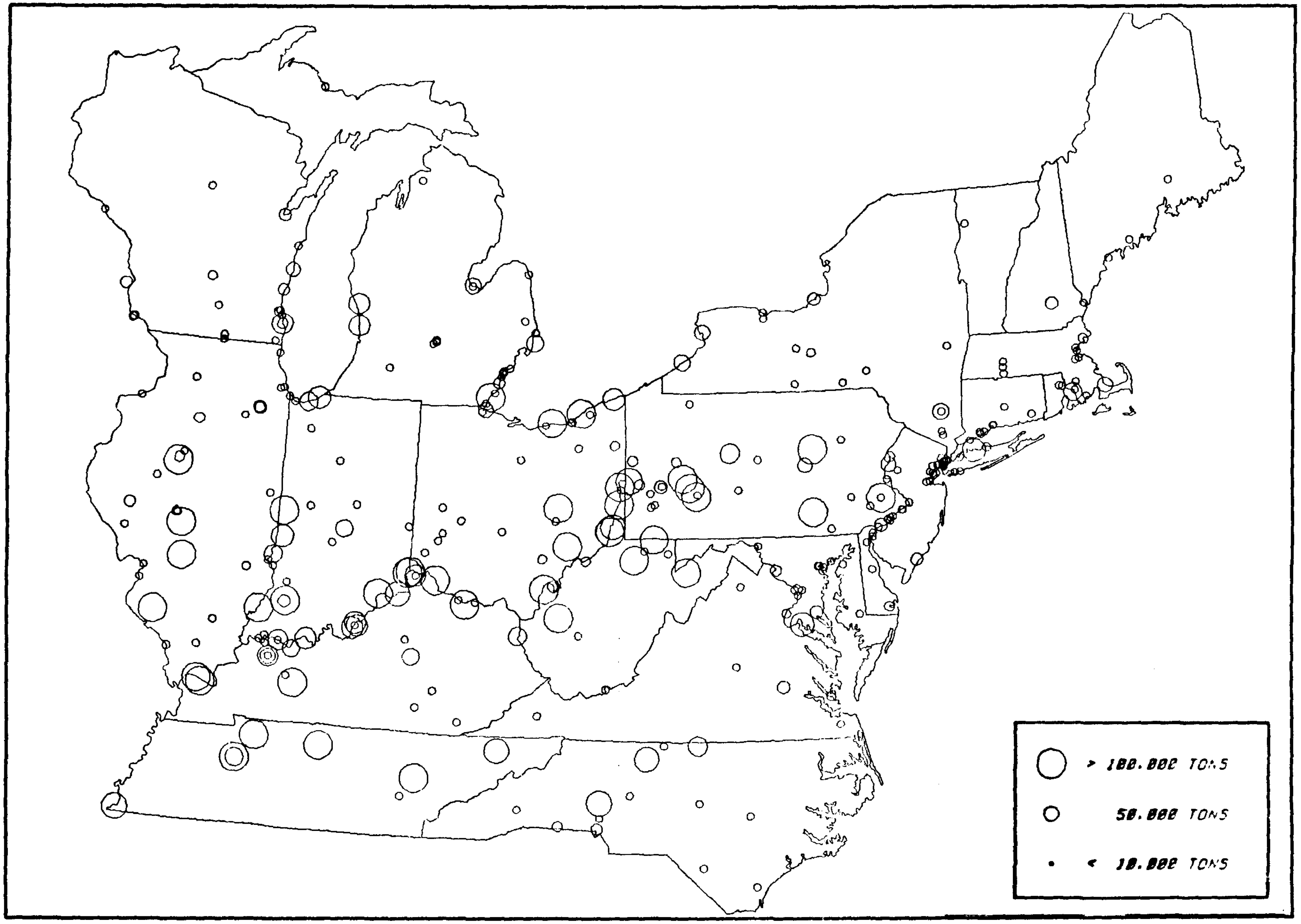

Figure 2. Electric Power Plants in the Northeastern United States and Their 1975 - 1982 Average Annual SO_2 Emissions

TABLE 5. Estimated sulfur dioxide emissions from electric power plants in 22 northeastern states, 1975 - 1982.

Emissions in 1000 tons per year

	1975	1976	1977	1978	1979	1980	1981	1982
Connecticut	32.0	25.0	23.3	25.8	27.3	31.4	29.7	46.0
Delaware	57.8	62.1	60.3	56.3	62.2	56.6	69.9	57.2
District of Columbia	7.0	7.0	12.4	9.8	6.3	4.2	2.4	0.7
Illinois	1502.7	1511.6	1451.0	1352.2	1218.7	1173.6	1029.2	1056.5
Indiana	1482.2	1485.3	1494.0	1384.4	1576.6	1584.9	1487.6	1345.1
Kentucky	1443.9	1549.9	1384.7	1244.1	1144.6	1072.9	1157.5	1042.8
Maine	20.0	12.9	9.8	8.7	10.8	16.1	13.2	12.6
Maryland	190.6	221.3	200.8	223.4	208.5	228.2	200.6	207.8
Massachusetts	109.8	158.7	159.6	257.1	261.5	275.4	264.6	263.2
Michigan	1028.6	891.4	907.4	820.7	761.2	569.0	604.6	587.7
New Hampshire	60.4	51.3	60.5	52.9	80.3	81.7	69.1	61.3
New Jersey	111.1	115.8	130.2	116.7	106.9	105.1	102.4	96.2
New York	539.0	515.6	552.0	522.8	511.3	479.4	509.4	474.1
North Carolina	383.9	423.1	439.2	408.2	391.0	446.8	456.8	420.2
Ohio	2794.0	2860.6	2833.3	2637.5	2713.2	2359.5	2383.0	2295.3
Pennsylvania	1499.4	1510.7	1451.6	1445.9	1591.9	1637.3	1509.8	1481.1
Rhode Island	4.1	3.0	3.6	3.4	2.8	5.2	5.0	3.1
Tennessee	1082.7	1263.1	1288.9	1062.5	922.3	960.6	900.3	646.7
Vermont	0.3	0.2	0.4	0.2	0.4	0.3	0.2	0.4
Virginia	210.5	226.4	238.5	224.2	204.0	165.1	142.7	125.6
West Virginia	1053.5	1034.5	1026.8	916.0	1010.4	1023.0	949.3	886.6
Wisconsin	442.9	475.5	535.1	482.8	501.7	472.9	412.6	375.4

TABLE 6. E. H. Pechan & Associates estimates of sulfur dioxide emissions from electric power plants in 22 northeastern states, 1976 - 1980.

	Emissions in 1000 tons per year				
	1976	1977	1978	1979	1980
Connecticut	25.2	23.5	26.0	27.6	32.1
Delaware	60.9	59.2	55.6	61.1	52.5
District of Columbia	7.2	12.6	10.4	6.7	4.6
Illinois	1428.8	1367.0	1292.9	1167.7	1125.6
Indiana	1443.1	1457.6	1351.2	1536.9	1539.6
Kentucky	1512.3	1356.5	1210.0	1130.0	1007.5
Maine	13.0	9.9	8.7	10.9	16.3
Maryland	218.2	198.0	220.5	205.2	223.2
Massachusetts	159.6	160.4	258.9	264.5	275.5
Michigan	887.6	905.1	806.9	741.0	565.4
New Hampshire	50.5	59.4	52.3	78.9	80.5
New Jersey	113.2	128.4	115.3	105.1	110.2
New York	512.8	548.0	520.0	508.1	480.3
North Carolina	410.2	427.2	396.4	379.5	435.4
Ohio	2749.8	2686.1	2462.6	2514.5	2171.6
Pennsylvania	1432.0	1381.1	1322.7	1415.1	1466.1
Rhode Island	3.0	3.6	3.4	2.8	5.2
Tennessee	1228.3	1257.6	1033.1	893.3	933.7
Vermont	0.4	0.4	0.3	0.4	0.5
Virginia	224.9	238.0	223.9	203.2	163.7
West Virginia	1010.4	1001.4	895.5	955.9	944.2
Wisconsin	469.7	514.7	471.7	496.3	485.7

Source: E. H. Pechan & Associates, "Estimates of Sulfur Dioxide Emissions from the Electric Utility Industry," 1982.

TABLE 7. Gschwandtner and Gschwandtner estimates of sulfur dioxide emissions from electric power plants in 22 northeastern states; 1975, 1978, and 1980.

	Emissions in 1000 tons per year		
	1975	1978	1980
Connecticut	31.4	25.9	28.9
Delaware	33.7	36.0	54.1
District of Columbia	13.2	4.7	1.9
Illinois	1778.8	1305.5	1190.5
Indiana	1600.2	1325.7	1644.3
Kentucky	1276.8	1243.6	1052.1
Maine	20.1	8.7	14.0
Maryland	204.2	211.8	245.0
Massachusetts	101.9	252.4	264.3
Michigan	1070.0	808.6	603.4
New Hampshire	62.7	50.7	82.2
New Jersey	117.4	101.8	107.0
New York	577.2	490.5	461.8
North Carolina	437.6	419.8	430.1
Ohio	2661.7	2265.6	2346.2
Pennsylvania	1439.9	1143.6	1415.1
Rhode Island	5.1	3.8	4.2
Tennessee	1351.0	896.4	1003.0
Vermont	0.5	0.0	0.0
Virginia	219.9	220.7	158.2
West Virginia	1300.4	1092.6	1059.7
Wisconsin	555.9	845.1	523.3

Source: Gschwtner and Gschwandtner, "Historic Emissions of Sulfur and Nitrogen Oxides in the United States from 1900 to 1980," 1983.

from their analyses all plants with less than one ton per year of SO_2 emissions. Second, EHPA assumed ash retention values of 5 percent for bituminous coal and 15 percent for subbituminous coal, while we used the EPA AP-42 recommendations of 2.3 and 12.3 percent, respectively.

Gschwandtner and Gschwandtner emission estimates are based on total annual fuel consumption figures in various Department of Energy reports (for complete details, see the Gschwandtner and Gschwandtner report) and EPA AP-42 emission factors. Their calculations were not done plant by plant, as were ours and those of EHPA. Differences between our state total SO_2 emission estimates (Table 5) and the Gschwandtner and Gschwandtner estimates in Table 7 are relatively large. Relative differences are especially large for those states with low SO_2 annual emissions, but the absolute differences for these states are relatively small; however, even in state-years with annual SO_2 emissions above 500,000 tons (by our estimate), the two sets of annual estimates vary by as much as 25 percent. We have not examined (and do not wish to speculate about) why our emission estimates differ from those of Gschwandtner and Gschwandtner.

TRENDS IN MONTHLY STATE TOTAL POWER PLANT SULFUR DIOXIDE EMISSIONS

Monthly total SO_2 power plant emissions are plotted by state in Figures D1 through D22. The power plant emissions for most states have a regular yearly pattern, with a summer peak in July and August and an even higher winter peak in December and January. In those states which have high SO_2 emissions, such as Ohio (Figure D15), Illinois (Figure D4), and Kentucky (Figure D6), significant decreases can be seen. In states with relatively few power plants and low emissions, such as Connecticut (Figure D1) and Delaware (Figure D2), trends in emissions are difficult to detect apart from the large seasonal variability.

4 CORRELATIONS BETWEEN MONTHLY POWER PLANT SULFUR DIOXIDE EMISSIONS AND SULFUR DIOXIDE AMBIENT CONCENTRATIONS

CORRELATIONS AT THE STATE LEVEL

Monthly statewide ambient SO_2 mean and average daily maximum concentrations are presented in Figures B1 to B22 and Figures C1 to C22, respectively. Monthly statewide power plant SO_2 emissions are presented in Figures D1 to D22. These plots reveal, in general, long-term reductions in ambient SO_2 concentrations in addition to long-term reductions in emissions; however, no clear pattern emerges with respect to short-term correlations between changes in emissions and changes in ambient SO_2.

Short-term correlations are not clearly apparent because of the highly seasonal nature of both emissions and ambient concentrations: ambient SO_2 concentrations peak during the winter, whereas emission levels have a winter peak as well as a summer peak. To examine the difference between actual monthly concentrations and "typical" monthly concentrations (i.e., averages for each month of the year), we applied the following statistical model to monthly emissions and SO_2 concentrations:

$$\hat{Y}_i = a_1 I_1 + a_2 I_2 + \ldots + a_{12} I_{12} \quad ,$$

where

I_j = 1 if the observation occurs in month j, 0 if otherwise, j = 1 to 12;

a_j = average emissions or SO_2 concentration for month j, j = 1 to 12; and

$\hat{Y}_i$ = predicted monthly emissions or SO_2 concentration, i = 1 to 96.

The difference between the actual values Y_i and the predicted values $\hat{Y}_i$, or the residuals, are the seasonally adjusted observations. As an example, the seasonally adjusted power plant emissions and monthly average daily maximum SO_2 concentrations for Illinois are shown in Figures 3 and 4, respectively; these values should be compared to actual emissions and maximum SO_2 concentrations shown in Figures D4 and C4, respectively.

The correlations of interest are between the seasonally adjusted emissions and the seasonally adjusted SO_2 concentrations. If the differences between actual and typical seasonal emissions are correlated with the differences between actual and typical seasonal SO_2 concentrations, then short-term changes in ambient SO_2 levels are related to short-term changes in emissions. Figures 5 and 6 show seasonally adjusted monthly power plant emissions in Illinois plotted against seasonally adjusted monthly mean and average daily maximum SO_2 concentrations, respectively. In both plots the correlations are relatively strong; the correlation in Figure 5 is 0.759, and the correlation in Figure 6 is 0.728. These correlations indicate that in Illinois monthly changes in emissions are reflected in monthly changes in ambient SO_2 concentrations.

Correlations between seasonally adjusted emissions and seasonally adjusted monthly mean SO_2 concentrations, and between seasonally adjusted emissions and monthly average daily maximum SO_2 concentrations are shown for all states in Table 8. These correlations are highest in those states with greater power plant SO_2 emissions. The degree of correlation depends to some extent on the number of SO_2 monitors and the amount of data at each of the monitors (see Figures A1 to A22); the more monitoring data there are, the less variability there is in average monthly SO_2 concentrations and the more likely it is that actual correlations between emissions and ambient SO_2 concentrations will be seen. In addition, the degree of the correlation depends on the locations of the SO_2 monitoring stations relative to the locations of the power plants with sizeable SO_2

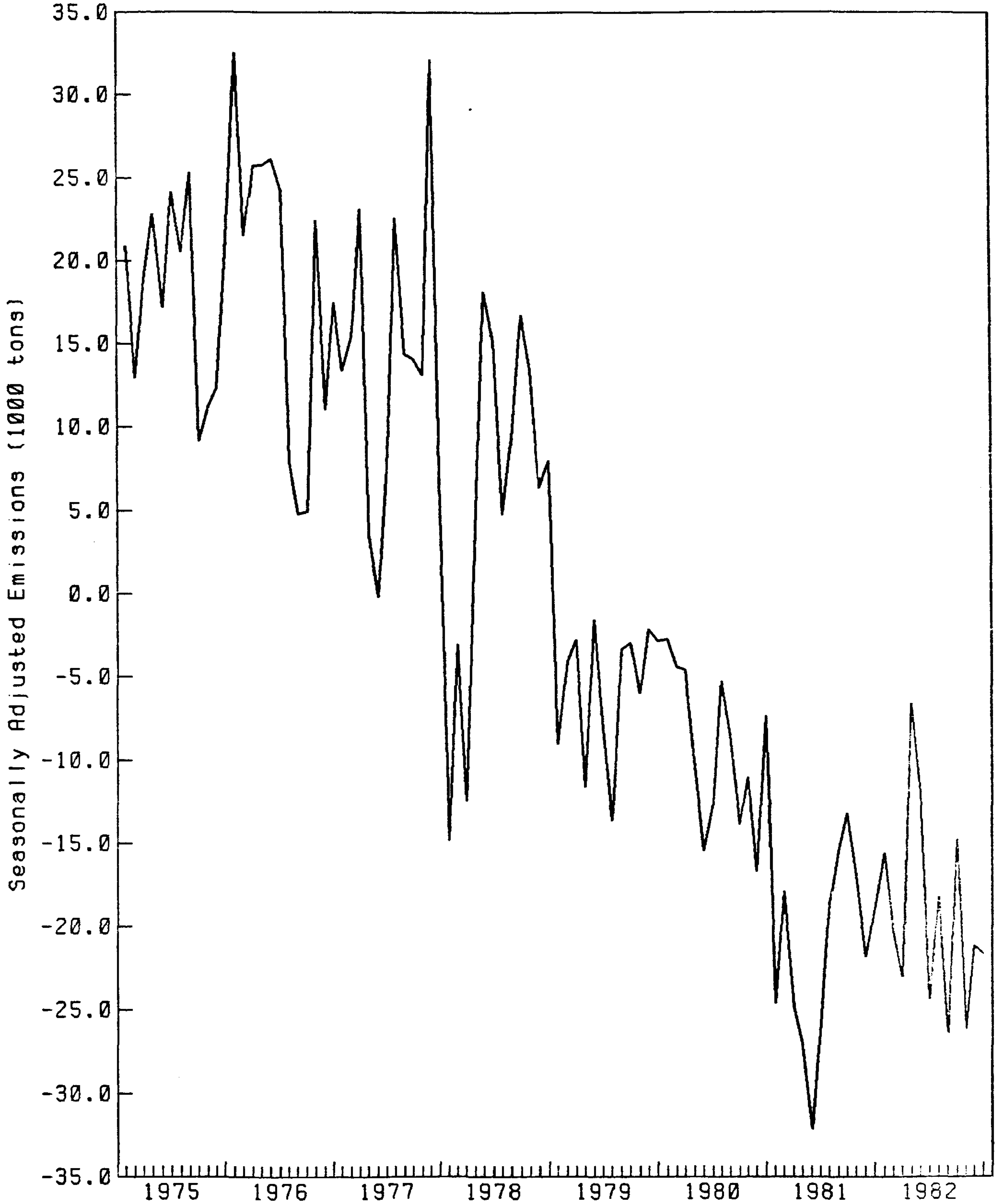

Figure 3. Seasonally Adjusted Total Monthly Power Plant SO2 Emissions, Illinois, 1975 - 1982.

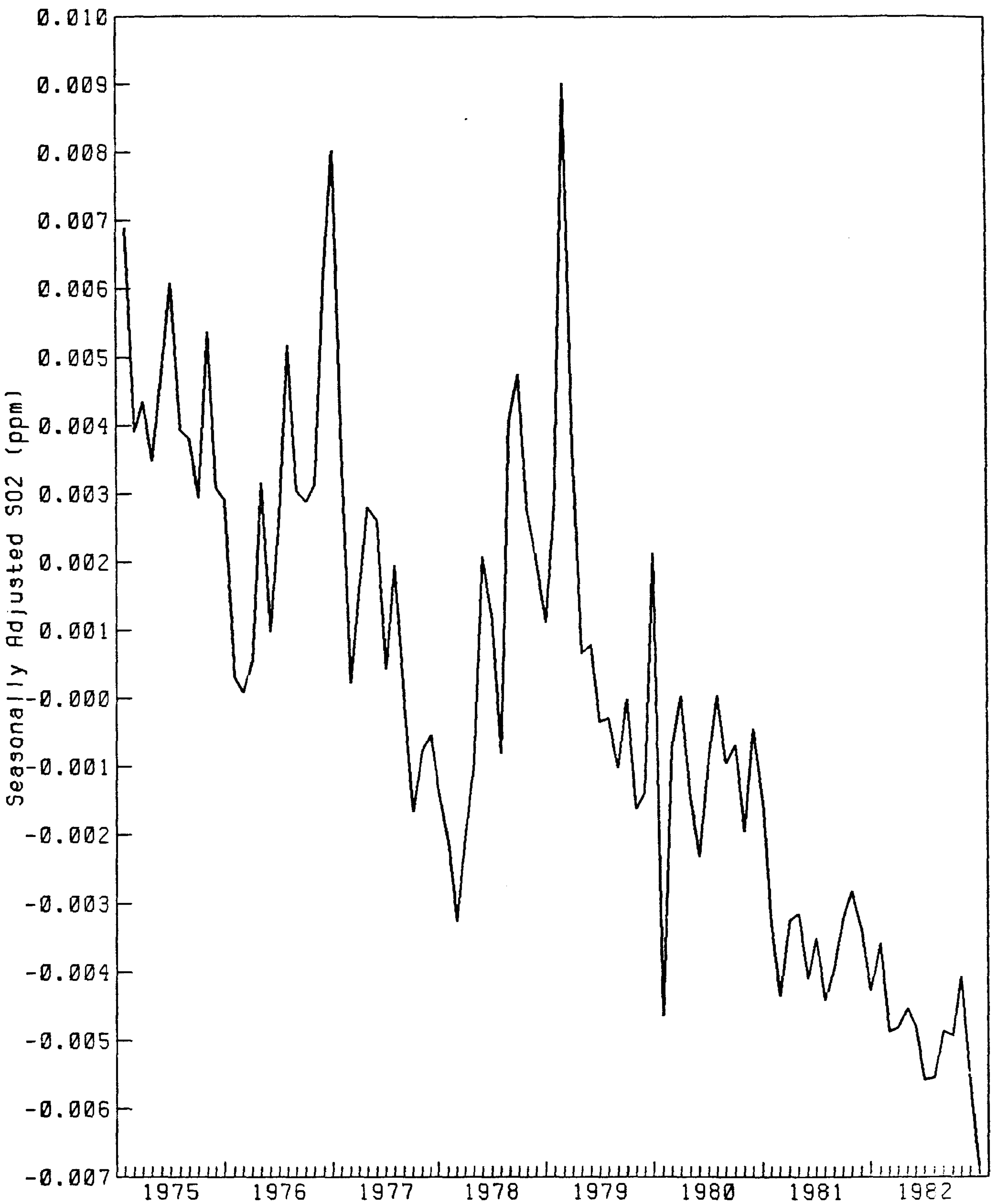

Figure 4. Seasonally Adjusted Monthly Average Daily Maximum SO_2 Concentration, Illinois, 1975 - 1982.

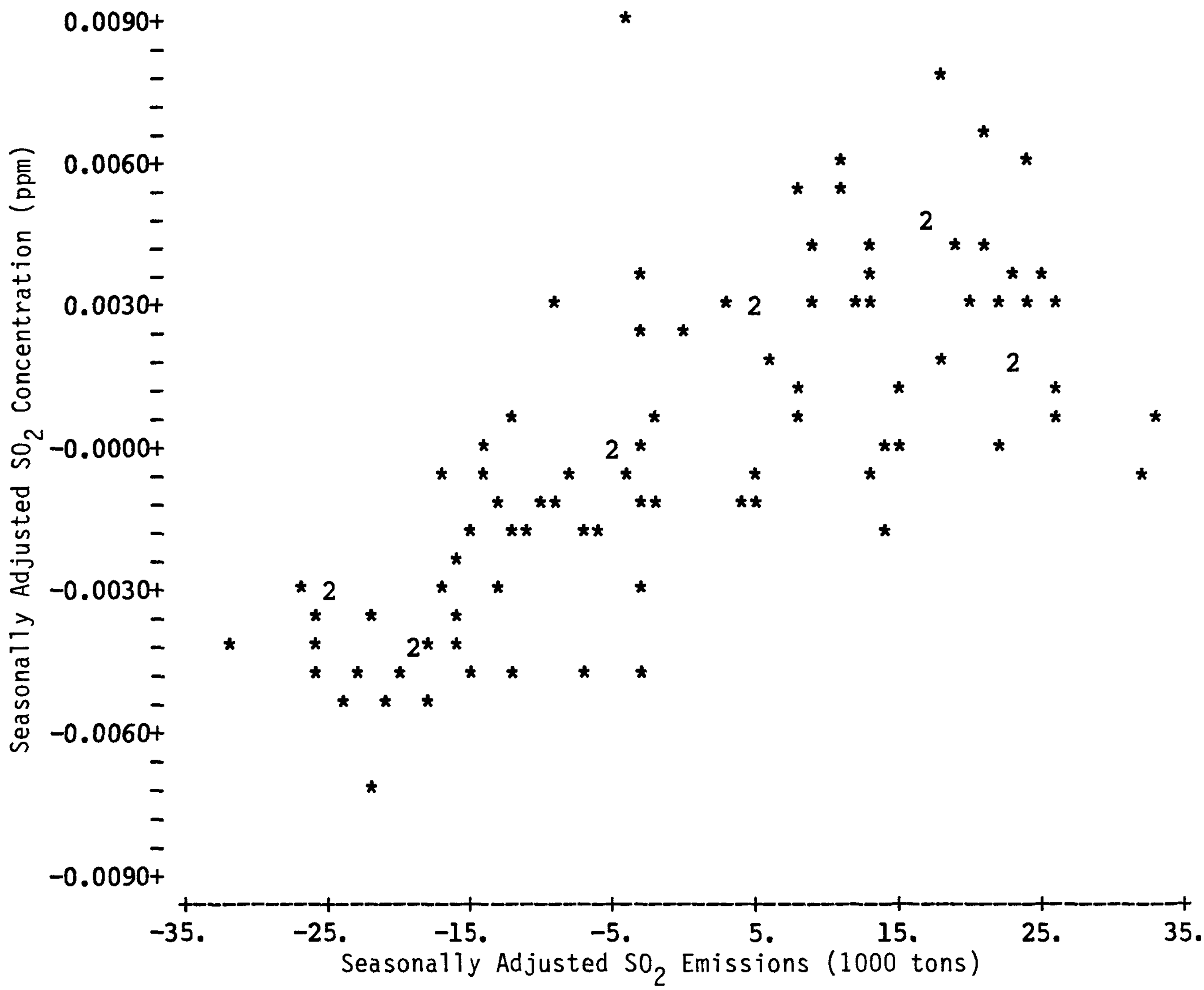

Figure 5. Seasonally Adjusted Average SO2 Concentration vs Seasonally Adjusted Power Plant SO2 Emissions, Illinois, 1975 - 1982, Monthly Data

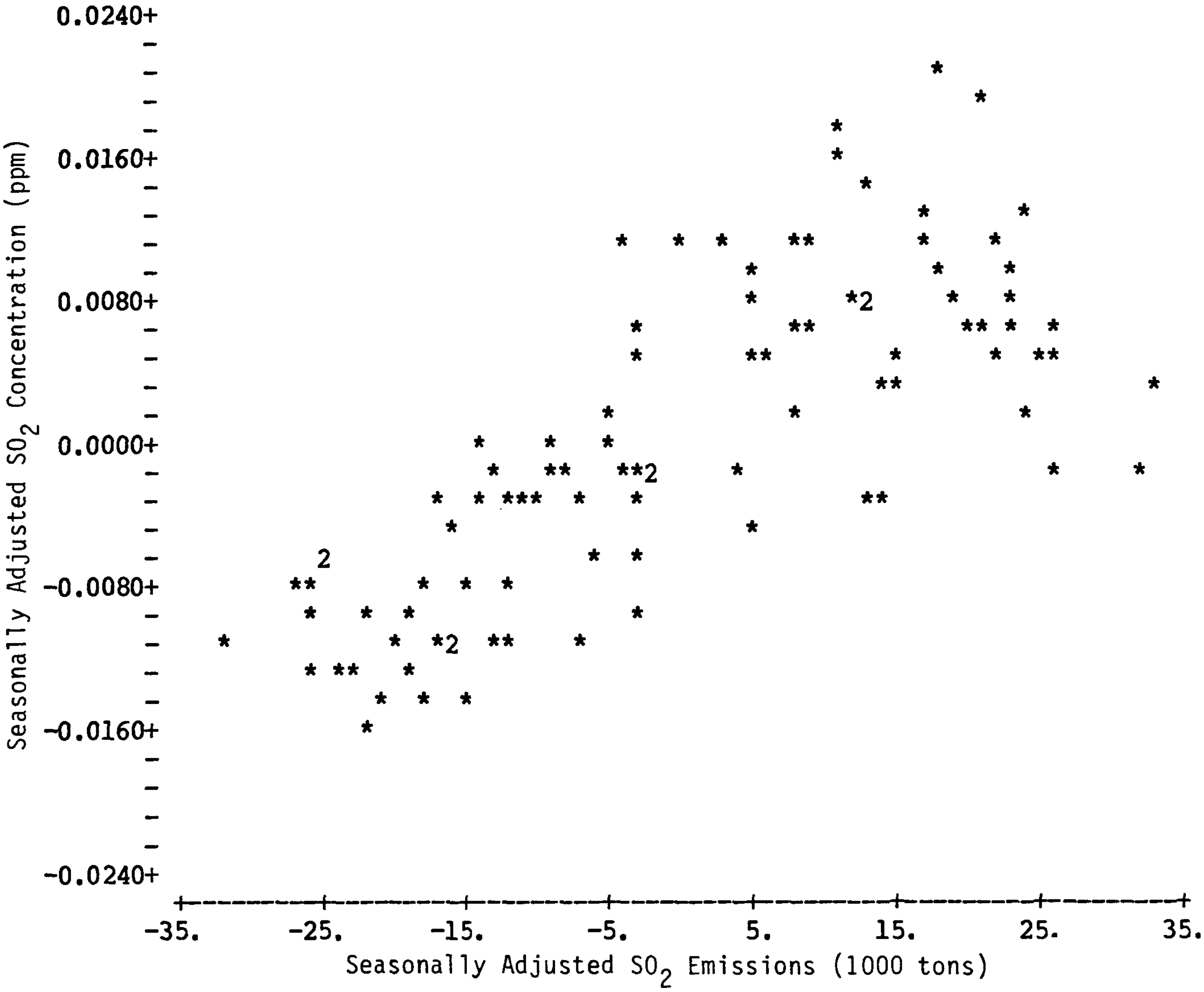

Figure 6. Seasonally Adjusted Average Daily Maximum SO2 Concentration vs Seasonally Adjusted Power Plant SO2 Emissions, Illinois, 1975 - 1982, Monthly Data

TABLE 8. Correlations between seasonally adjusted utility sulfur dioxide emissions and seasonally adjusted ambient sulfur dioxide concentrations

	(1)	(2)	(3)	(4)	(5)	(6)
Ohio	2609.6	0.484	0.598	15.7	38.0	26.6
Pennsylvania	1516.0	0.522	0.486	24.7	47.4	10.7
Indiana	1480.0	0.280	0.262	13.3	46.4	45.5
Illinois	1286.9	0.759	0.728	15.4	30.5	20.3
Kentucky	1255.1	0.715	0.367	15.2	55.9	22.0
Tennessee	1015.9	0.729	0.444	10.8	48.8	21.9
West Virginia	987.5	0.319	0.370	14.5	21.2	13.8
Michigan	771.3	0.808	0.659	14.9	42.7	7.3
New York	513.0	0.117	0.346	20.2	82.9	57.1
Wisconsin	462.4	-0.198	-0.017	13.9	19.9	26.7
North Carolina	421.1	0.080	-0.046	9.4	7.5	45.0
Massachusetts	218.7	-0.080	-0.044	25.5	90.0	10.9
Maryland	210.1	-0.129	-0.082	54.9	53.4	34.4
Virginia	192.1	0.771	0.757	34.4	49.8	24.1
New Jersey	110.5	0.428	0.465	74.1	83.1	41.9
New Hampshire	64.7	0.445	0.242	48.8	63.5	31.0
Delaware	60.3	0.071	0.003	9.4	16.1	35.3
Connecticut	30.1	0.215	0.053	80.7	81.1	26.9
Maine	13.0	-0.287	-0.206	12.3	42.6	31.3
District of Columbia	6.2	0.101	0.206	48.5	68.3	20.6
Rhode Island	3.8	0.106	-0.030	46.8	70.0	38.8
Vermont	0.3	0.115	0.167	76.4	81.4	22.9

(1) Average annual SO_2 emissions from electric power plants, 1000 tons, 1975 - 1982.

(2) Correlation between seasonally adjusted SO_2 emissions and seasonally adjusted monthly average SO_2 concentration.

(3) Correlation between seasonally adjusted SO_2 emissions and seasonally adjusted monthly average daily maximum SO_2 concentration.

(4) R^2 for seasonal adjustment regression model for SO_2 emissions.

(5) R^2 for seasonal adjustment regression model for monthly average SO_2 concentration.

(6) R^2 for seasonal adjustment regression model for monthly average daily maximum SO_2 concentration.

emissions. In Michigan, for example, all of the SO_2 monitors except one are located near major power plants.

The R^2 values in the last three columns in Table 8 indicate the percentage of variation in emissions and SO_2 concentrations that is explained by the seasonal adjustment model. Low R^2 values indicate that variation in emissions or SO_2 concentrations from monitor to monitor cannot be explained by the seasonal adjustment model, i.e., that no regular seasonal pattern can be detected; high R^2 values indicate that most of the variation is explained by the seasonal adjustment model, i.e., that emissions or SO_2 concentrations follow a very regular seasonal pattern. In general, the seasonal adjustment models fit better with states having low emissions and few SO_2 monitors. In states that have many power plants and SO_2 monitors, greater levels of aggregation reduce effects of seasonal patterns relative to long-term trends.

CORRELATIONS AT THE LOCAL LEVEL

Relationships between individual power plant emissions and monitored SO_2 concentrations were examined for a few selected sites. Such relationships, however, are inherently difficult to analyze because of missing data at most SO_2 monitoring stations. Very few stations were in existence during the entire eight-year period under study, and even when monitors are operating they rarely record measurements for all of the hours in a given year. From the set of monitors with at least four years of at least 50 percent of the total possible hours each year, we selected three with power plants nearby for further analysis; two of the monitor pairs are in New York near the Pennsylvania border, and the third is in eastern Virginia.

The first power plant-monitor pair chosen is located near Binghamton, New York, near the Pennsylvania border. The Goudey power plant, owned by New York State Electricity and Gas, is located in Johnson City, just east of Binghamton. The generating capacity of the plant was 145.7 MW from 1975 to 1978, was decreased to 103.7 MW in 1979 and 1980, and was increased to 118.7 MW in 1981. The SO_2 monitor (SAROAD identification 330480007F01) is a population-oriented monitor located at a water treatment plant southeast of the Goudey plant.

The second power plant-monitor pair is also located in upstate New York near the Pennsylvania border but further east near Corning and Elmira. The Hickling power plant is owned and operated by New York State Electricity and Gas, and is located in East Corning. The generating capacity of the plant was 70 MW between 1975 and 1980, and was increased to 83 MW in 1981. The SO_2 monitor (SAROAD ID 331880003F01), is located at a water treatment plant southeast of the plant, and is population-oriented.

The third power plant chosen for analysis serves a much larger population base, Richmond, Virginia. The Chesterfield plant is owned and operated by Virginia Electric Power and is located in Chester, south of Richmond. The plant had a generating capacity of 1484 MW until late 1981, when it was decreased slightly to 1352 MW. The source-oriented SO_2 monitor (SAROAD identification 481560004F02) is located in Hopewell, a few miles southeast of the plant.

Of the three SO_2 monitors, only the Chester monitor has nearly complete data. For that monitor sufficient SO_2 monitoring data are available to compute average daily maximums for all but one month (there were some values recorded, however, for that month, so a monthly mean could be calculated). The two New York SO_2 monitors, though, are missing many months of data; the monitor near Goudey is missing 14 consecutive months in 1977 and 1978, and the monitor near Hickling begins in 1977 and is missing a month at the end of 1978.

Figures 7, 8, and 9 show the estimated power plant emissions and monthly mean and average daily maximum SO_2 concentrations for each of the three sites chosen. The thicker line in the upper portion of the plots shows power plant emissions; the scale for emissions is on the right-hand side of the plots. The thinner lines in the bottom portion are monthly mean

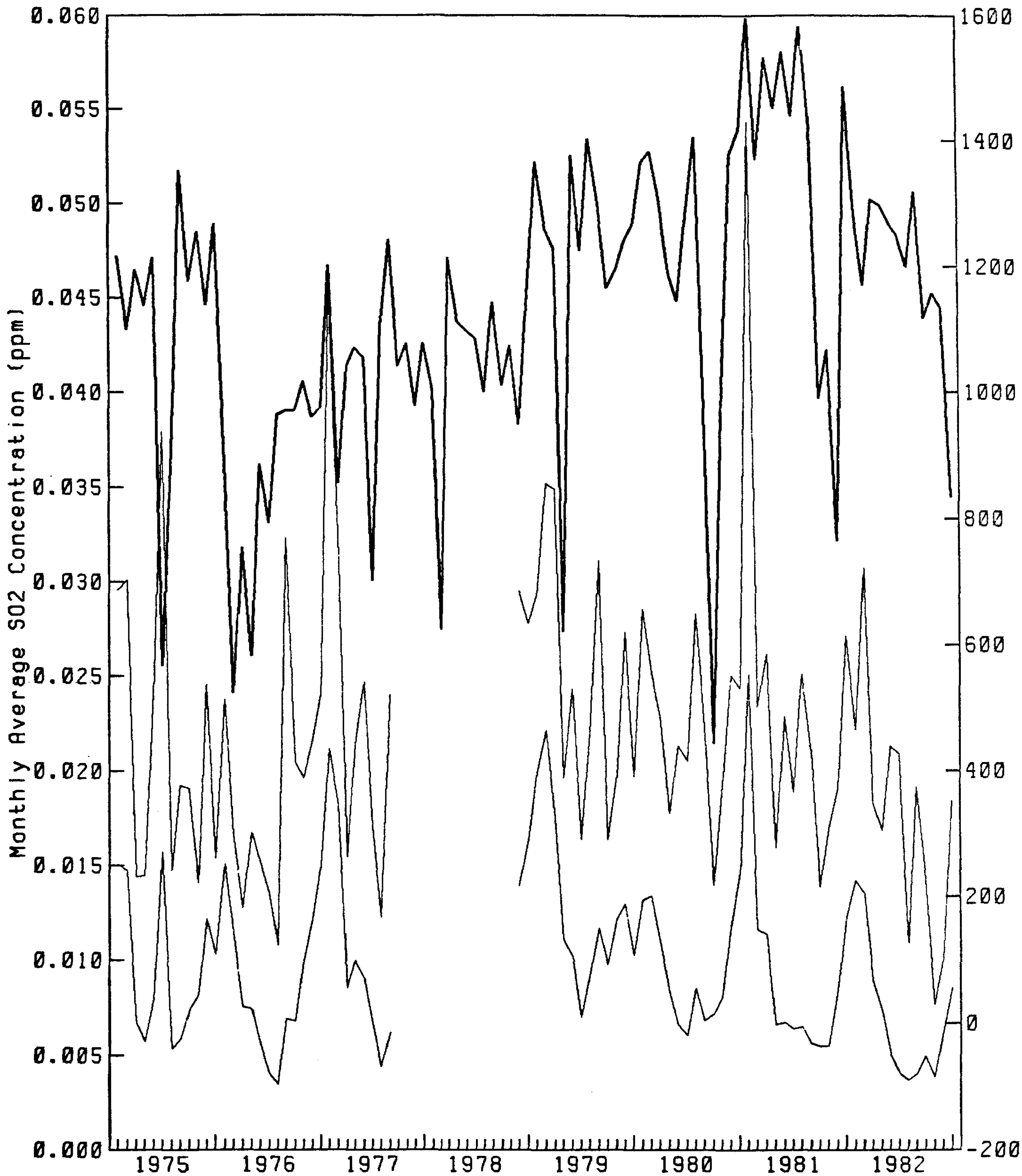

FIGURE 7. Monthly average SO_2 emissions and ambient concentration. Goudey Power Plant and monitor 330480007F01; Binghamton, New York.

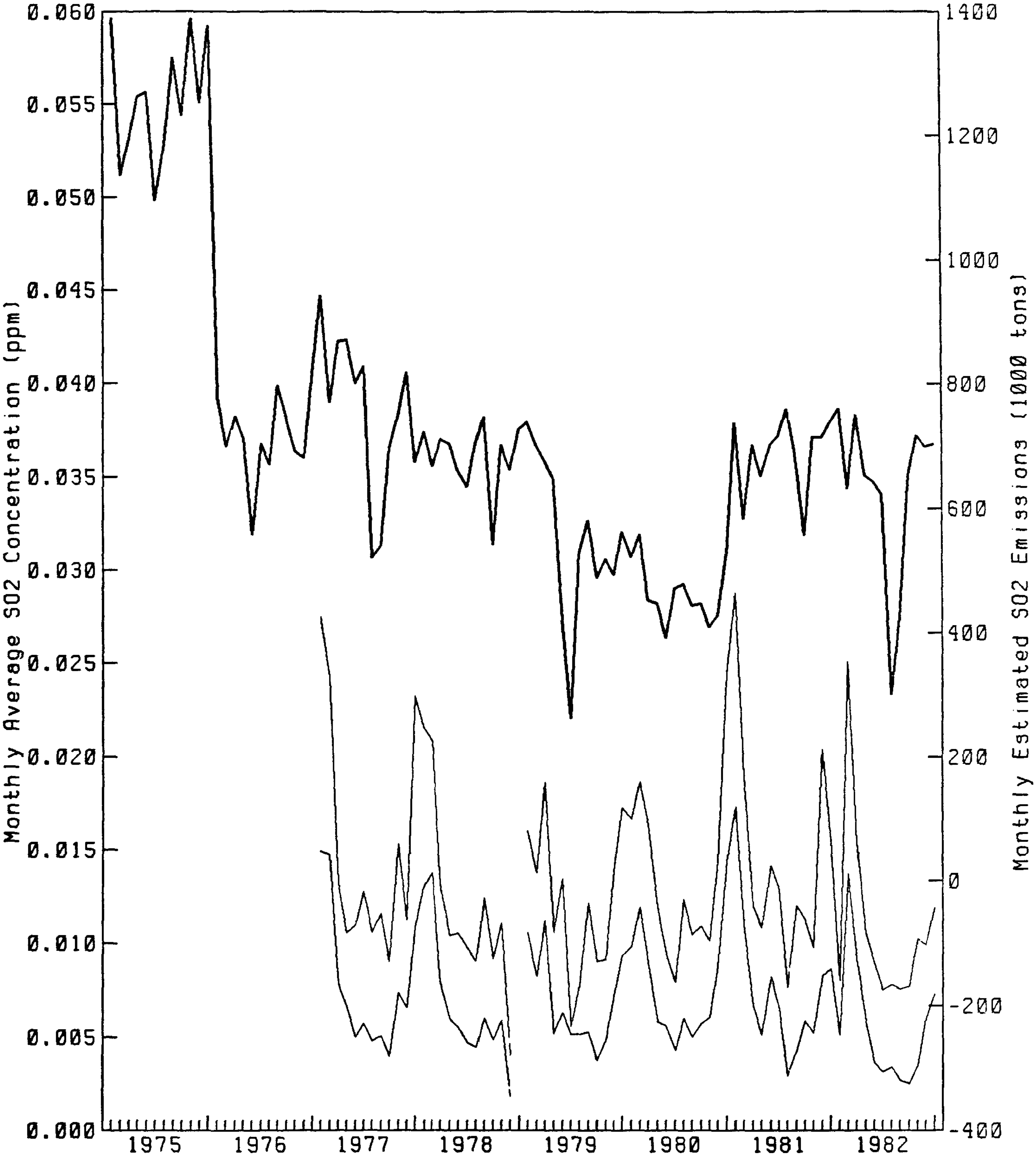

FIGURE 8. Monthly average SO_2 emissions and ambient concentration. Hickling Power Plant and monitor 331880003F01; Elmira, New York.

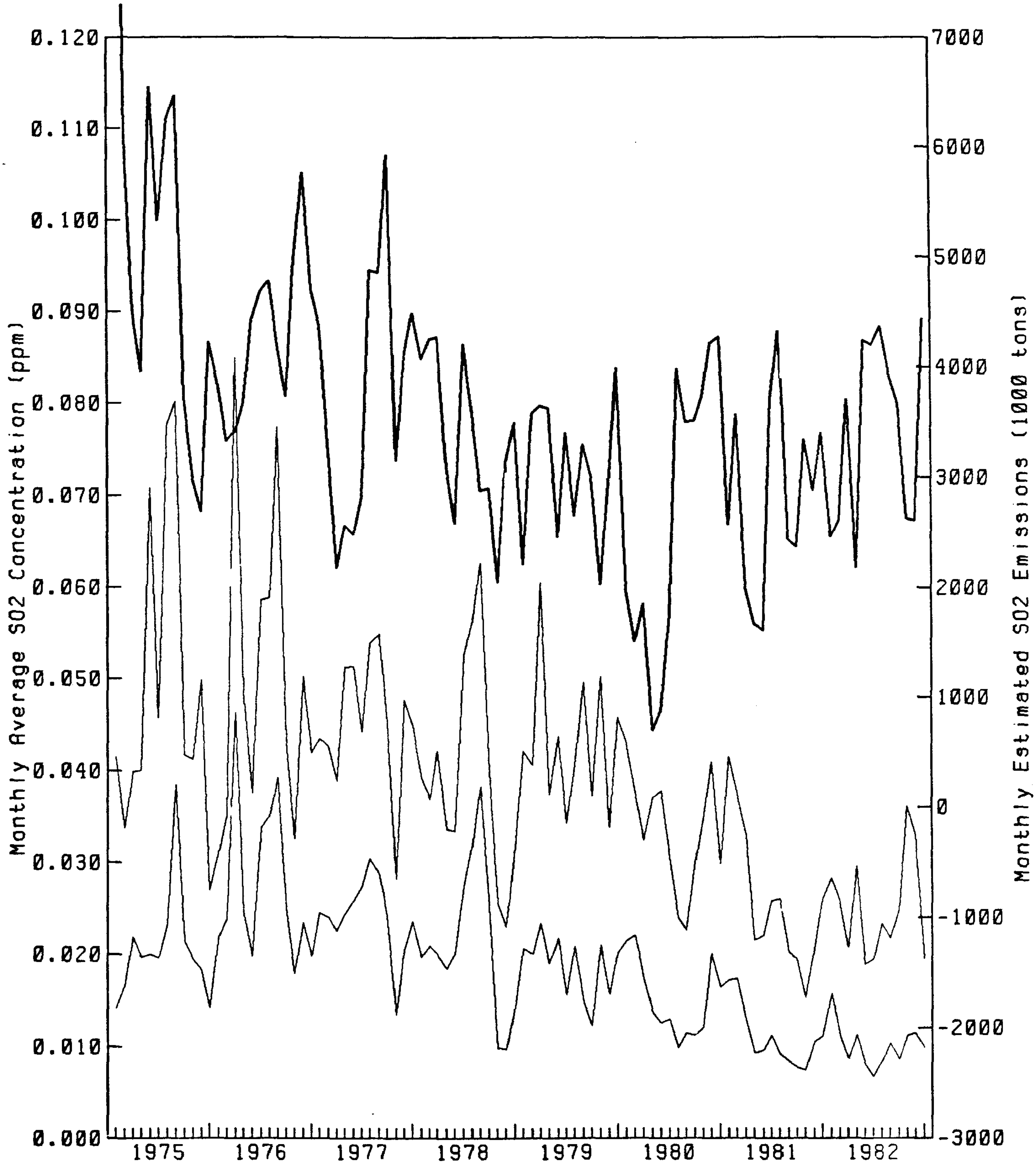

FIGURE 9. Monthly average SO_2 emissions and ambient concentration. Chesterfield Power Plant and monitor 481560004F02; Richmond, Virginia.

SO_2 concentration (the lower of the two lines) and average daily maximum SO_2 concentration; the scale for SO_2 concentrations is on the left-hand side of the plot. Statewide power plant emissions and SO_2 concentration patterns are relatively smooth because of the large number of data values across each state; however, at these individual power plants and SO_2 monitors, there are no regular seasonal patterns, and the seasonal adjustment model fits relatively poorly.

Because of the irregular patterns in emissions and SO_2 concentrations, and because monthly mean concentrations are sometimes based on only a few data values, correlations betwen emissions and SO_2 concentrations are not very high, especially at the New York sites, as can be seen in Table 9. Table 9 also shows correlations between monthly emissions and SO_2 concentrations in the summer months only, April through October, inclusive. Because there is only low-level mixing during the winter months, these months are more likely to represent ground-level sources; for this reason, we examined summer months separately. Restricting attention to just the summer months improves the correlations slightly at the two New York sites, even more so for the Virginia site. The second half of Table 9 presents correlations between yearly average SO_2 concentrations and total annual emissions at each site, both for all months in each year and for just summer months. In general, because of the effect of smoothing the data by averaging within each year, correlations between annual emissions and annual SO_2 levels are higher.

Correlations between emissions and average daily maximum SO_2 concentrations are higher than correlations between emissions and monthly mean SO_2 concentrations, in general. The largest by far of the three plants, Chesterfield, shows the highest correlations between SO_2 emissions and ambient SO_2 concentrations, most likely because the large power plant is the dominant SO_2 source near the monitor. The two New York power plants are much smaller and may not be the dominant SO_2 source in the vicinity of their respective associated SO_2 monitors.

TABLE 9. Correlations between monthly SO_2 power plant emissions and ambient SO_2 concentrations (monthly average and monthly average daily maximum).

(1) Goudey power plant, SO_2 monitor 330480007F01; Binghamton, New York

	Monthly data		Yearly data	
	All months	Summer months	All months	Summer months
Average	.122	-.165	-.108	-.111
Maximum	.266	.112	.118	-.115

(2) Hickling power plant, SO_2 monitor 331880003F01; Elmira, New York

	Monthly data		Yearly data	
	All months	Summer months	All months	Summer months
Average	.242	.187	-.062	.332
Maximum	.286	.355	.425	.505

(3) Chesterfield power plant, SO_2 monitor 481560004F02; Richmond, Virginia

	Monthly data		Yearly data	
	All months	Summer months	All months	Summer months
Average	.195	.367	.534	.586
Maximum	.292	.461	.687	.725

The correlations between emissions and SO_2 concentrations in these local sites can be summarized as follows:

Correlations are highest for point-source monitors near large power plants;

Correlations between monthly emissions from power plants and monthly average daily maximum SO_2 concentrations are somewhat higher than correlations between emissions and mean SO_2 concentrations;

Correlations between power plant emissions and ambient SO_2 concentrations are improved when the monthly data are aggregated to yearly averages; and

Correlations between power plant emissions and ambient SO_2 concentrations are higher when just the subset of summer months is considered relative to all months. This is a period in which emissions are high and mixing of emissions from elevated sources is greatest.

CORRELATIONS AT THE REGIONAL LEVEL

We now examine the correlation between power plant SO_2 emissions and ambient SO_2 concentrations for a large region of the northeastern United States. This region, which includes and surrounds the Ohio River Valley, consists of the six states Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia. These states are among the seven states with the highest annual SO_2 emissions from power plants.

Total monthly power plant emissions for these six states are presented in Figure 10. As was seen for many state total emission plots, there is a regular seasonal pattern of emissions peaking in both summer and winter, with the winter peak higher than the summer peak. Total annual emissions for the region are listed in Table 10; a consistent decrease in emissions

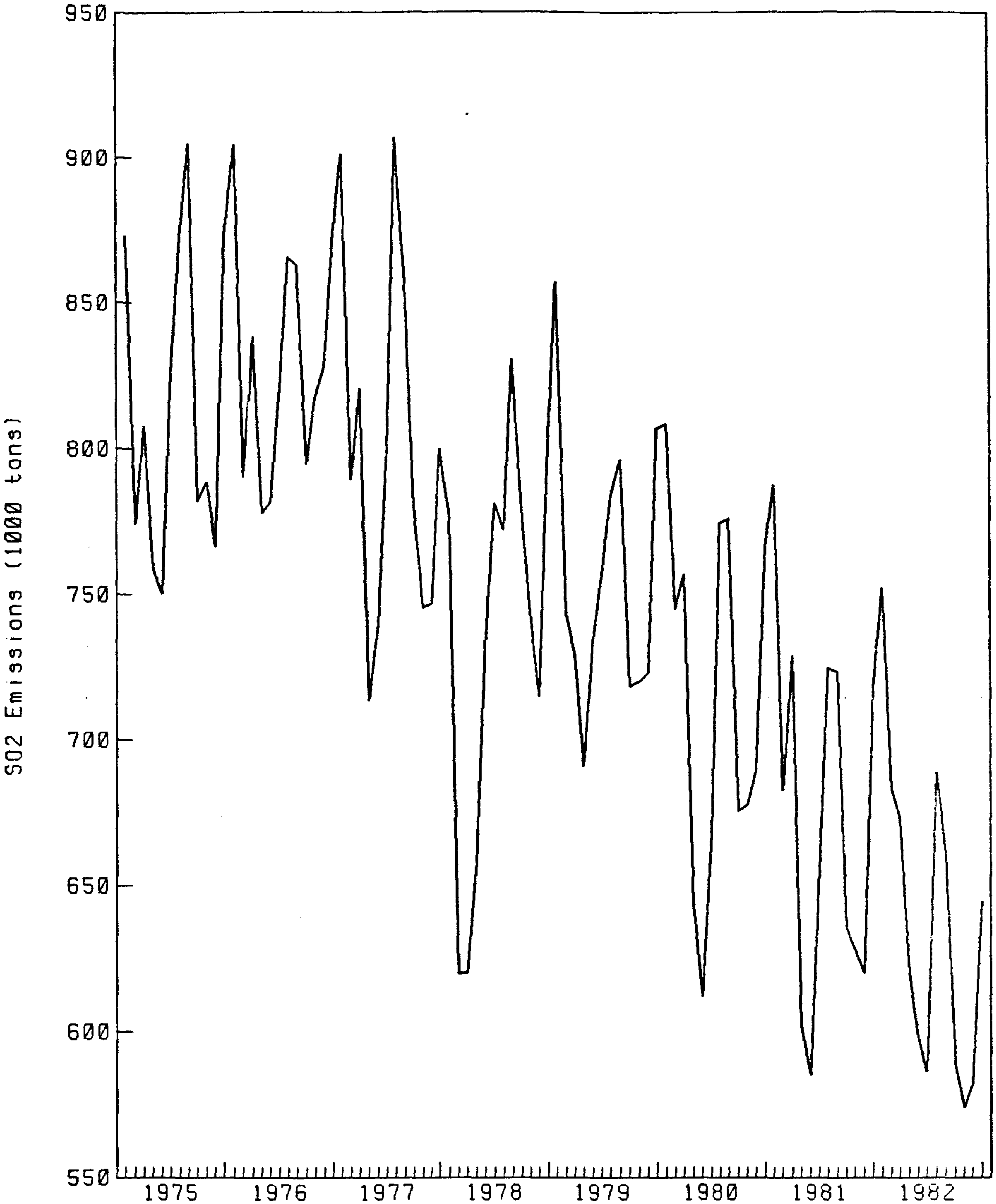

Figure 10. Monthly Total Power Plant SO2 Emissions, Ohio River Valley States, 1975 - 1982.

TABLE 10. Ohio River Valley states annual power plant SO_2 emissions and ambient SO_2 concentrations, 1975 - 1982.
(Includes Illinois, Indiana, Kentucky, Ohio, Pennsylvania, and West Virginia)

Year	Annual power plant SO_2 emissions, 1000 tons	Annual average SO_2, ppm	Annual average daily maximum SO_2, ppm
1975	9775.7	.0185	.0499
1976	9952.3	.0184	.0506
1977	9599.7	.0177	.0477
1978	8828.2	.0167	.0432
1979	9057.6	.0169	.0417
1980	8590.9	.0142	.0371
1981	8088.2	.0119	.0326
1982	7648.5	.0123	.0338

took place beginning in 1976. Monthly average SO_2 and average daily maximum SO_2 concentrations for these six states are presented in Figures 11 and 12, respectively. The SO_2 concentrations also show fairly regular seasonal cycles, with peaks occurring during the stagnant winter months; this pattern is more pronounced for mean SO_2 levels than for average daily maximum SO_2 levels.

As can be seen in Table 10, regional power plant SO_2 emissions and ambient SO_2 concentrations have decreased substantially in the region during the study period. From 1975 to 1982, total six-state SO_2 emissions from power plants decreased 22 percent, average ambient SO_2 concentrations decreased 33 percent, and average daily maximum SO_2 concentrations decreased 32 percent, indicating that emission reductions from sources other than power plants have occurred. Indeed, if 71 percent of SO_2 emissions are from power plants in the 1975 base year (as estimated by Gschwandtner and Gschwandtner, 1983, p. 692) for the entire United States, then we estimate that a 60 percent reduction in emissions occurred from 1975 to 1982 from all sources in the area other than power plants (assuming a linear relationship between SO_2 emissions and ambient concentrations).

The seasonal adjustment model applied to statewide monthly emissions and ambient SO_2 concentrations was applied to regional emissions and ambient SO_2 concentrations. The residuals from these models were then correlated. There is a correlation of 0.749 between changes in emissions from the seasonal pattern and changes in monthly average SO_2 from seasonal patterns; for monthly average daily maximum SO_2 concentrations the correlation is 0.766. Simple regression analyses reveal that an emissions decrease of 100,000 tons of SO_2 from power plants in the region in a given month from what would normally be expected for that month of the year is associated with a decrease of .031 ppb in monthly average SO_2 (from what would normally be expected for monthly average SO_2 for that month) and a decrease of .084 ppb in monthly average daily maximum SO_2 (from what would normally be expected for the month).

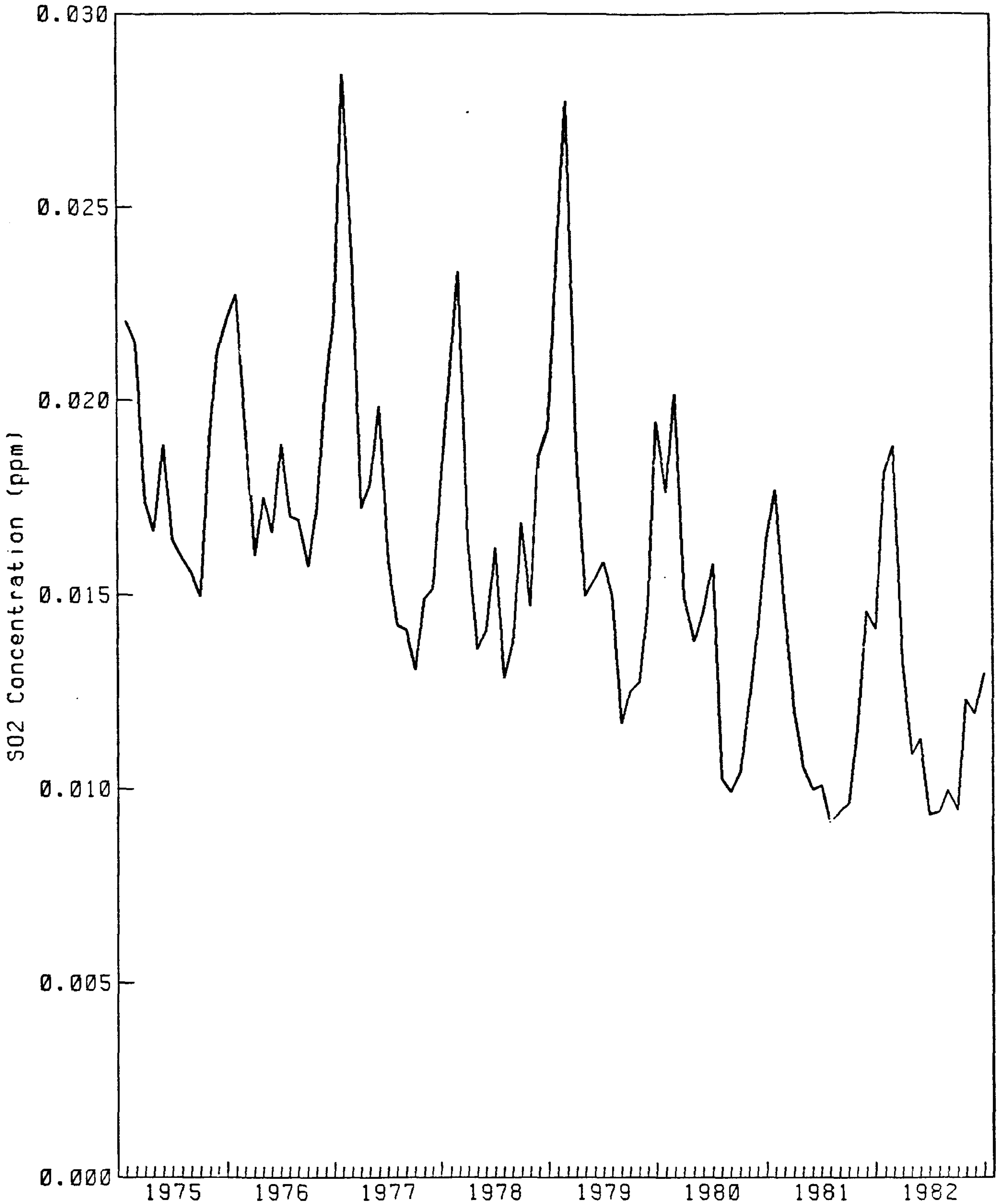

Figure 11. Monthly Average SO2 Concentrations, Ohio River Valley States, 1975 - 1982.

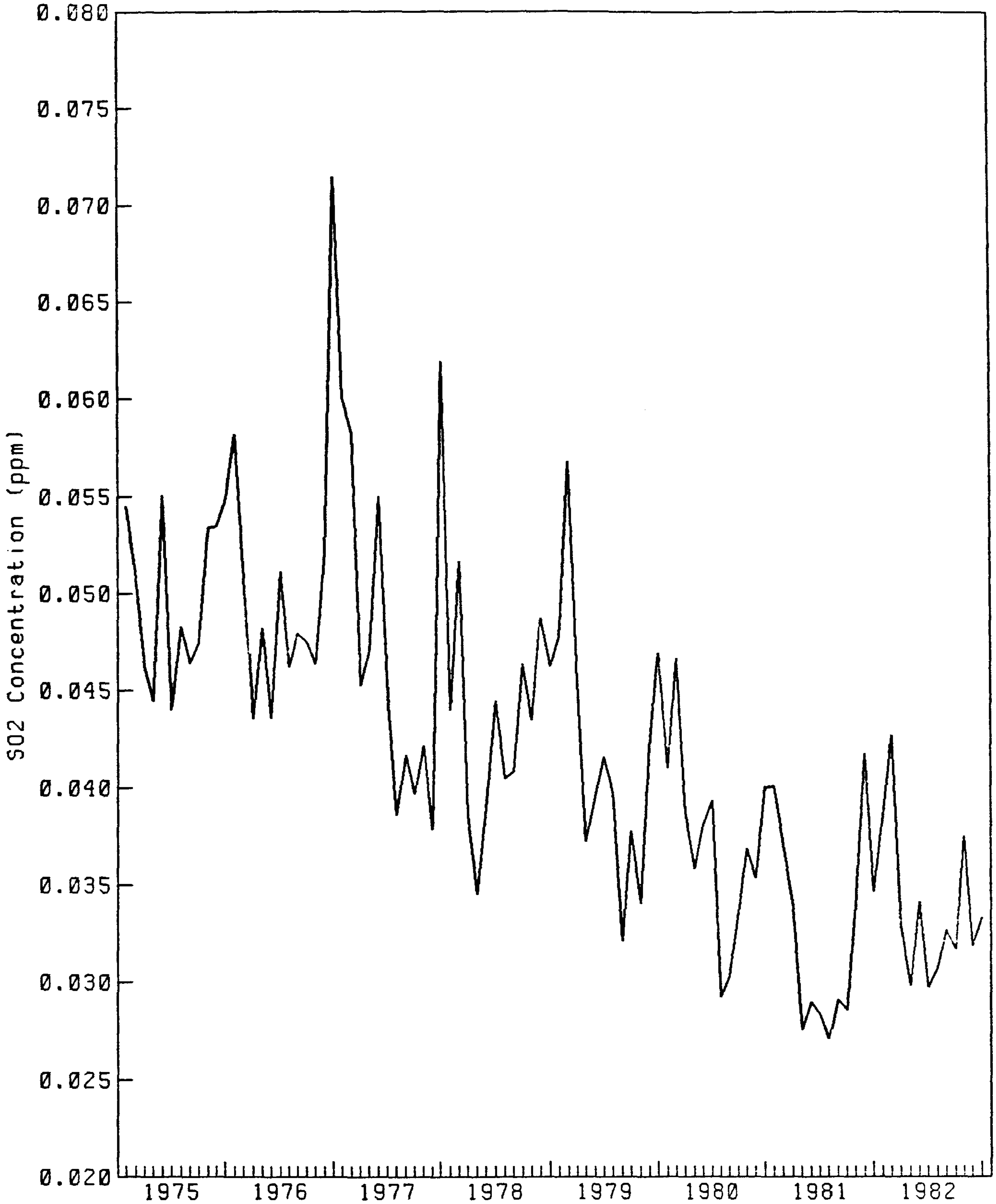

Figure 12. Monthly Average Daily Maximum SO2 Concentrations, Ohio River Valley States, 1975 - 1982.

5 SUMMARY, FINDINGS, AND RECOMMENDATIONS FOR FURTHER WORK

For this project we have constructed two large data bases that are of interest to researchers in the problems of acidic deposition. The first data base consists of estimates of sulfur dioxide emissions from the electric power industry in the northeastern United States for the years 1975 to 1982. The emissions estimates for individual plants were calculated from (1) monthly reports of fossil fuel consumption, and (2) descriptive annual reports of fuels delivered to each plant. We believe that this monthly emissions data base for individual plants is unique. The second data base consists of monthly patterns of ambient sulfur dioxide. Using data from the SAROAD system of the National Aerometric Data Branch, we calculated monthly mean and average daily maximum concentrations for all SO_2-recording monitors in the 22 northeastern states.

Examination of trends in monthly power plant SO_2 emissions and ambient SO_2 concentrations revealed seasonal patterns in both. Emissions of SO_2 from power plants peak during the summer cooling season and the winter heating season, whereas ambient SO_2 peaks during the stagnant winter months, with some evidence of a secondary summer peak. Substantial decreases in both emissions and ambient SO_2 occurred during the 1975-to-1982 study period. For example, annual power plant emissions from the heavily industrialized six-state Ohio River Valley region decreased 22 percent from 1975 to 1982, and annual average ambient sulfur dioxide in the region decreased 32 percent during the same period.

Correlations between power plant SO_2 emissions and ambient SO_2 were also examined. Because emissions and ambient SO_2 exhibit regular seasonal patterns, but not the same seasonal patterns, emissions and ambient SO_2 trends were seasonally adjusted before correlations were examined.

Correlations were then calculated at the local, state, and regional levels. In general, the higher is the level of aggregation, the higher are the observed correlations. Our conclusions from examination of a select set of individual power plant and SO_2 monitor pairs are as follows:

(1) Correlations are highest for point-source monitors near large power plants;

(2) Correlations between monthly emissions from power plants and monthly average daily maximum SO_2 concentrations are somewhat higher than correlations between monthly emissions and monthly mean SO_2 concentrations;

(3) Correlations between power plant emissions and ambient SO_2 concentrations are improved when the monthly data are aggregated to yearly averages; and

(4) Correlations between power plant emissions and ambient SO_2 concentrations are higher when just the subset of summer months is considered relative to all months. This is a period in which emissions are high and mixing of emissions from elevated sources is greatest.

At the state level, correlations between seasonally adjusted power plant SO_2 emissions and ambient SO_2 concentrations vary. In general, higher correlations are observed in those states with higher levels of emissions. The calculated correlations are affected by the availability of ambient SO_2 monitoring data--e.g., in a given state the number of operating monitors can vary greatly across time; monitors are not evenly distributed but rather are centered in urban industrialized areas; and most monitors, even if operating during the entire study period, have many periods of missing data.

Correlations are highest at the regional level, where the greatest amount of aggregation was performed. In the six-state Ohio River Valley region, the correlation between seasonally adjusted monthly power plant emissions and seasonally adjusted monthly average ambient SO_2 was 0.749. With a simple regression analysis, we calculated a decrease of 0.031 ppb average SO_2 concentration for a 100,000 ton decrease in SO_2 emissions in the region.

Since most of our work effort consisted of constructing the heretofore nonexistent data bases of monthly power plant emissions for individual plants and monthly summary statistics for individual SO_2 monitoring stations in the 22 northeastern states, data bases of sulfate concentrations (or a surrogate measure such as visibility) and sulfate emissions in the area need to be compiled, and available acid precipitation measurements need to be acquired. We feel that we have only begun to analyze the needed data bases, and therefore have recommendations for further analysis of these data bases.

The ambient SO_2 data base is considerably complicated by the irregular periods of data measured by the existing monitors, and by the different times when the monitors began recording. One possible solution is to use only long-term monitors with a minimum amount of data each month or each year. Another possibility is to construct weighted averages, where the weights are proportional to the amount of data available for a monitor in a given month. Two possible methods can be used to account for the heavy concentration of SO_2 monitors in industrialized urban areas. One calculates a weighted average of monitors in a given geographical area where the weights are evenly distributed among urban, suburban, and rural areas; the other calculates separate averages for urban, suburban, and rural areas. Spatial averaging techniques, such as Kriging, two-dimensional moving averages, and two-dimensional splines, can also be applied to the monitoring data to down-weight monitors that occur in clusters.

The emissions data base consists of SO_2 emissions from power plants only. Although the majority of SO_2 emissions occur from power plants, we do not know the extent to which SO_2 emission trends in the power plant sector are the same as those from other sources. It would be useful to estimate monthly SO_2 emissions from other sources and then examine trends in total SO_2 emissions. Many studies have estimated annual SO_2 emissions from sources other than power plants (e.g., Gschwandtner and Gschwandtner, 1983); these annual estimates can be disaggregated into monthly estimates and added to our monthly emissions for specified geographical areas. In addition, because ambient SO_2 concentrations in certain parts of the northeastern United States are affected by Canadian sources, it would be useful to include in the data base monthly estimates of Canadian emissions, especially those from southeastern Ontario.

It is often postulated that shorter stacks are associated with local impacts and that taller stacks, through long-range transport, are associated with regional impacts over larger areas downwind of the stacks. In our emissions data base, we did not consider stack height because of project resource constraints. It would be useful, then, to apportion emissions from each power plant by stack height. One difficulty to overcome in carrying out this analysis arises in associating fuel consumption data reported by the electricity generating unit with the appropriate stacks at each plant.

Many additional statistical analyses can be performed on the SO_2 emissions and ambient SO_2 data bases. For example, time series analyses can be used not only to seasonally adjust trends but also to relate trends with different seasonal patterns. Regression analyses can be used to relate emissions from multiple sources to ambient SO_2 recorded at one monitoring station. In addition, principal components analysis and canonical correlation are two techniques that can be applied to sets of emissions sources and SO_2 monitors to determine relationships among them.

A key question that we have not attempted to answer in our analyses is that of data requirements for detecting relationships. For example, how are the emissions data and ambient SO_2 data best utilized to detect associations, and what improvements, if any, can or need to be made to the data bases? Also, once a relationship, linear or nonlinear, has been detected, how is variability in the estimated degree of strength of the relationship best estimated, considering the many sources of variability in the data bases?

Finally, one of the most obvious research efforts to follow is that of studying trends in acid precipitation data and relating them to trends in emissions and acid precipitation precursors. Many acid precipitation monitoring networks are currently operating throughout the northeastern United States, some have been in operation for most of the 1975-1982 study period. Such monitoring networks are operated by the U.S. Geological Survey, National Acidic Deposition Program, and the Utility Acid Precipitation Study Program. Analysis of acid precipitation data, however, must proceed carefully, for it is necessary to take into account not only different sampling schedules (e.g., bulk monthly collection versus event-only collection), but also different measurement methodologies and site locations.

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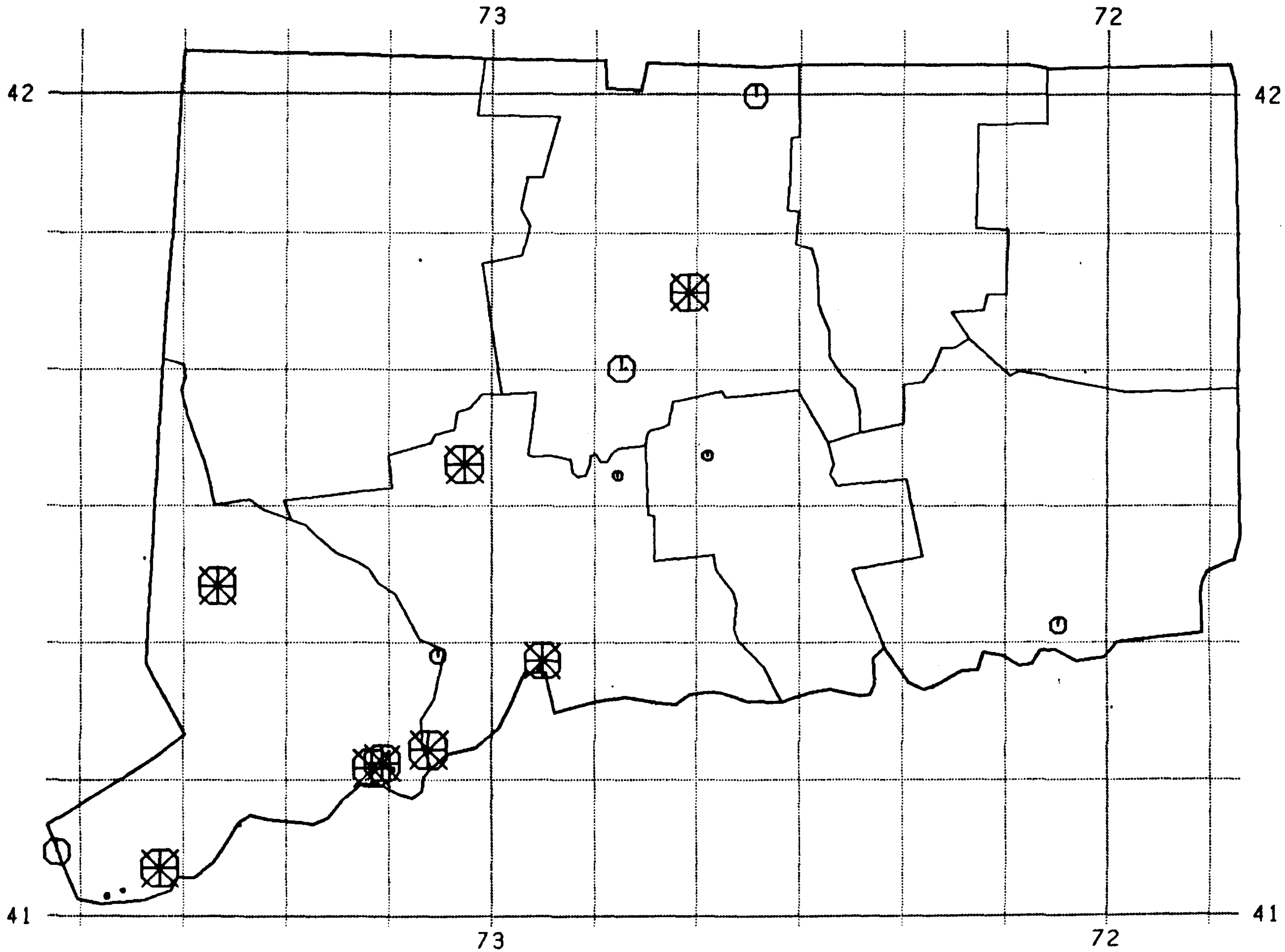
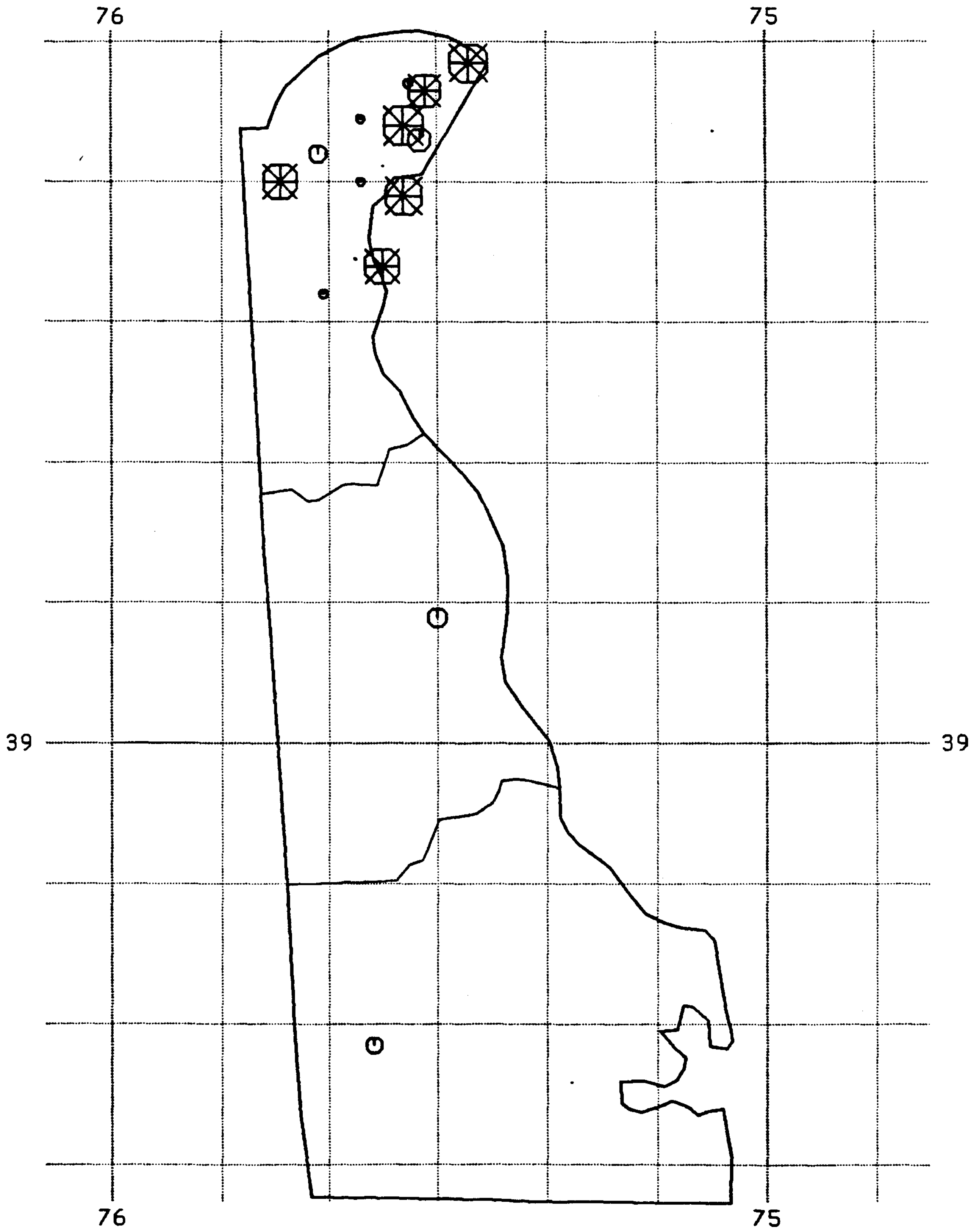


Figure A1. Connecticut SO_2 Monitoring Sites



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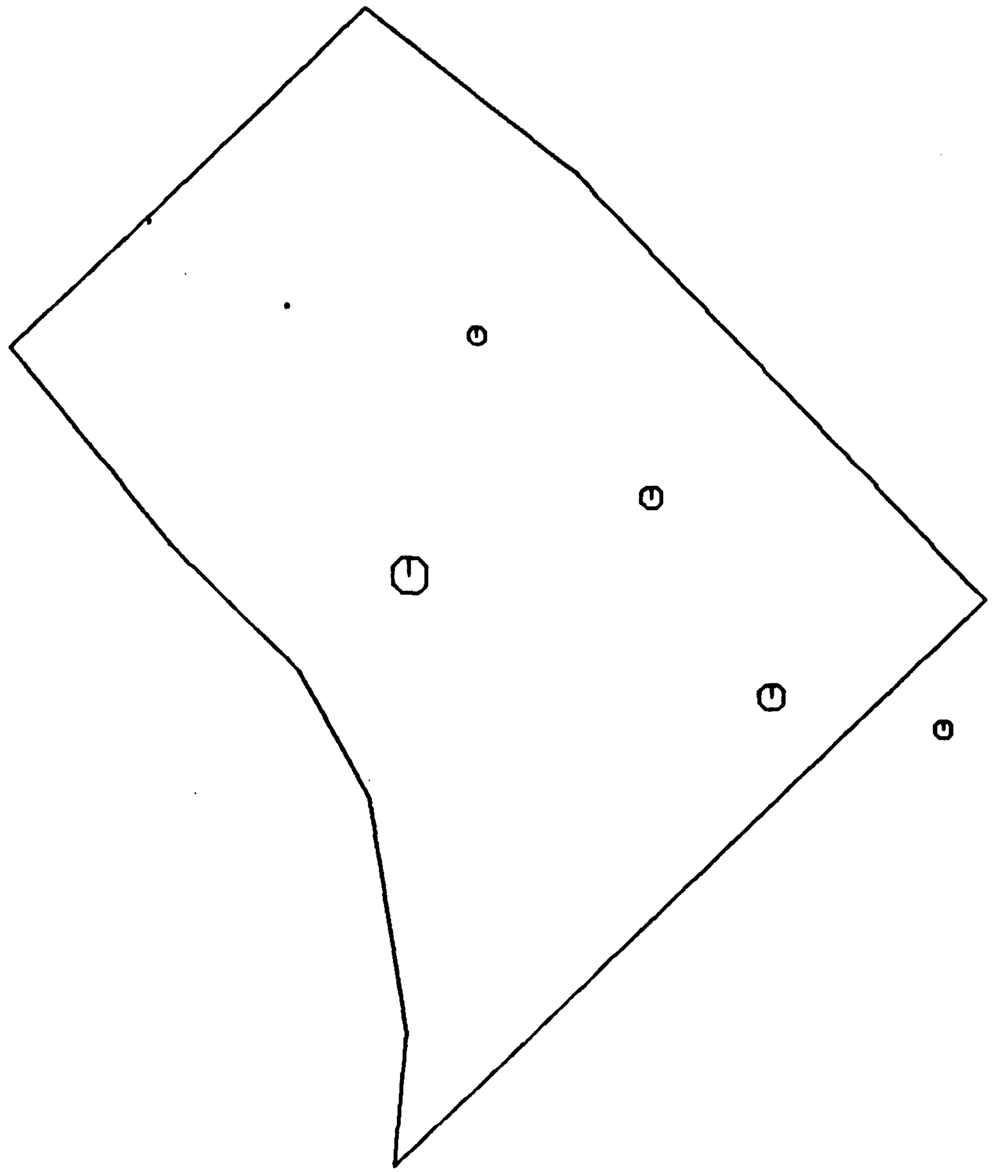

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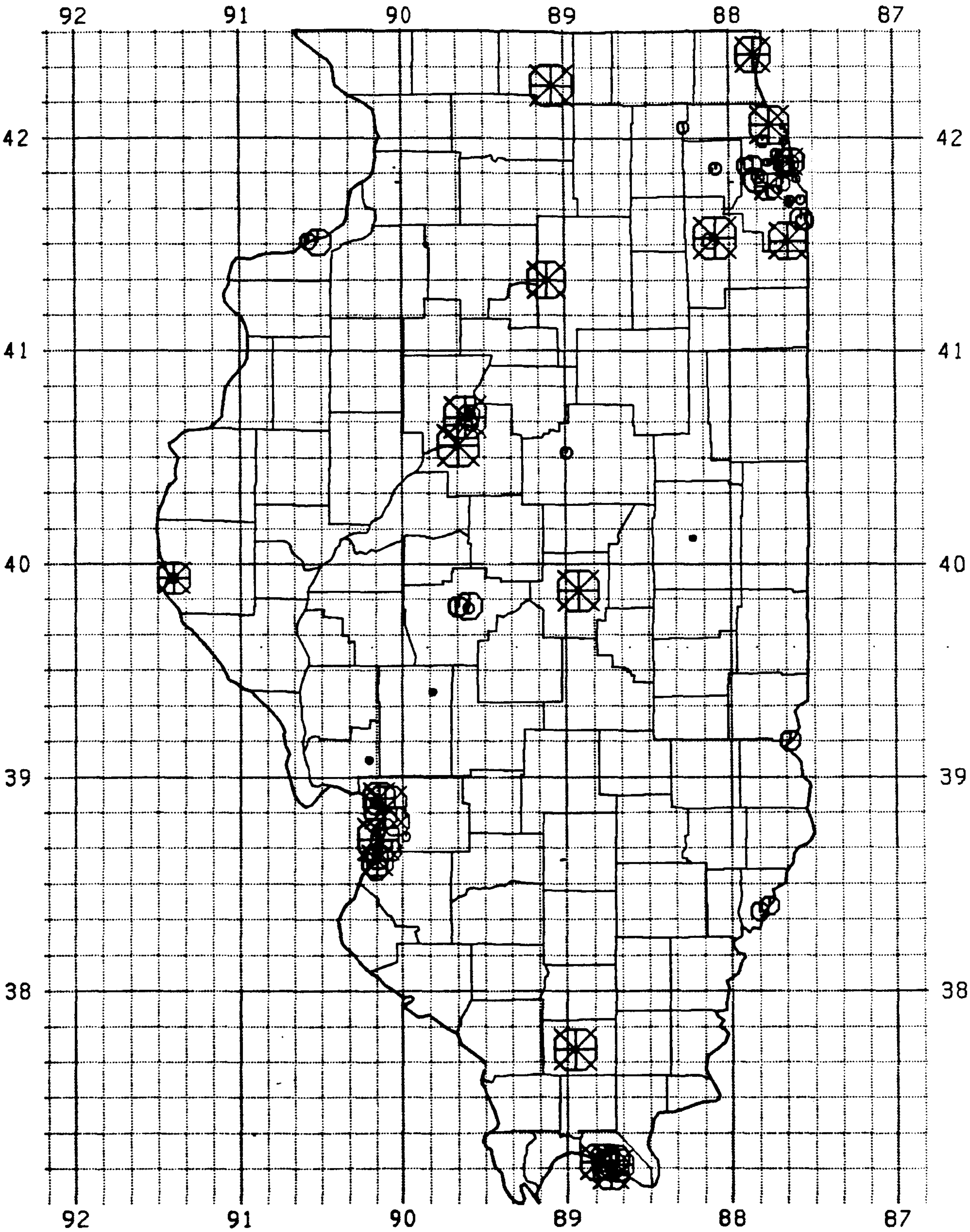

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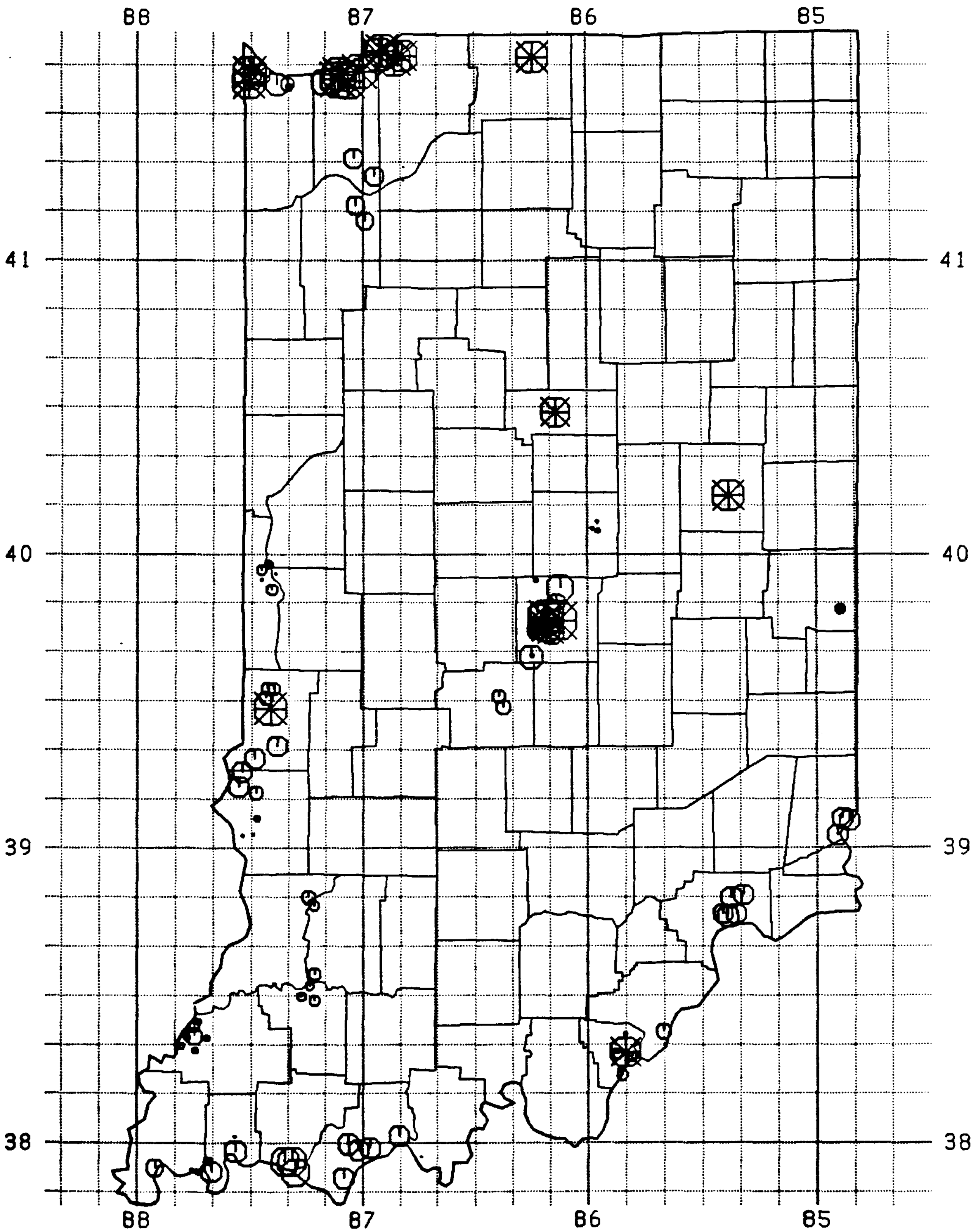

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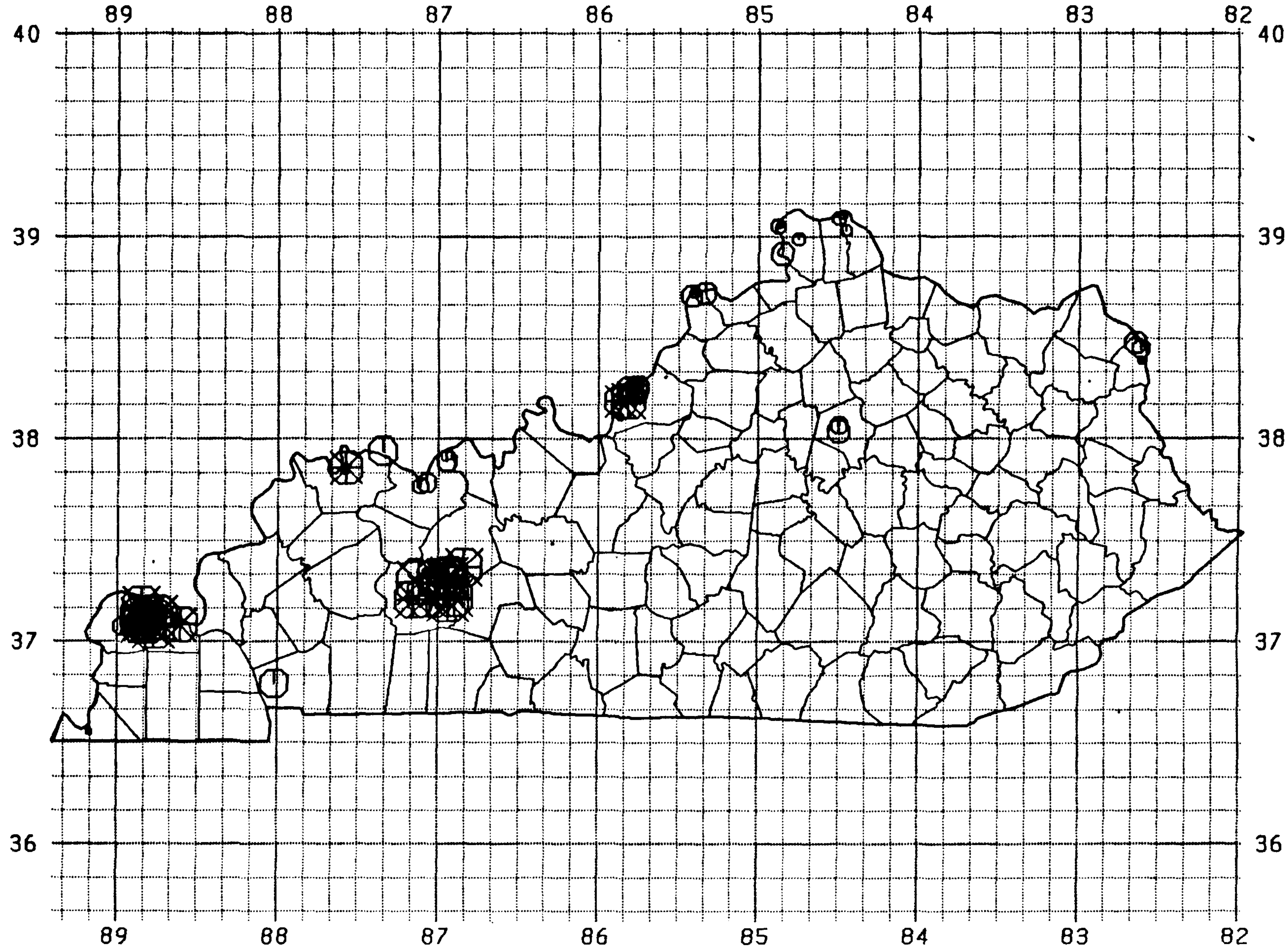

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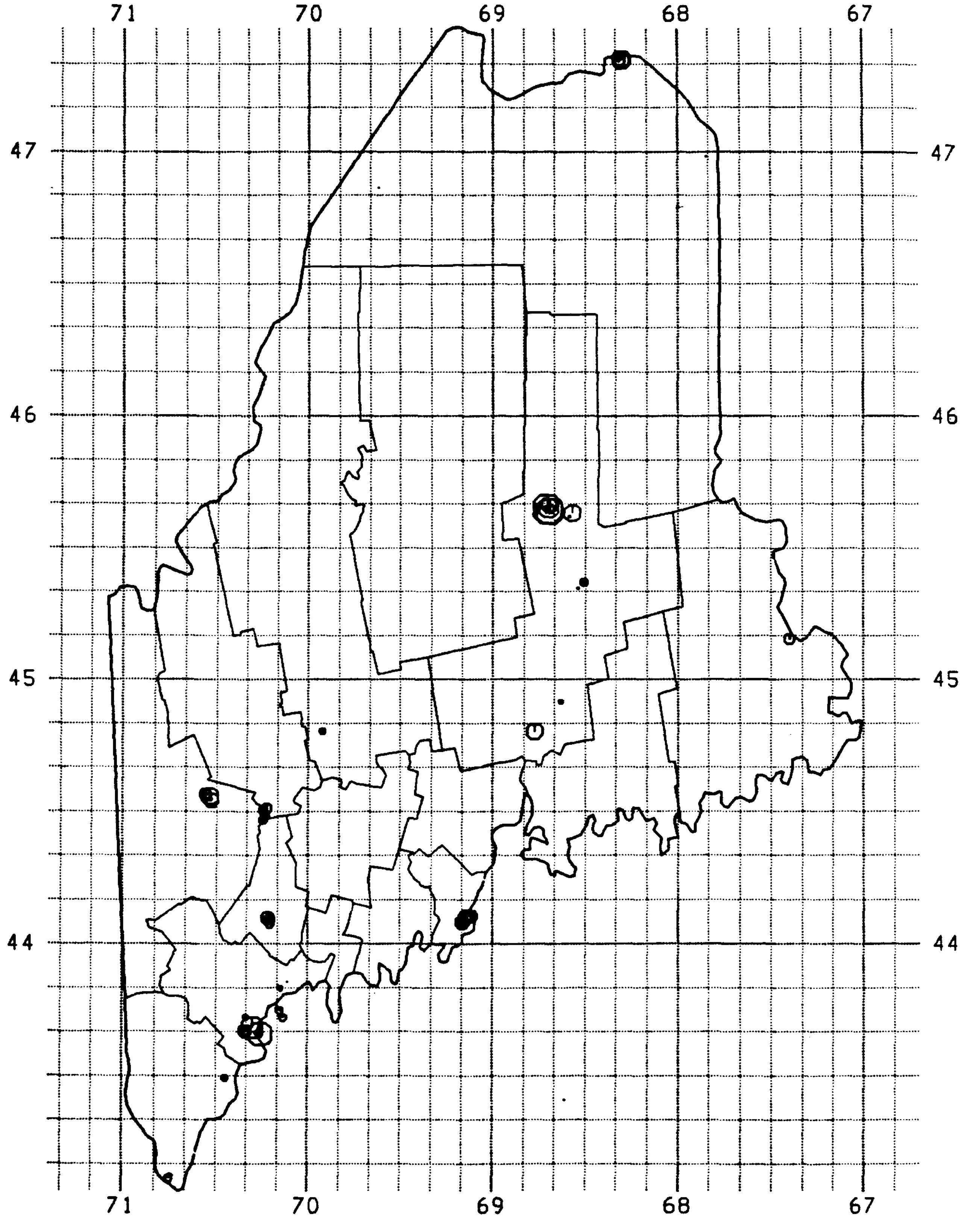

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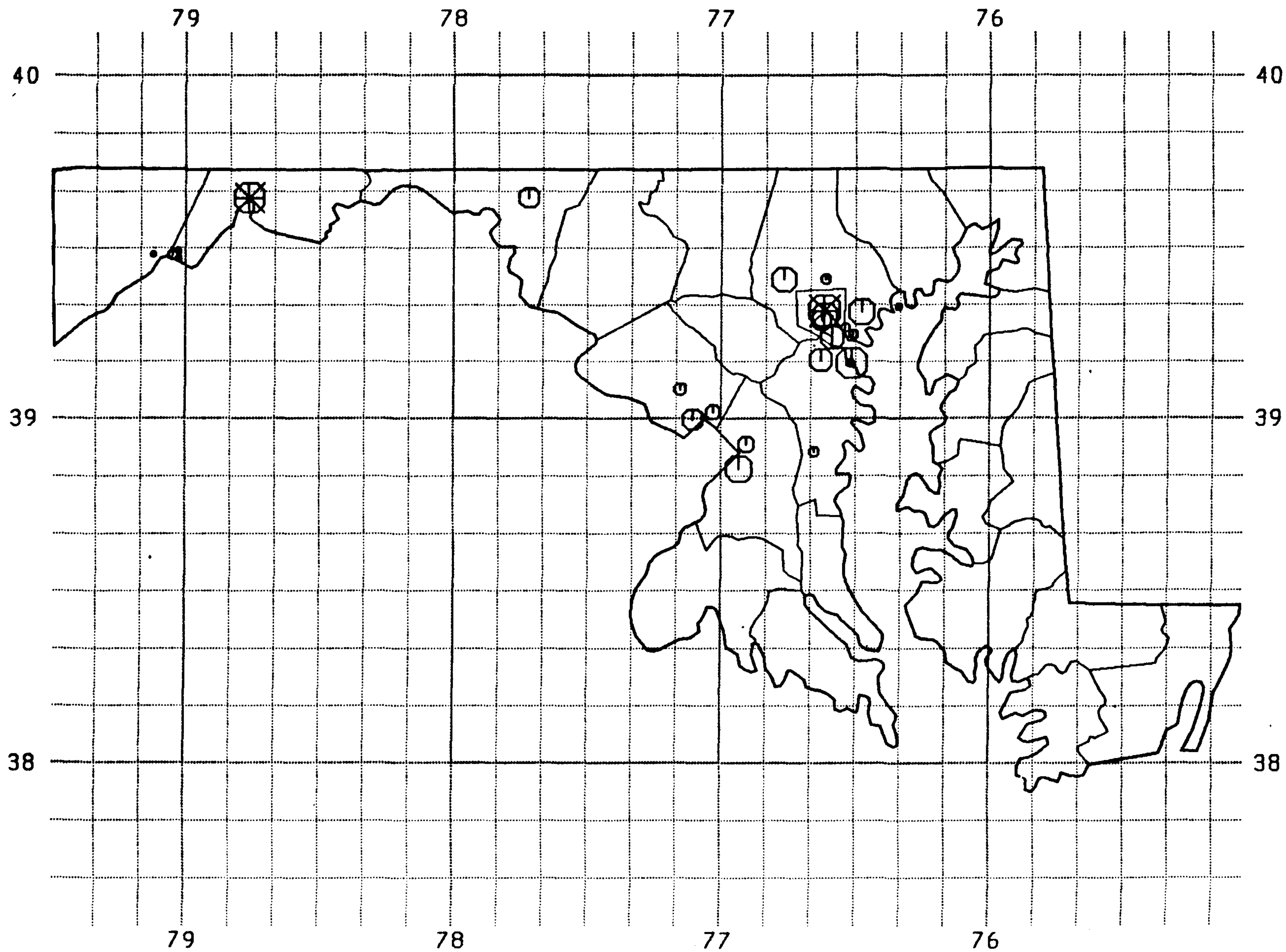

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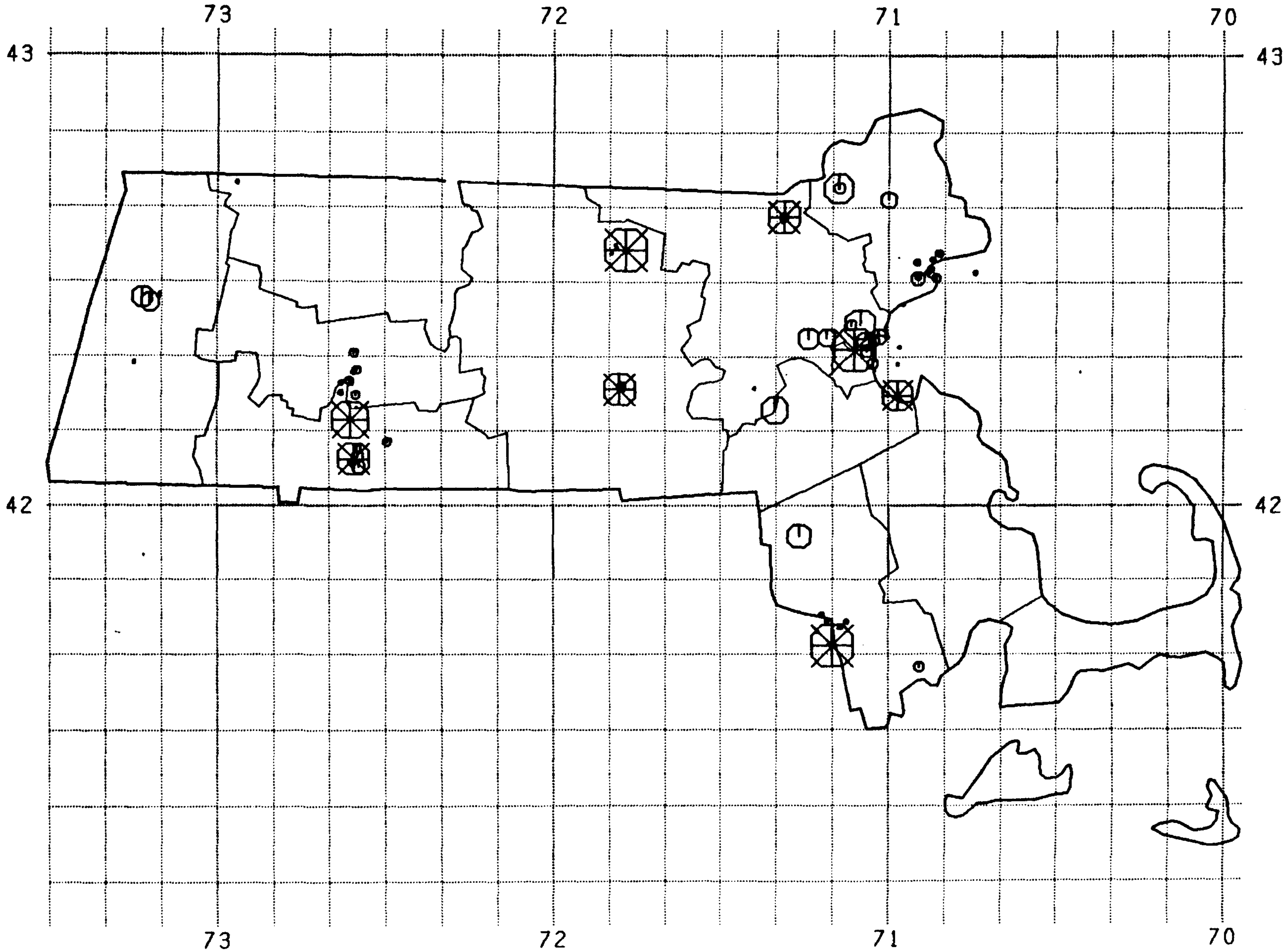

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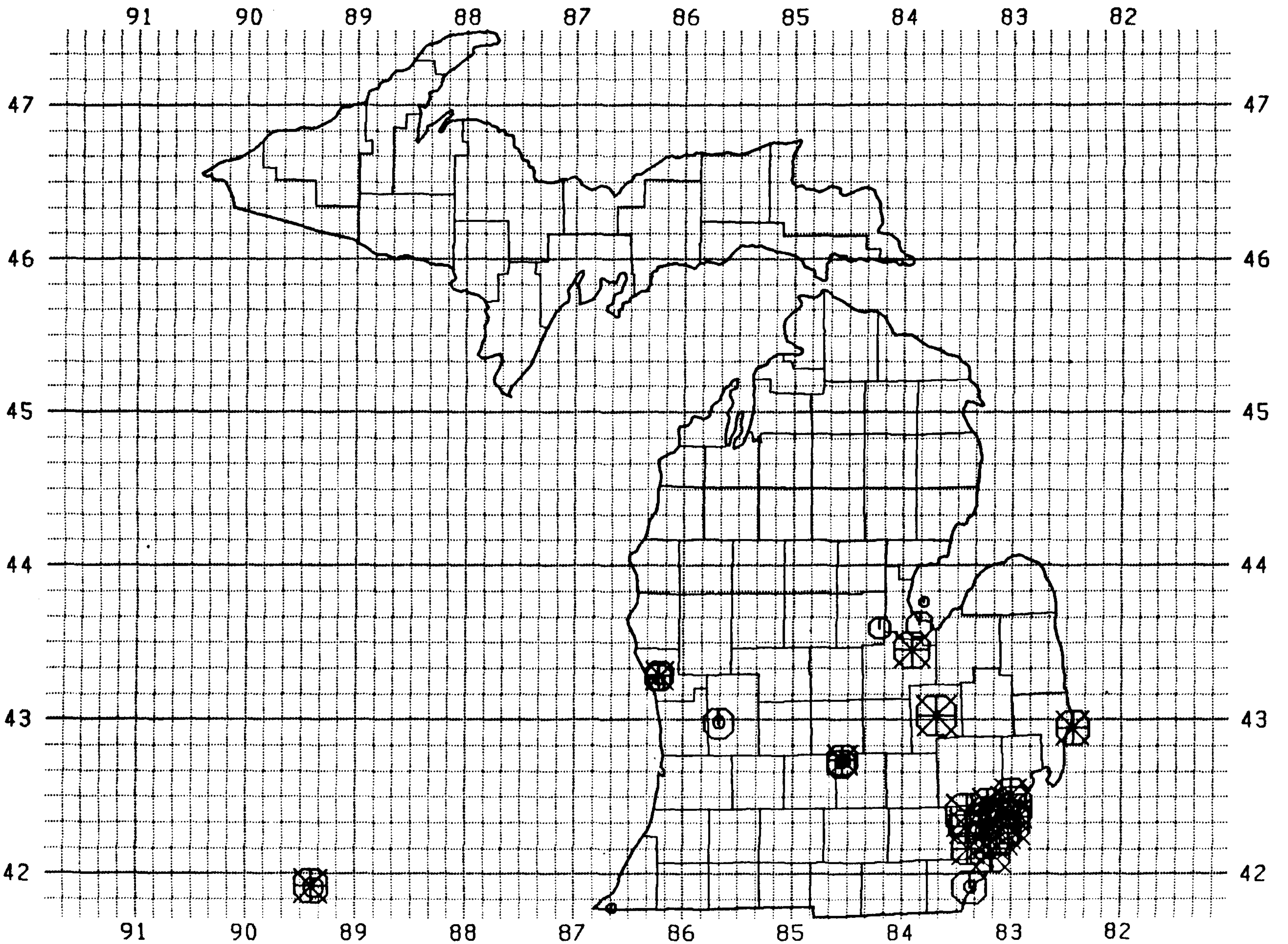

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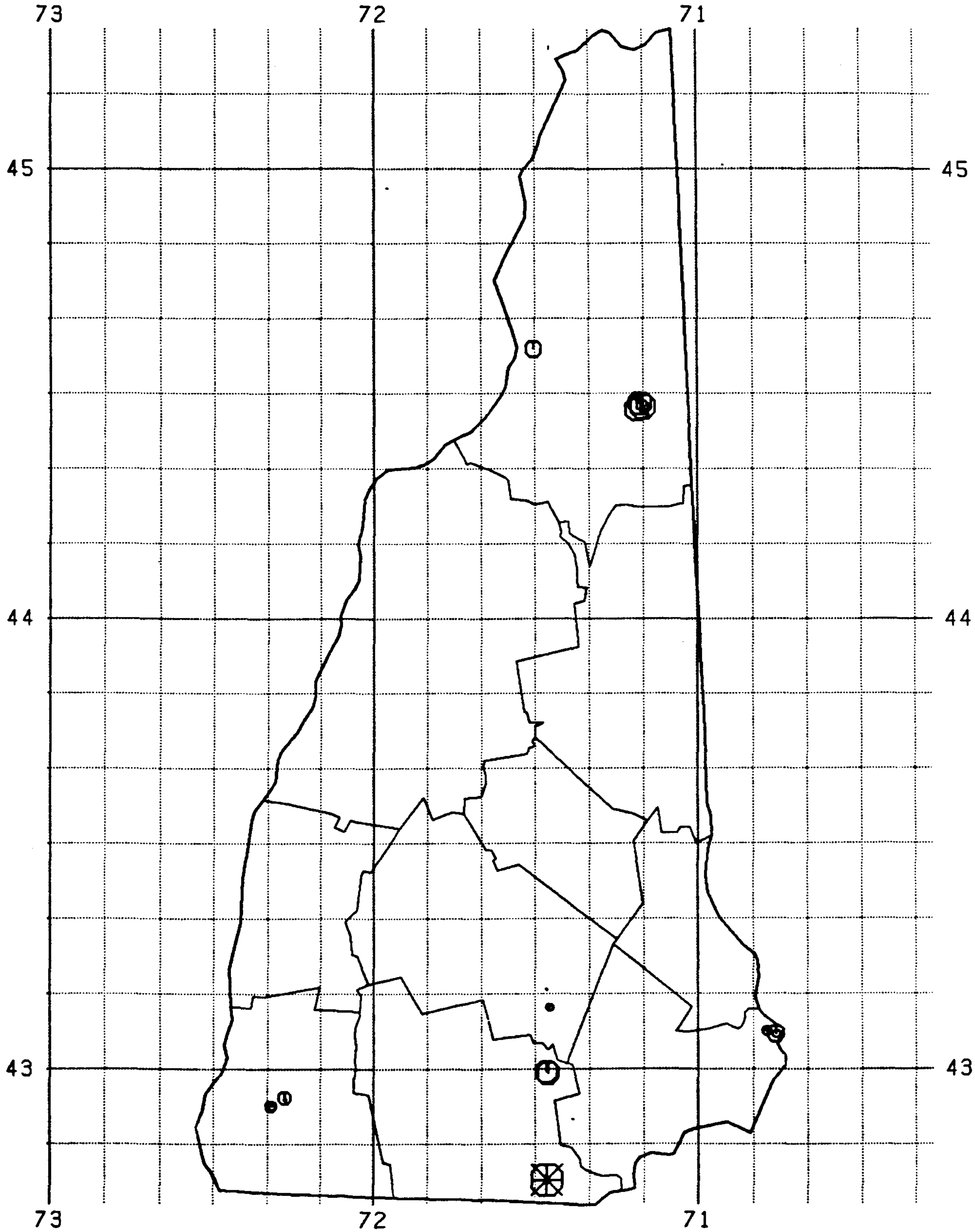

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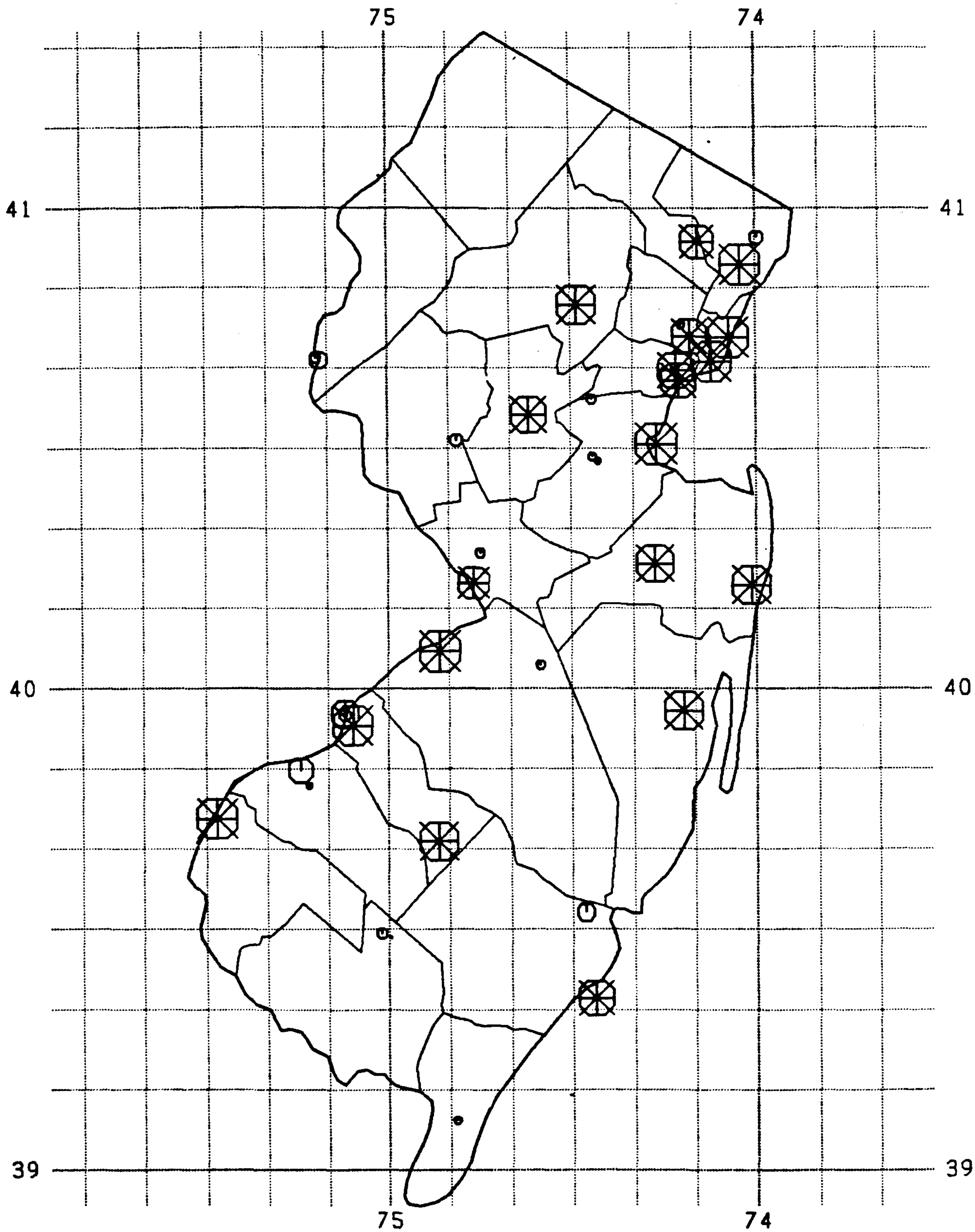

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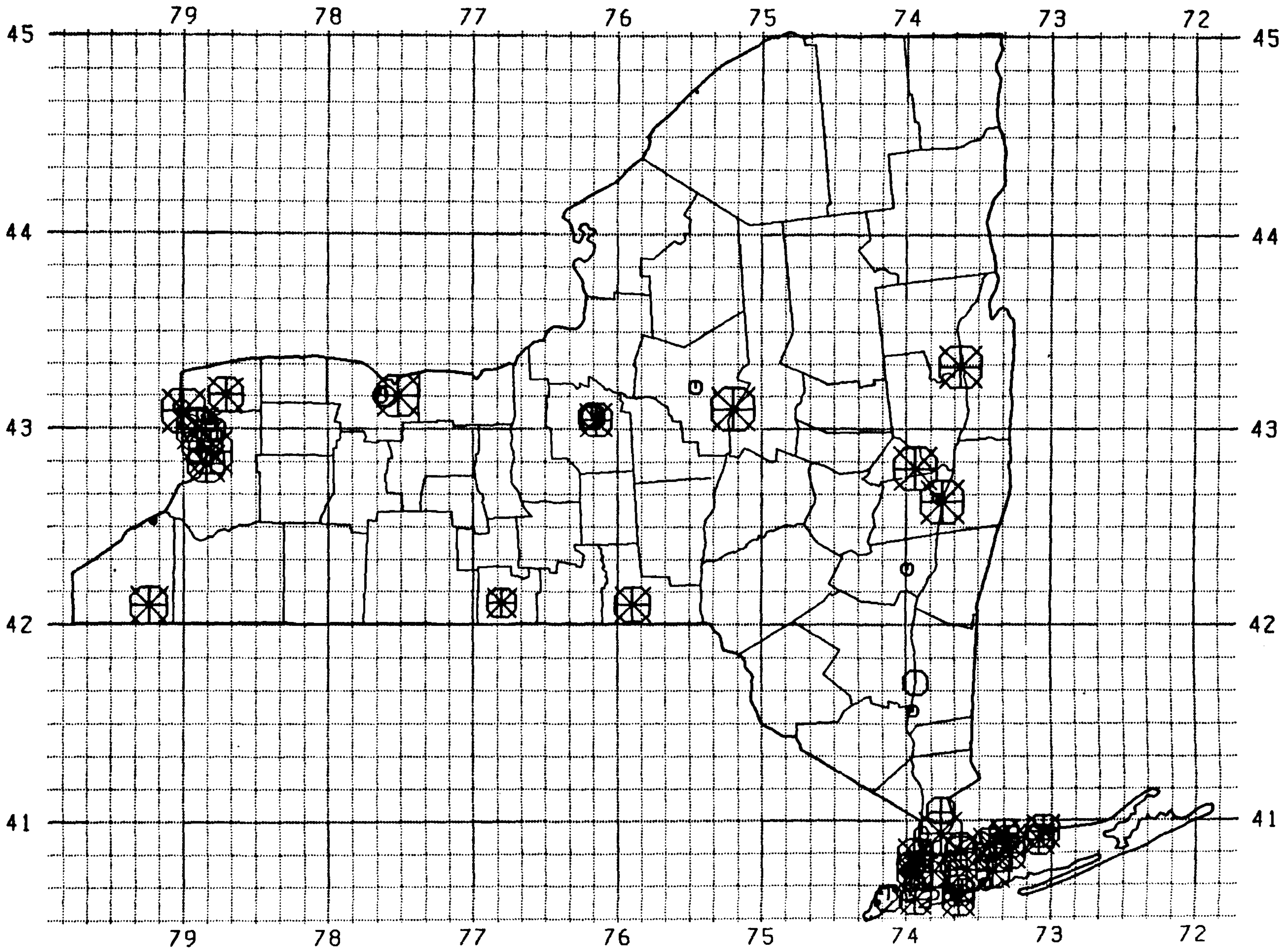

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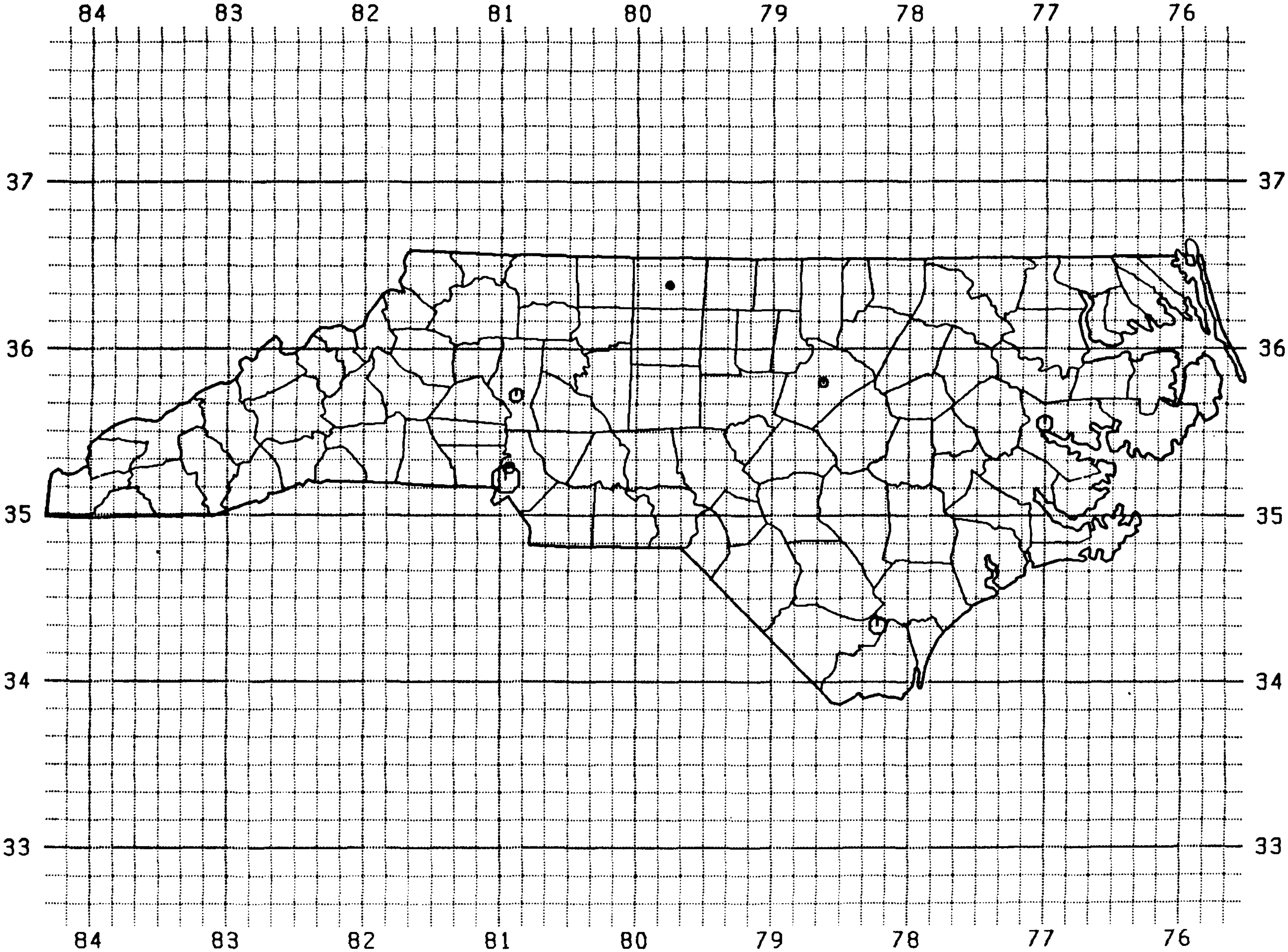

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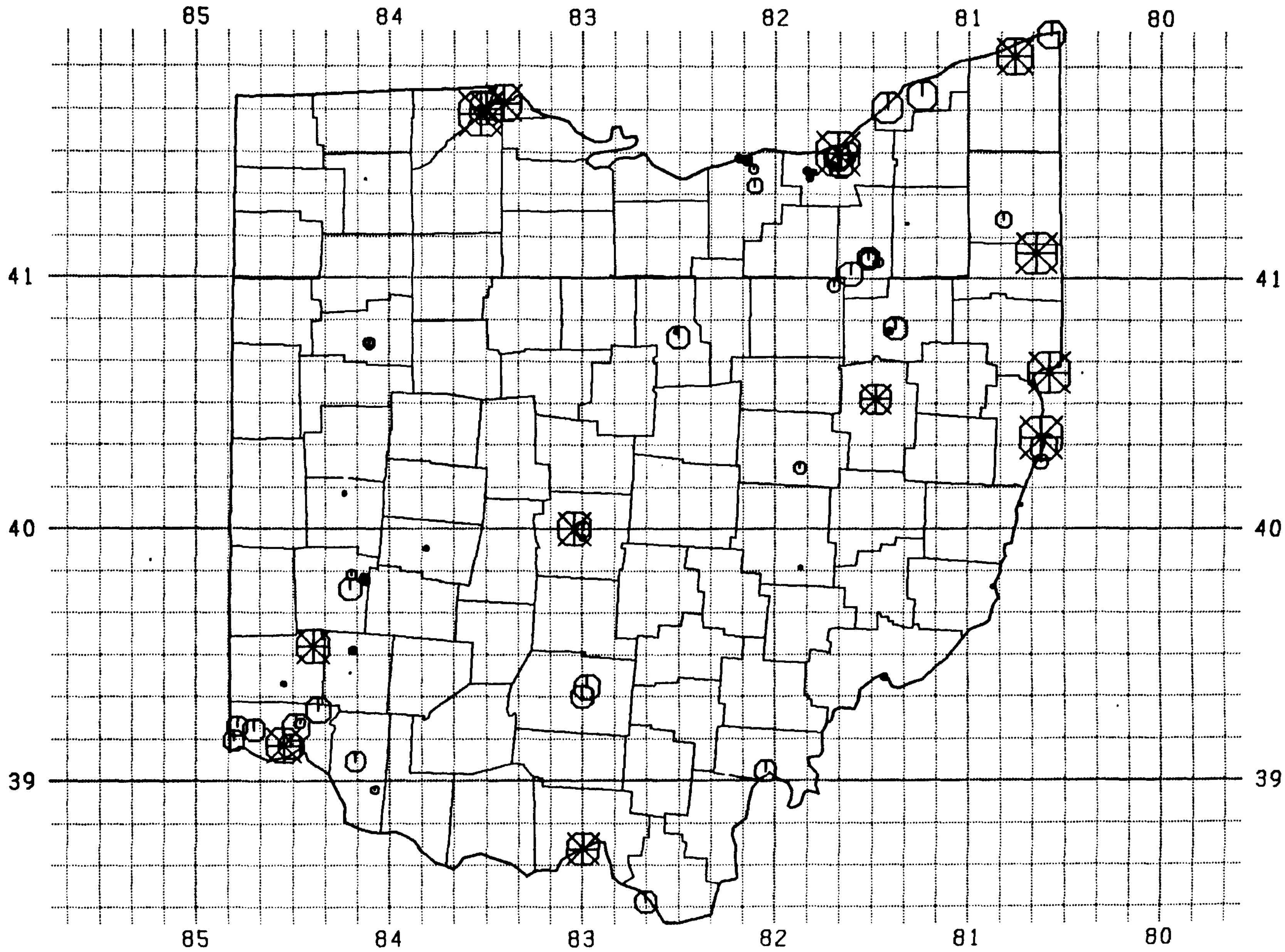

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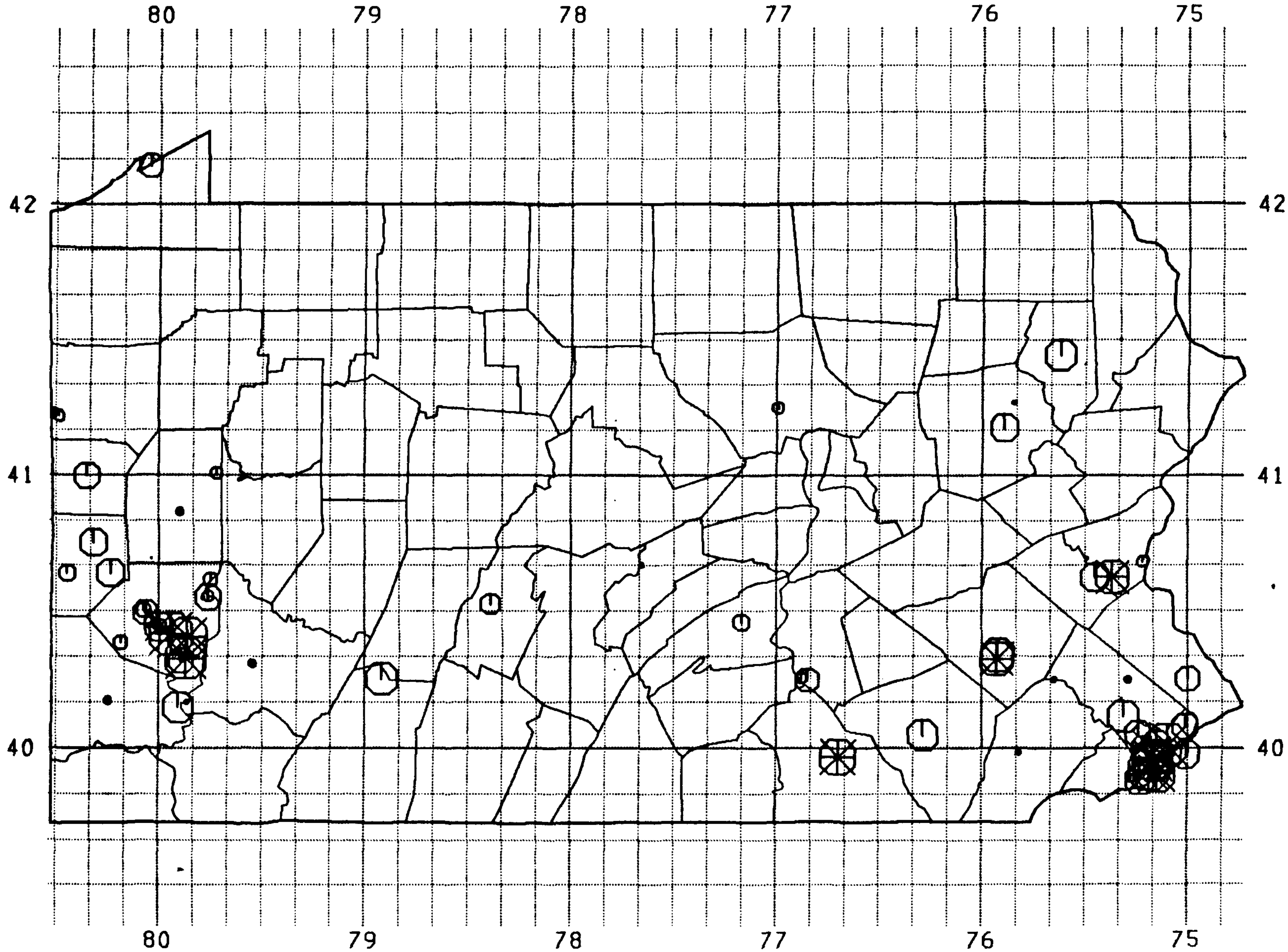

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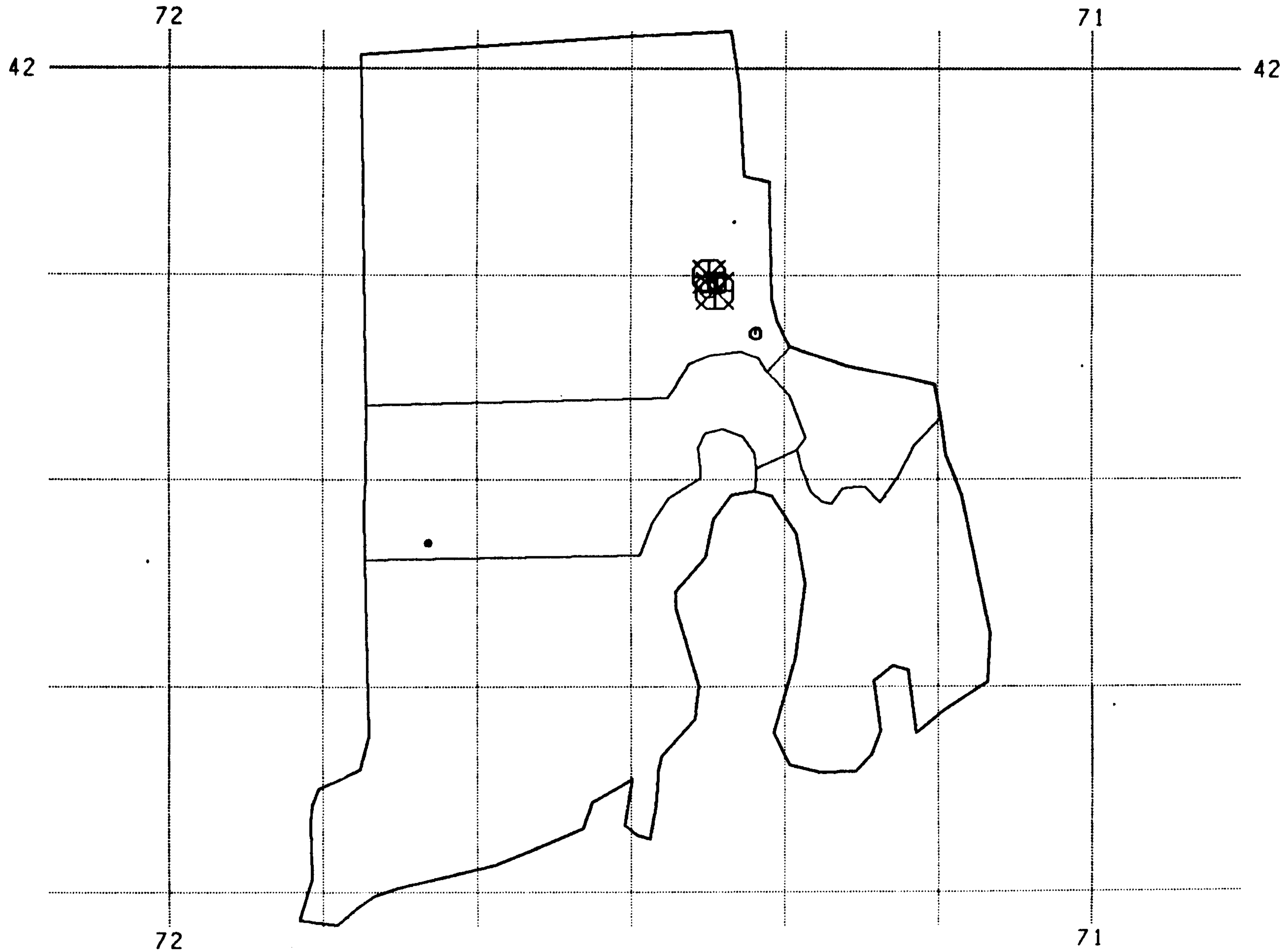

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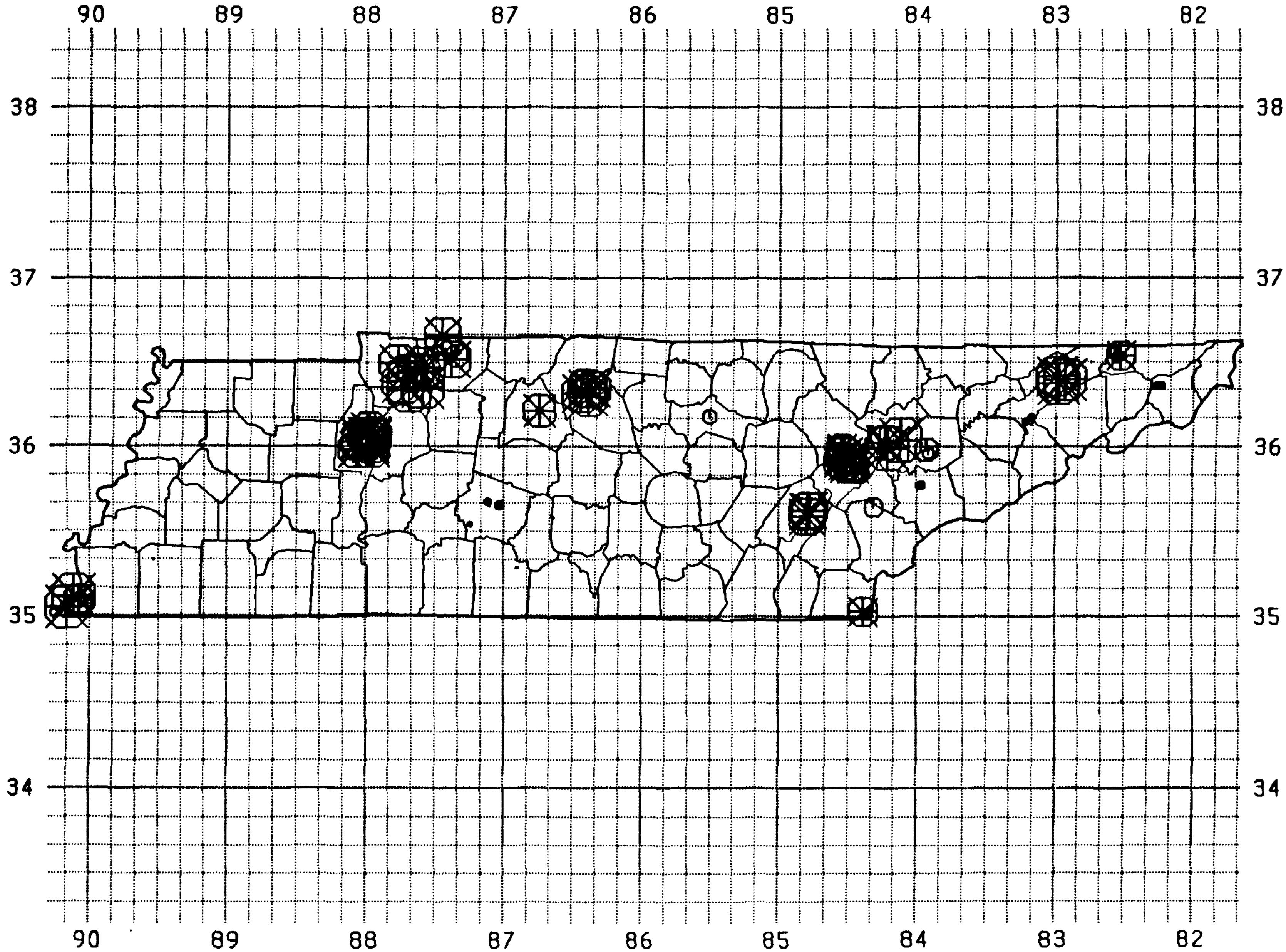

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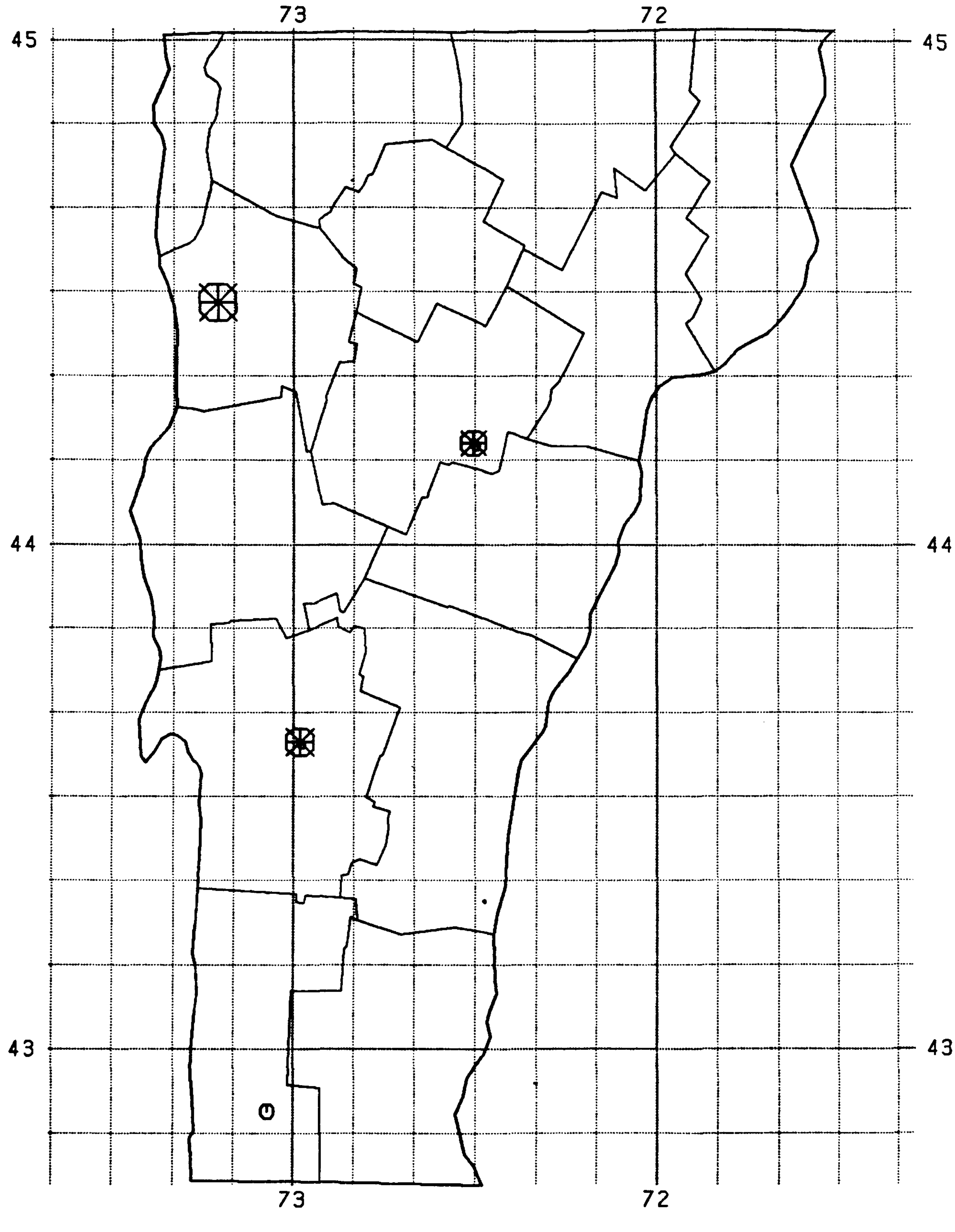

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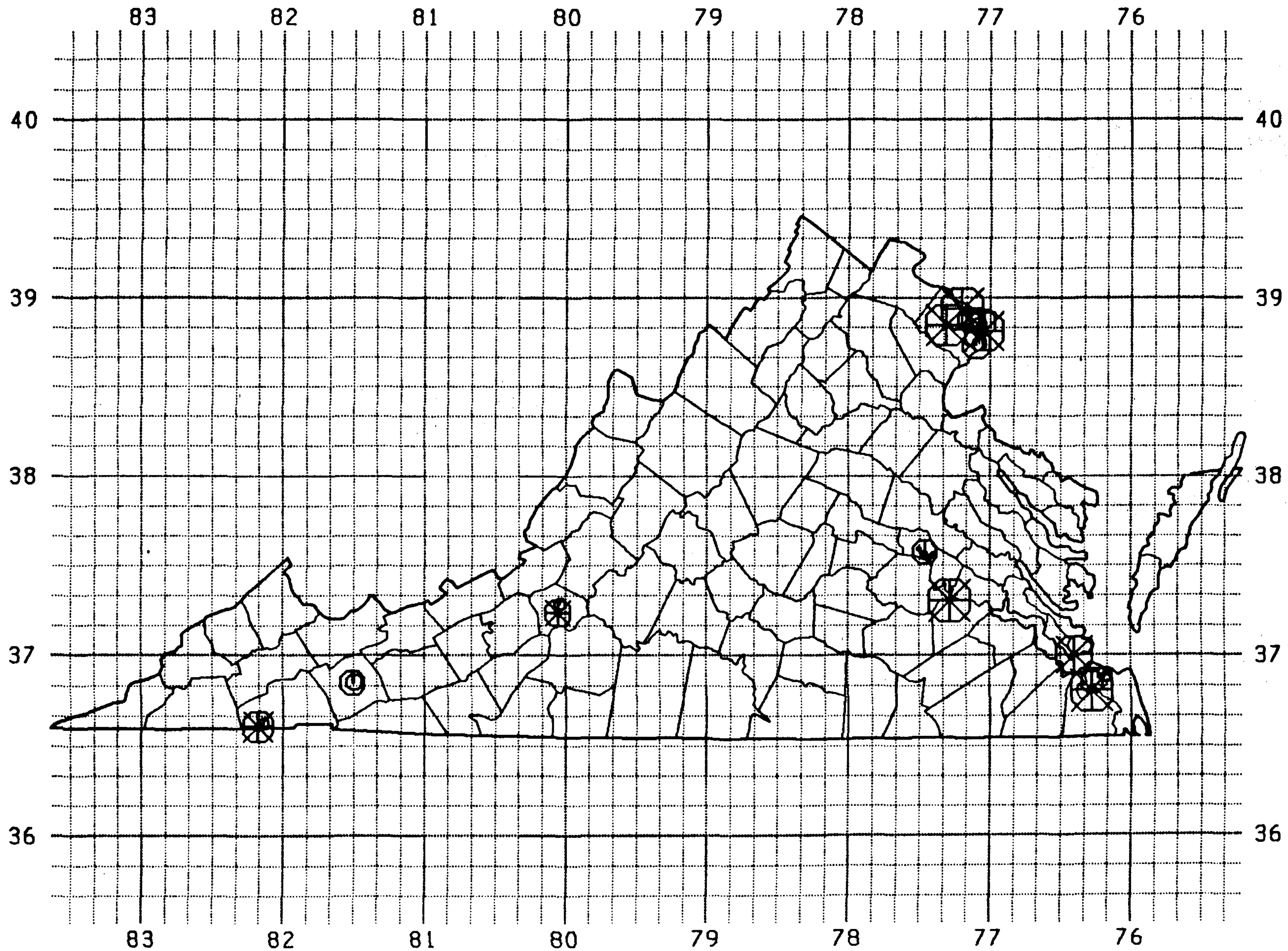

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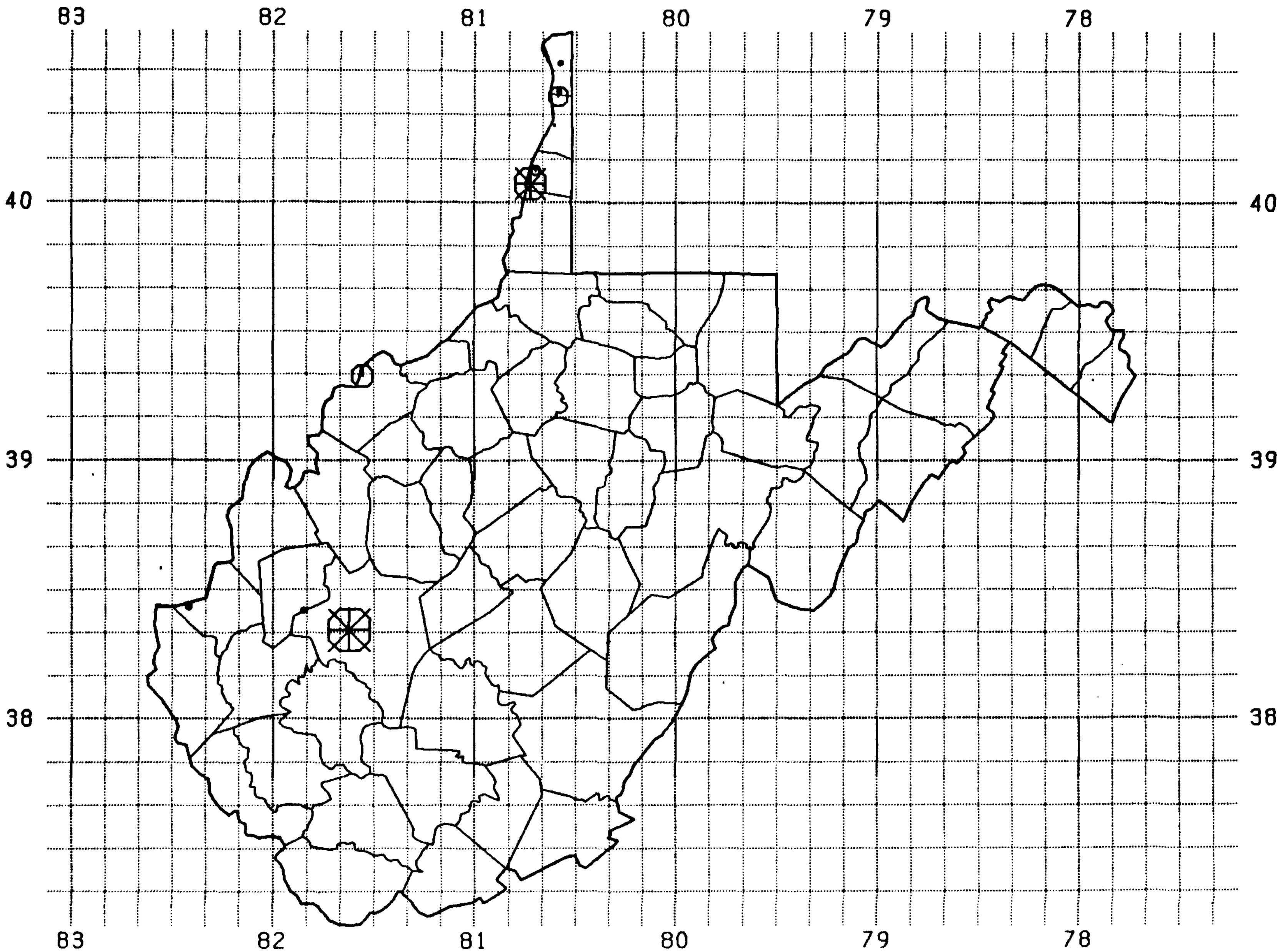

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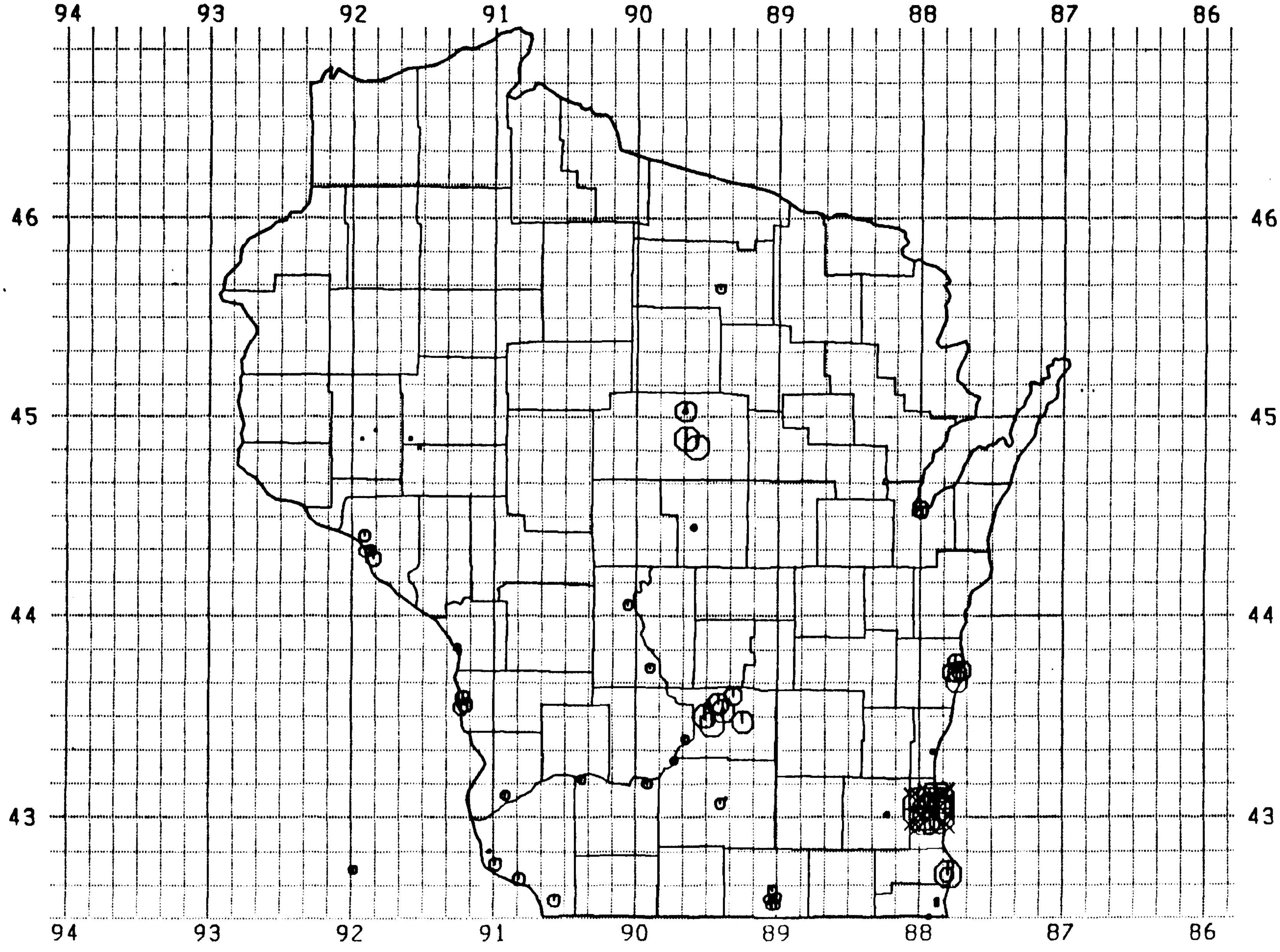

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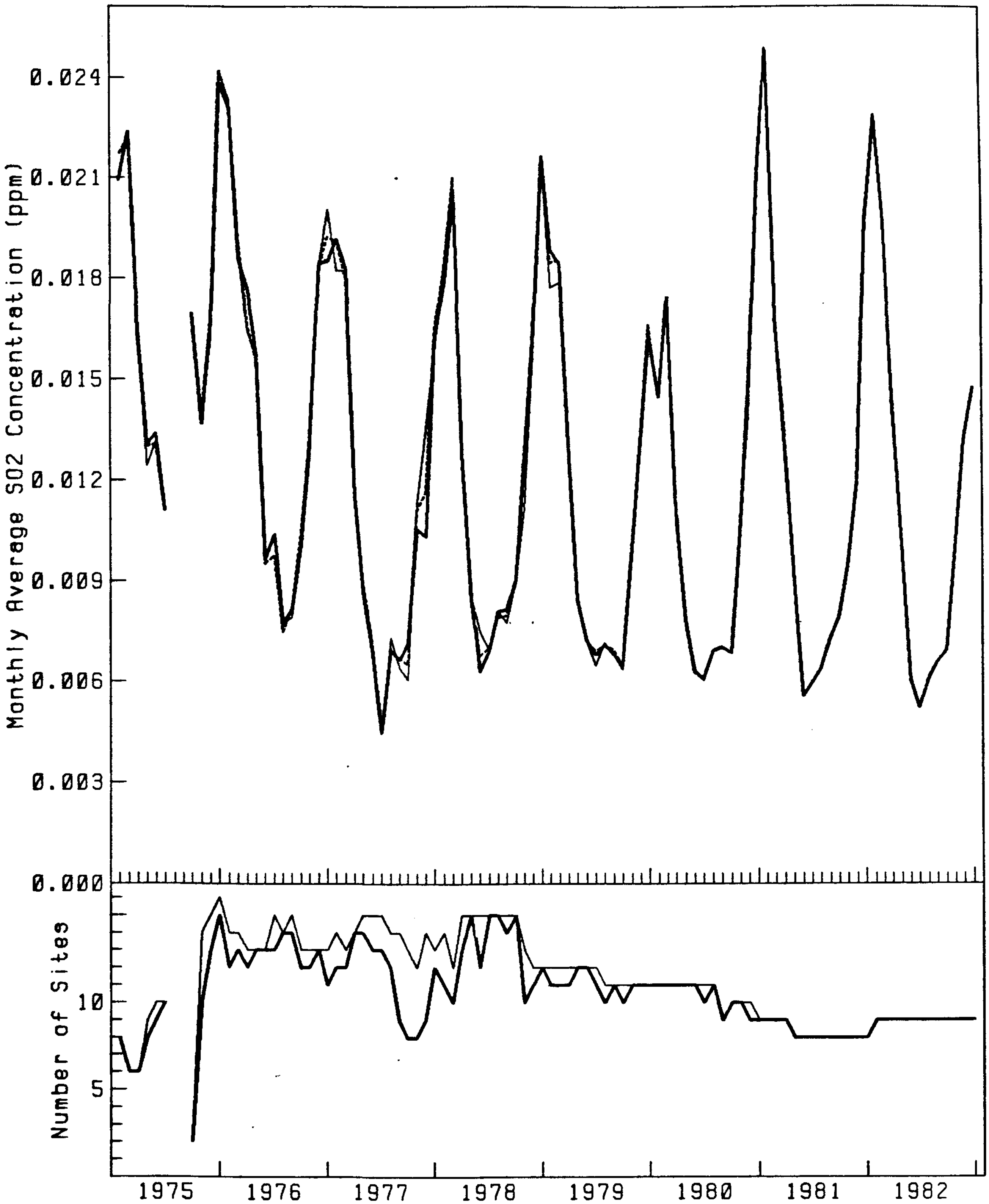
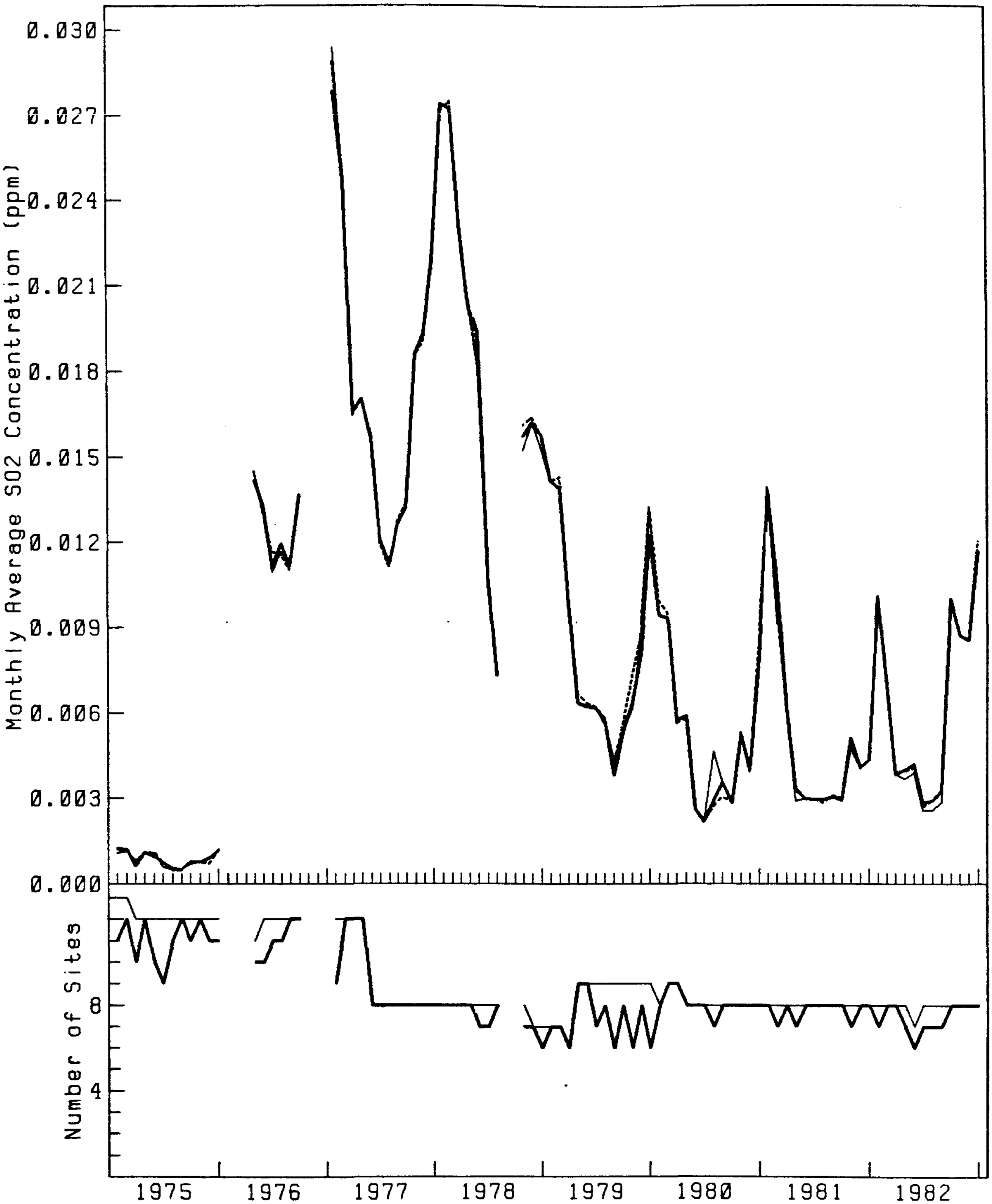


Figure B1. Monthly Average SO2 Concentration and Number of Reporting Sites, Connecticut, 1975 - 1982.



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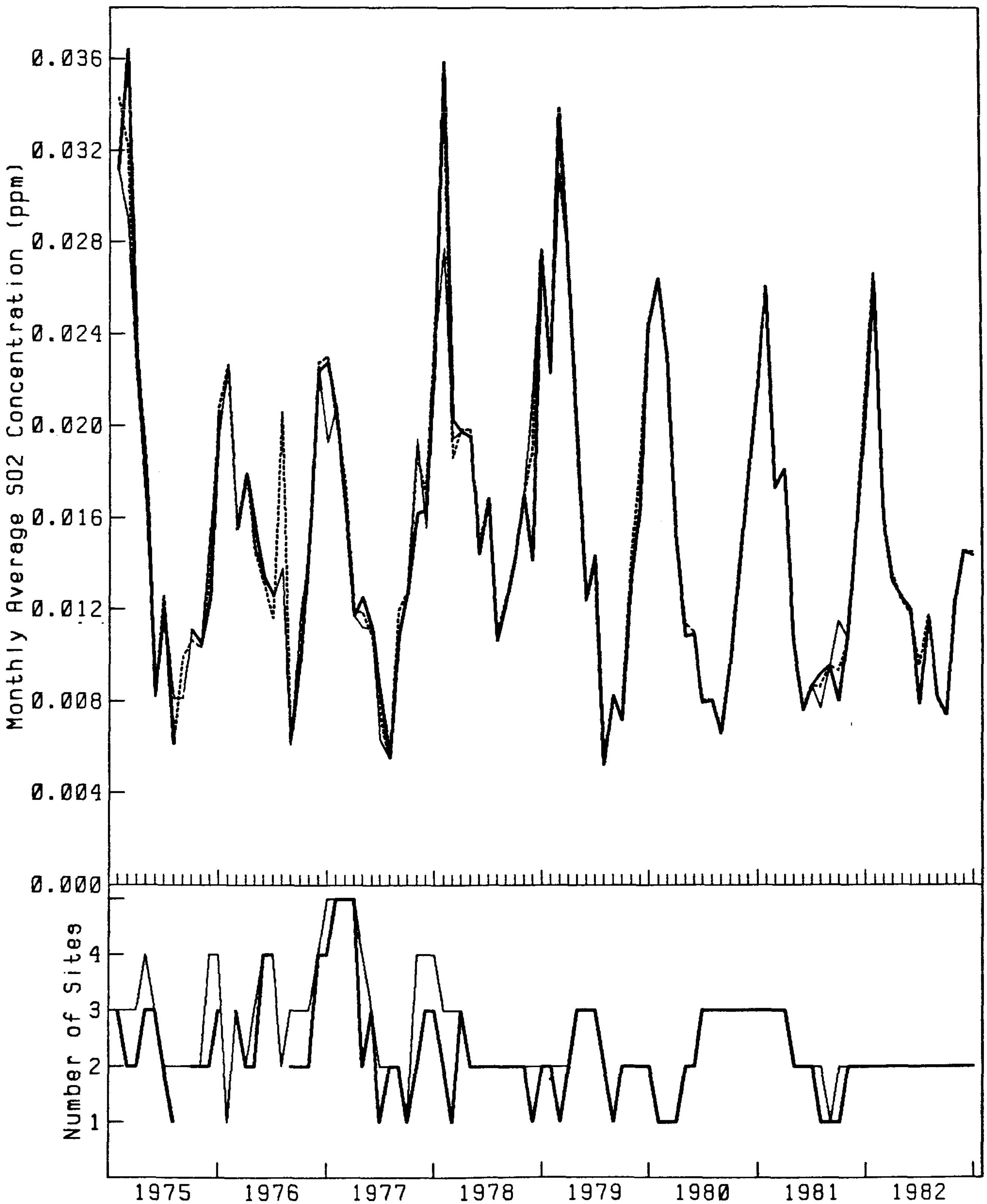

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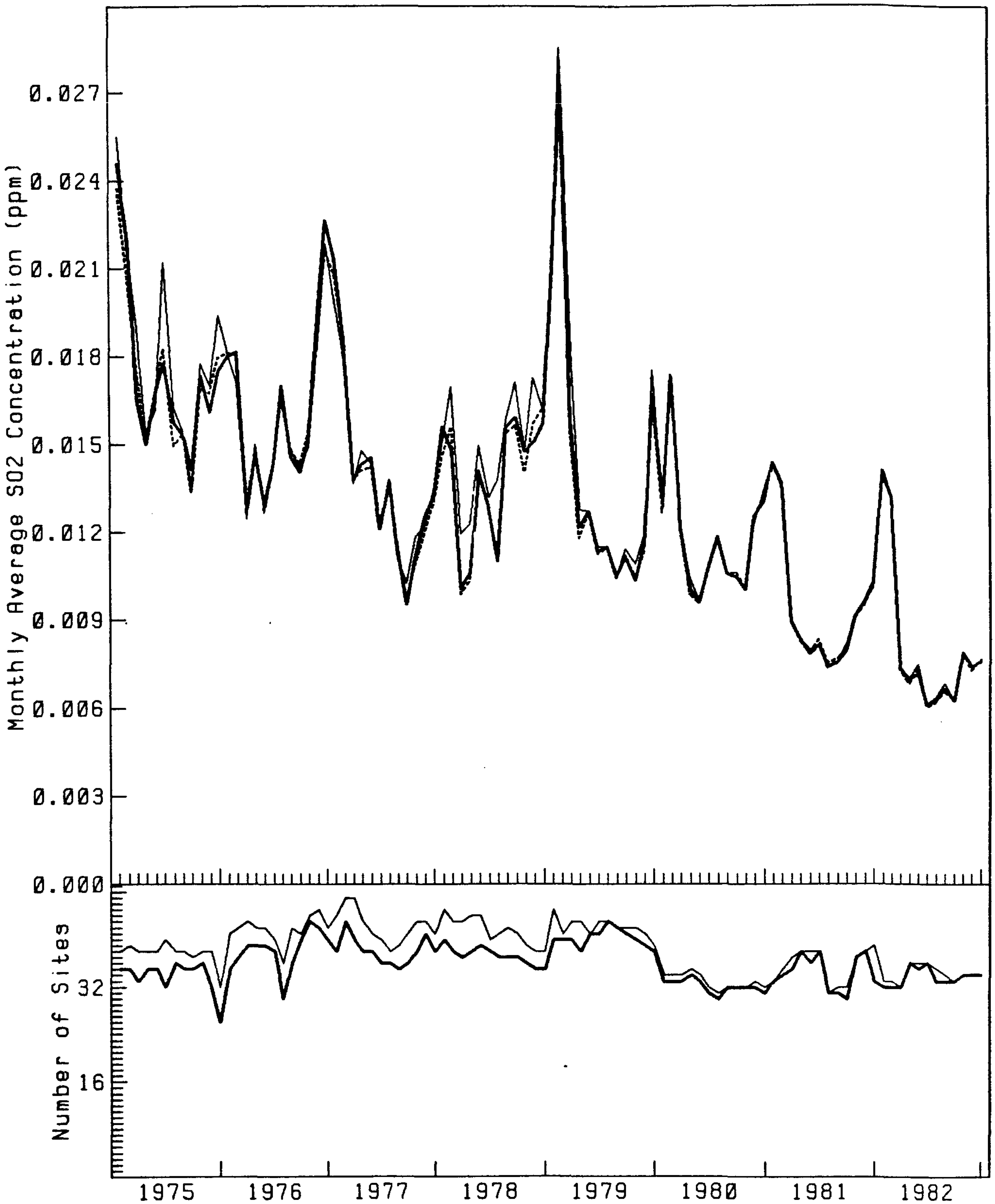

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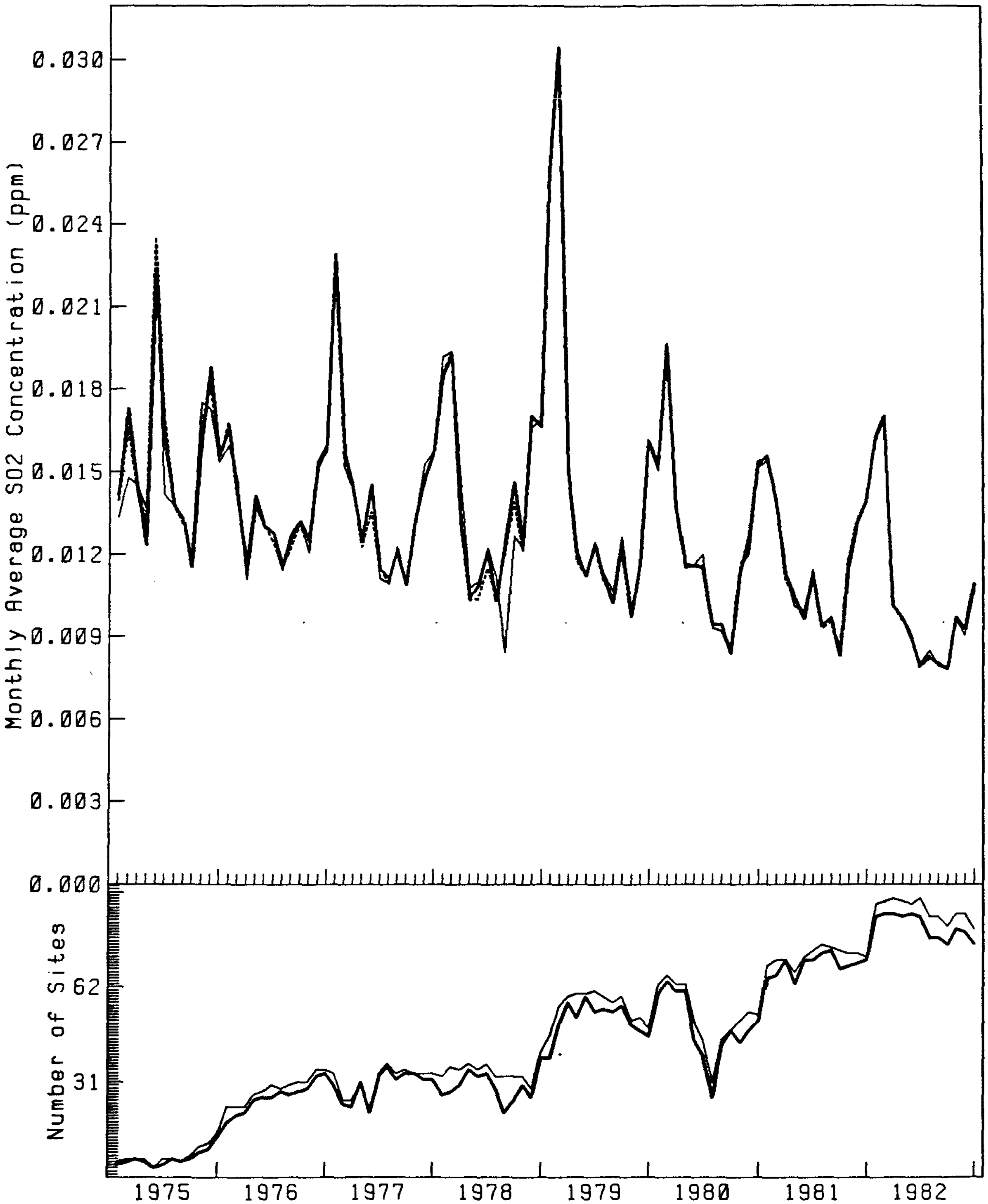

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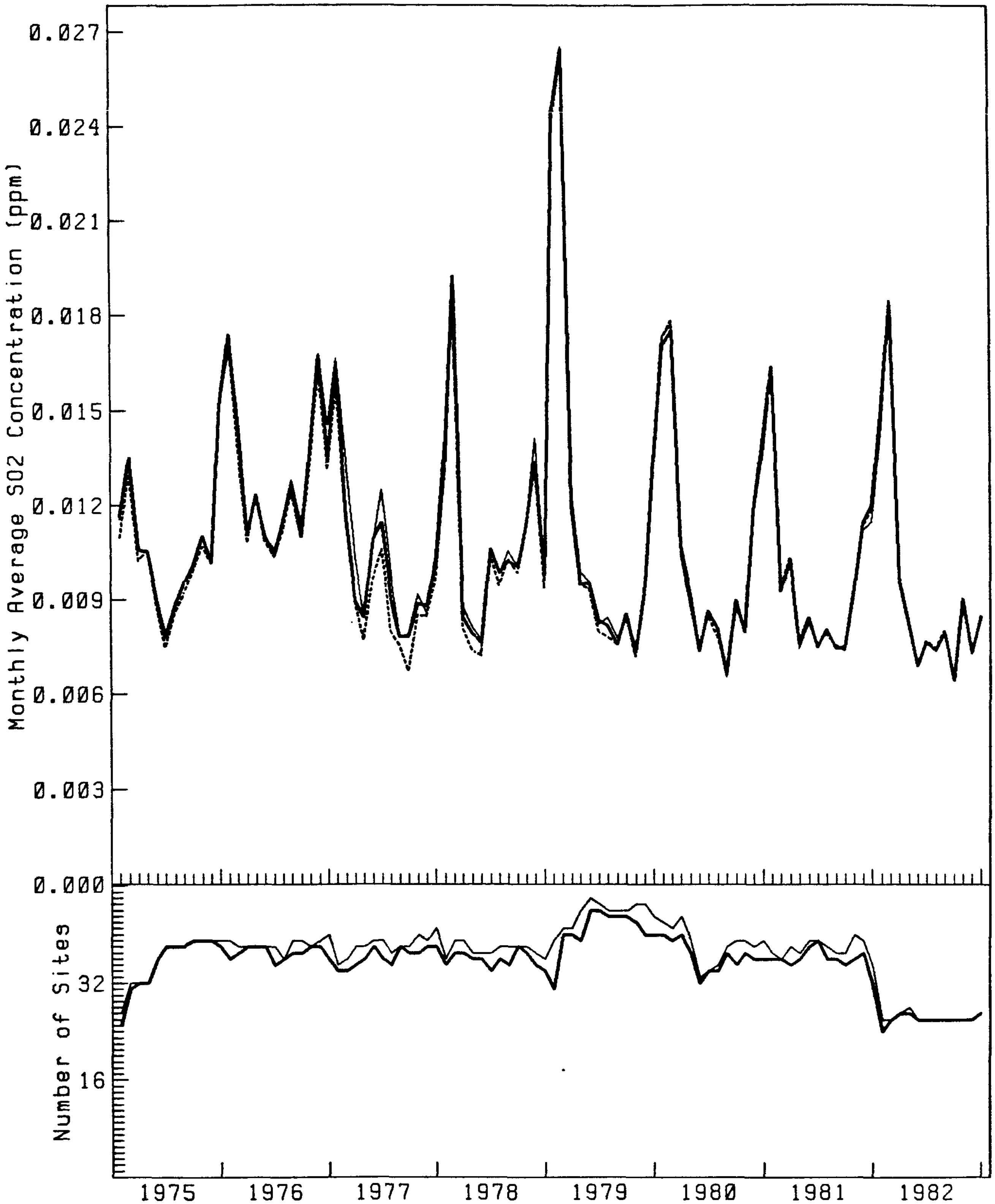

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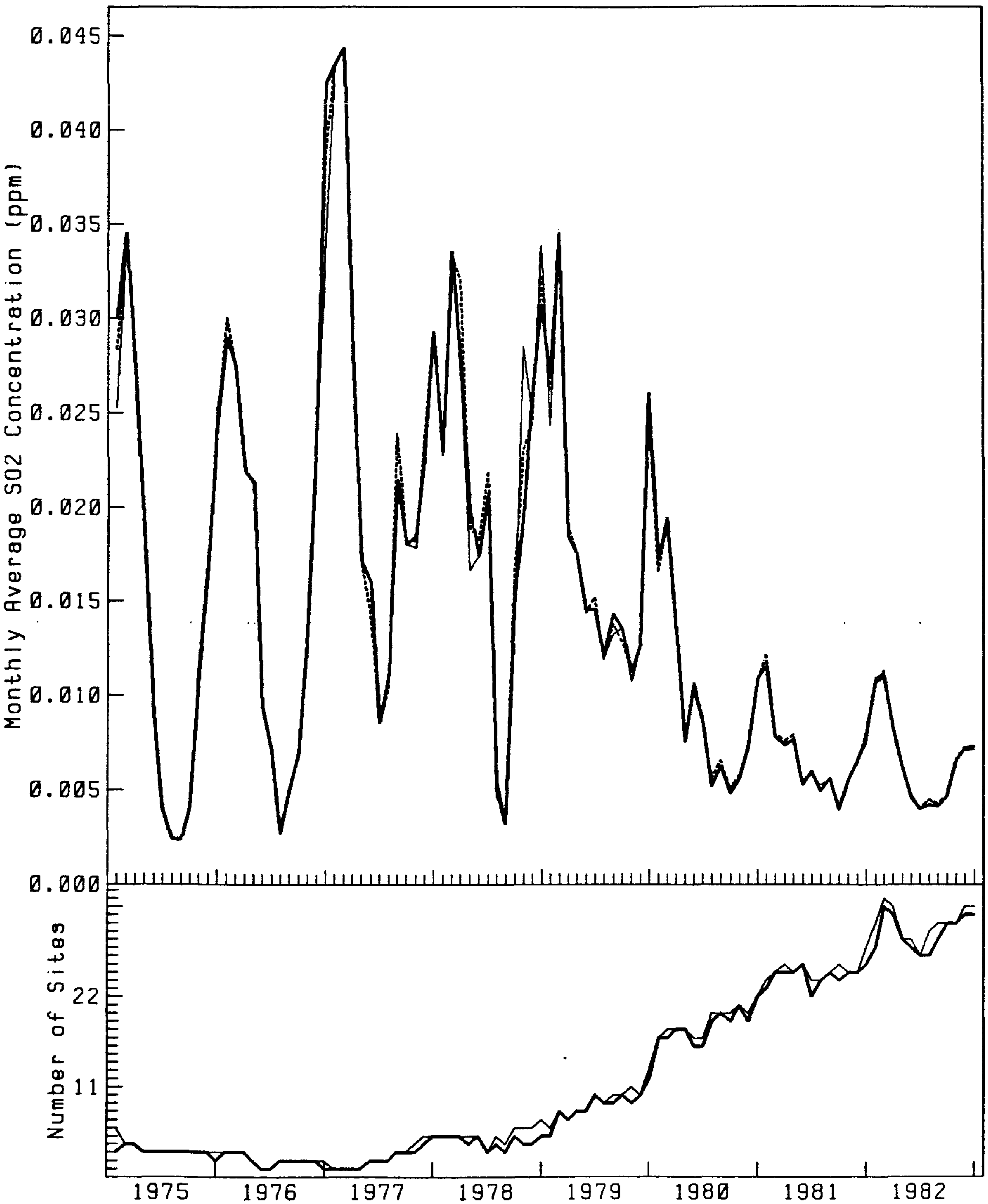

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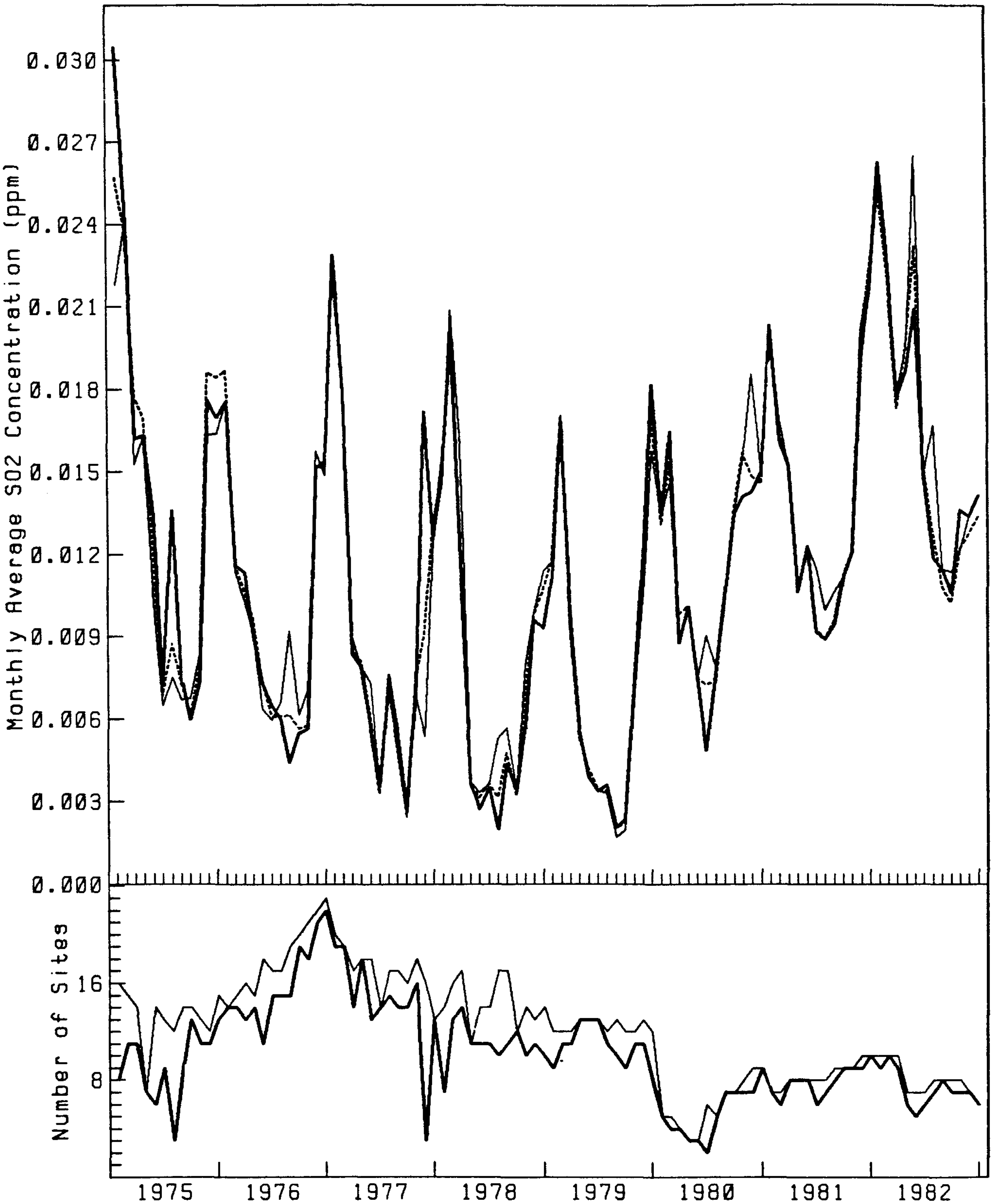

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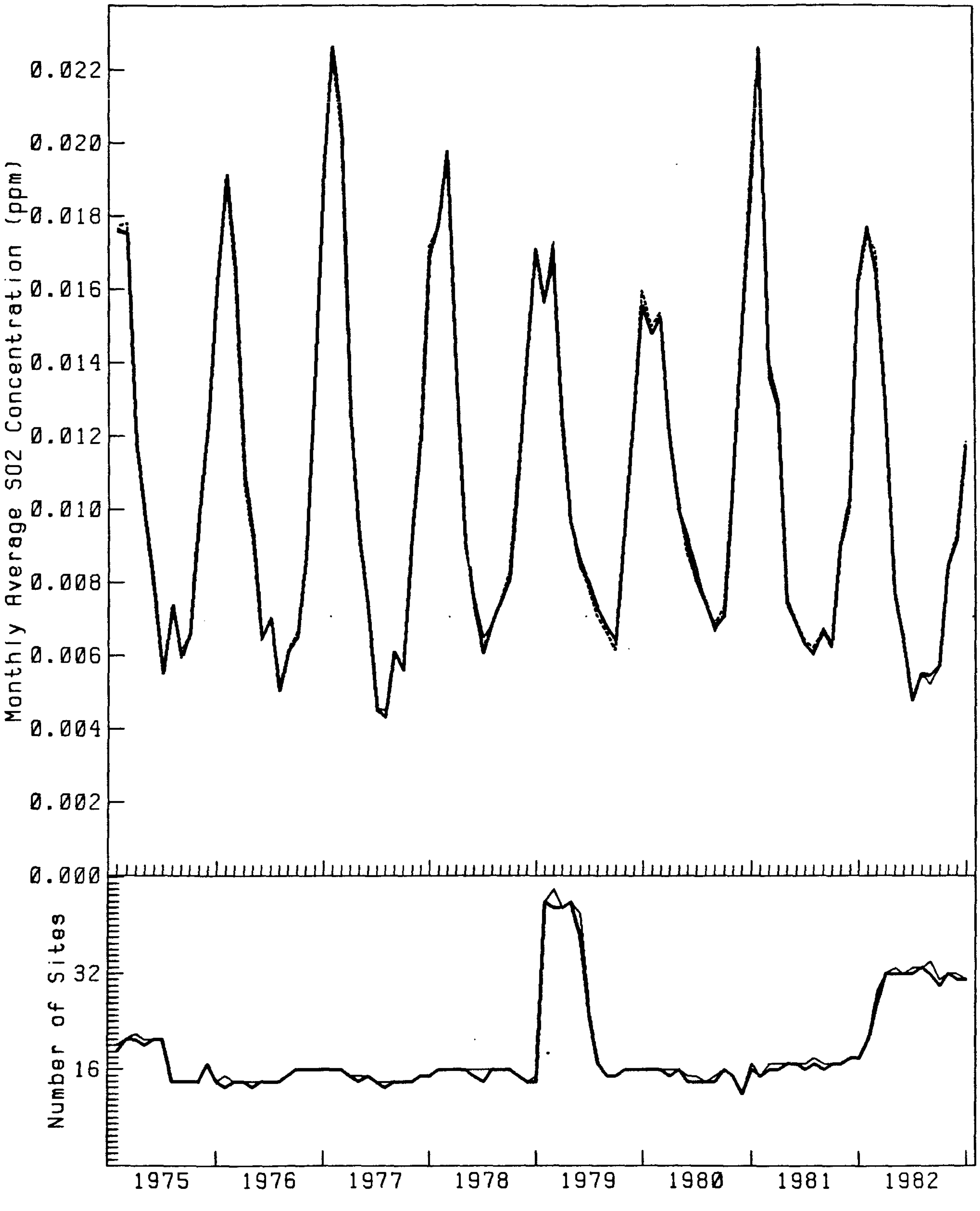

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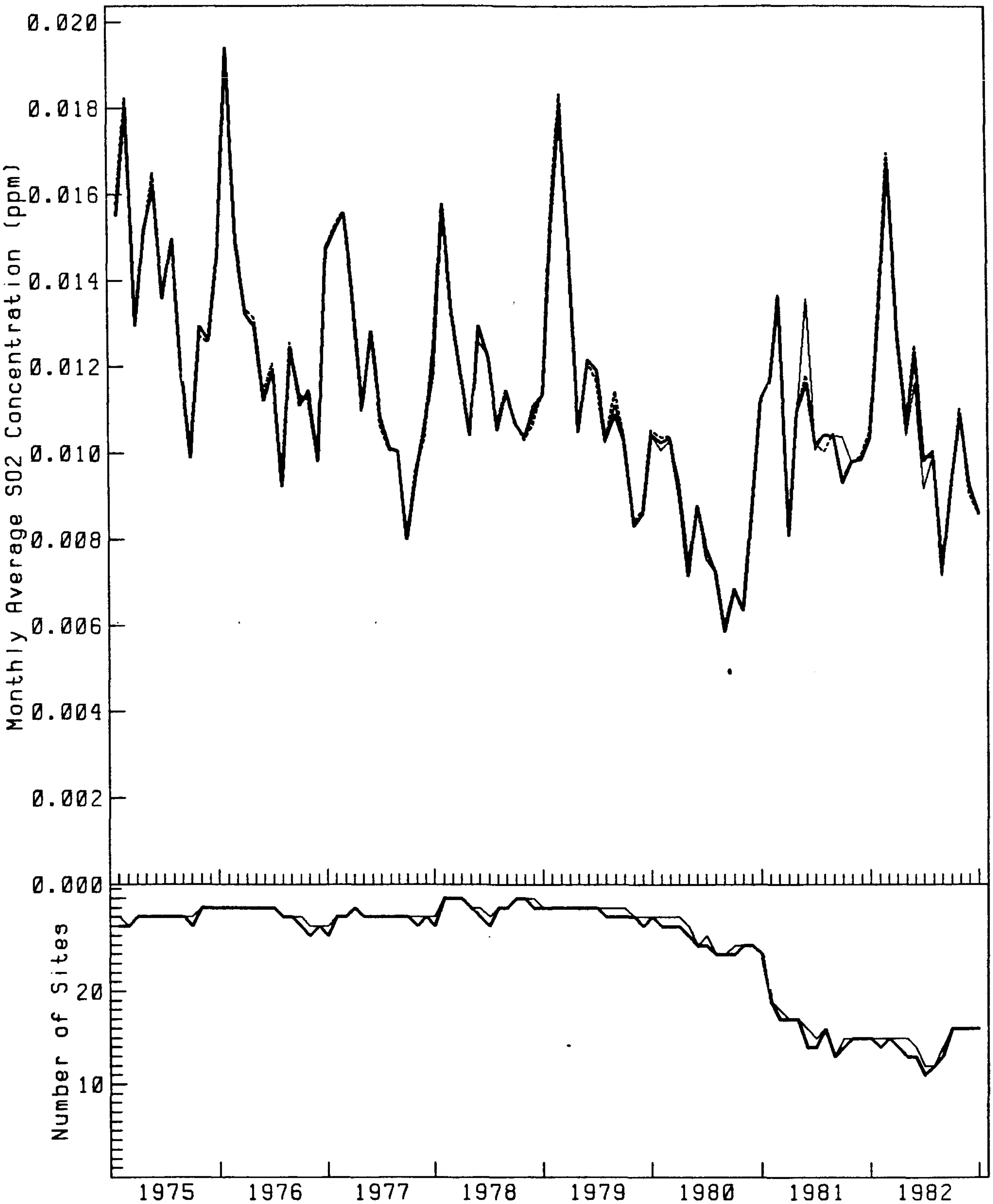

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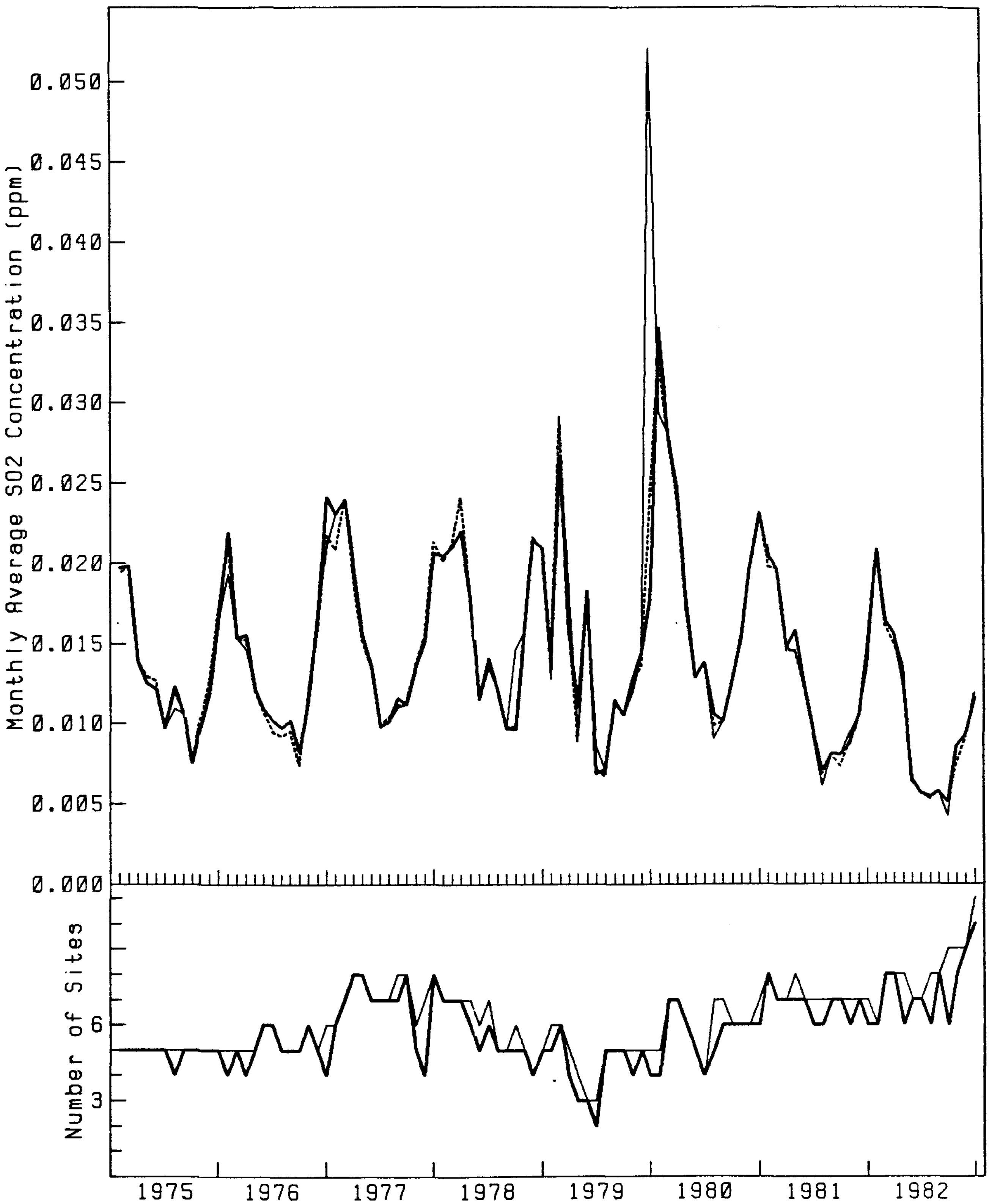

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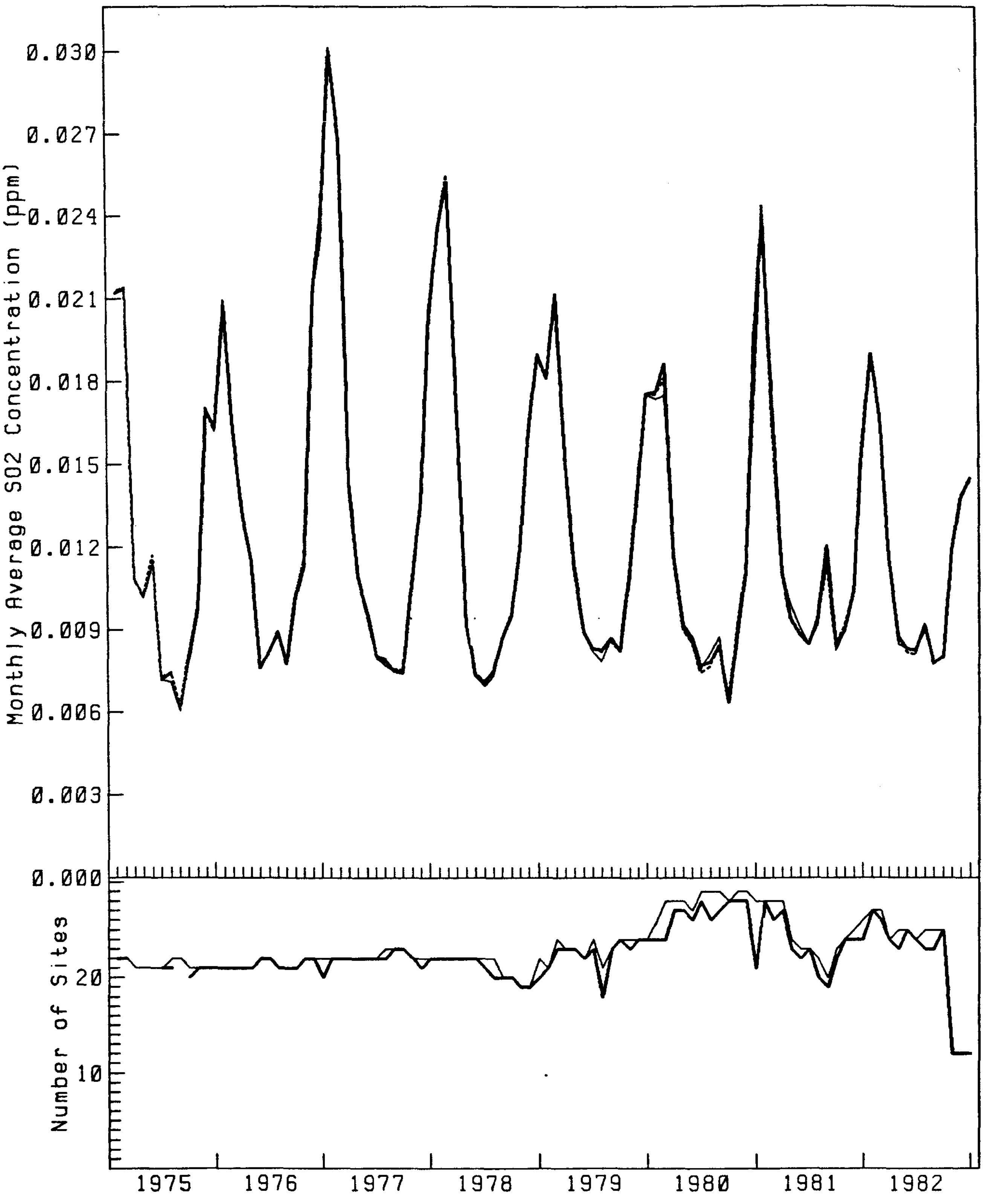

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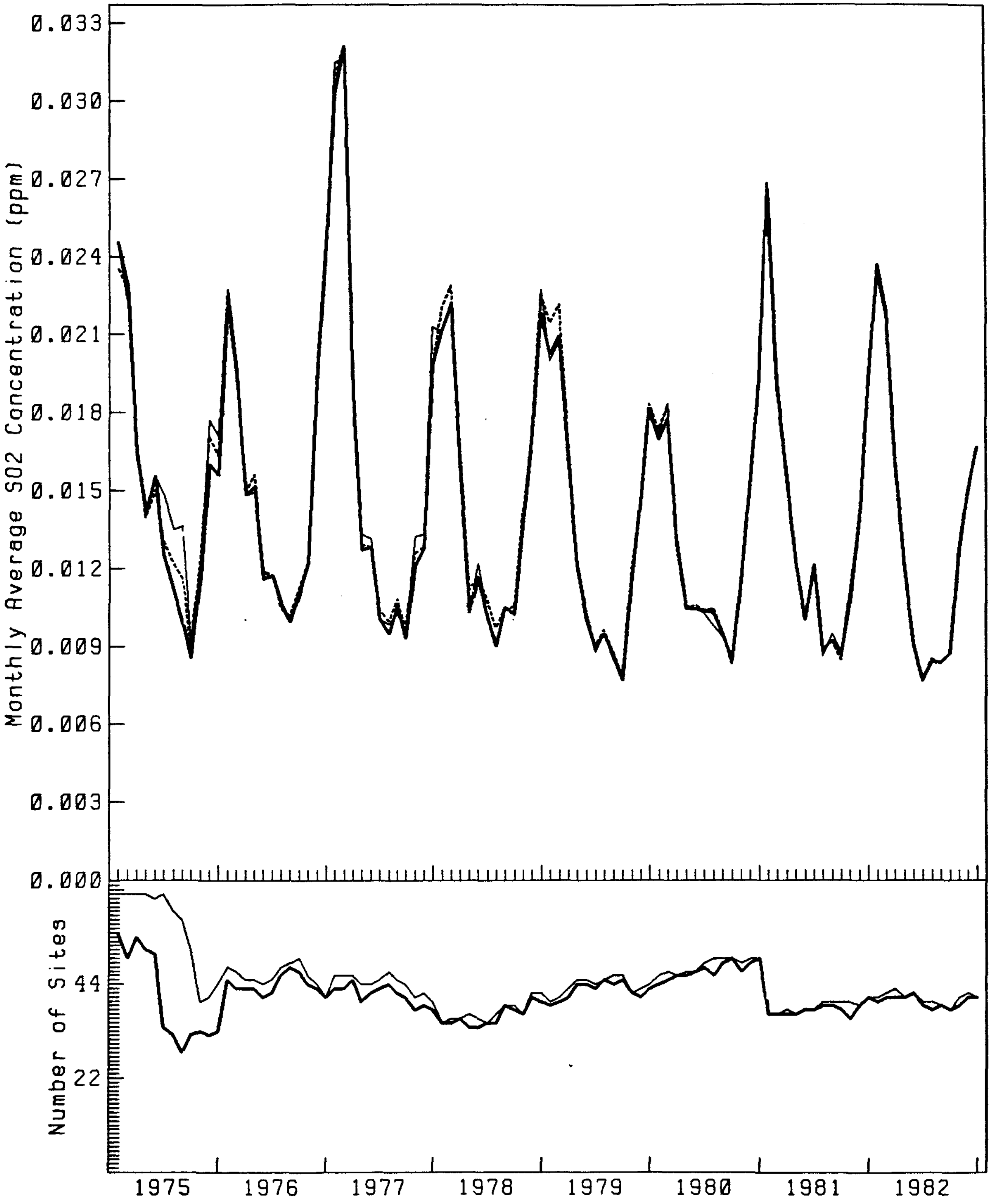

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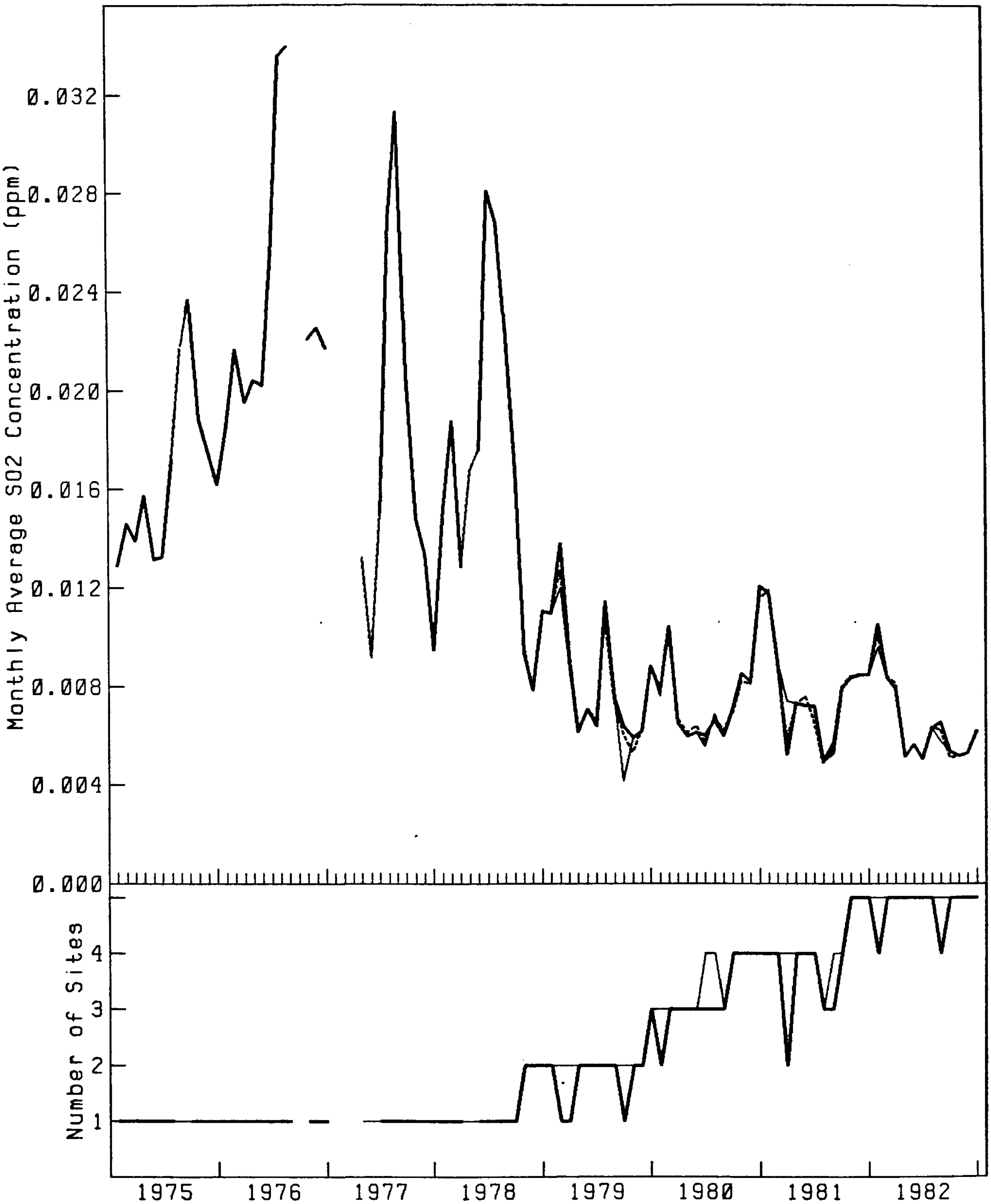

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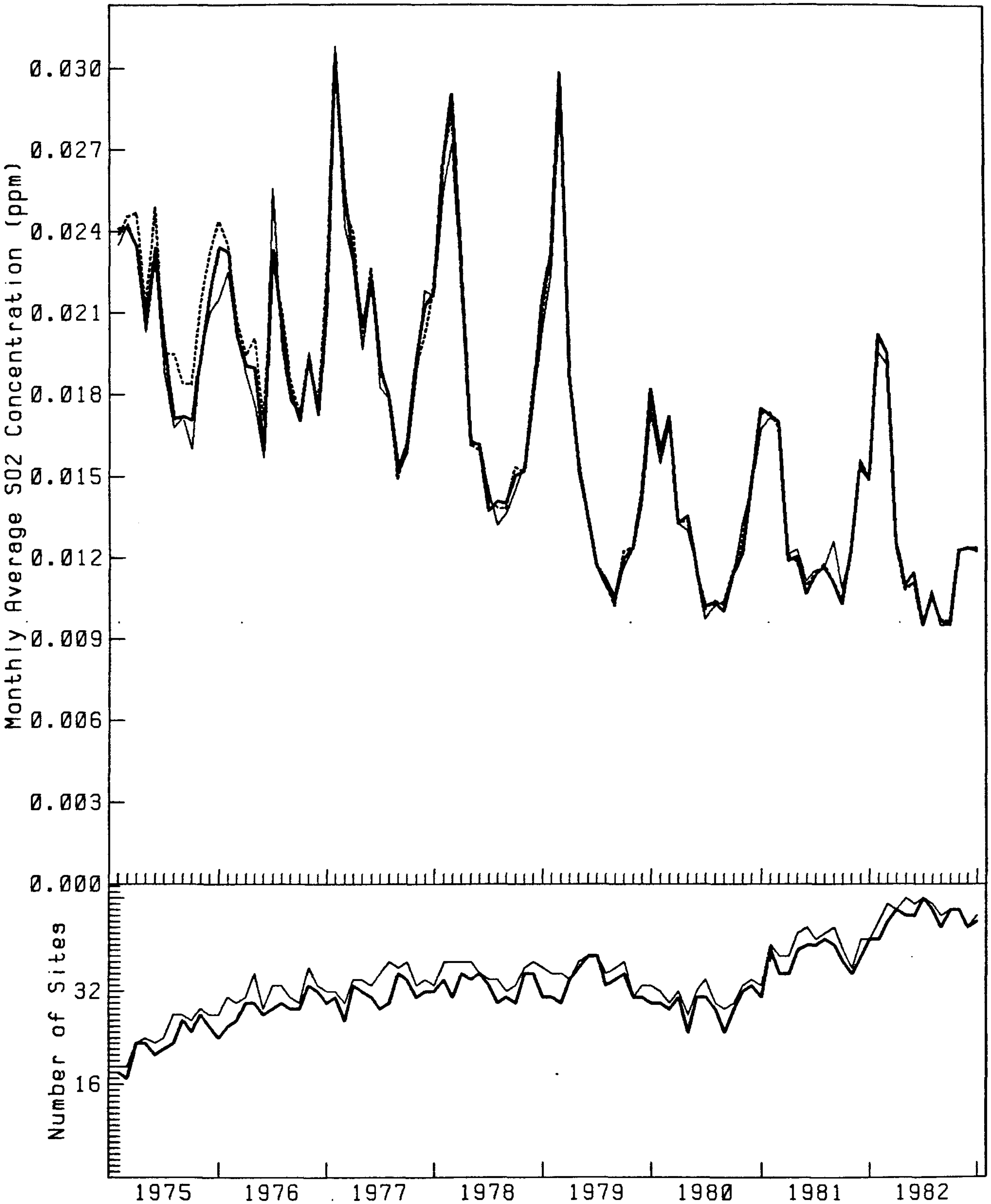

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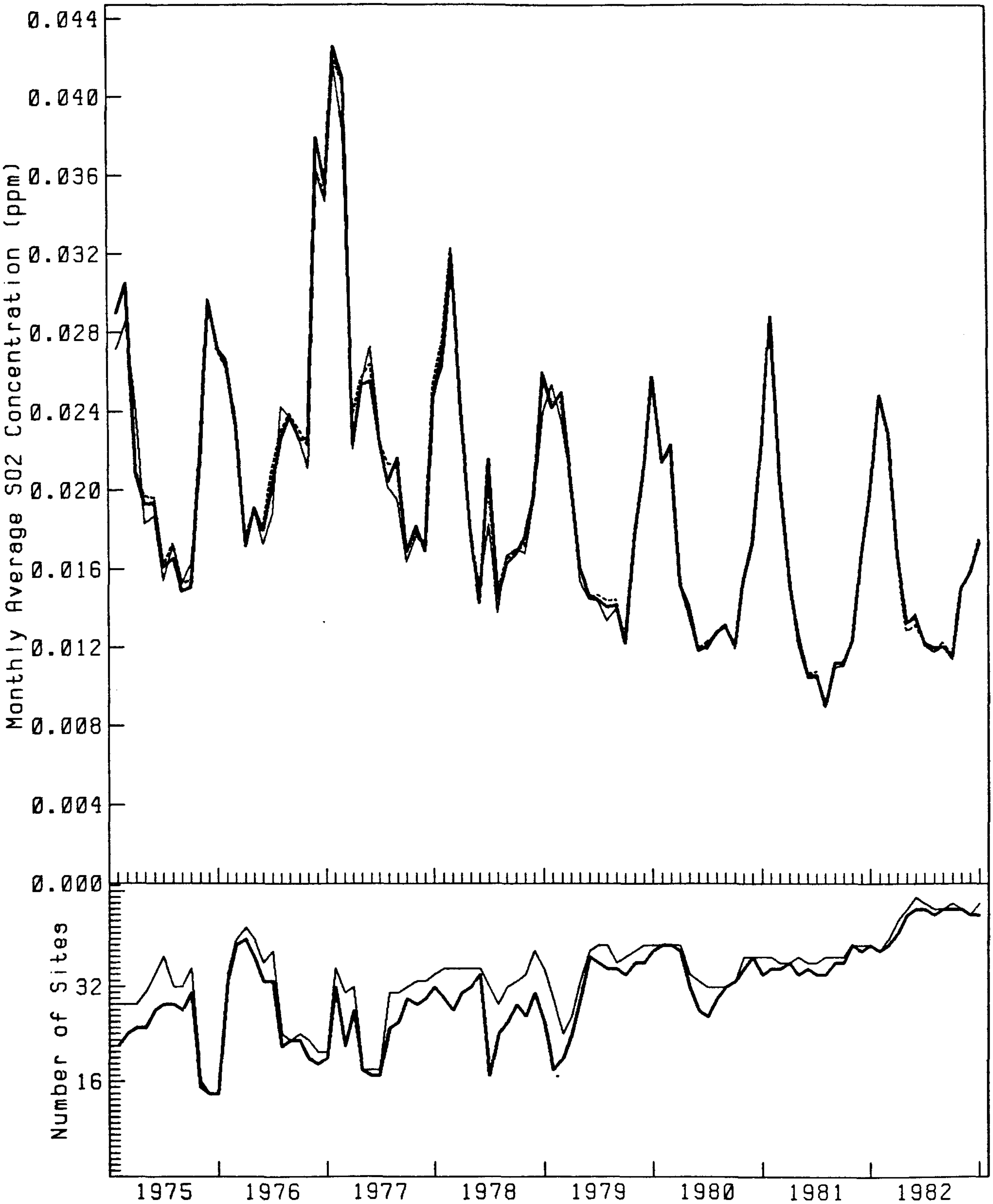

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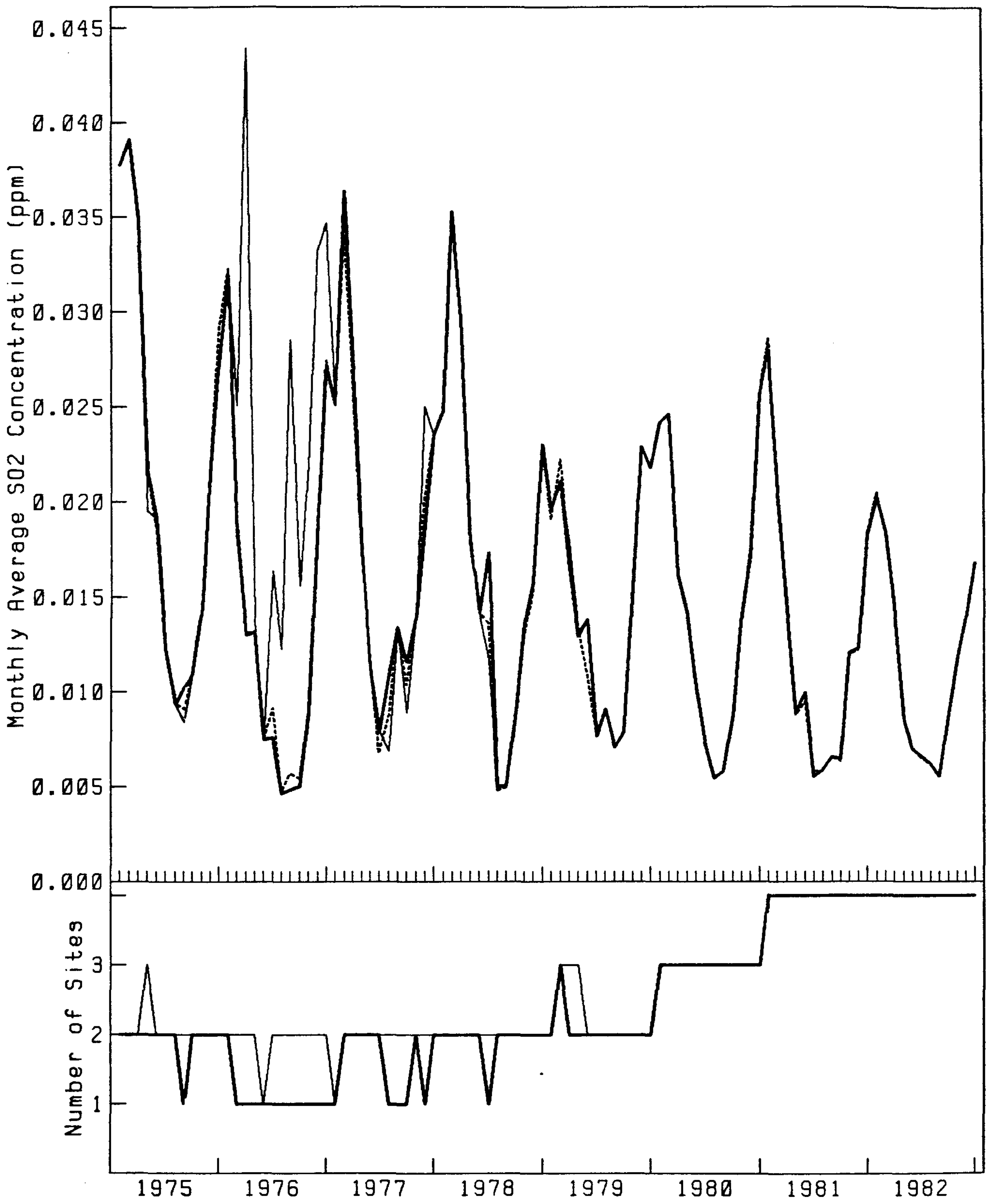

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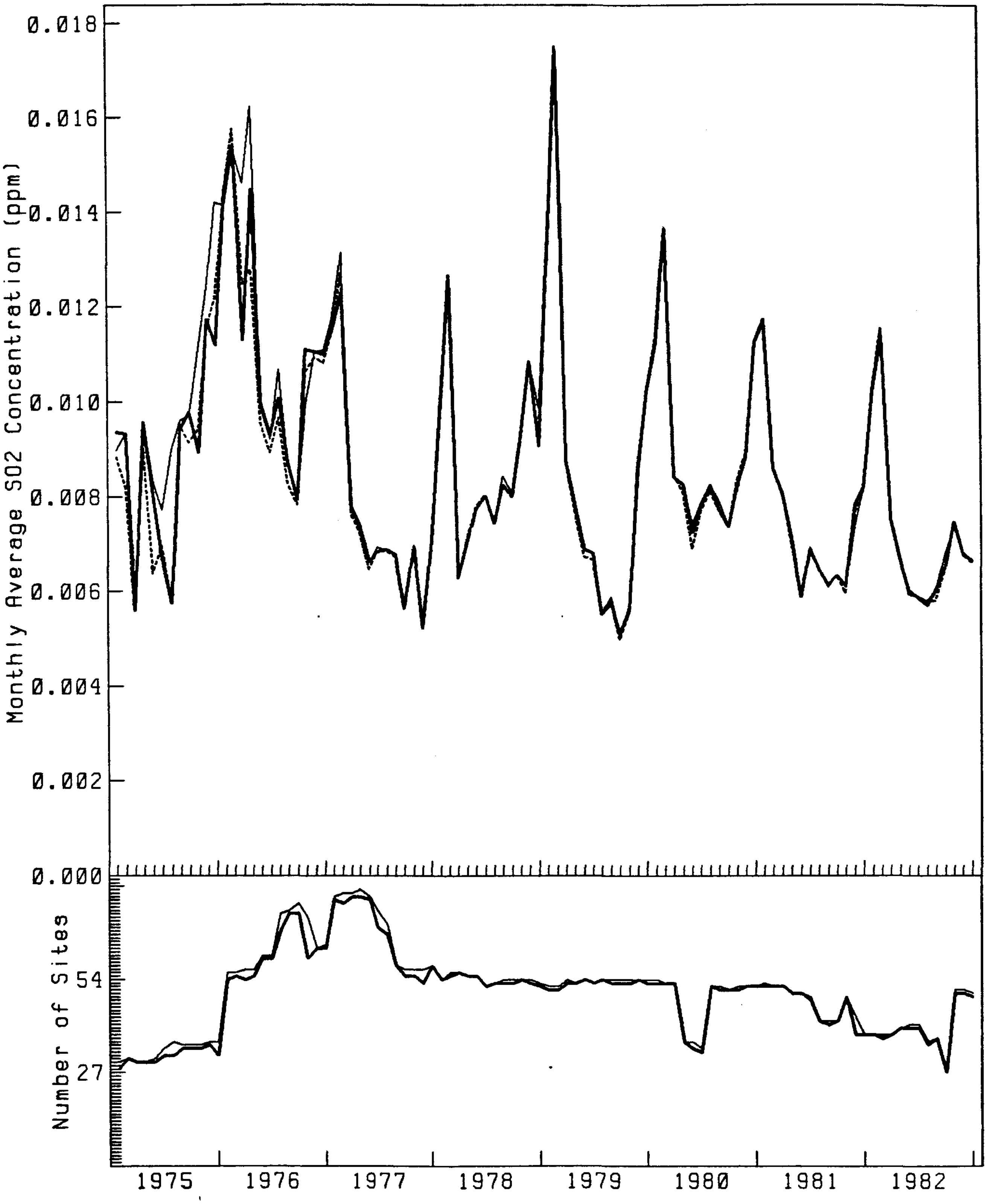

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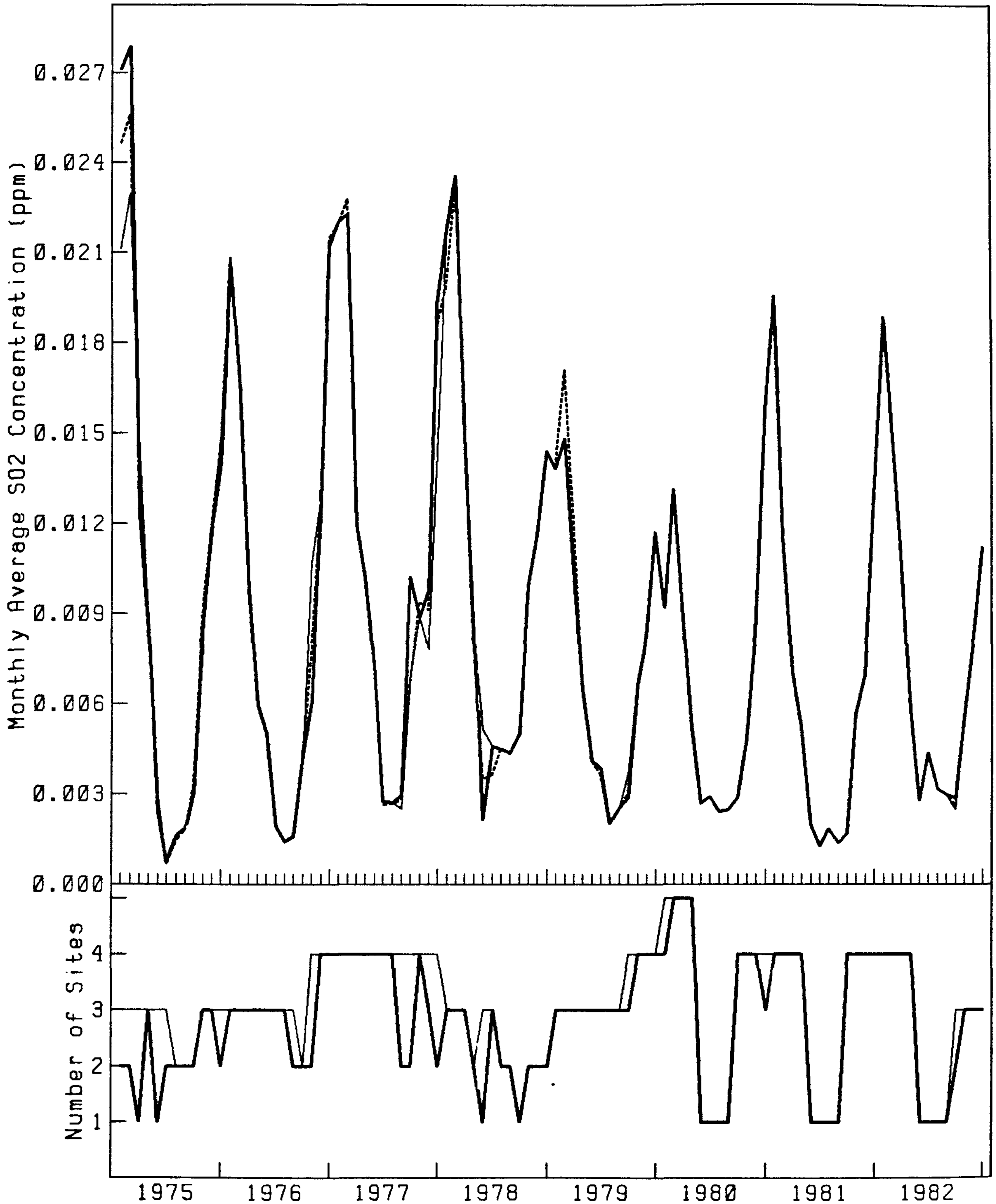

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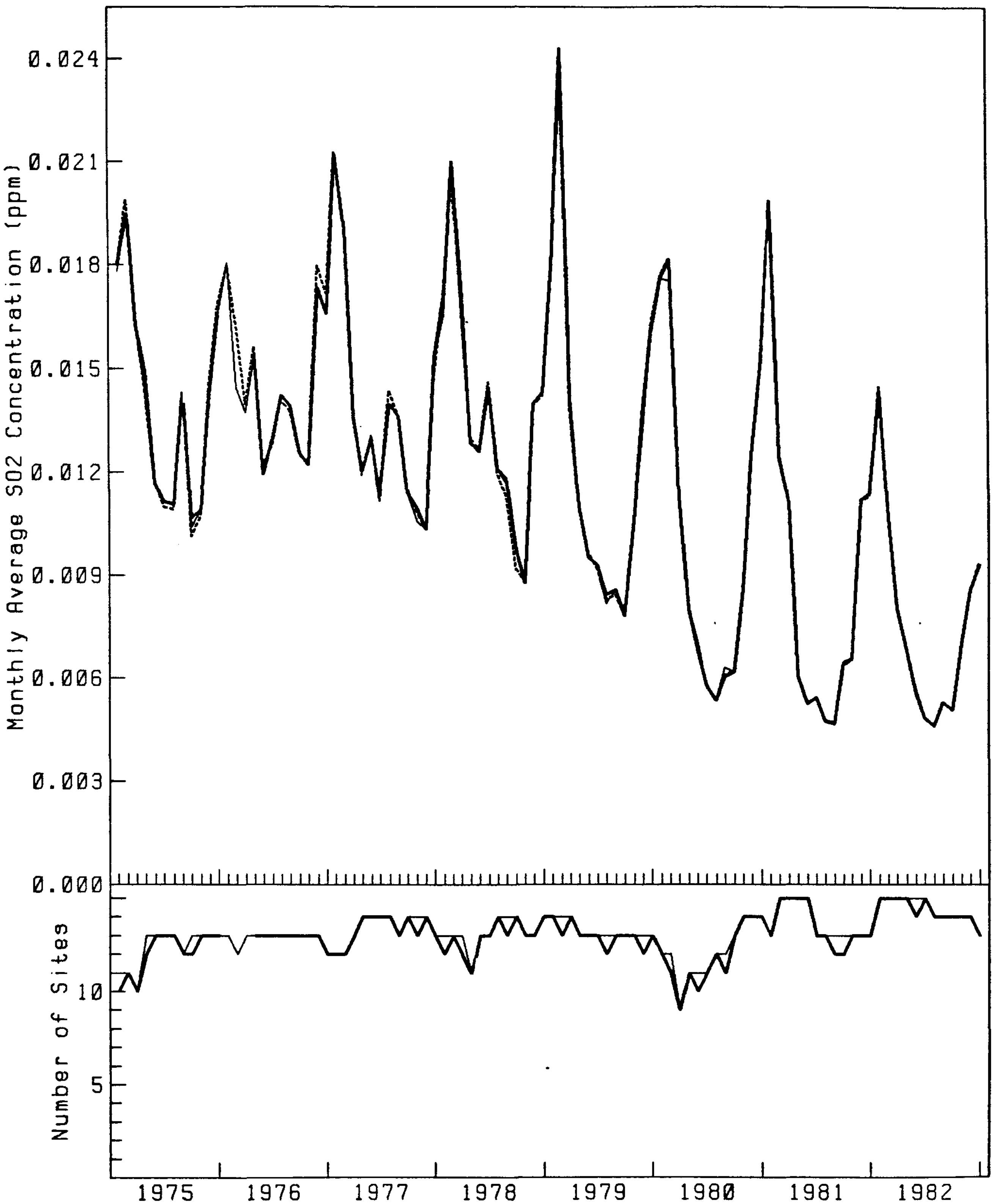

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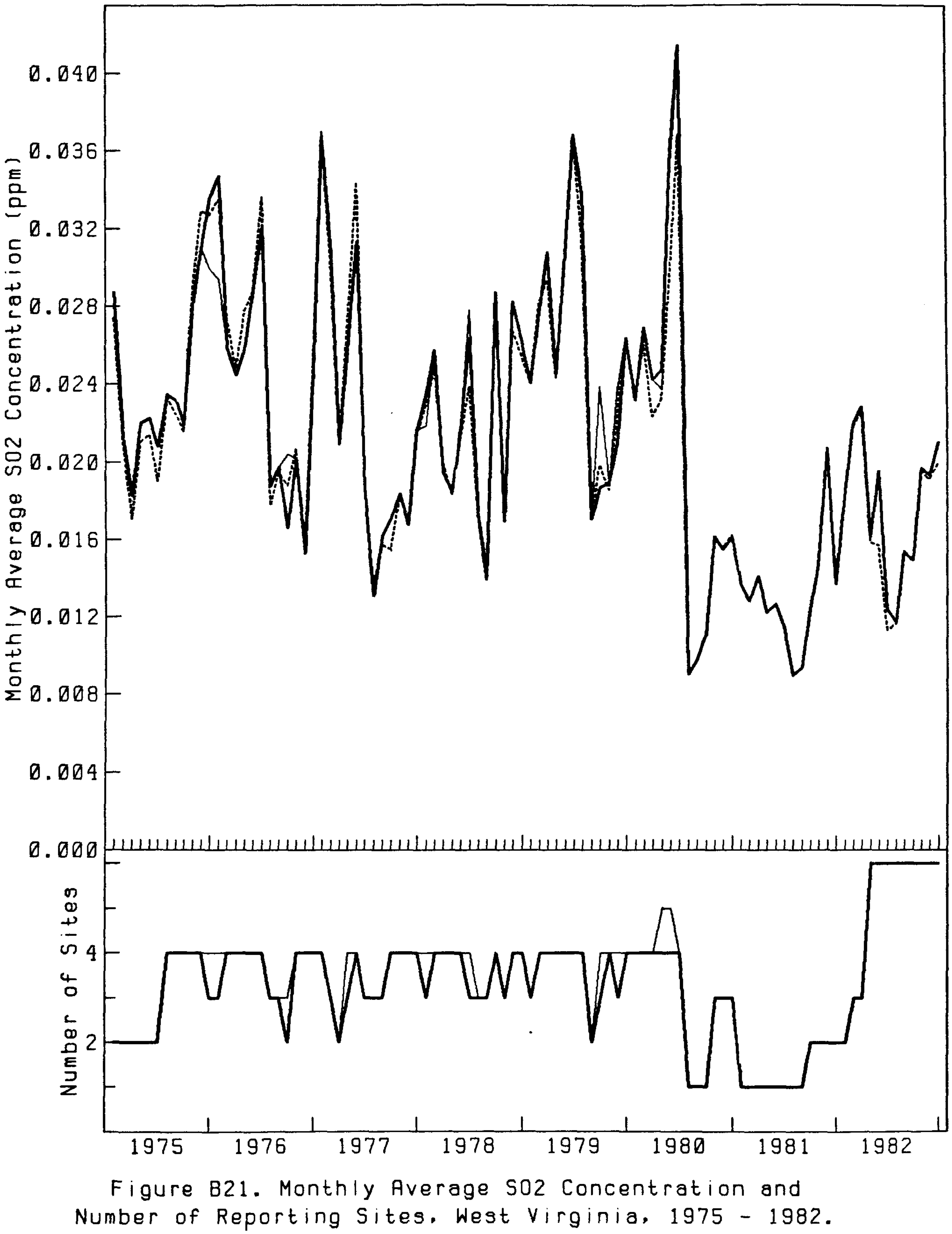

Figure B21. Monthly Average SO2 Concentration and Number of Reporting Sites, West Virginia, 1975 - 1982.

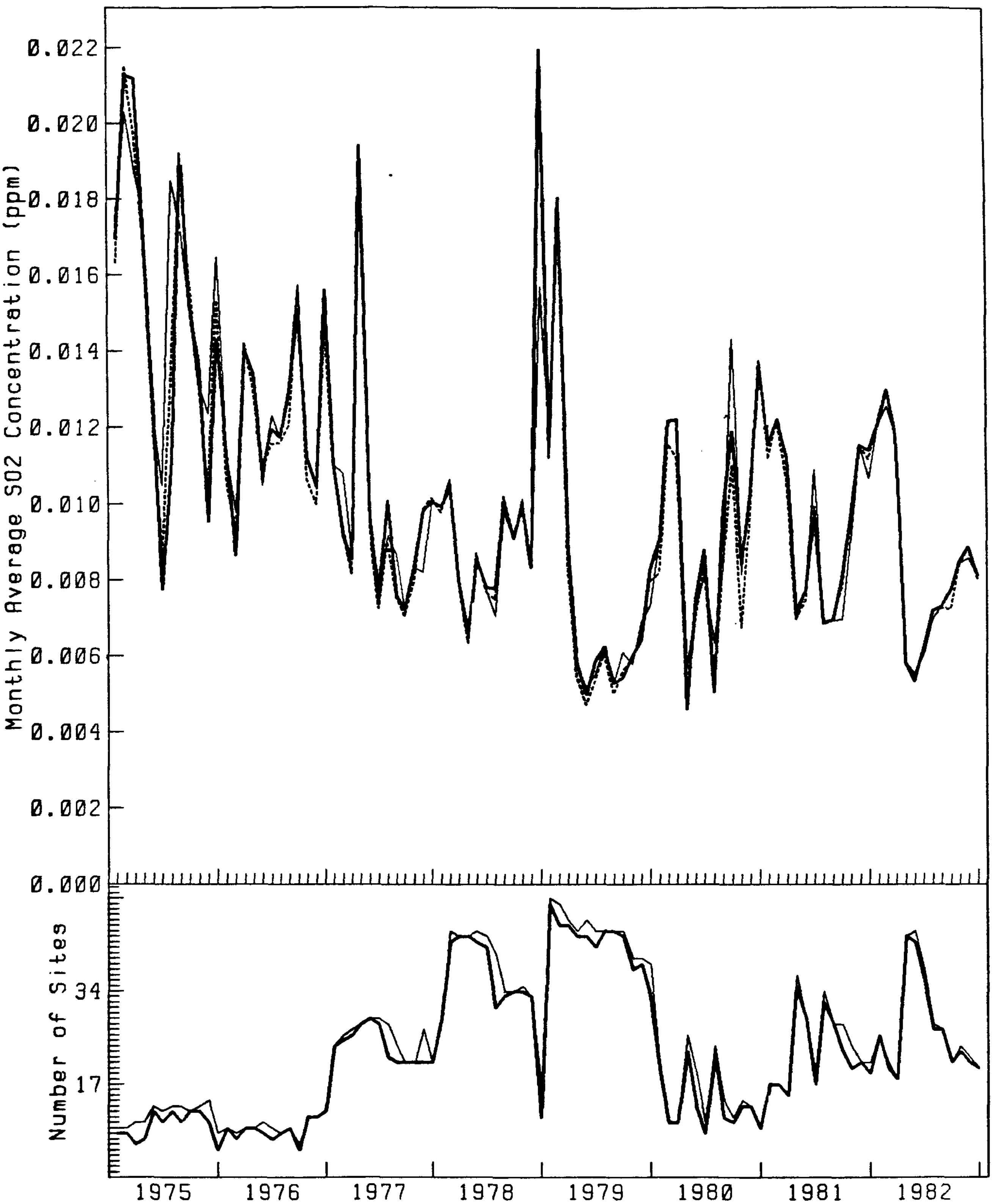

Figure B22. Monthly Average SO2 Concentration and Number of Reporting Sites, Wisconsin, 1975 - 1982.

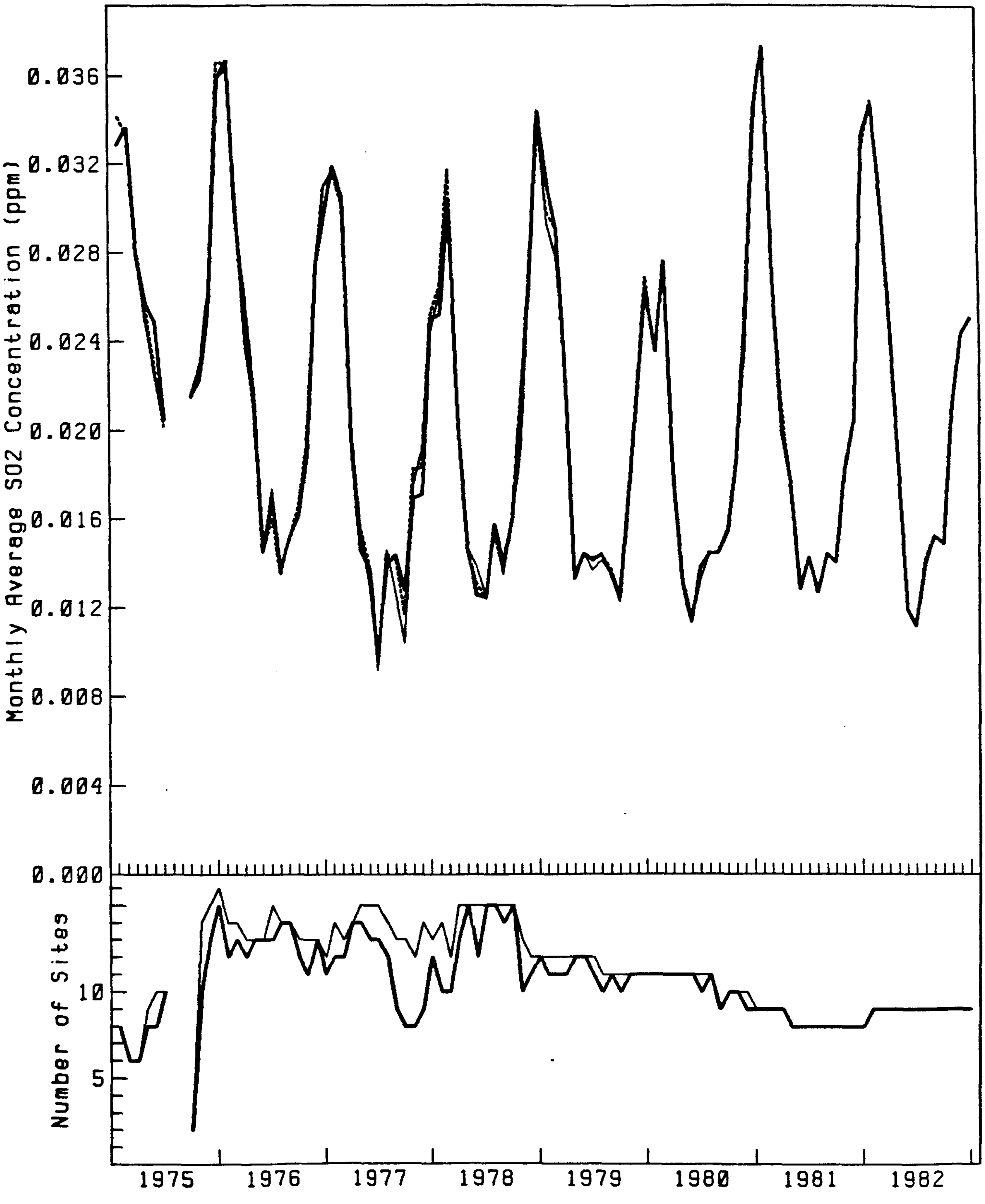

Figure C1. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites. Connecticut. 1975 - 1982.

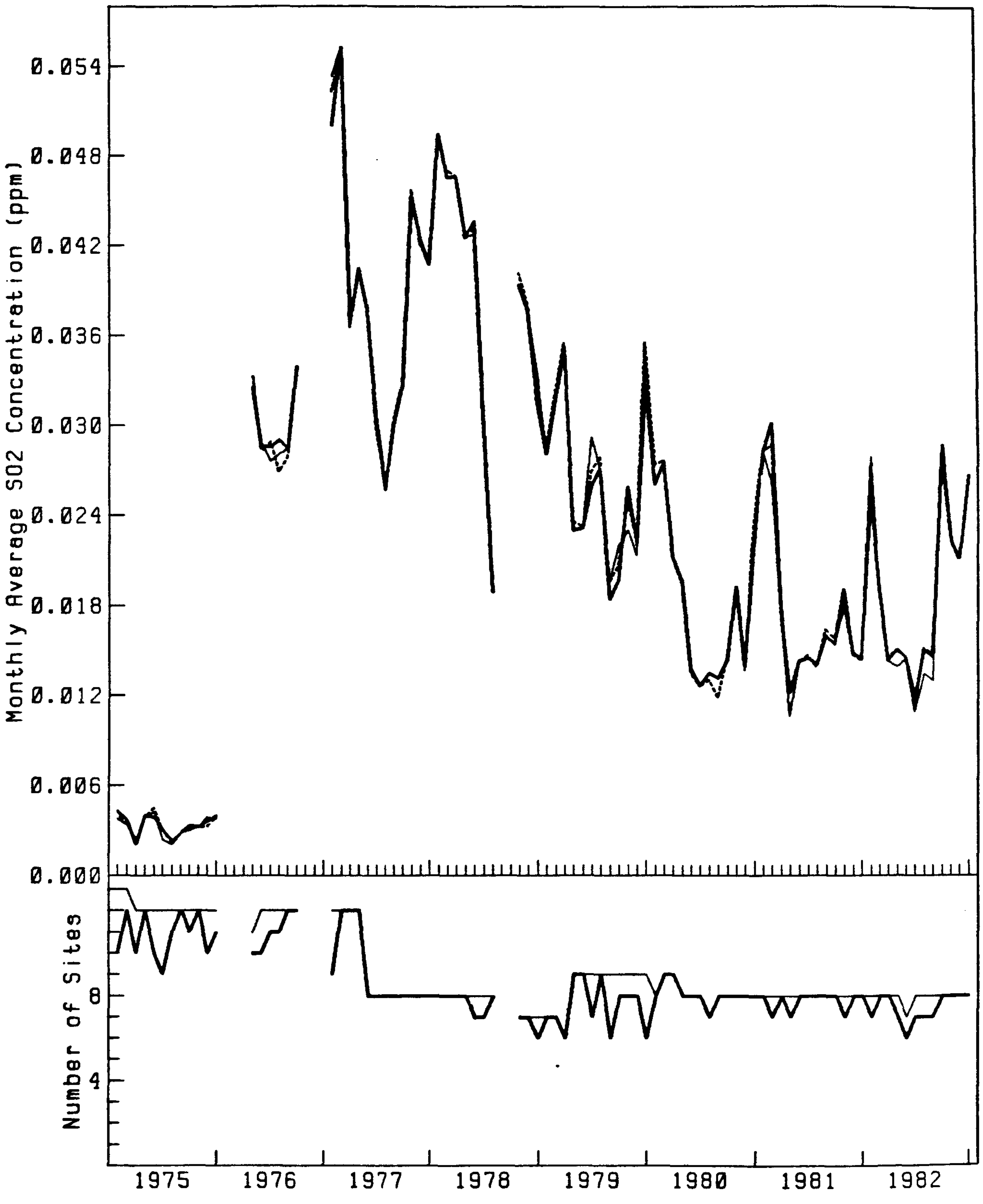

Figure C2. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Delaware, 1975 - 1982.

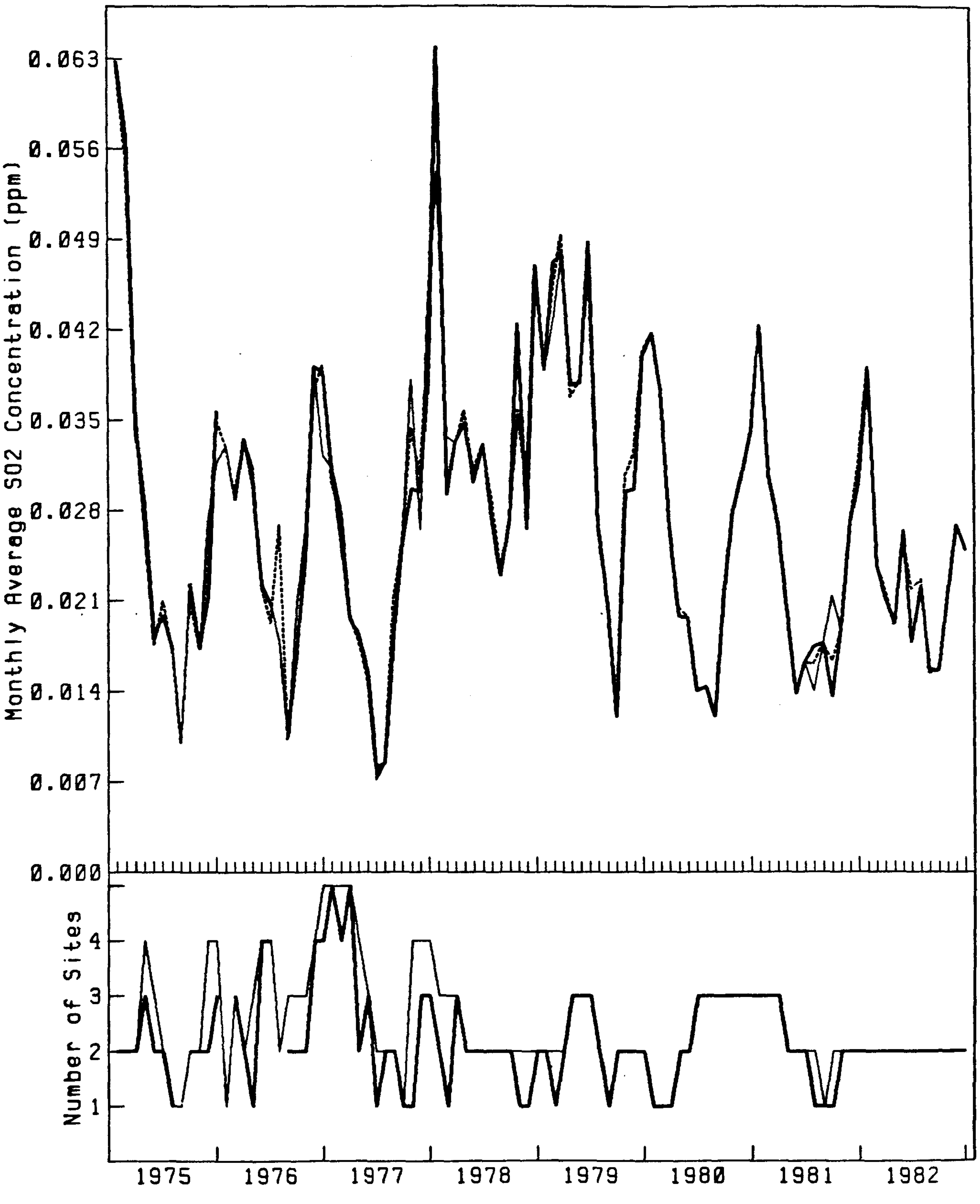

Figure C3. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, District of Columbia, 1975 - 1982.

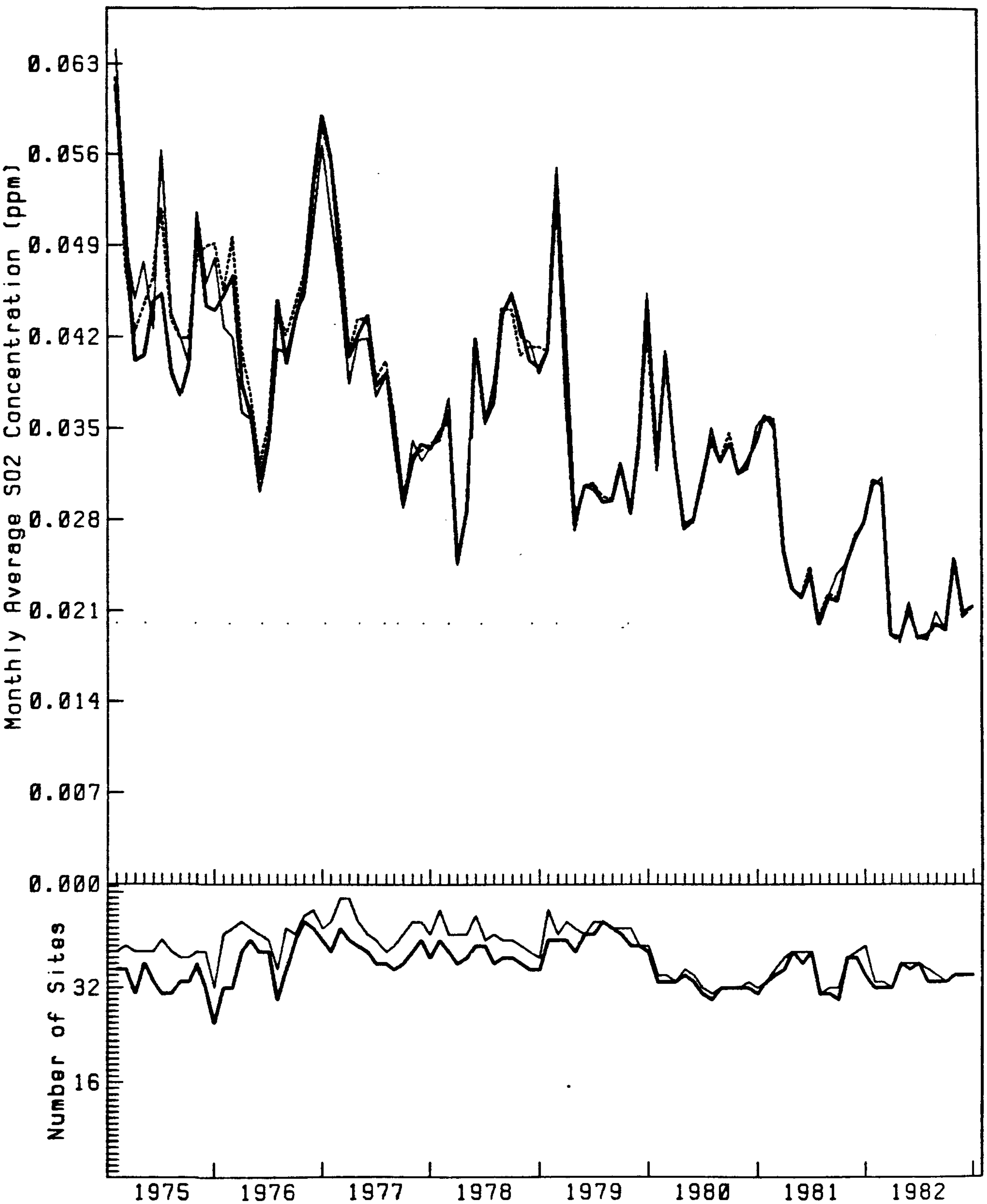

Figure C4. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Illinois, 1975 - 1982.

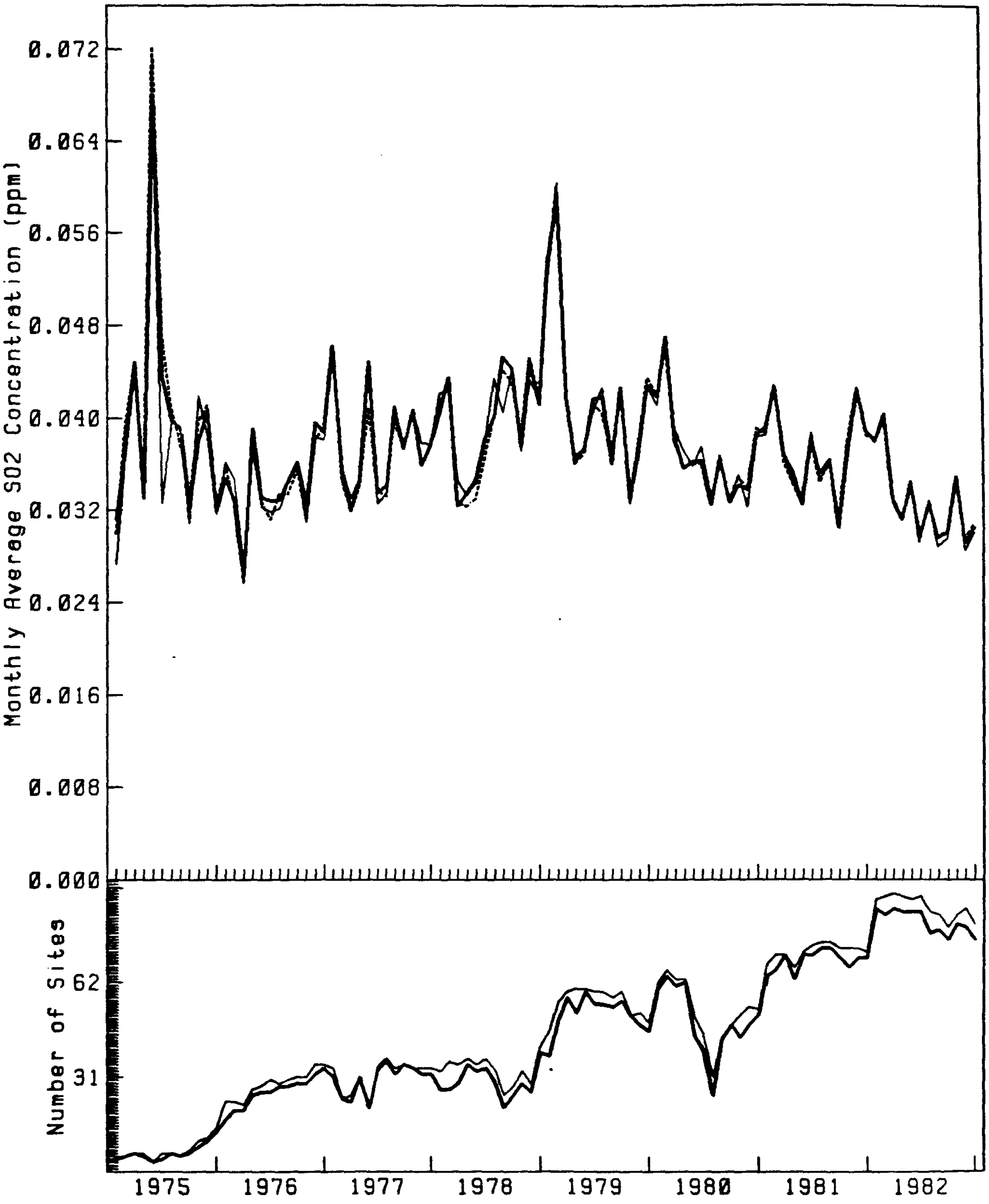

Figure C5. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Indiana, 1975 - 1982.

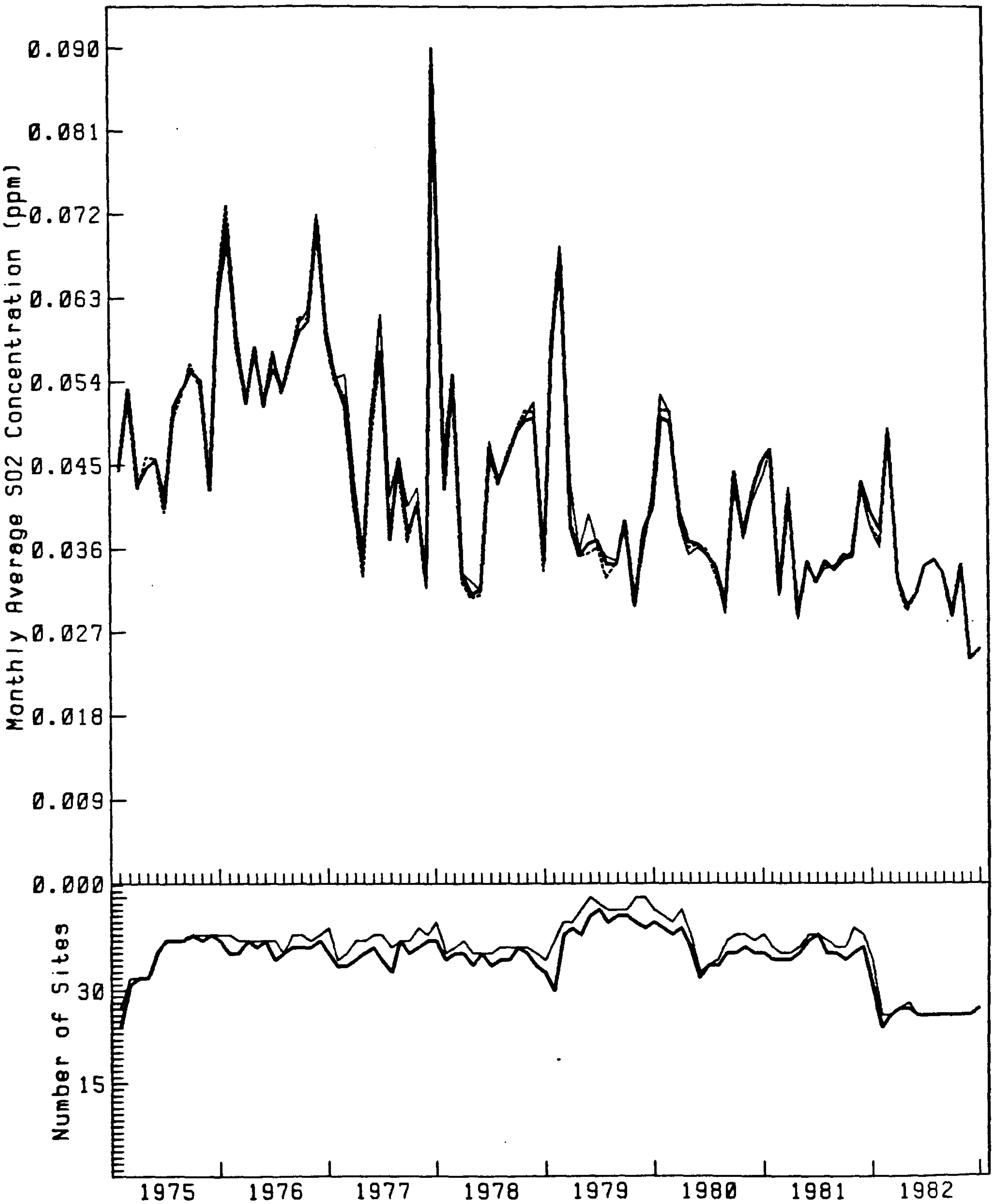

Figure C6. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Kentucky, 1975 - 1982.

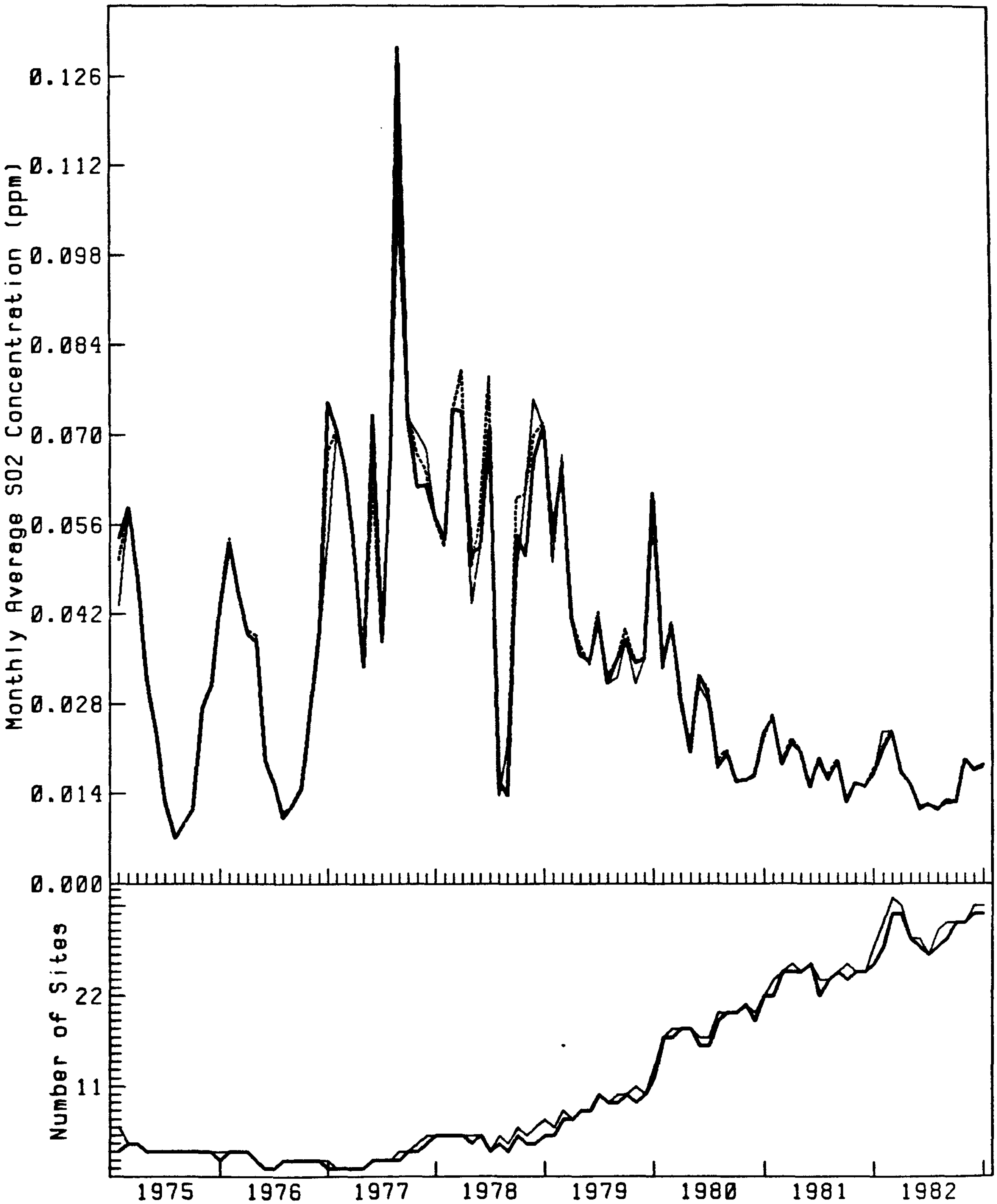

Figure C7. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Maine, 1975 - 1982.

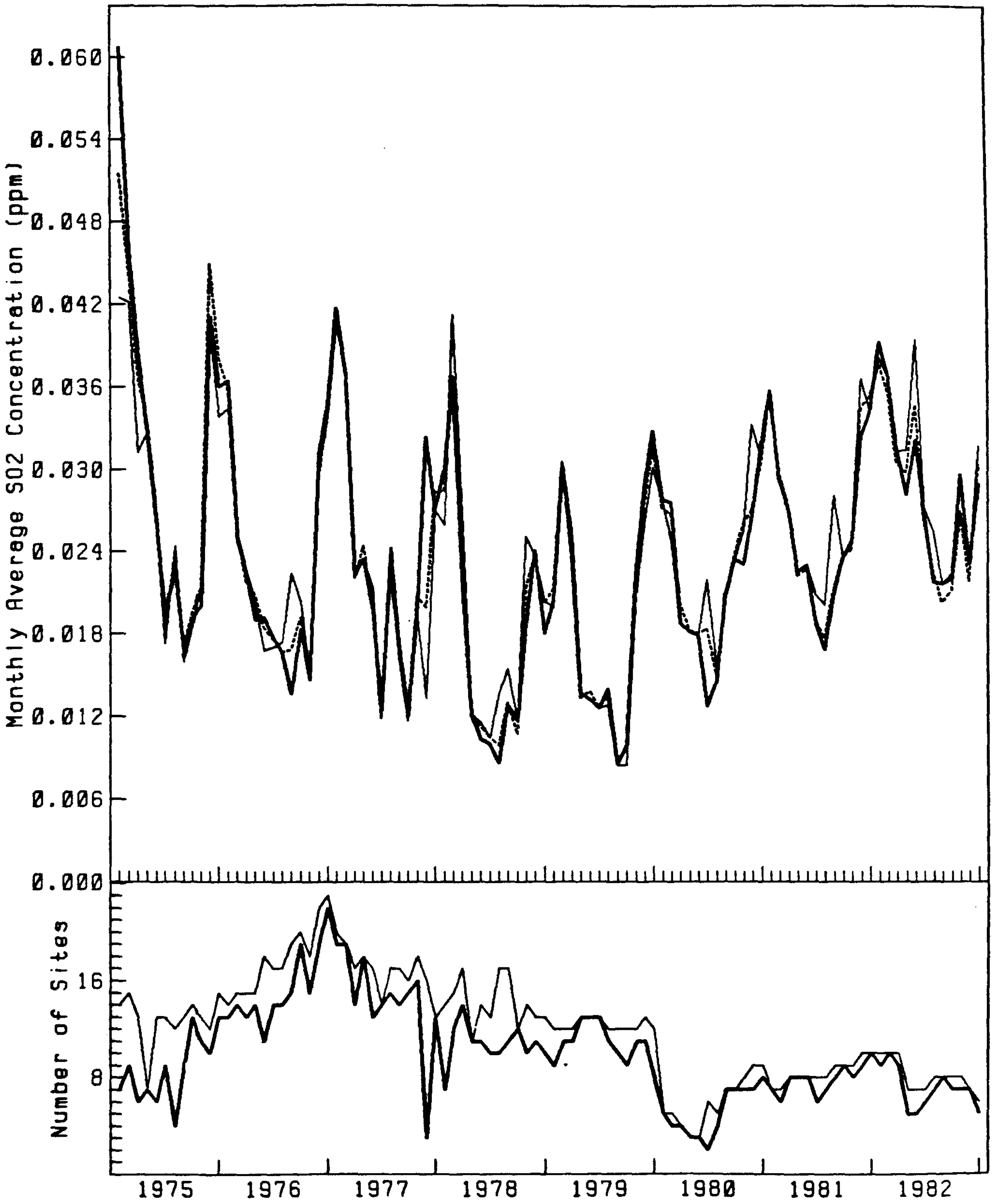

Figure C8. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Maryland, 1975 - 1982.

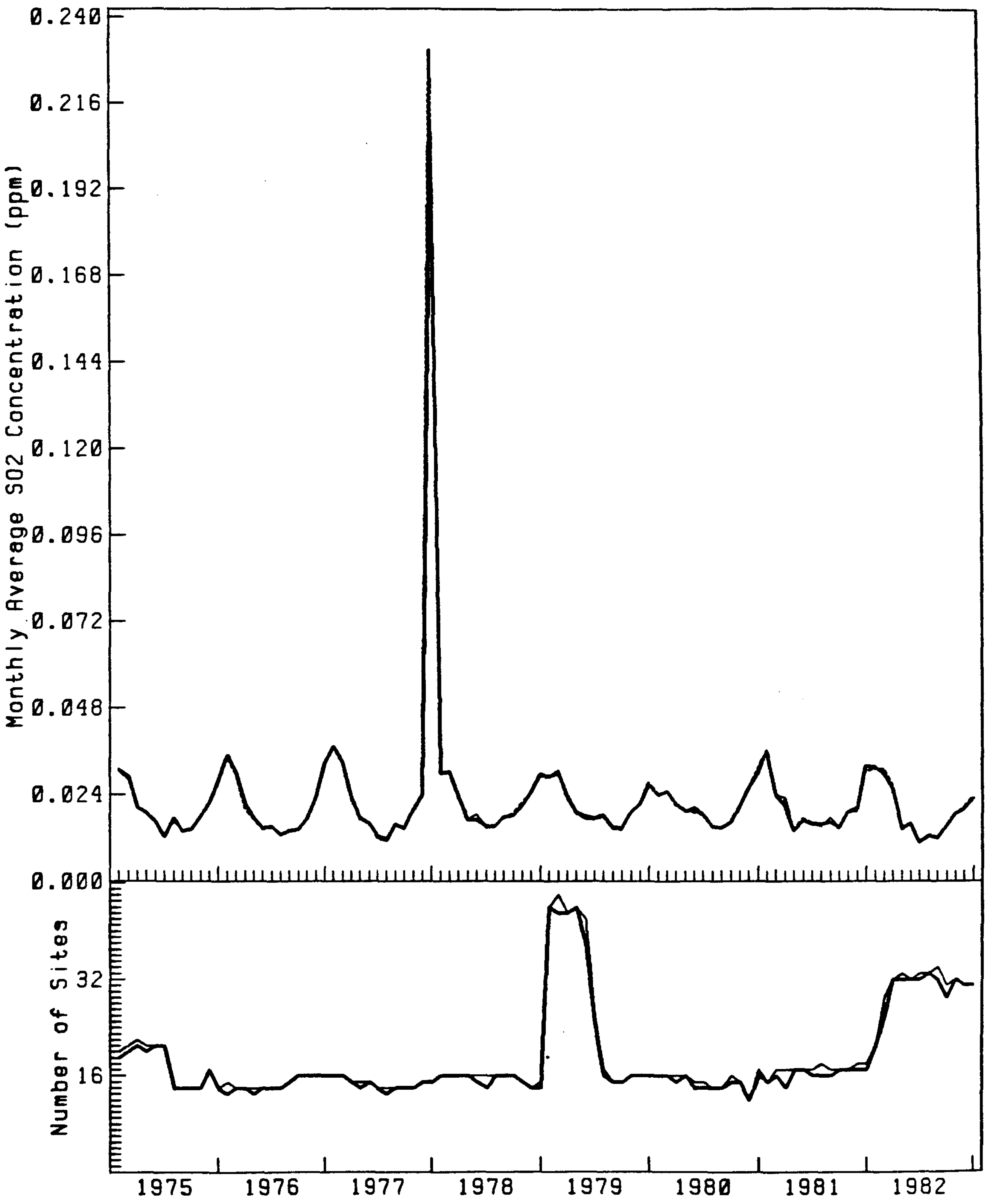

Figure C9. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Massachusetts, 1975 - 1982.

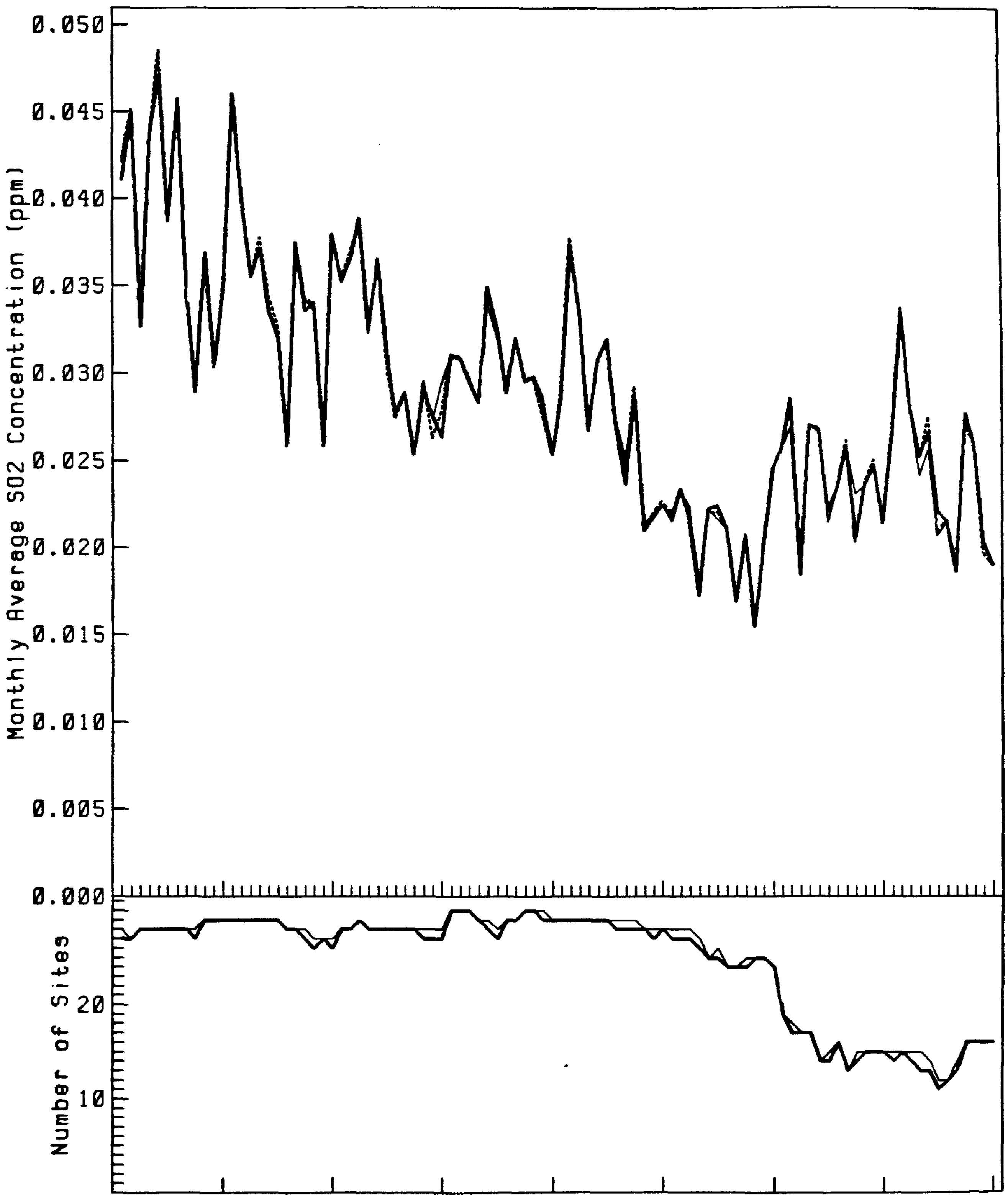

Figure C10. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Michigan, 1975 - 1982.

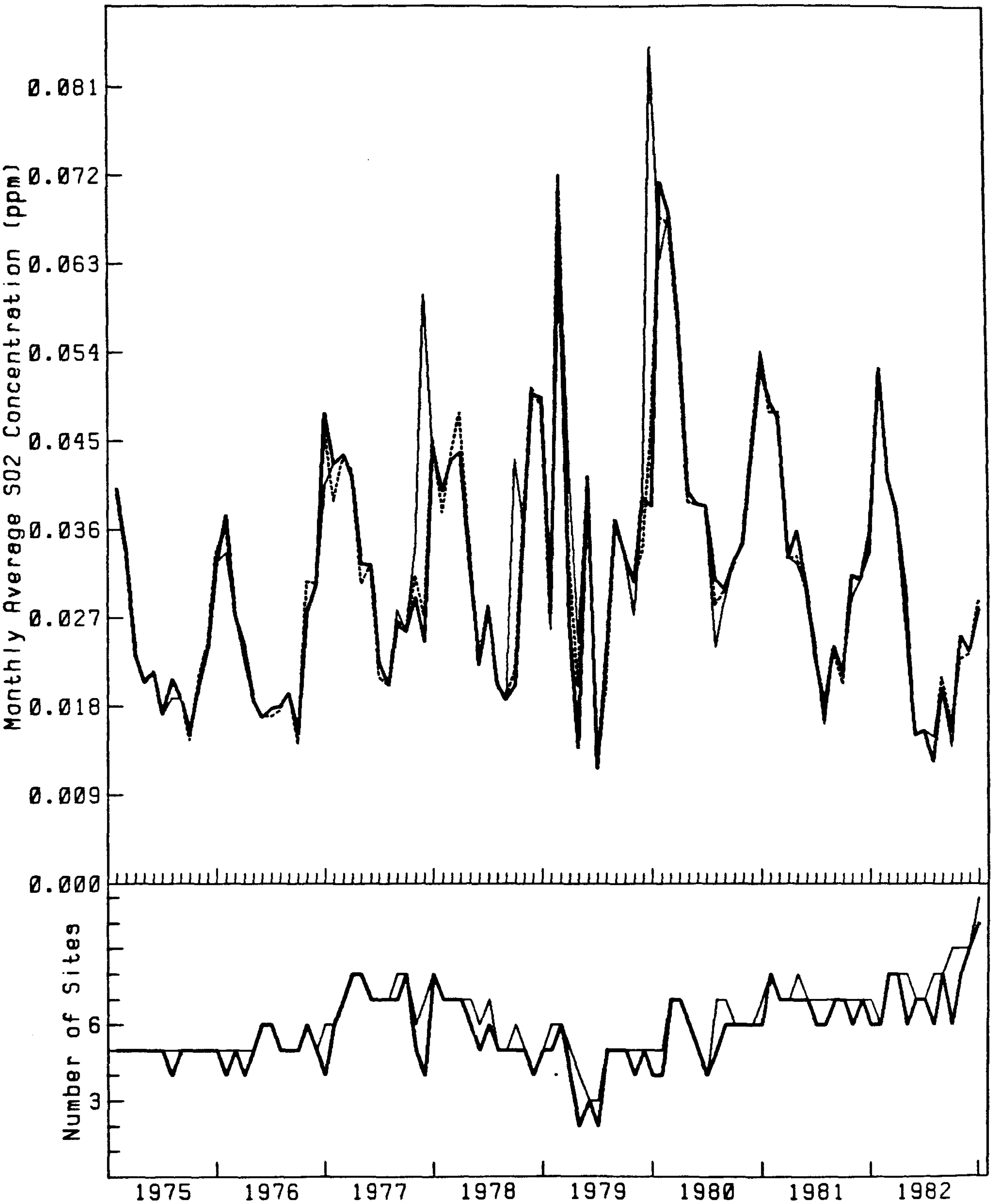

Figure C11. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, New Hampshire, 1975 - 1982.

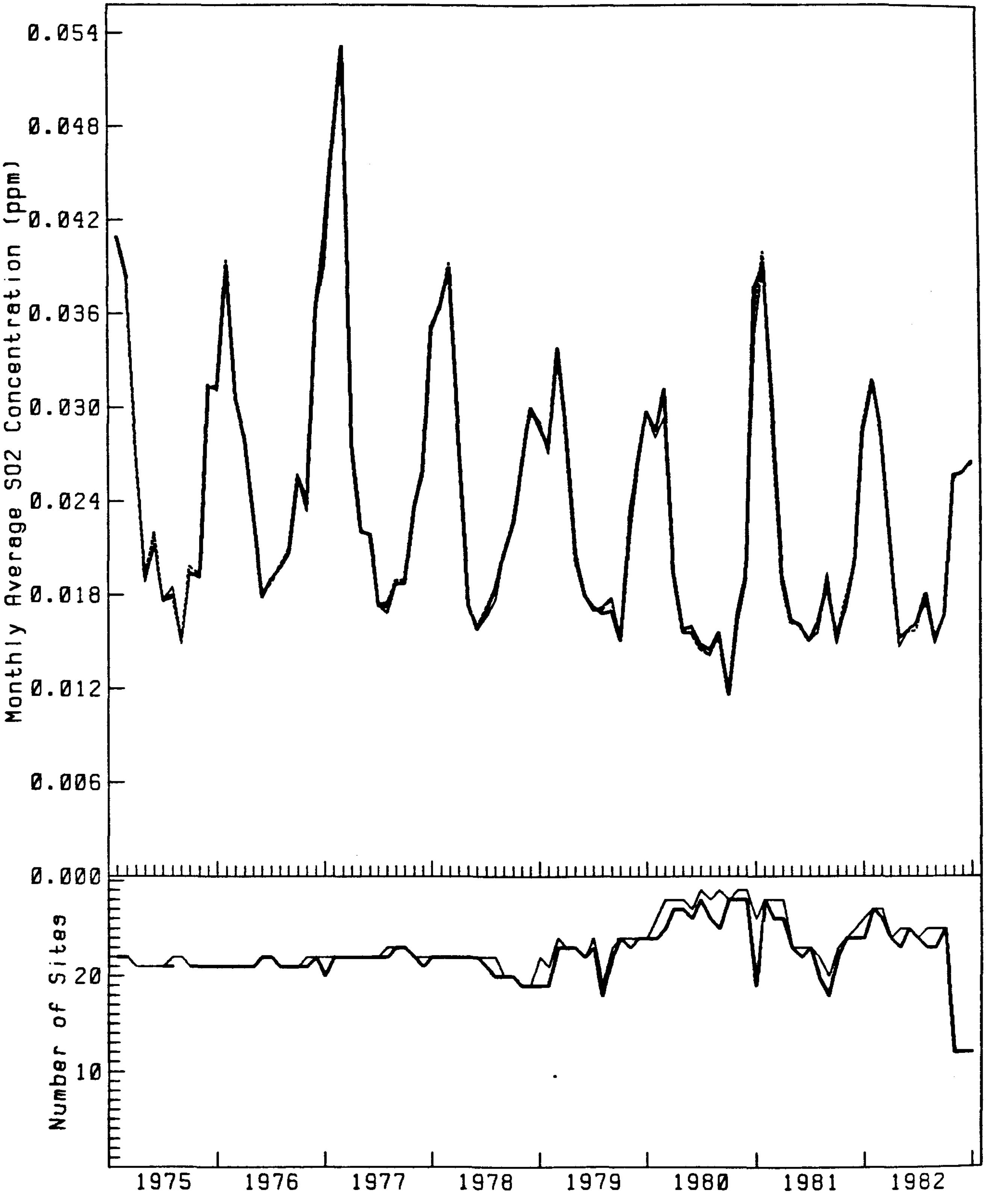

Figure C12. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, New Jersey, 1975 - 1982.

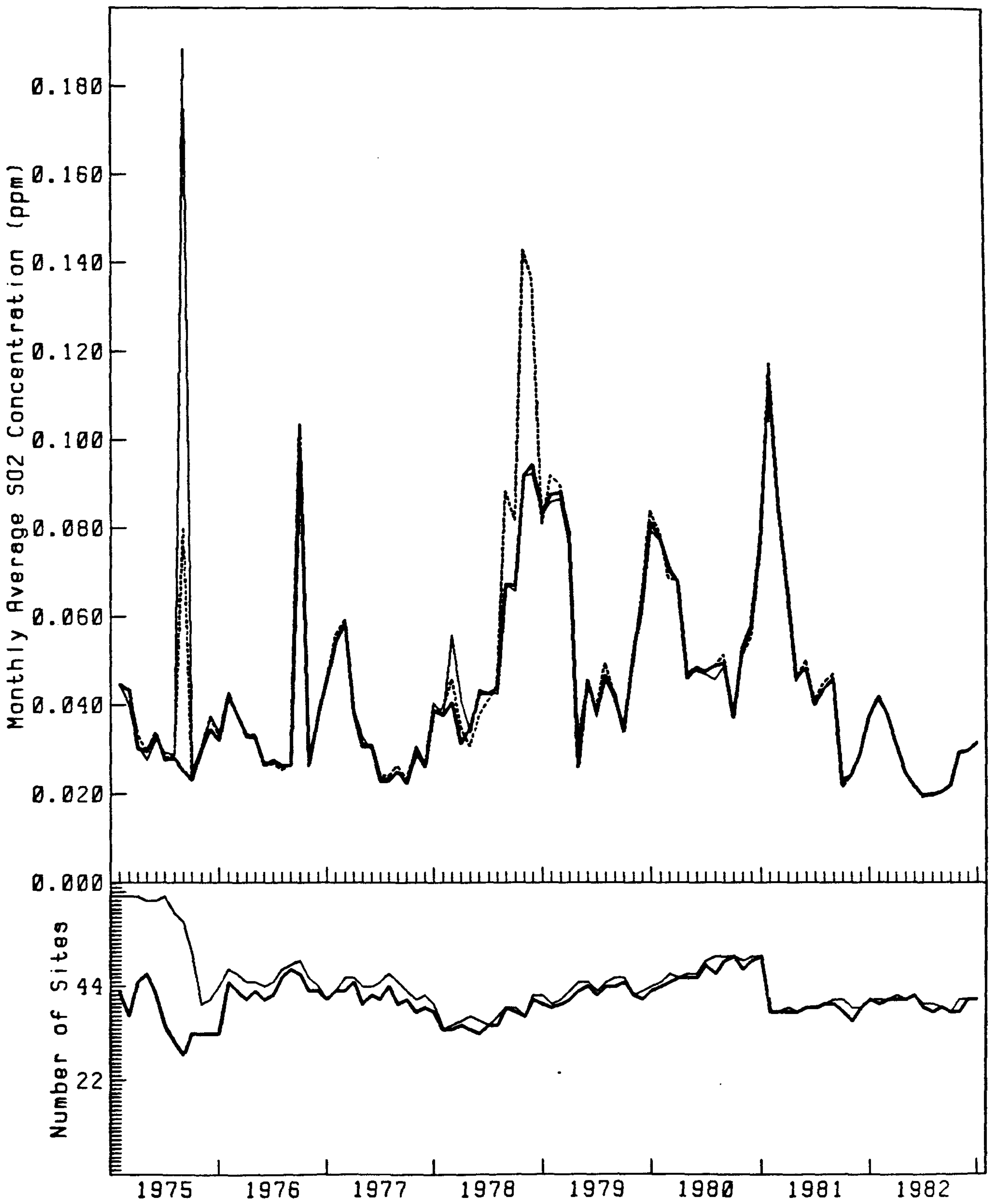

Figure C13. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, New York, 1975 - 1982.

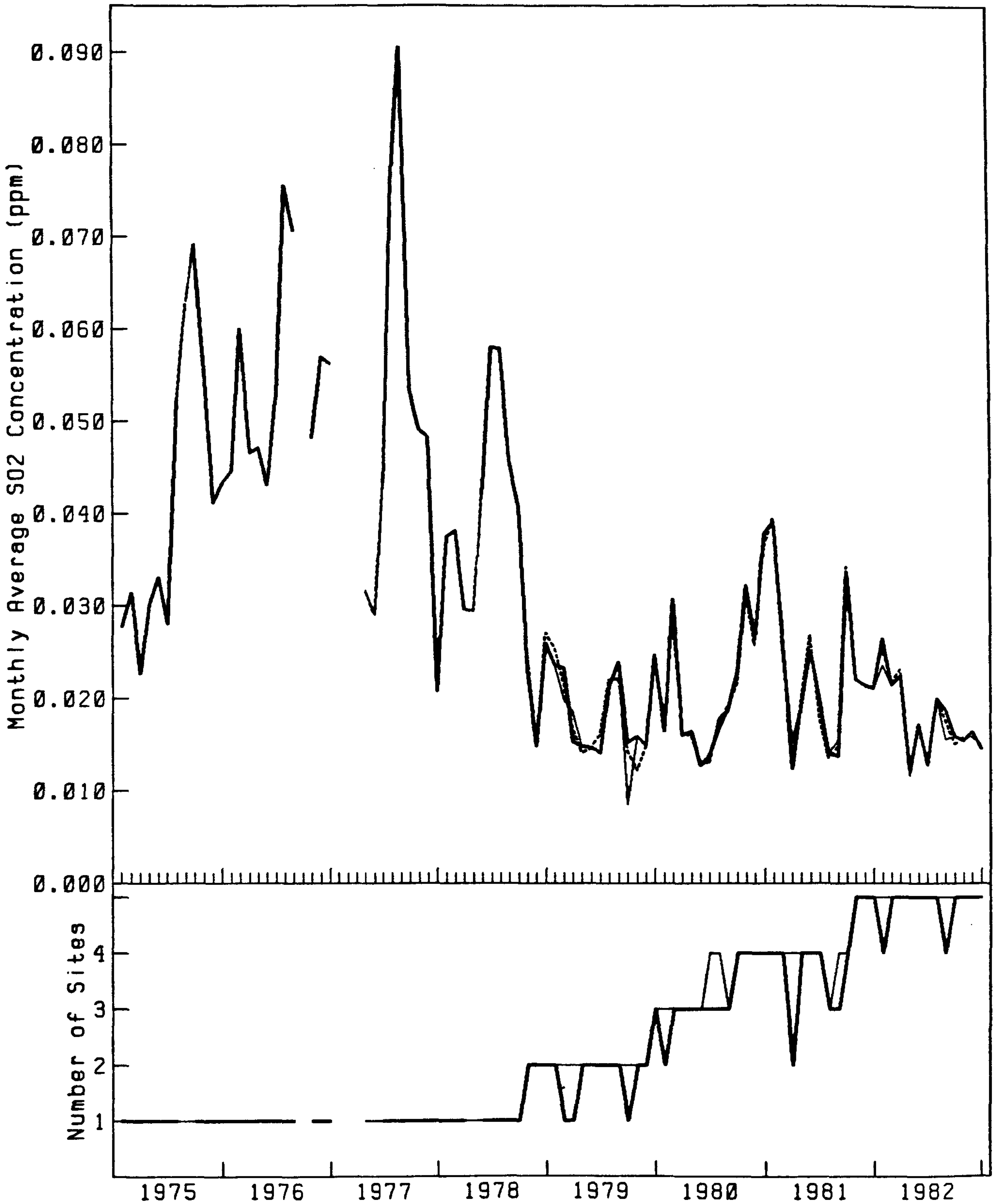

Figure C14. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, North Carolina, 1975 - 1982.

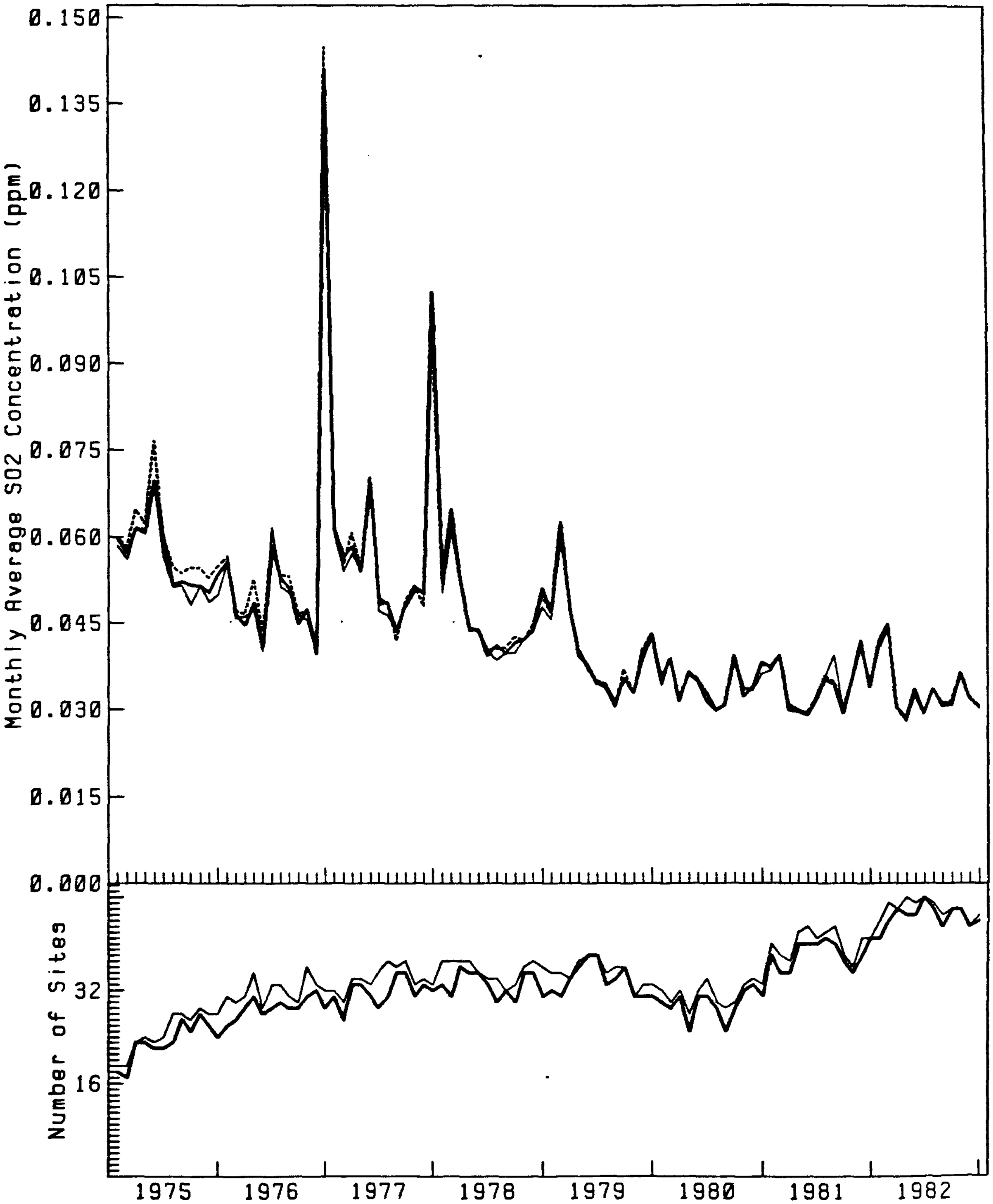

Figure C15. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Ohio, 1975 - 1982.

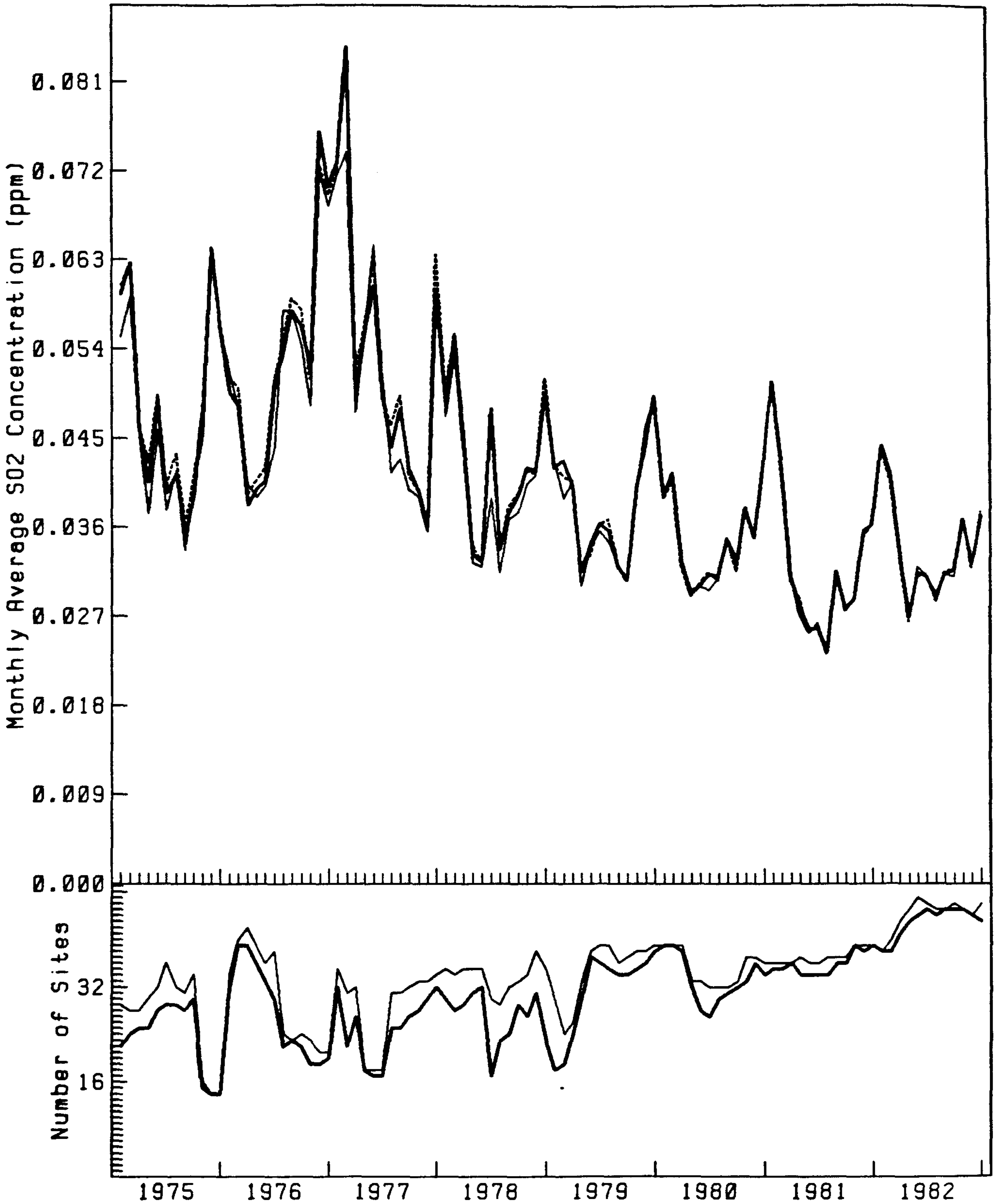

Figure C16. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Pennsylvania, 1975 - 1982.

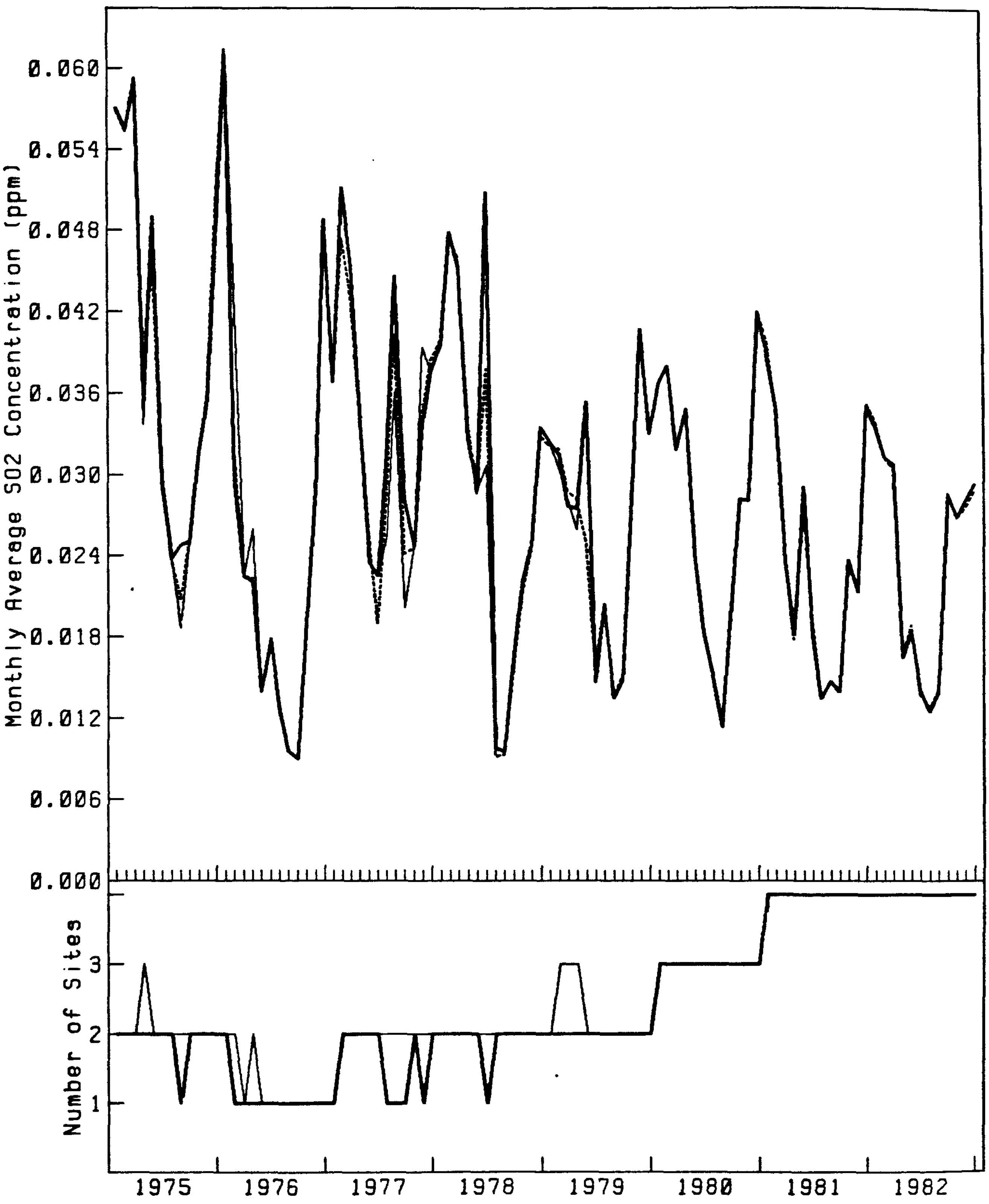

Figure C17. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Rhode Island, 1975 - 1982.

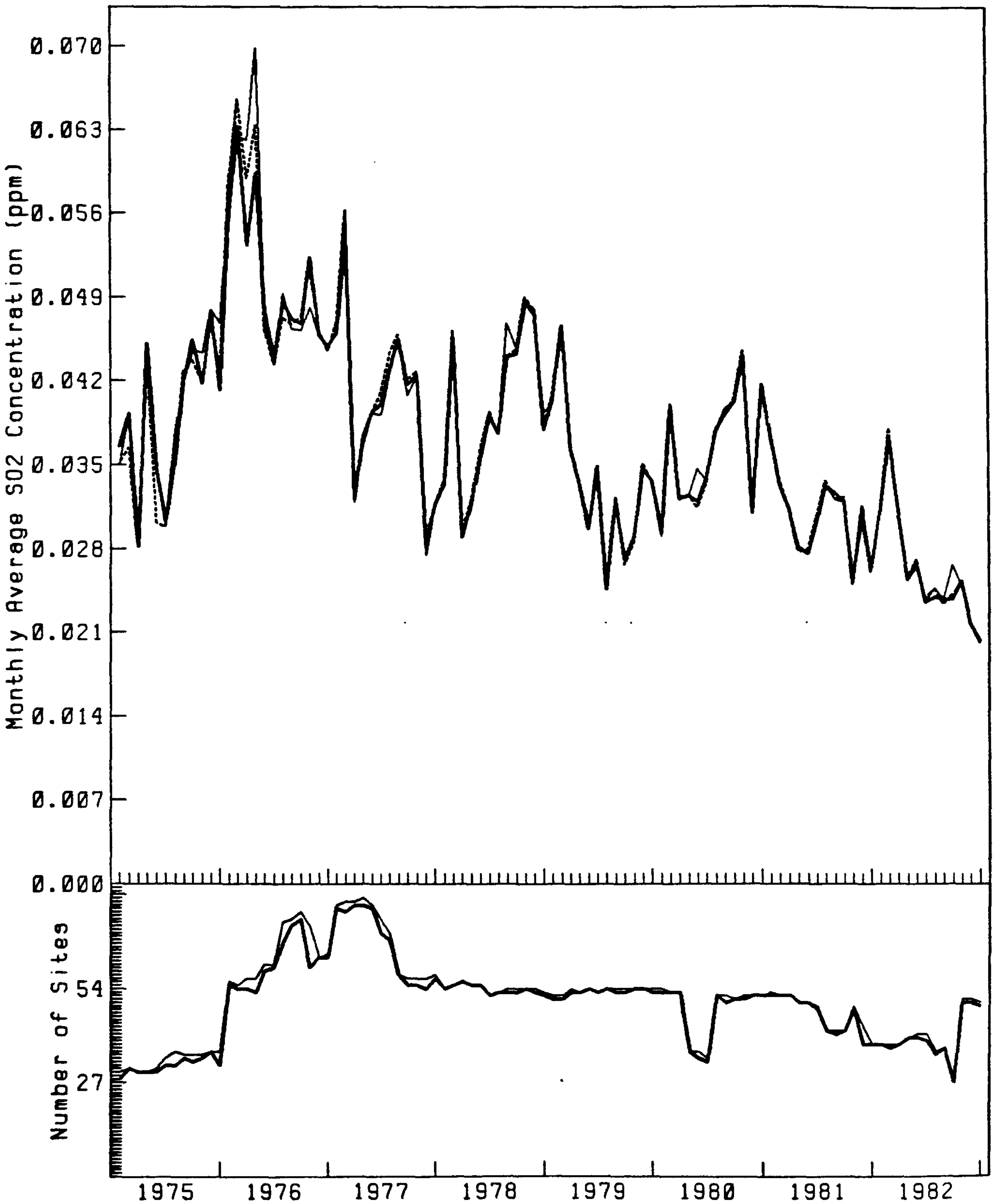

Figure C18. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Tennessee, 1975 - 1982.

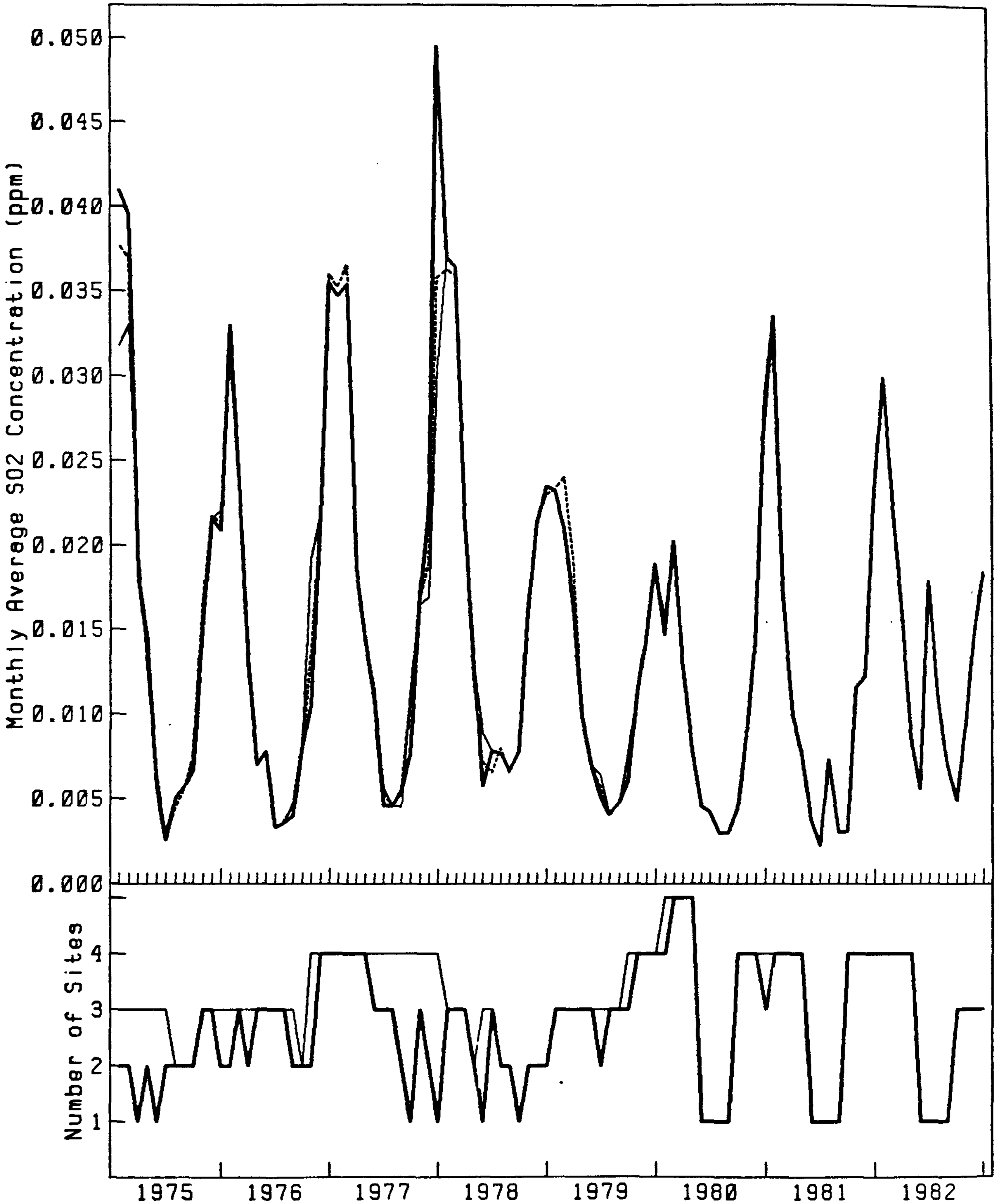

Figure C19. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Vermont, 1975 - 1982.

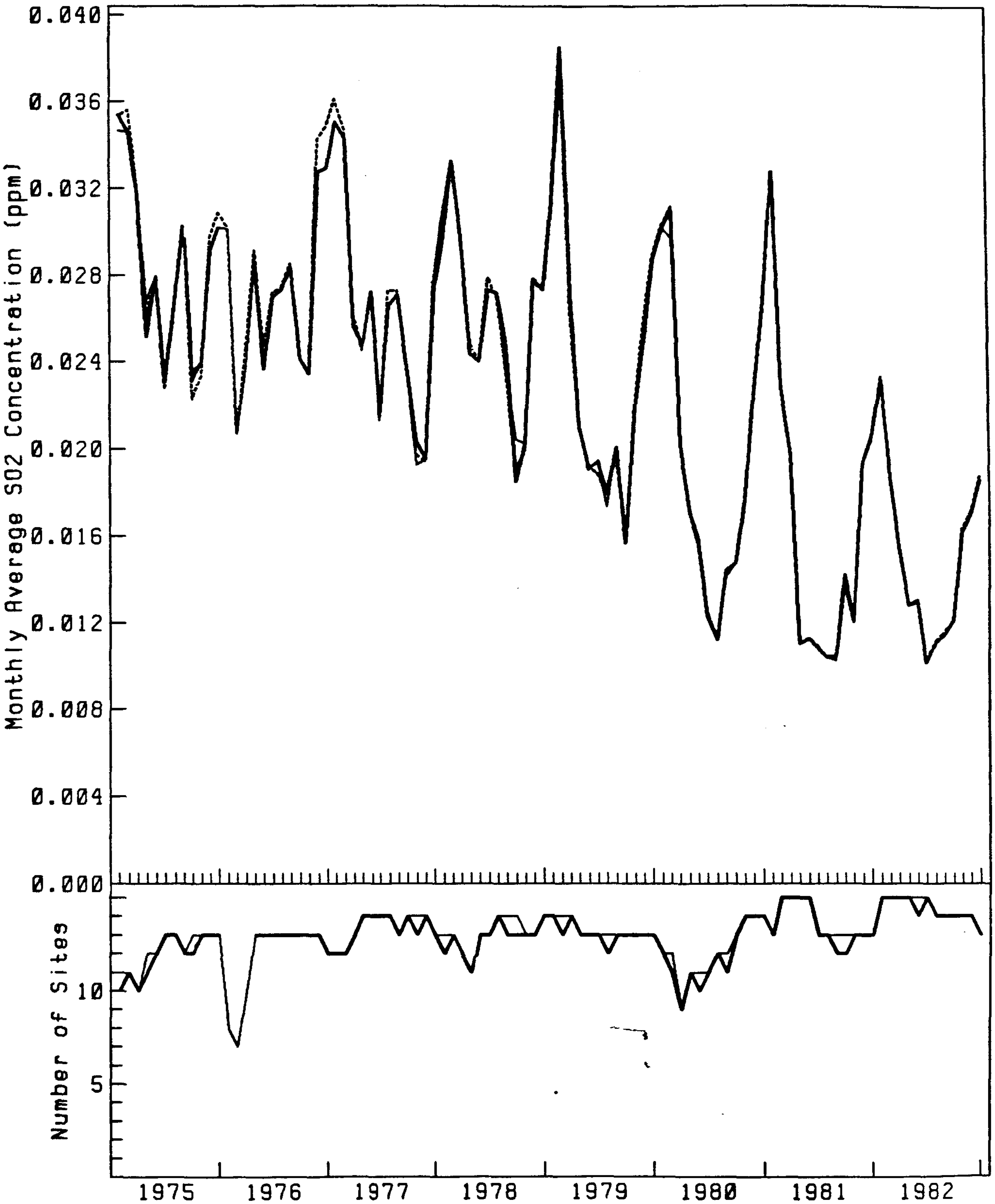

Figure C20. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Virginia, 1975 - 1982.

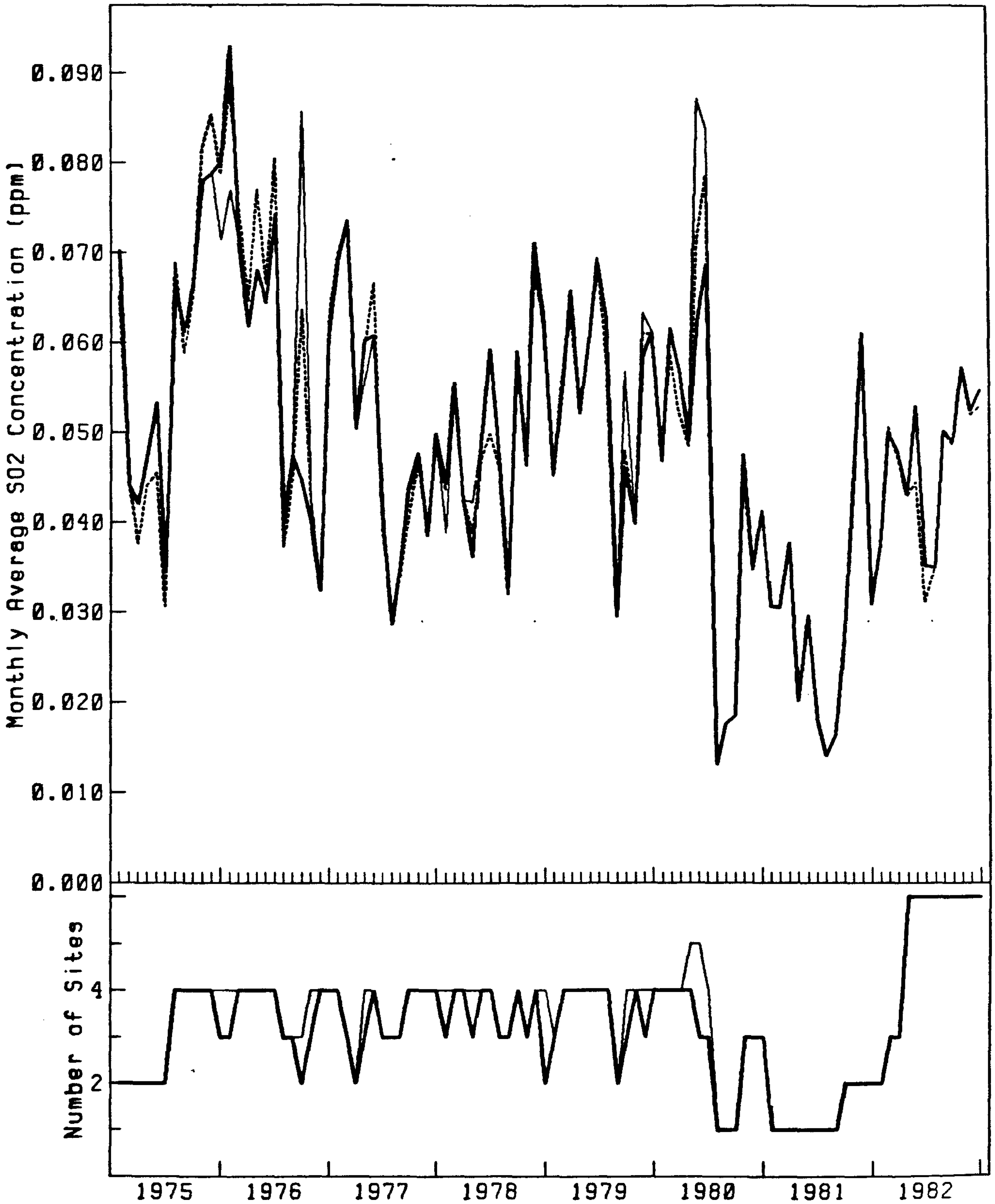

Figure C21. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, West Virginia, 1975 - 1982.

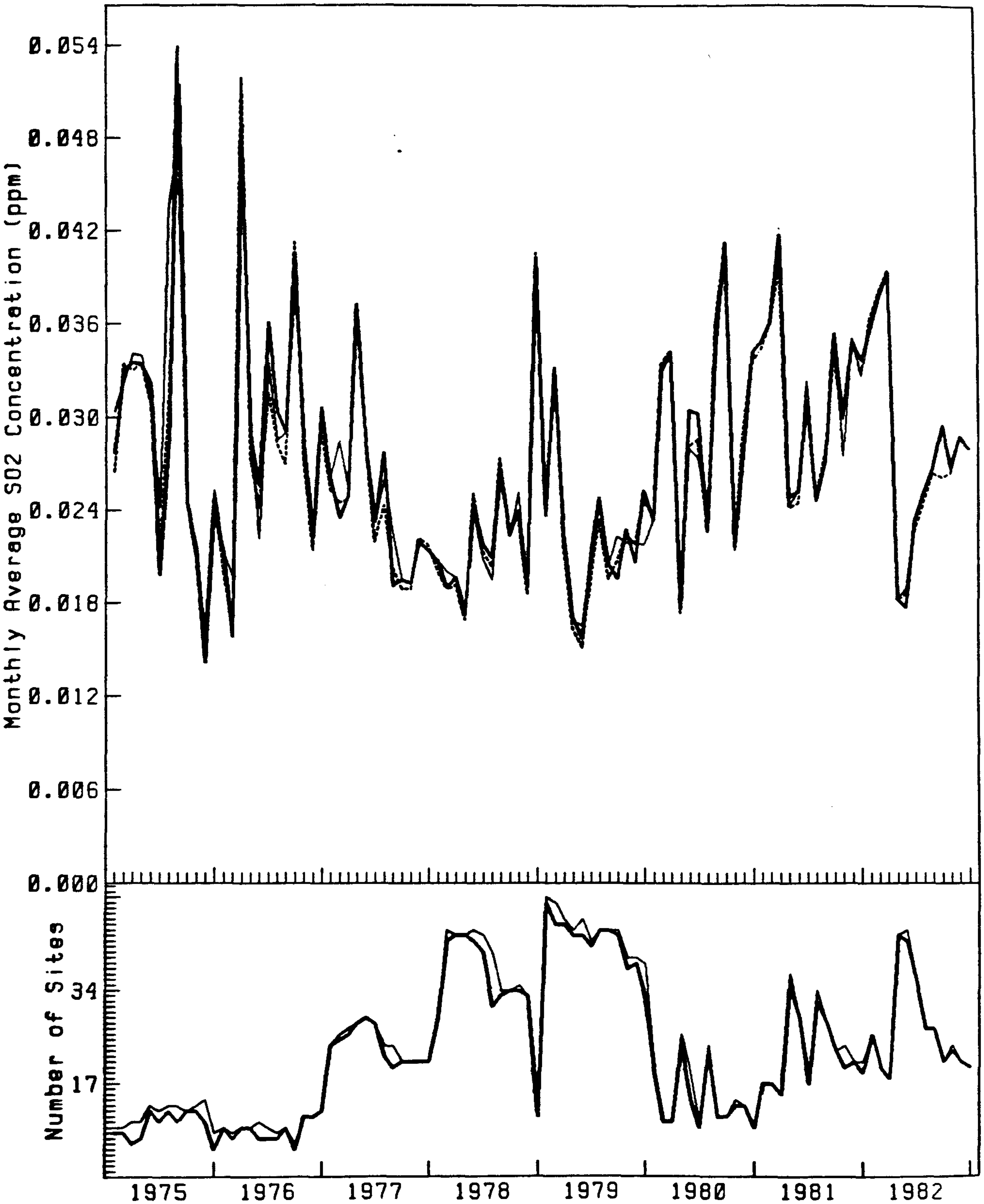

Figure C22. Monthly Average Daily Maximum SO2 Concentration and Number of Reporting Sites, Wisconsin, 1975 - 1982.

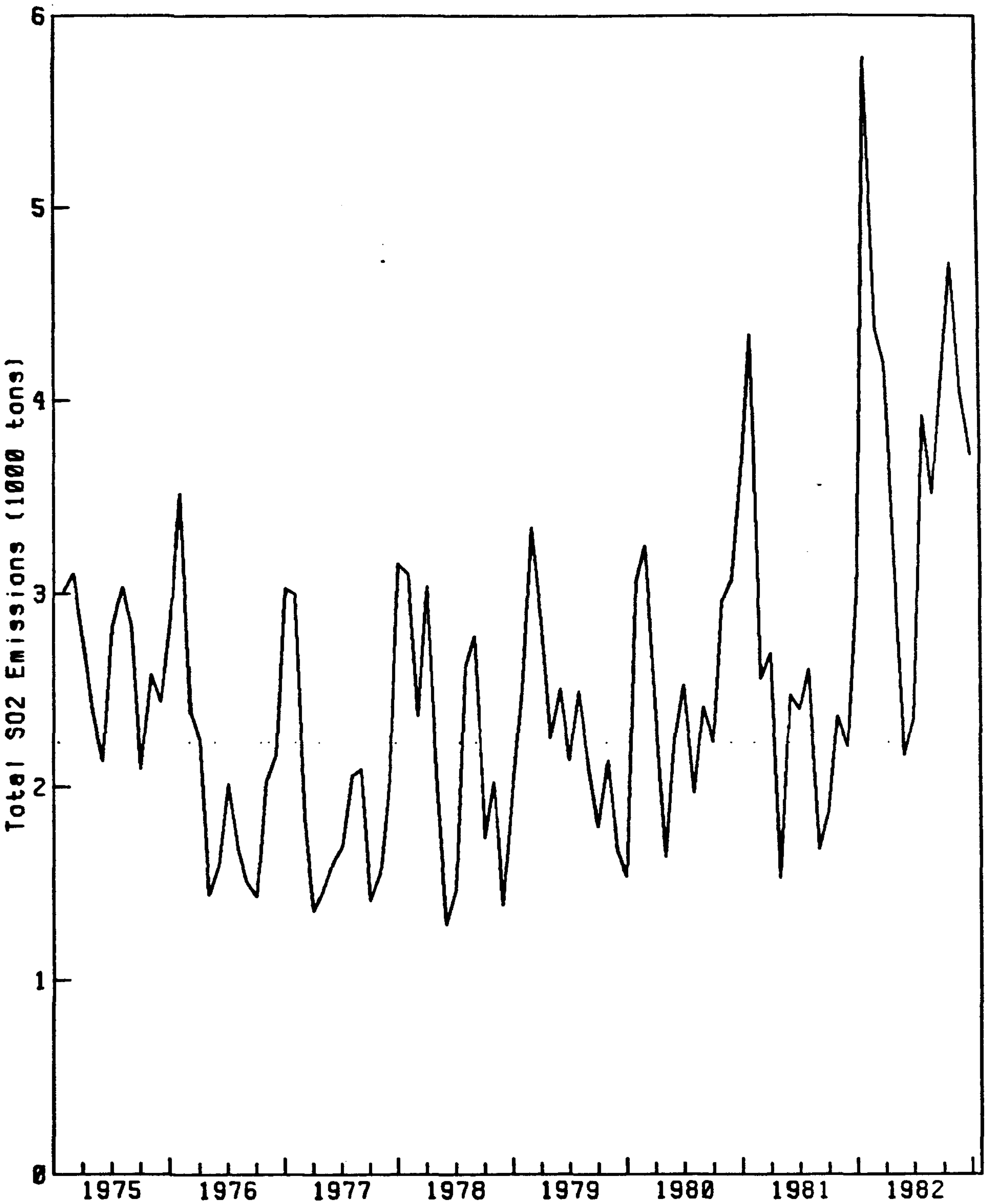

Figure D1. Monthly Total Electric Utility SO2 Emissions, Connecticut, 1975 - 1982.

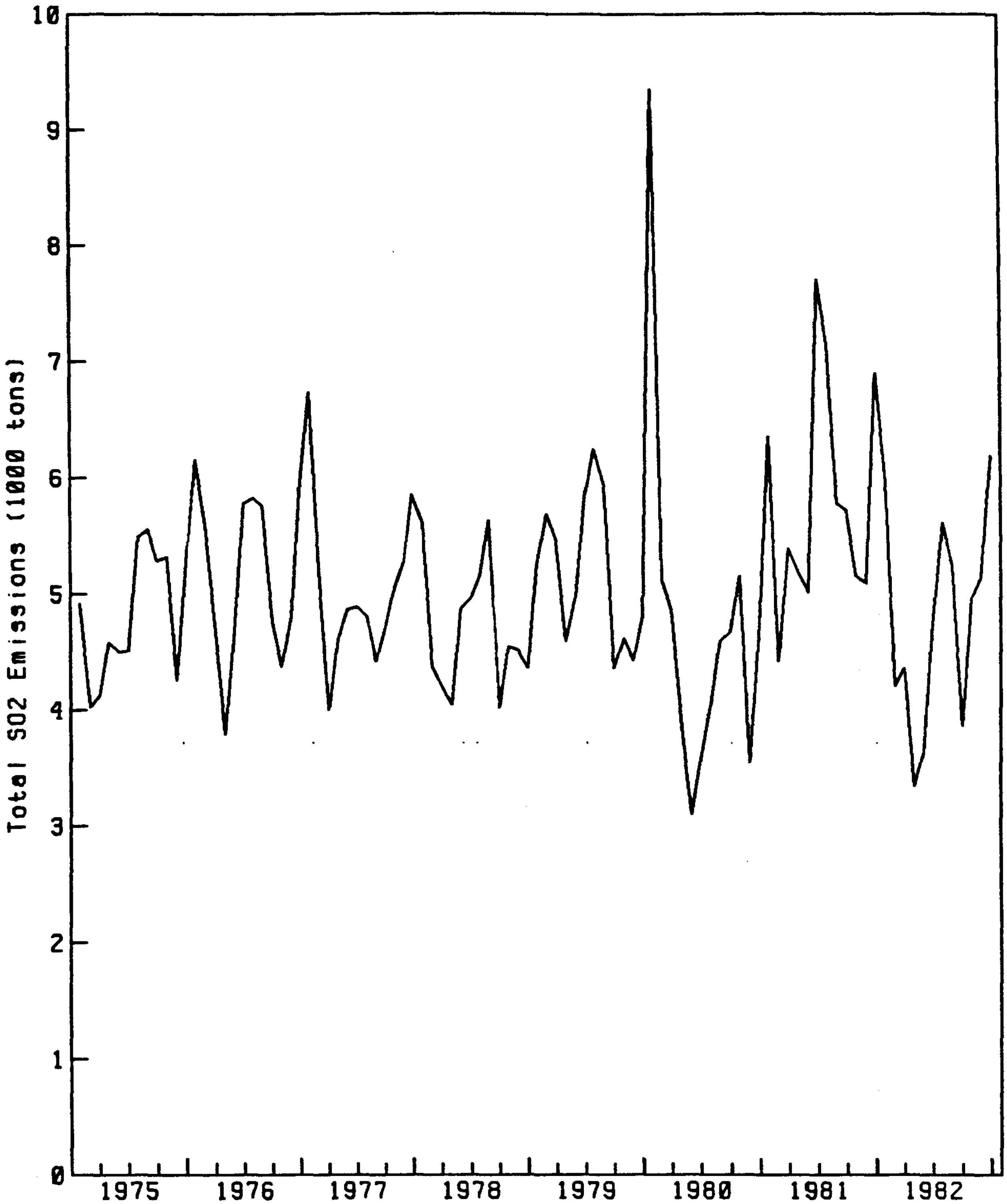

Figure D2. Monthly Total Electric Utility SO2 Emissions, Delaware, 1975 - 1982.

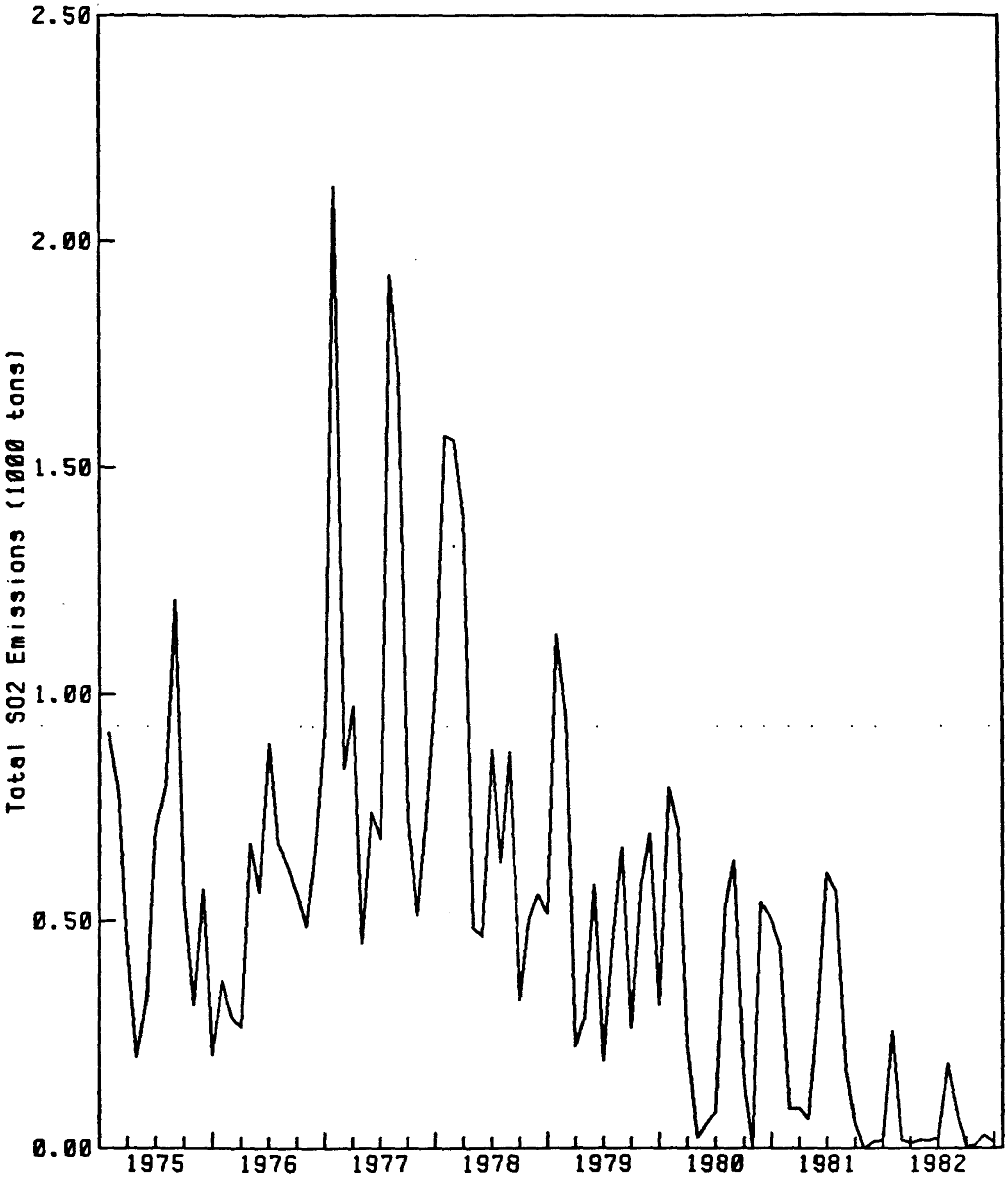

Figure D3. Monthly Total Electric Utility SO2 Emissions. District of Columbia. 1975 - 1982.

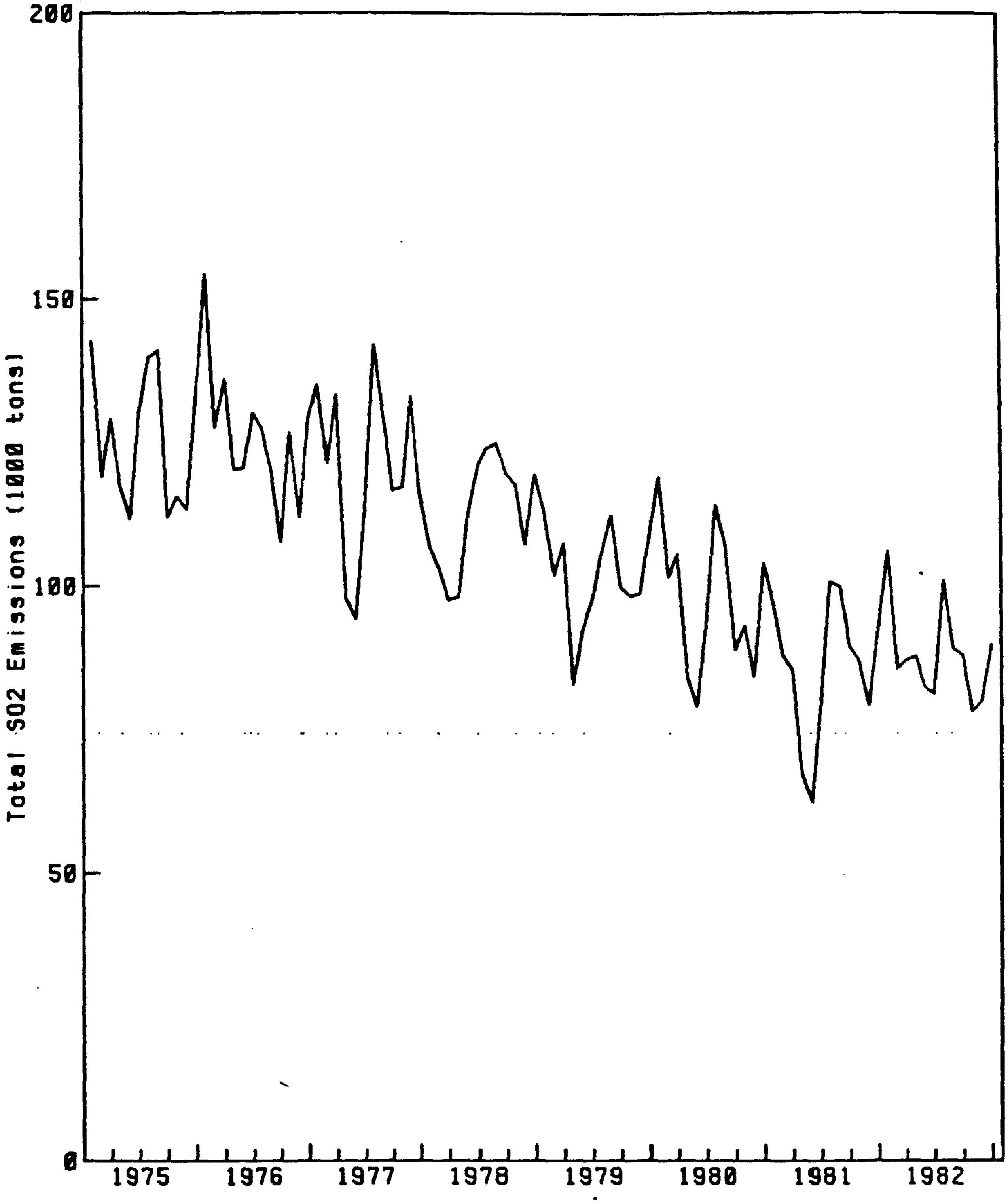

Figure D4. Monthly Total Electric Utility SO2 Emissions, Illinois, 1975 - 1982.

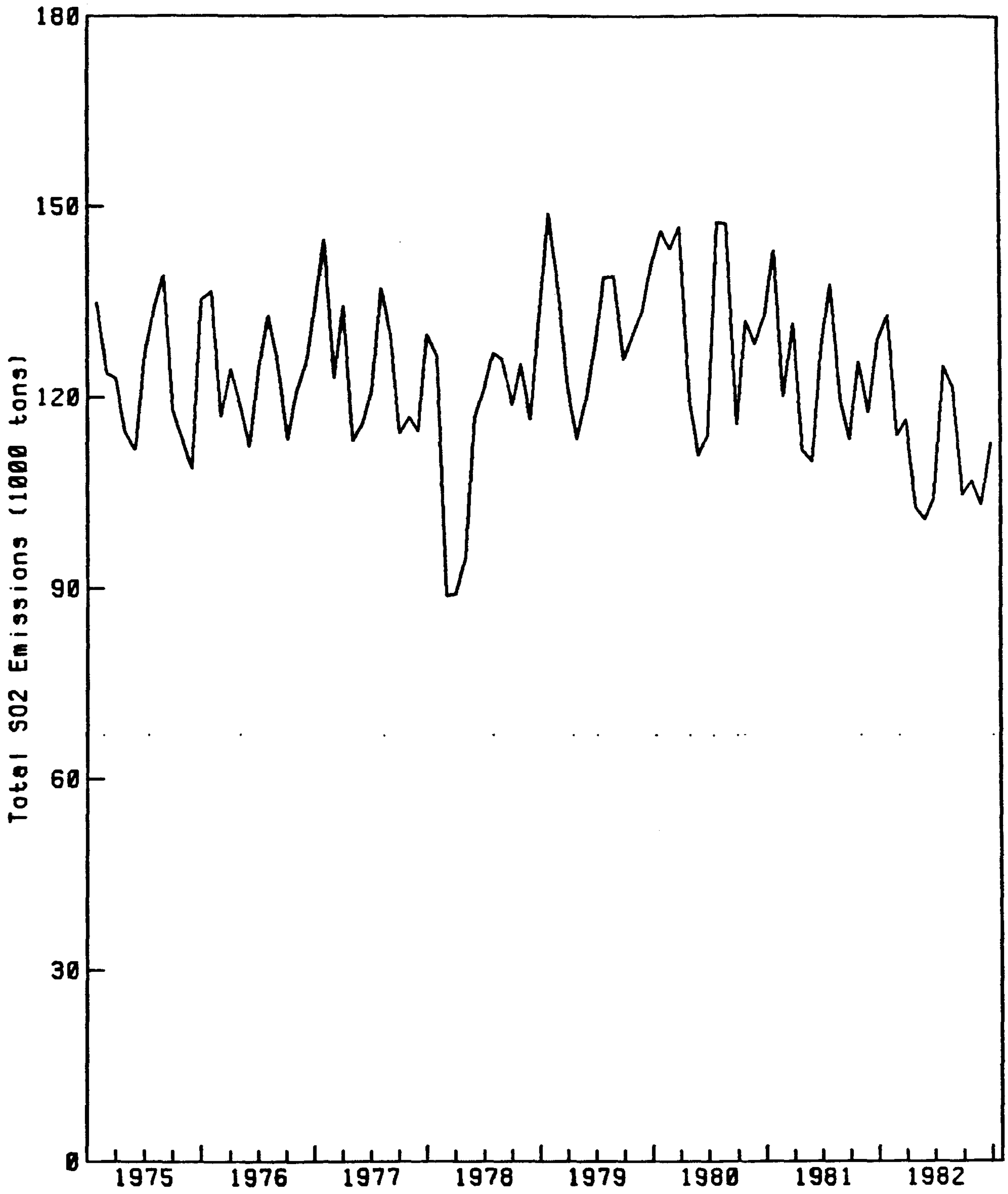

Figure D5. Monthly Total Electric Utility SO2 Emissions, Indiana, 1975 - 1982.

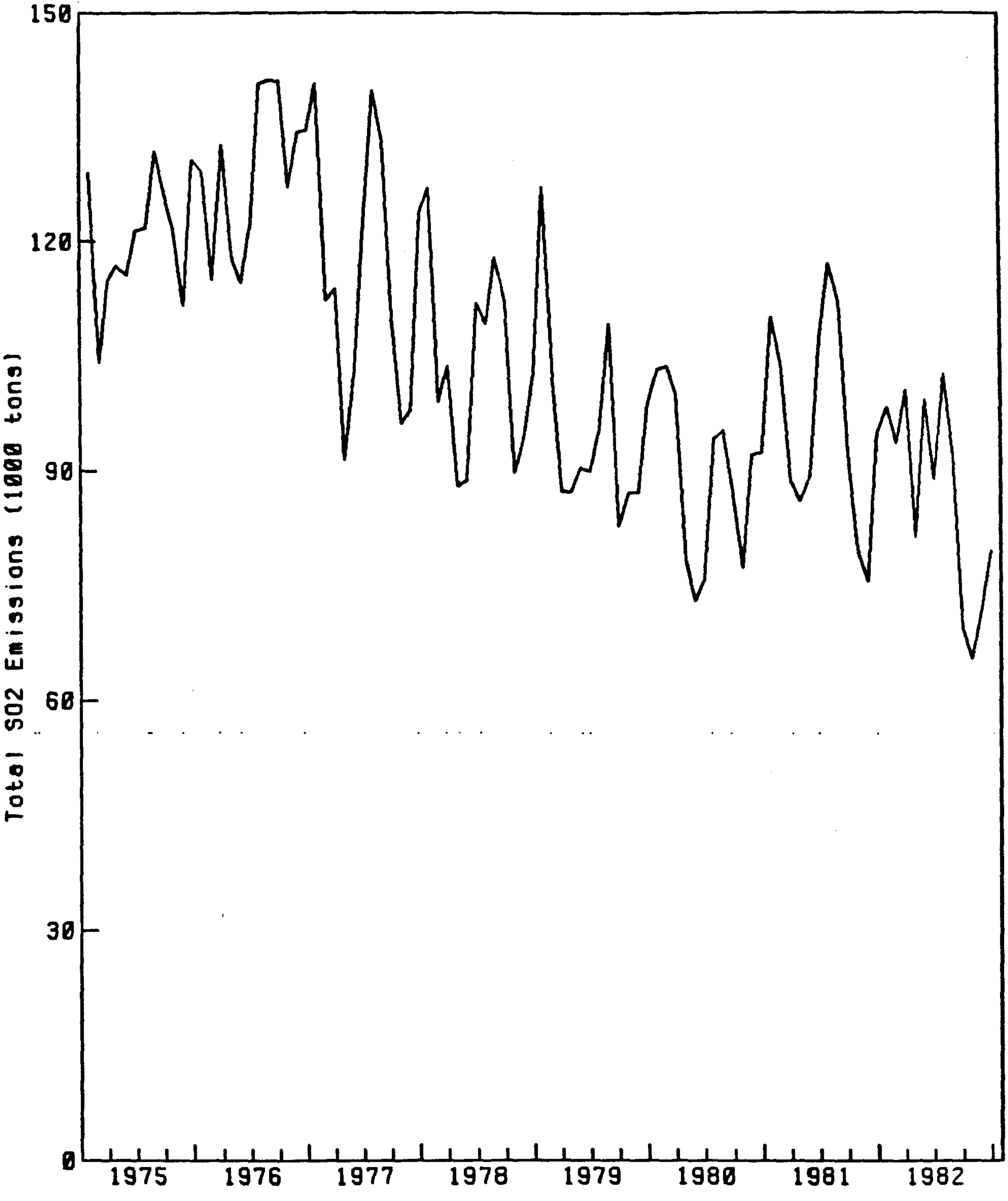

Figure D6. Monthly Total Electric Utility SO2 Emissions. Kentucky. 1975 - 1982.

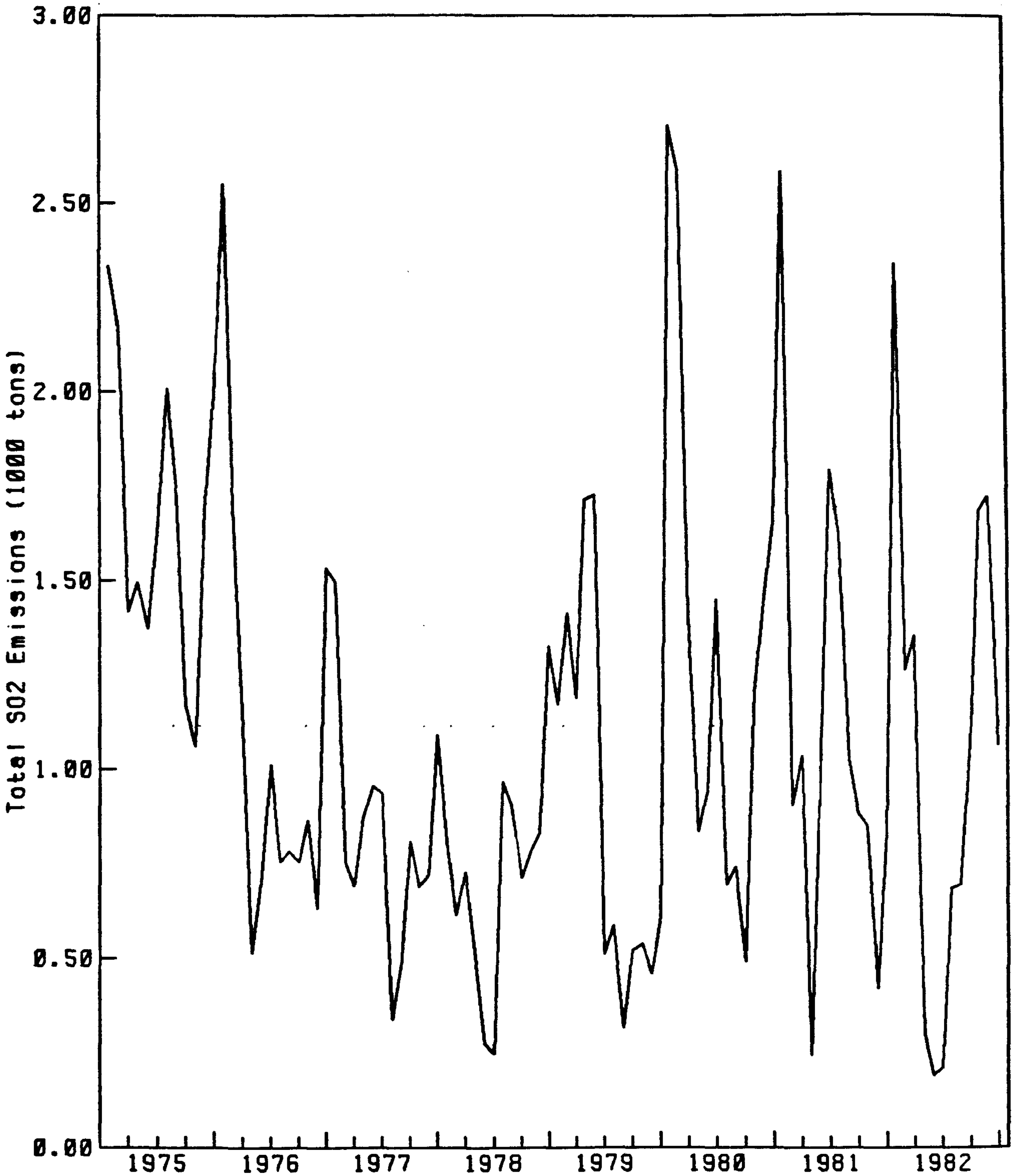

Figure D7. Monthly Total Electric Utility SO2 Emissions. Maine. 1975 - 1982.

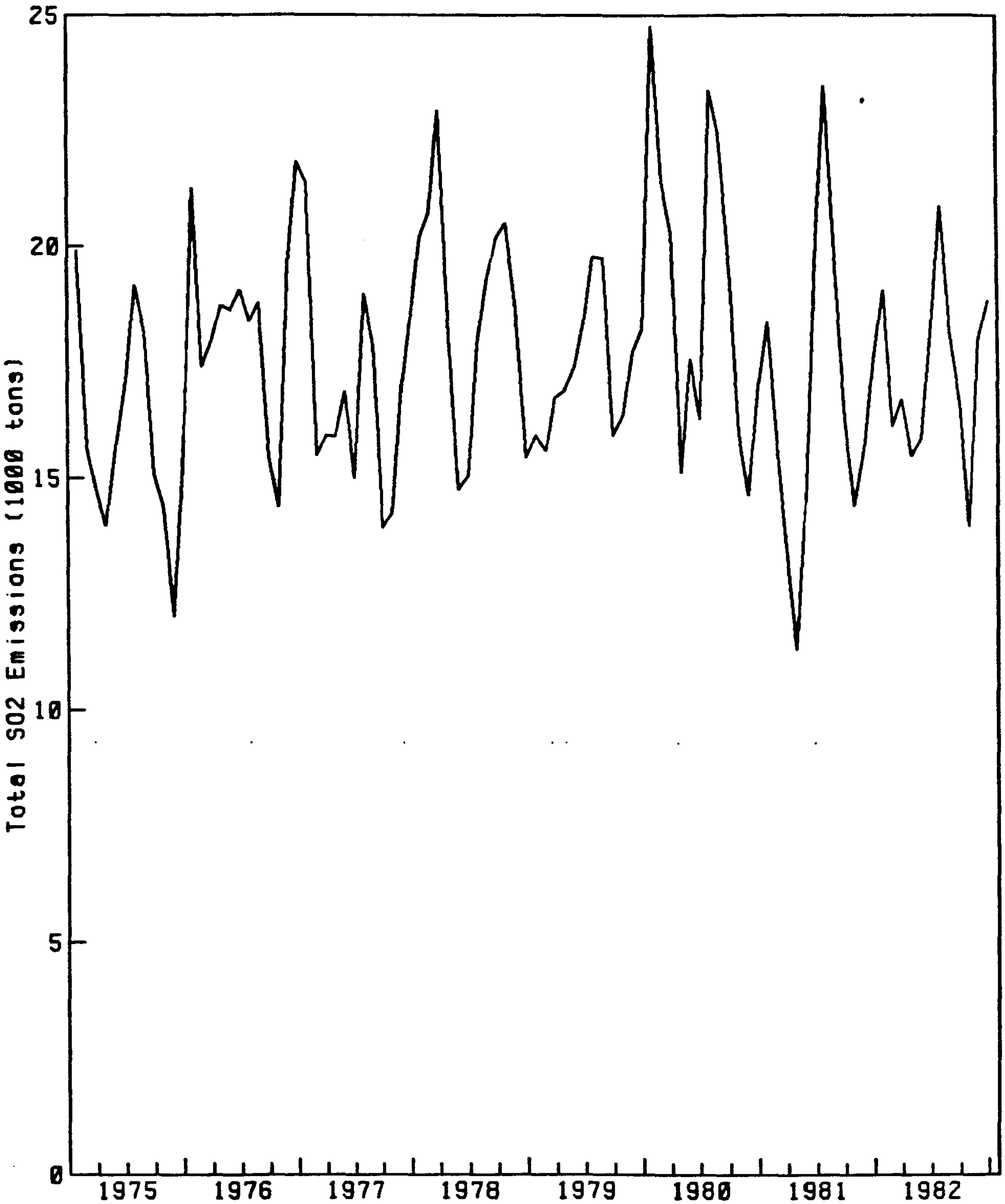

Figure D8. Monthly Total Electric Utility SO2 Emissions, Maryland, 1975 - 1982.

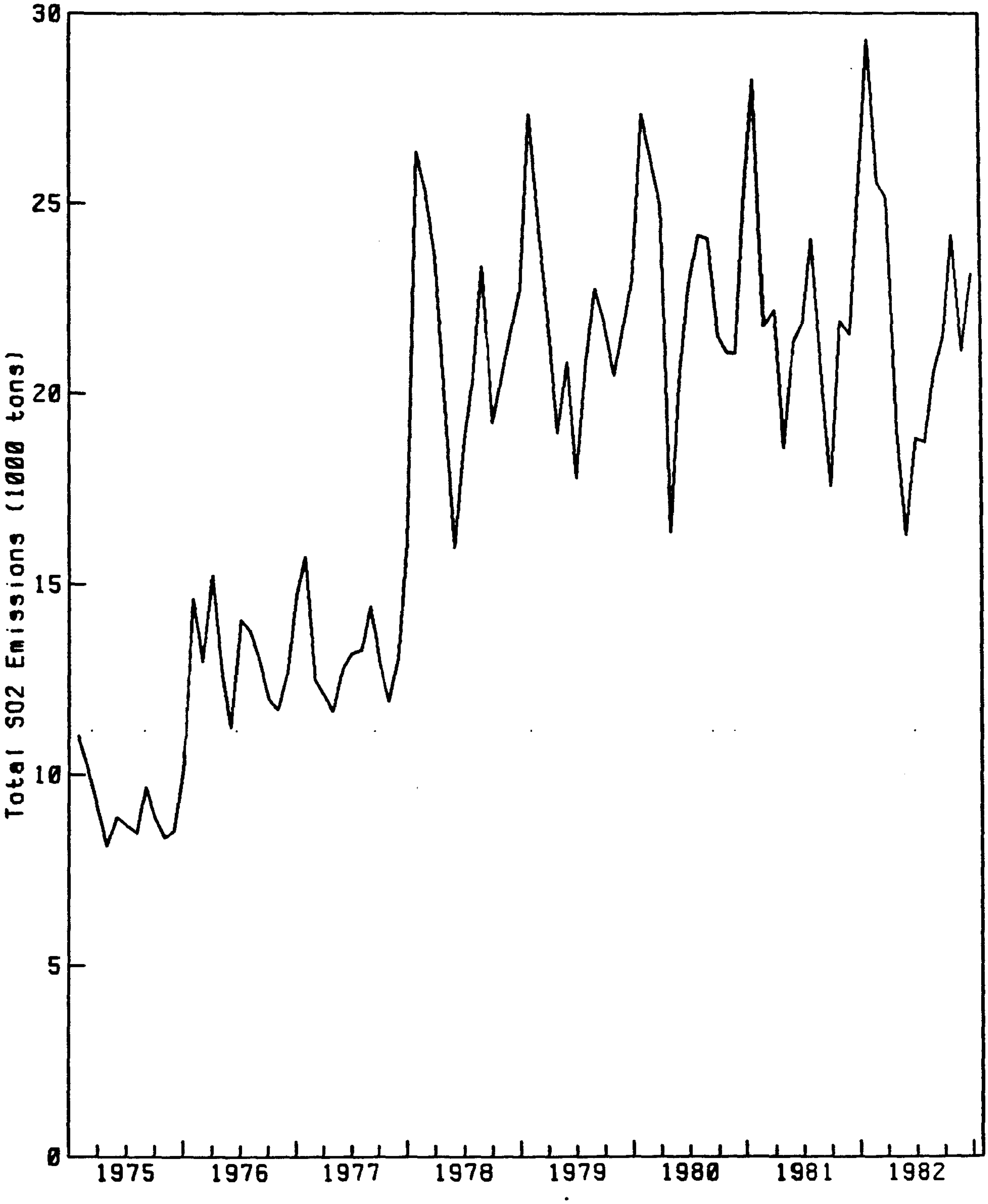

Figure D9. Monthly Total Electric Utility SO2 Emissions, Massachusetts, 1975 - 1982.

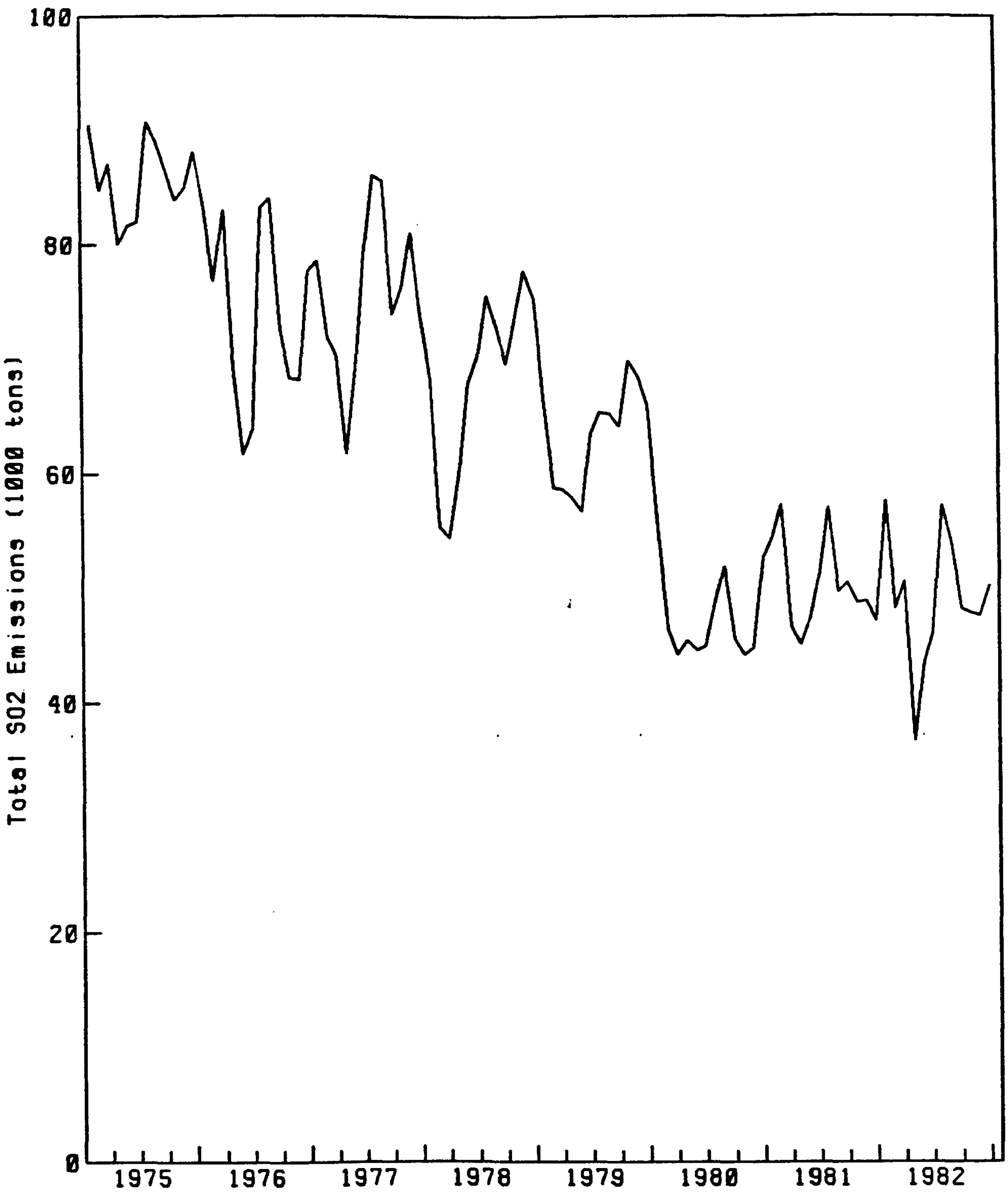

Figure D10. Monthly Total Electric Utility SO2 Emissions, Michigan, 1975 - 1982.

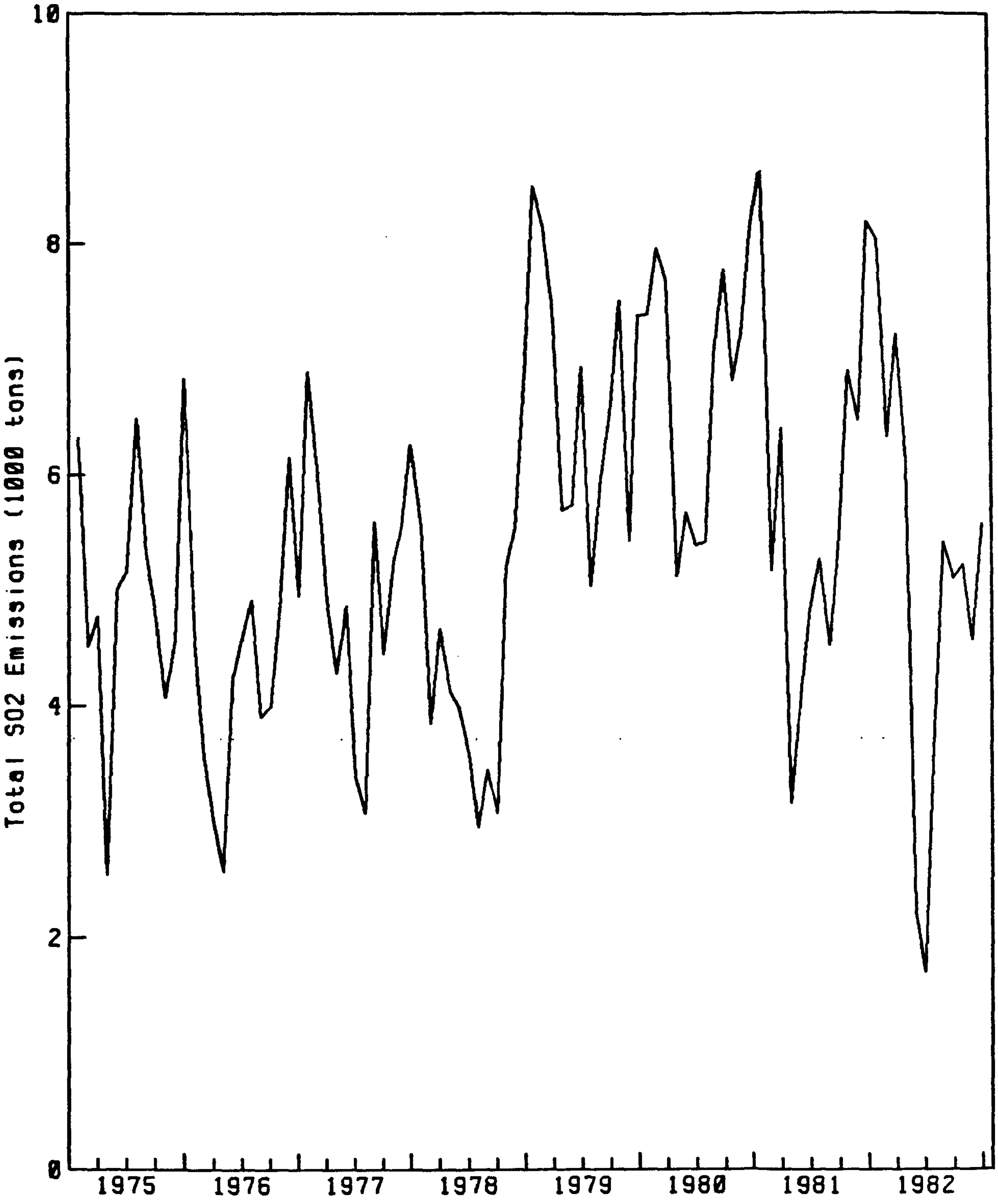

Figure D11. Monthly Total Electric Utility SO2 Emissions, New Hampshire, 1975 - 1982.

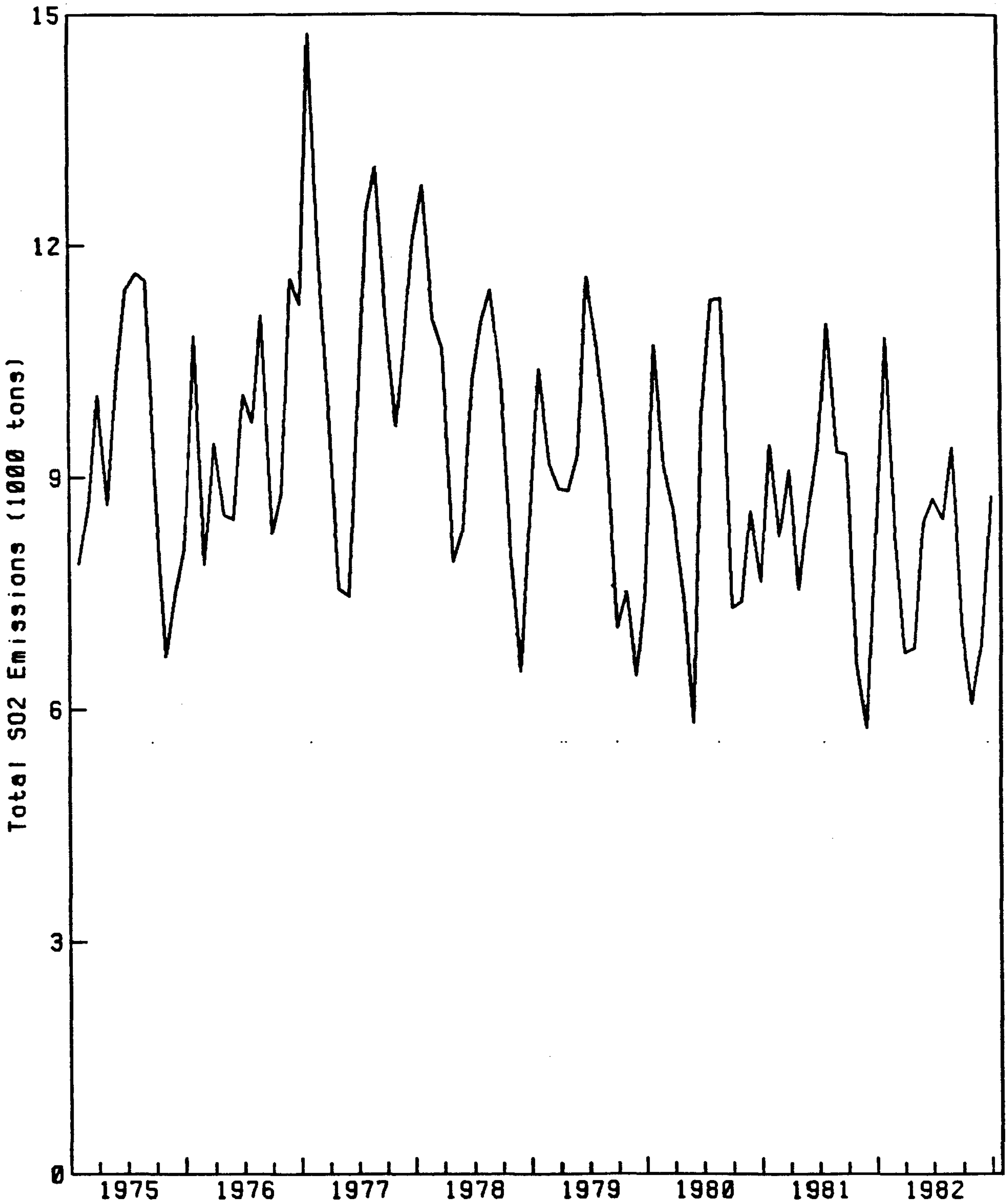

Figure D12. Monthly Total Electric Utility SO2 Emissions, New Jersey, 1975 - 1982.

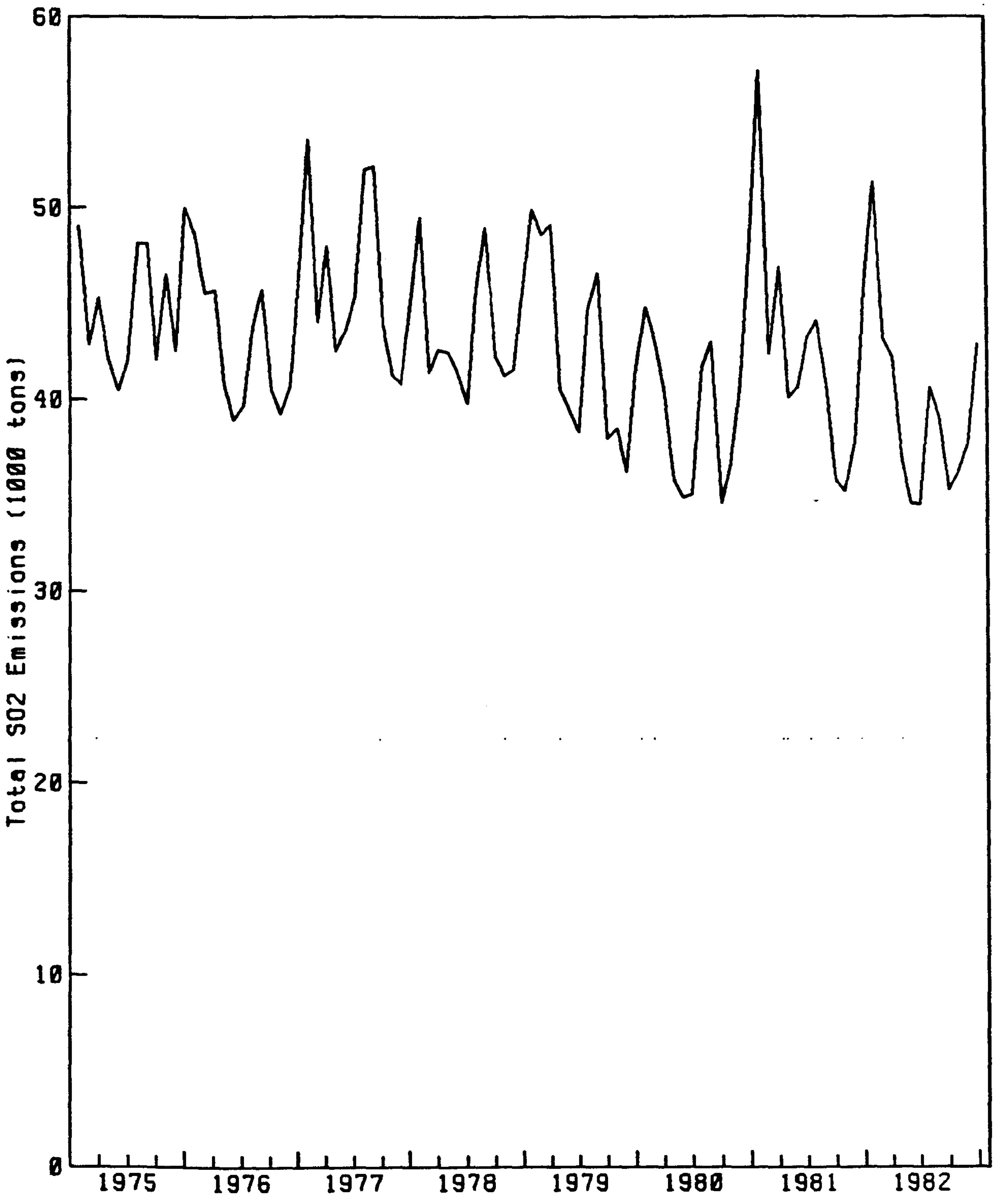

Figure D13. Monthly Total Electric Utility SO2 Emissions, New York, 1975 - 1982.

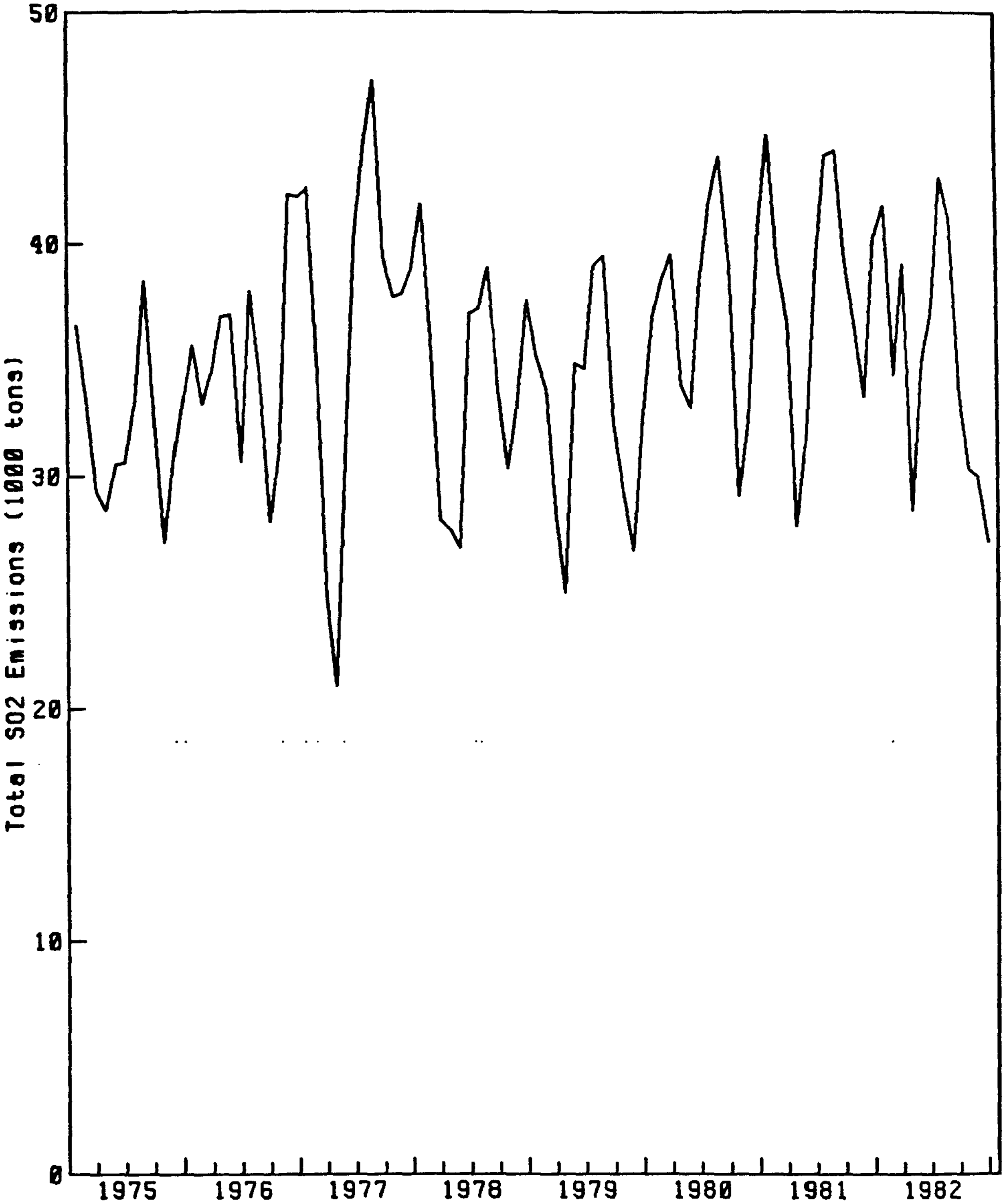

Figure D14. Monthly Total Electric Utility SO2 Emissions, North Carolina, 1975 - 1982.

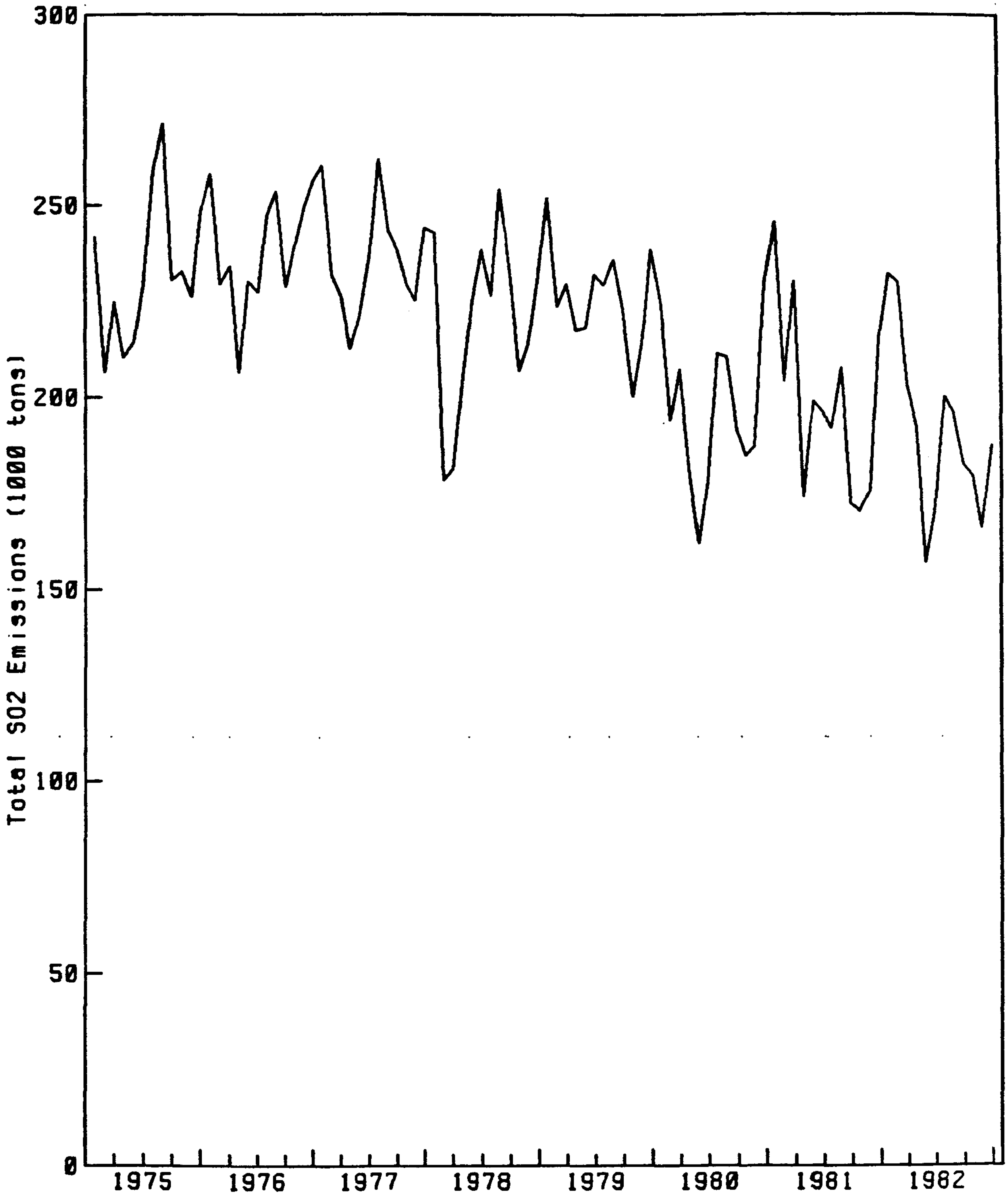

Figure D15. Monthly Total Electric Utility SO2 Emissions, Ohio, 1975 - 1982.

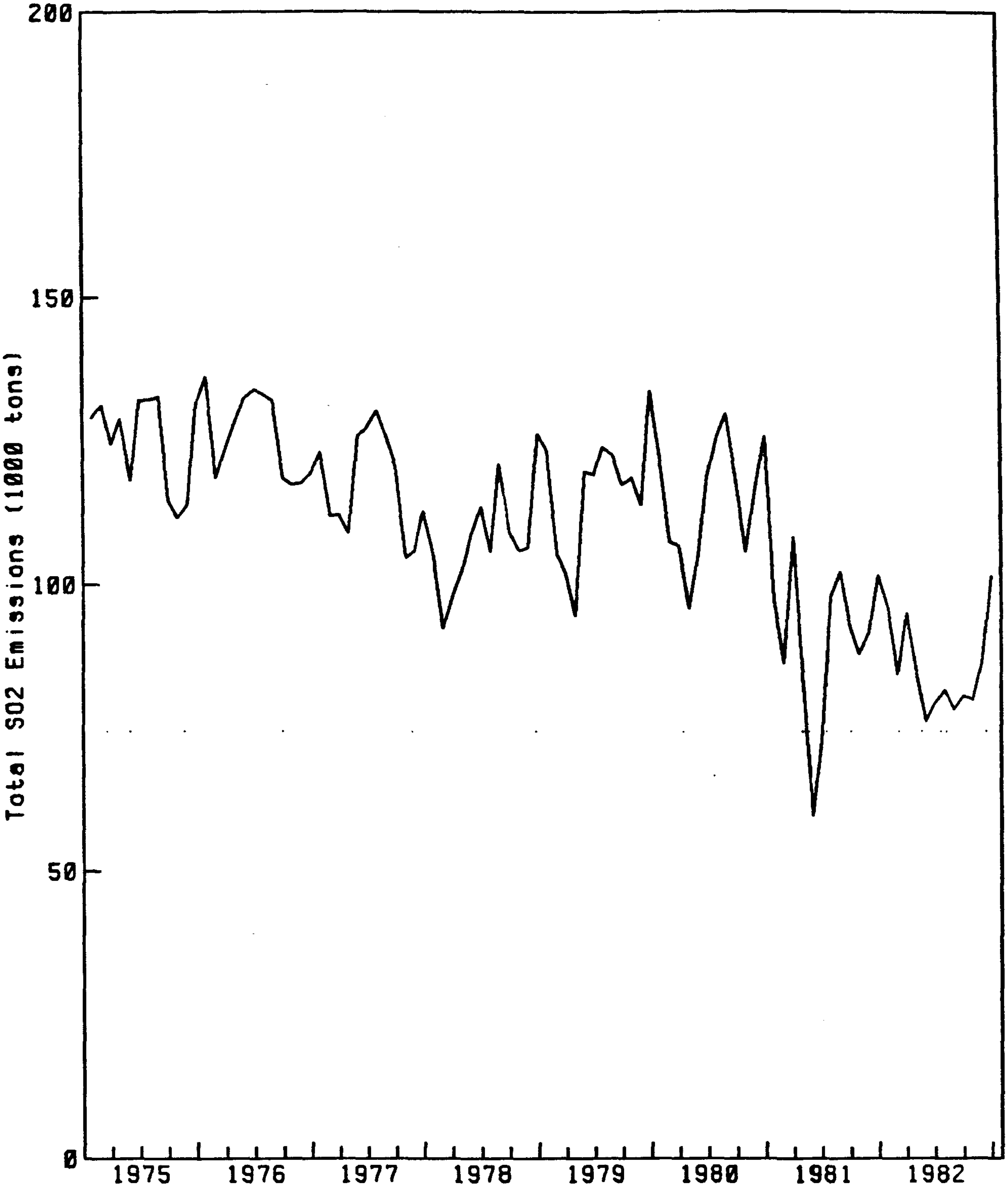

Figure D16. Monthly Total Electric Utility SO2 Emissions, Pennsylvania, 1975 - 1982.

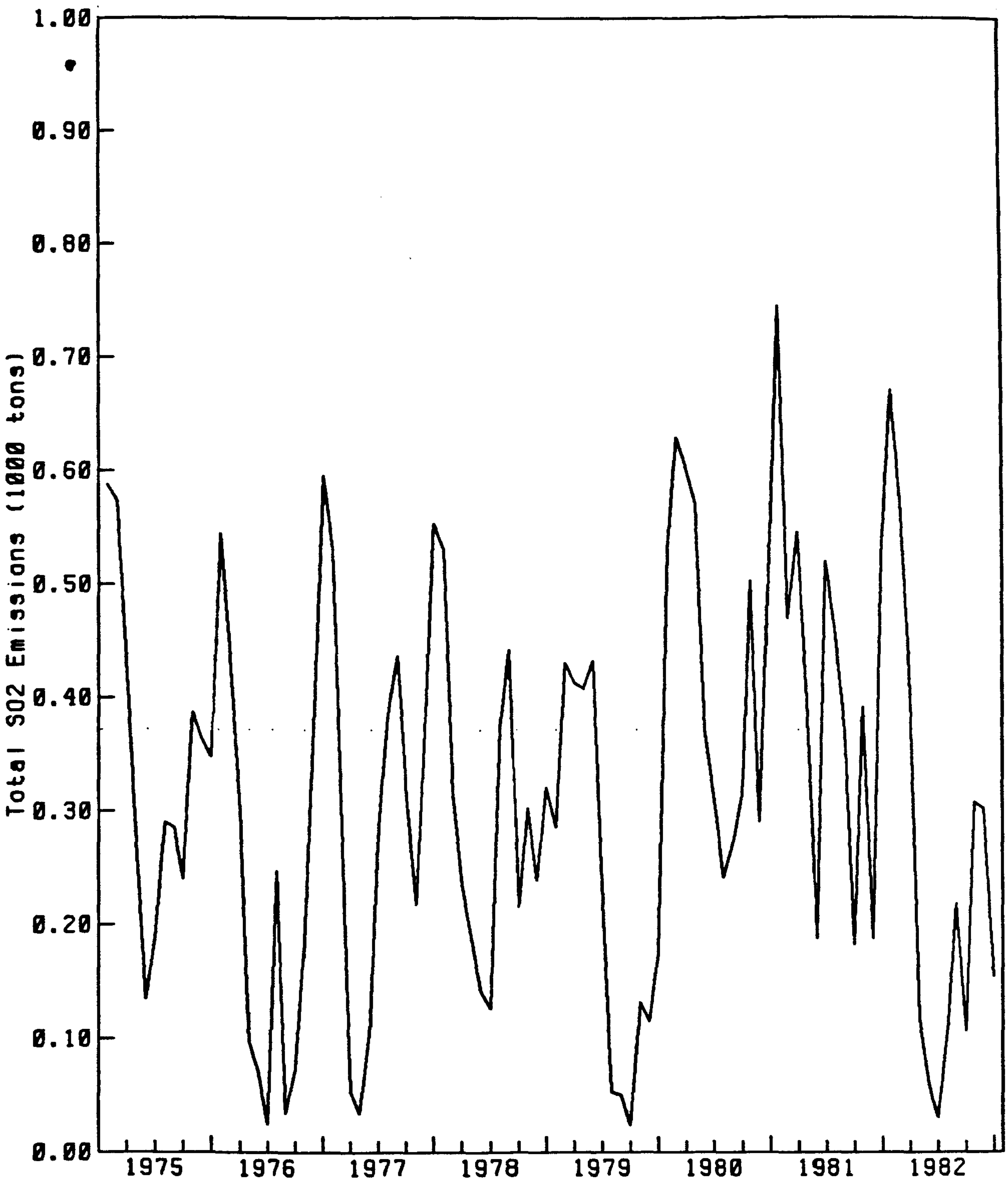

Figure D17. Monthly Total Electric Utility SO2 Emissions, Rhode Island, 1975 - 1982.

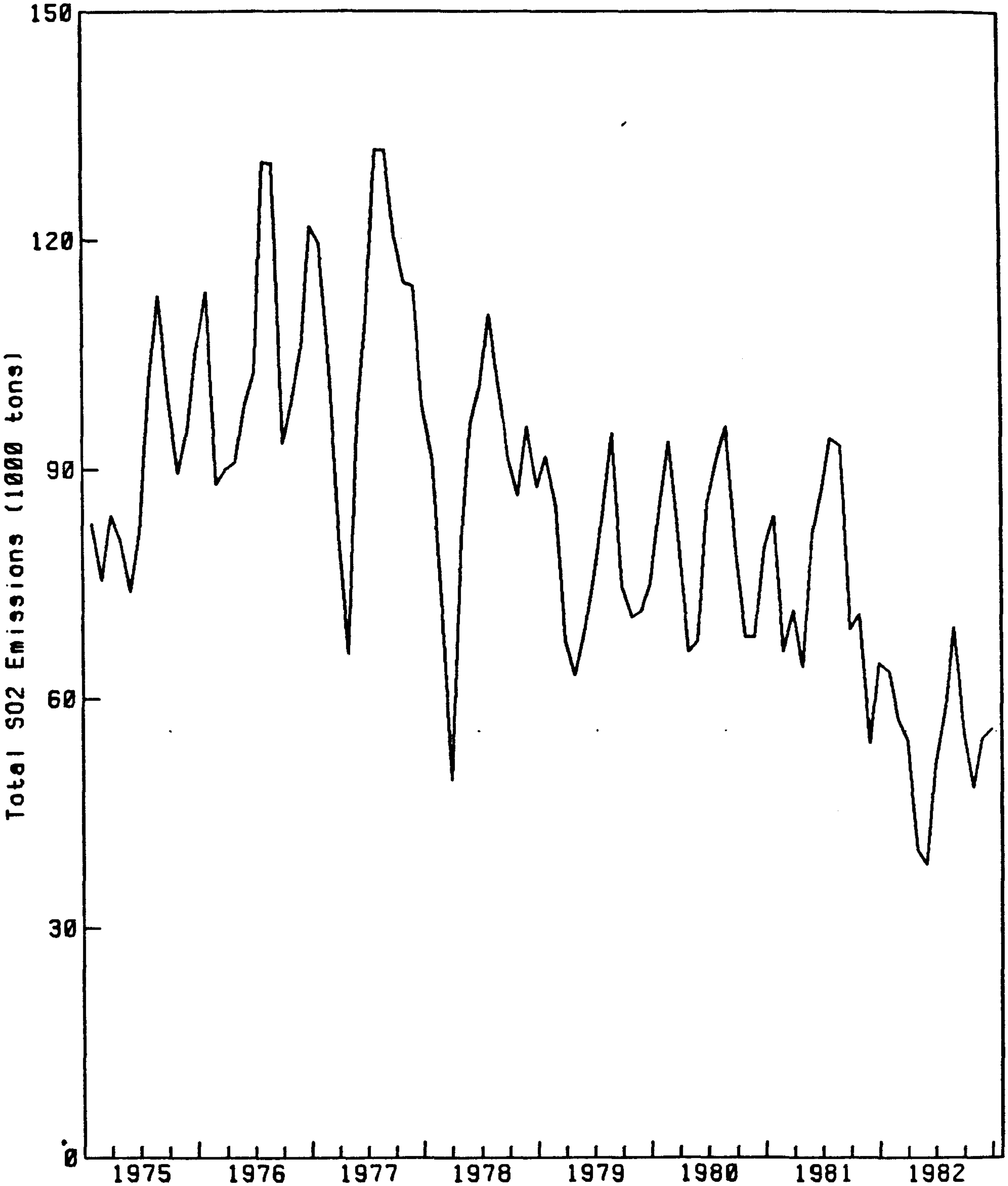

Figure D18. Monthly Total Electric Utility SO2 Emissions, Tennessee, 1975 - 1982.

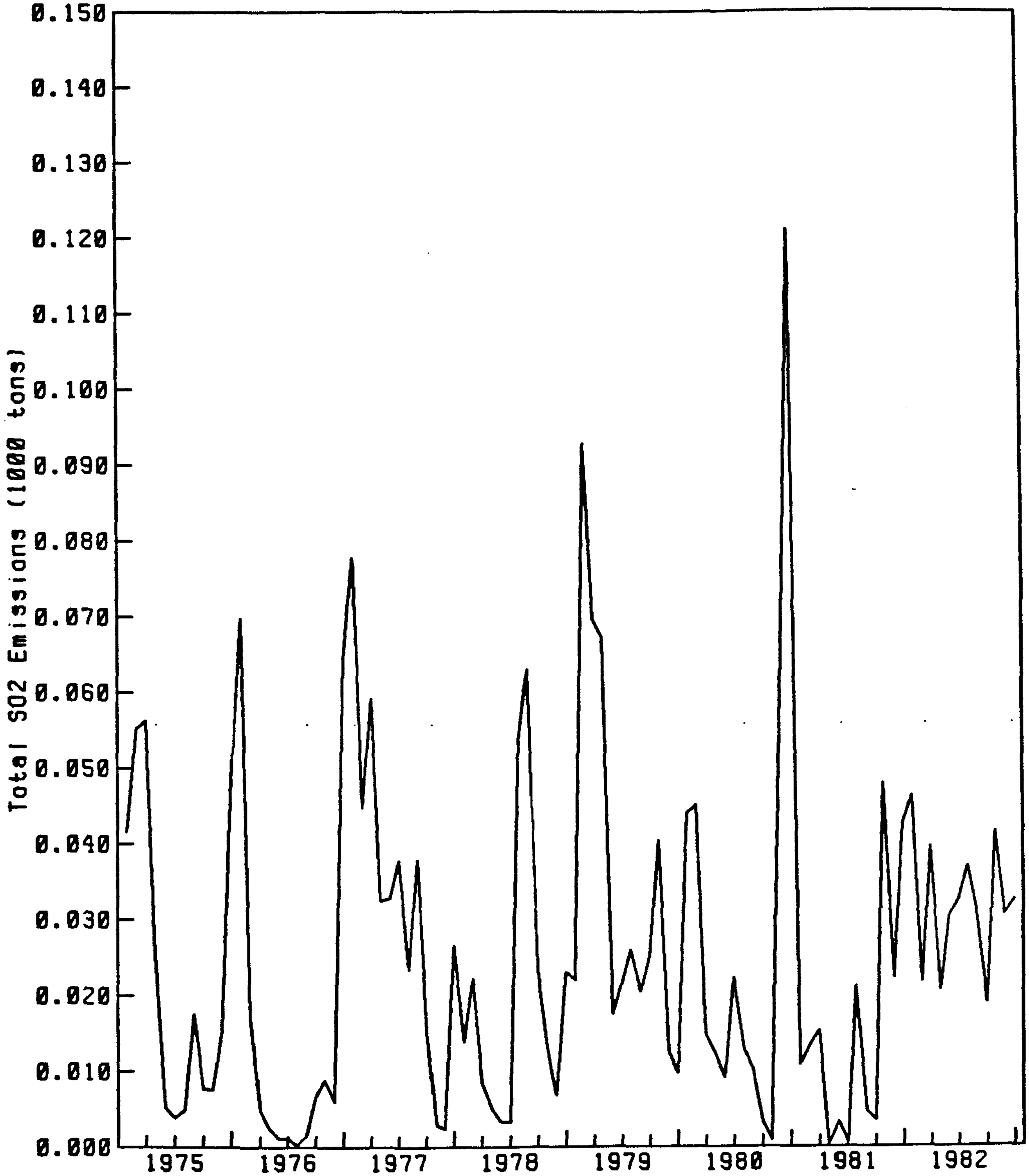

Figure D19. Monthly Total Electric Utility SO2 Emissions, Vermont, 1975 - 1982.

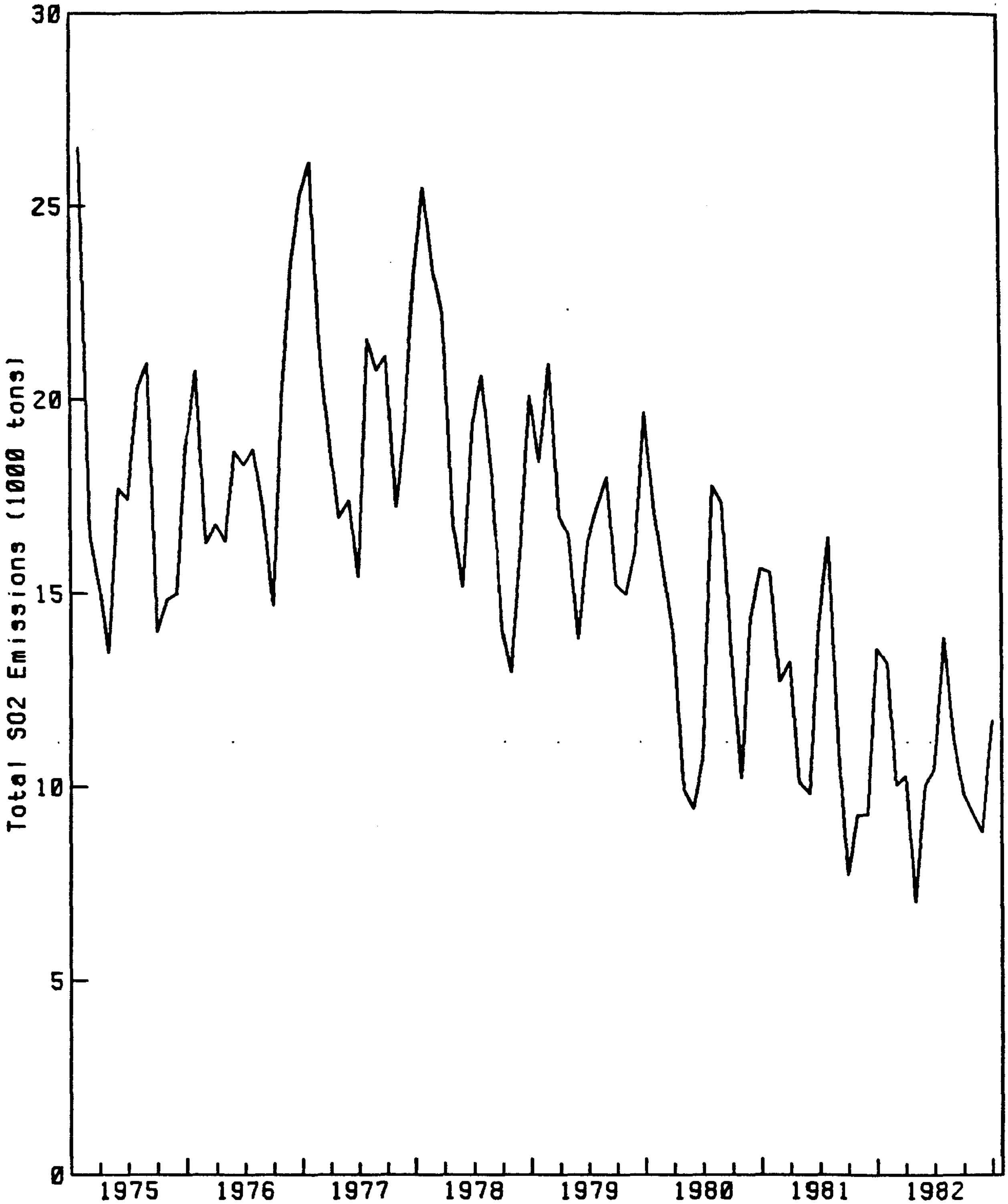

Figure D20. Monthly Total Electric Utility SO2 Emissions, Virginia, 1975 - 1982.

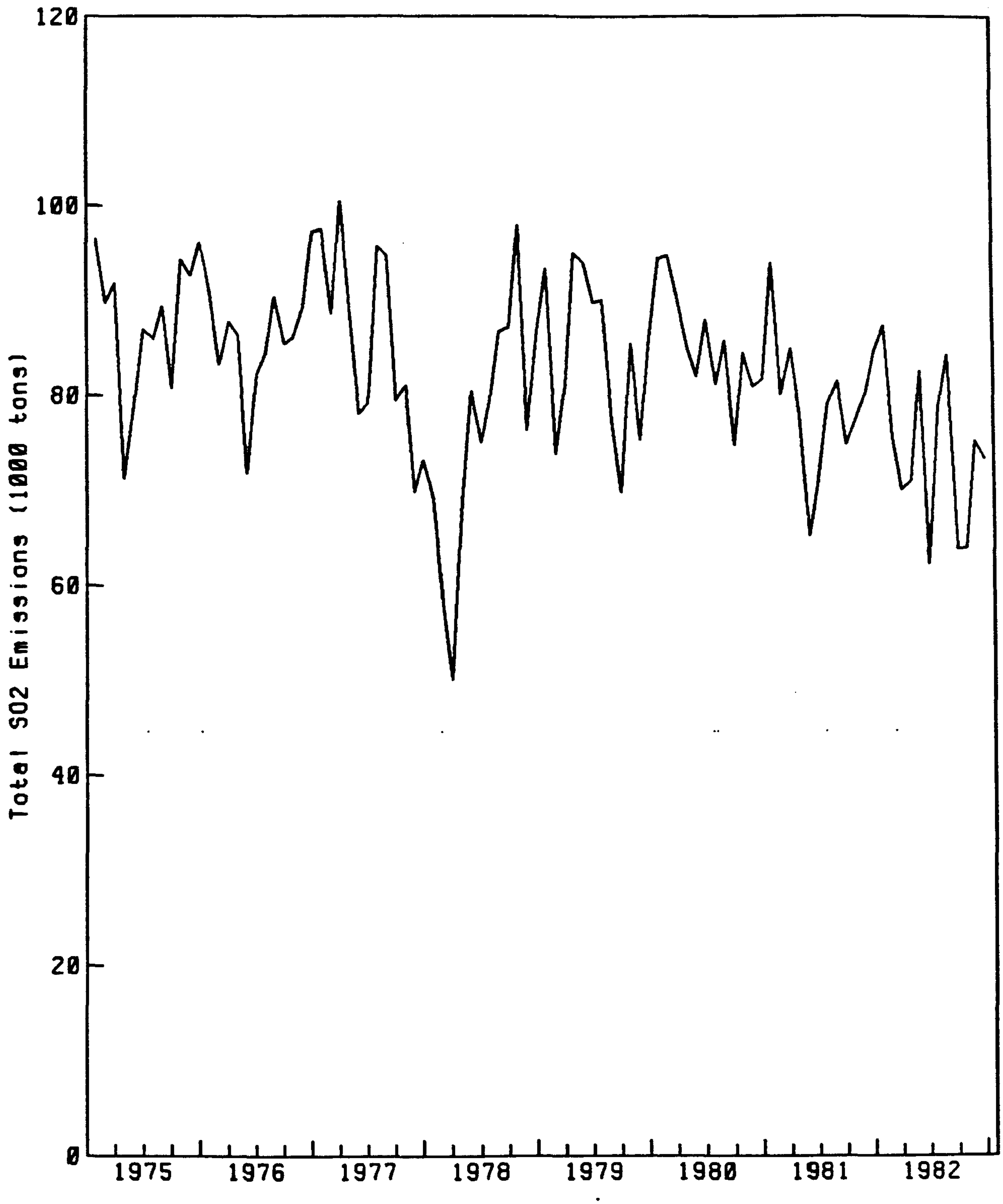

Figure D21. Monthly Total Electric Utility SO2 Emissions, West Virginia, 1975 - 1982.

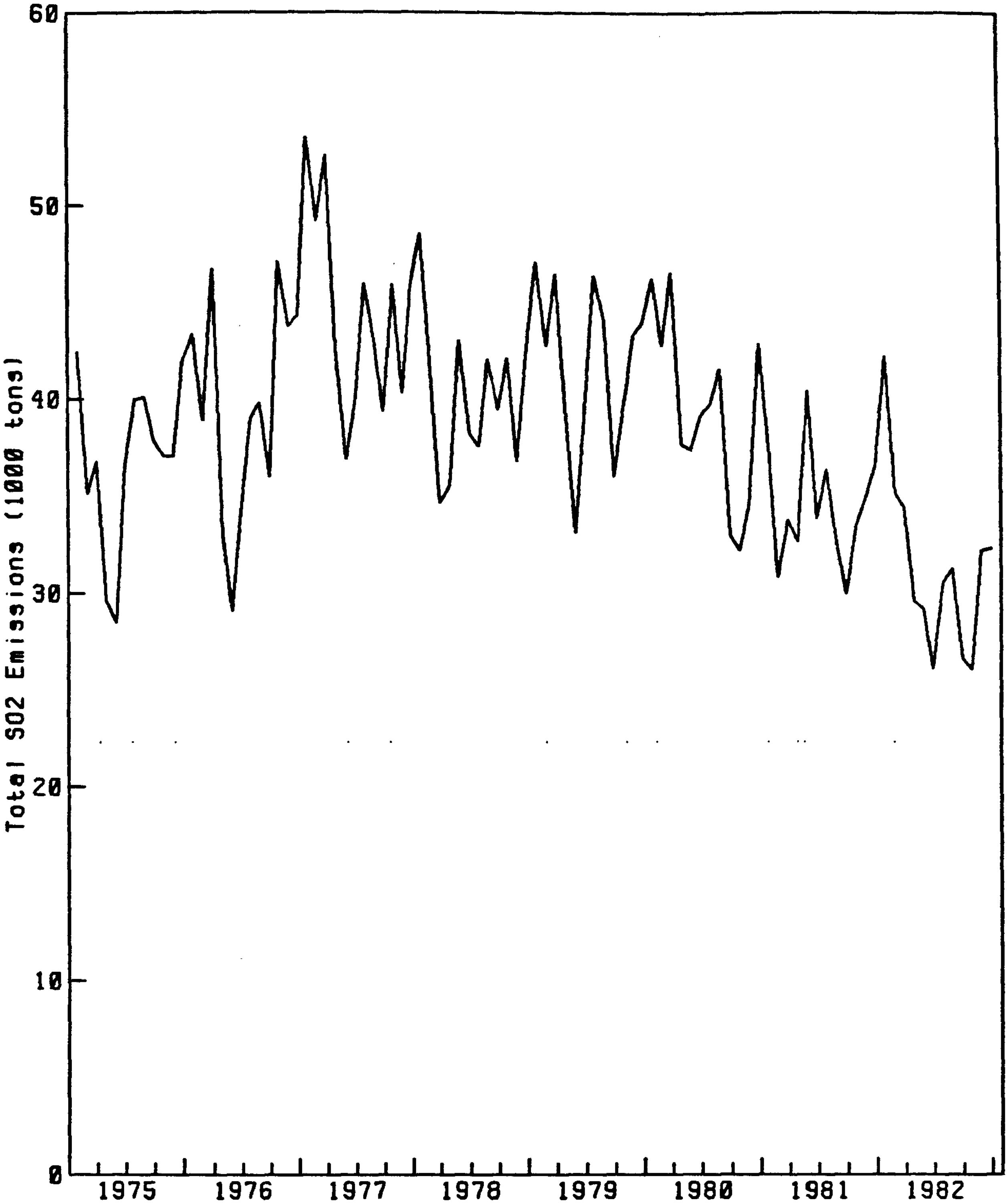

Figure D22. Monthly Total Electric Utility SO2 Emissions, Wisconsin, 1975 - 1982.