Final Report

Maine Ecological Assessment Project

Emissions-related acidic deposition trends in Maine and New England

Prepared for

Rona Birnbaum
Acid Rain Program
U.S. Environmental Protection Agency
Mail Stop 6204J
401 M Street, SW
Washington, DC 20460

Prepared by

Paul J. Miller
Northeast States for Coordinated Air Use Management
129 Portland Street
Boston, MA 02114
pmiller@nescaum.org
ph: 617-367-8540
fax: 617-742-9162

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Introduction and Summary

The results presented in this report focus on the correlation between regional emissions of the acid-forming precursors sulfur dioxide (SO_2) and nitrogen oxides (NO_X) with downwind deposition of sulfates and nitrates in Maine and the greater New England region. A separate portion of this project assesses trends in the chemistry of Maine's lakes and possible influences from changes in acidic deposition over recent years. The Water Research Institute at the University of Maine, Orono, is performing the lake chemistry task and the results appear in a separate report.

A number of recent studies have investigated acidic deposition trends since the 1980s in areas of the United States (Lynch et al., 1996; Husain et al., 1998; Holland et al., 1999; Shannon, 1999). Our work focuses on the New England region and extends the period of analysis to 1998, which is the most recent year for which deposition data are currently available. Consistent with the results of the earlier studies, we find a decreasing trend in annual sulfate deposition in the New England region since 1980. The decline after 1990 is presumably a result of SO_2 emission reductions under Title IV of the 1990 Clean Air Act Amendments, although SO_2 power plant emissions have increased somewhat since 1995 following a period of significant decline. Nitrate deposition trends show no discernable change over the same period, nor do NO_X emissions. The nitrate deposition trend, however, forms a baseline with which to compare changes expected from future regional NO_X reductions as part of ozone control and Title IV efforts.

In general, we find that the decreasing sulfate deposition trend strongly correlates with the SO_2 emissions trend from fossil fuel power plants located within a group of eastern States and the Province of Ontario. We find a less strong correlation between sulfate deposition and emissions from all SO_2 sources (as opposed to only power plants) within the same region, which may be the result of year-to-year data reporting inconsistencies in the emission inventories we use. The following sections present the result of our analyses in greater detail.

I. Data sources

Deposition data

We obtained annual sulfate and nitrate deposition data from the National Atmospheric Deposition Program (NADP, 1999). We use precipitation-weighted mean concentrations in milligram per liter (mg/L) and total deposition in kilograms per hectare (kg/ha). We omitted deposition data from monitoring sites for years that did not meet any one of the four following completeness criteria recommended by NADP.

- Percentage of the summary period for which there are valid samples is $\geq 74.5\%$.
- Percentage of the summary period for which precipitation amounts are available either from the rain gauge or from the sample volume is $\geq 89.5\%$.
- Percentage of the total measured precipitation associated with valid samples is $\geq 74.5\%$.
- Sum of the sample precipitation in the summary period divided by the sum of the rain gauge amounts for all valid samples where both values are available is $\geq 74.5\%$ (called the collection efficiency).

We reduced the sulfate deposition data prior to 1994 by 2.6% to reflect a change in sample handling procedures used at NADP sites. We reduced nitrate deposition values prior to 1994 by 0.9% for the same reason.

Table 1 gives the locations and site IDs of the NADP sites we used in the emissions-related correlation and deposition trends analyses. Table 2 displays how many sites in the New England region met NADP's recommended completeness criteria for each year from 1980 to 1998.

Table 1. NADP site locations and NADP ID numbers used in the emissions-related correlation and deposition trends analyses.

NADP site name	**Location**	**Site ID**
Caribou	Aroostook Co., Maine	ME00
Bridgton	Cumberland Co., Maine	ME02
Greenville Station	Piscataquis Co., Maine	ME09
Acadia National Park – MacFarland Hill	Hancock Co., Maine	ME98
North Atlantic Coastal Lab	Barnstable Co., Massachusetts	MA01
Quabbin Reservoir	Franklin Co., Massachusetts	MA08
East	Middlesex Co., Massachusetts	MA13
Hubbard Brook	Grafton Co., New Hampshire	NH02
Bennington	Bennington Co., Vermont	VT01
Underhill	Chittenden Co., Vermont	VT99

Table 2. Number of NADP monitoring sites in the New England region that met the data completeness criteria recommended by NADP from 1980 to 1998.

Year	Maine	Massachusetts	New Hampshire	Vermont	Total sites
1980	0	0	1	0	1
1981	3	0	1	0	4
1982	2	2	1	1	6
1983	2	1	1	1	5
1984	4	2	1	1	8
1985	3	3	0	1	7
1986	4	2	1	1	8
1987	3	2	1	2	8
1988	4	2	1	0	7
1989	4	3	1	2	10
1990	4	3	1	2	10
1991	4	2	1	2	9
1992	4	3	1	2	10
1993	3	3	1	2	9
1994	4	2	1	2	9
1995	3	3	1	2	9
1996	4	2	1	2	9
1997	4	2	1	2	9
1998	4	2	1	2	9

Emissions data

We obtained sulfur dioxide emissions data for the United States from several sources. For the years 1985 through 1996, emissions data come from the U.S. EPA National Emissions Trends (NET) Viewer, 1985-1996 (U.S. EPA NET Viewer, 1998). Power plant emissions in the United States for 1980 come from the U.S. EPA, Emissions Scorecard 1996, Table A2 Phase I & II Units (1997). Power plant emissions data for 1997 and 1998 come from the U.S. EPA, Emissions Scorecard 1997, Table A2 Phase I & II Units (1998a) and Emissions Scorecard 1998, Table A2 Phase I & II Units (1999), respectively. In the emissions-related correlation plots, we do not include the years 1981 through 1984 because we did not have state-level utility sector emissions for those years.

For emissions in Ontario, data come from Environment Canada (1995, 1998) and the Canada-United States Air Quality Agreement Progress Report (1996). We did not have emissions data for Ontario during the years 1985, 1986, 1987, and 1989. Therefore, we estimated annual emissions based on a linear extrapolation of emissions data from 1980, 1988, and 1990. We also did not have Ontario emissions for 1998, and estimated them as comparable to 1997 emissions. This introduces some additional uncertainty in the trend analysis, but Ontario's contribution to the overall regional inventory is small, so the additional uncertainty is also small.

We discovered a problem in using annual total SO_2 emissions from the EPA NET Viewer, 1985-1996. In several states, large increases occurred in SO_2 emissions from industrial fossil fuel combustion sources. The increases are unrealistically large and almost all occur between 1989 and 1990. We display an example of this in the following three plots. Figure 1 plots the total SO_2 emission trend in an eight-state region (CT, ME, MA, NH, NJ, NY, RI, VT) over 1985 to 1996 based on the data in the EPA NET Viewer. We chose these states because they comprise the membership of the Northeast States for Coordinated Air Use Management (NESCAUM). As seen in Figure 1, a sharp peak occurs in total emissions from 1989 to 1990. Figure 2 shows the SO_2 emission trend from only fossil fuel power plants in the NESCAUM region, which is more uniformly decreasing. Figure 3 shows the trend from fossil fuel industrial combustion sources, which has a large step increase from 1989 to 1990. The one-year increase almost doubles SO_2 emissions from industrial sources over their previous year's level, which is unrealistically large. This large increase offsets the decreasing trend in fossil fuel power plant emissions. As a result, the overall trend in total SO_2 emissions from the EPA NET Viewer may not reflect, even on a qualitative basis, the actual change in total SO_2 emissions between 1985 and 1996 in the NESCAUM region.

Upon further inquiry, we learned from U.S. EPA that industrial SO_2 emissions data for 1990 and later years are based on information from the Ozone Transport Assessment Group (OTAG) and data submitted to the Aerometric Information Retrieval System (AIRS) (Nizich, 1999). OTAG collected NOx emissions data, and the NET inventory estimated SO2 emissions by applying a NOx:SO_2 emission rate ratio appropriate for the particular source type. Prior to 1990, EPA derived SO2 inventory information from data collected by the National Acid Precipitation Assessment Project (NAPAP). Therefore, the large change in SO2 emissions from 1989 to 1990 in the EPA NET Viewer is due to a change in the source of SO2 emissions data used by EPA in developing the NET Viewer database. This change appears to have affected the industrial source inventory much more than the power plant inventory.

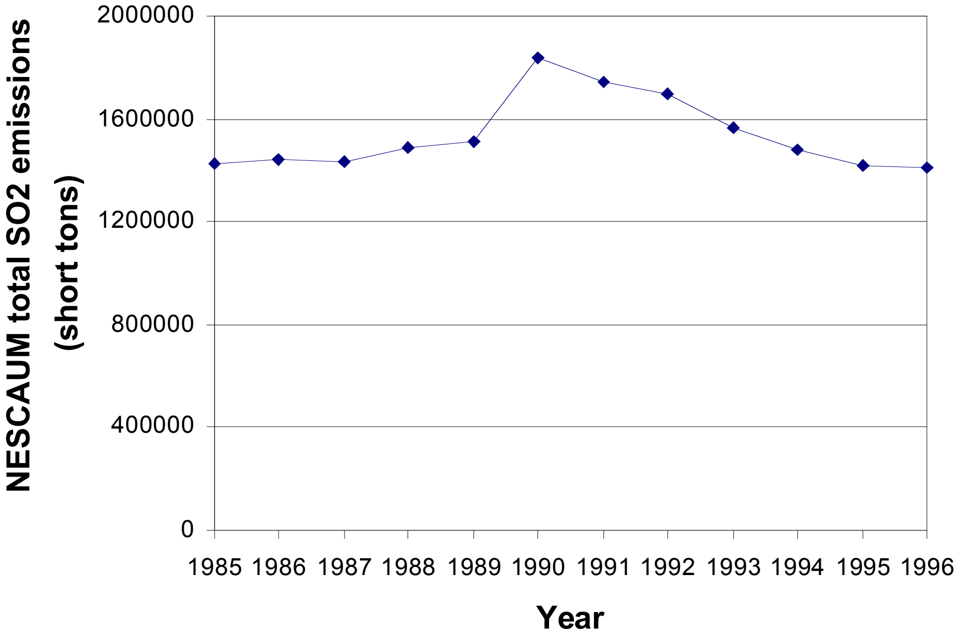


Figure 1. Total SO_2 emissions trend from 1985-1996 in the eight-state NESCAUM region. The SO_2 emissions data come from the EPA NET Viewer, 1985-1996.

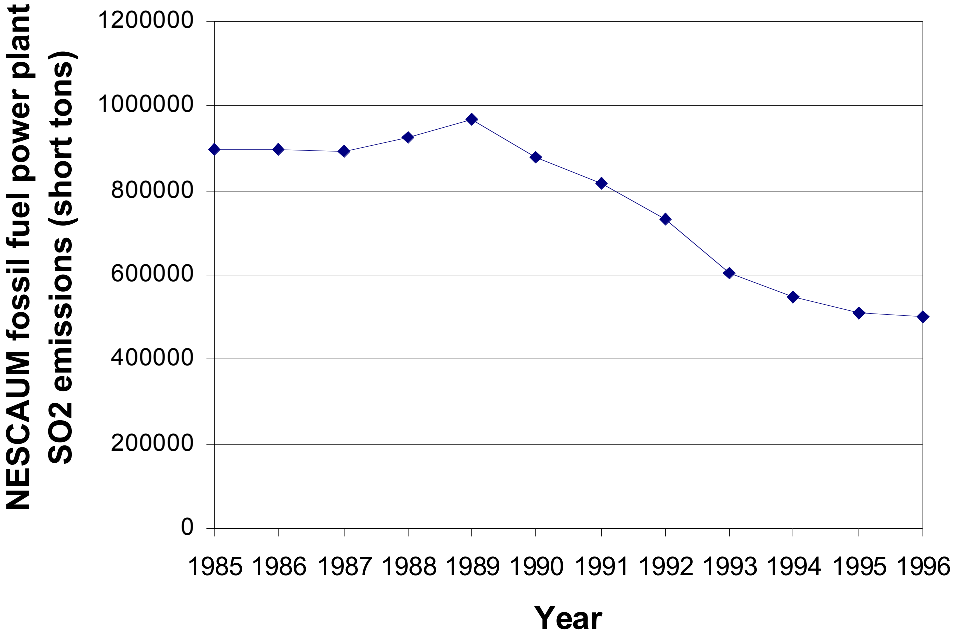


Figure 2. Fossil fuel power plant SO_2 emission trend from 1985-1996 in the eight-state NESCAUM region. The power plant SO_2 emissions data come from the EPA NET Viewer, 1985-1996.

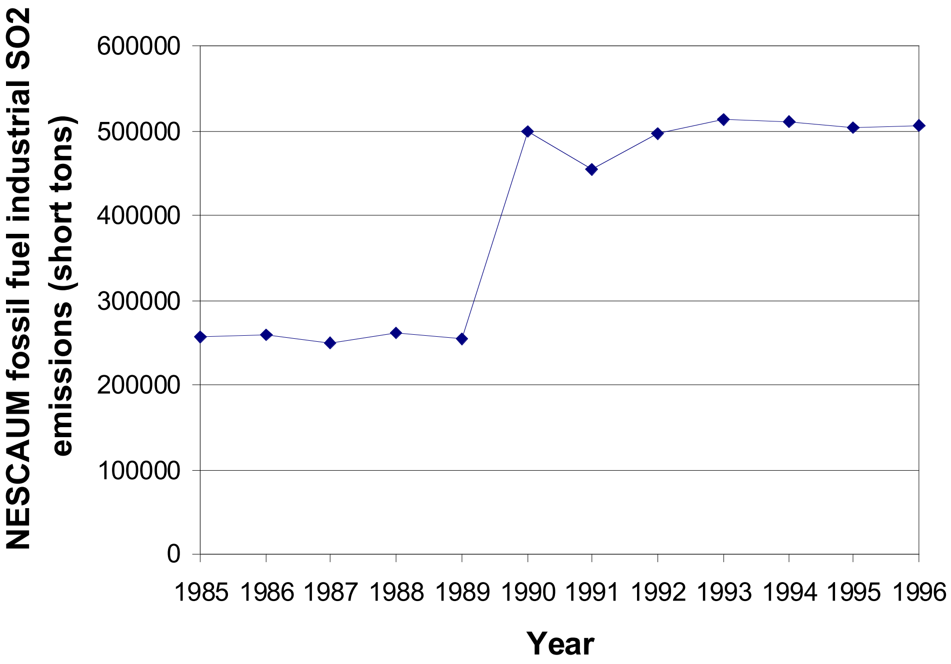


Figure 3. Industrial combustion SO_2 emission trend from 1985-1996 in the eight-state NESCAUM region. The industrial SO_2 emissions data come from the EPA NET Viewer, 1985-1996.

Several individual states in the NESCAUM region have even more drastic changes from 1989 to 1990 than suggested by the above figures. New Hampshire is the most extreme, with a 9-fold increase in SO_2 emissions from industrial combustion sources between 1989 and 1990 (and another doubling between 1991 and 1992). Tables 3, 4 and 5 display the annual SO_2 emissions by state total, fossil fuel power plants, and industrial combustion sources, respectively, for the eight-state NESCAUM region as given in the EPA NET Viewer, 1985-1996. Other states outside the NESCAUM region also have similar large step-wise increases in their industrial source emissions between 1989 and 1990, such as Delaware, Maryland, Ohio, and Virginia. Not all states, however, have such large SO_2 emission jumps over the 1989 to 1990 period in the EPA NET Viewer.

Table 3. EPA NET Viewer, 1985-1996, total SO_2 emissions (short tons) for the eight-state NESCAUM region.

State/year	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
CT	81343	86713	78102	90297	94500	93536	89353	73364	64639	57377	56705	68339
ME	77759	86287	82115	90128	87566	95172	93570	86955	83629	80029	79010	90063
MA	310877	343598	322822	336128	336714	348660	352008	322532	254243	226128	226890	204377
NH	86408	76757	84138	94858	92904	126621	102092	153738	149755	152792	147381	146192
NJ	203276	190984	194445	194688	196507	301435	290730	289649	289059	283137	248405	248395
NY	652415	643164	655289	664819	686400	848007	789848	738953	694558	650968	633845	623983
RI	9015	11316	9514	11571	8782	14336	13398	13138	12269	11631	11378	11719
VT	6064	5766	5803	6017	6271	12765	14712	16294	16580	16115	16109	16681
Total	**1427157**	**1444585**	**1432228**	**1488506**	**1509644**	**1840532**	**1745711**	**1694623**	**1564732**	**1478177**	**1419723**	**1409749**

Table 4. EPA NET Viewer, 1985-1996, fossil fuel power plant SO_2 emissions (short tons) for the eight-state NESCAUM region.

State/year	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
CT	55208	58349	50178	61598	64852	53045	48928	35792	29542	25526	25621	35660
ME	9604	14148	13761	14590	15066	11507	11407	7559	5685	4628	4204	5656
MA	235245	265625	248888	263028	266210	233317	237546	210665	150113	126581	128616	105759
NH	74740	64564	70370	81569	79140	68508	48226	57270	52548	57231	51803	50469
NJ	125758	111912	115703	113085	116774	89940	77480	73937	75380	75201	56439	61218
NY	395861	379208	391290	386200	423637	420264	393760	346360	291017	259358	245519	243569
RI	2100	4420	2455	4712	2392	1092	374	493	161	218	0	0
VT	0	69	25	4	14	0	6	10	35	53	53	54
Total	**898516**	**898295**	**892670**	**924786**	**968085**	**877673**	**817727**	**732086**	**604481**	**548796**	**512255**	**502385**

Table 5. EPA NET Viewer, 1985-1996, industrial combustion SO_2 emissions (short tons) for the eight-state NESCAUM region.

State/year	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**
CT	7868	8095	8363	8100	8067	9446	8609	8624	8755	8125	7492	7418
ME	50016	51666	50446	51613	51884	47100	46211	46898	47109	46980	47049	55153
MA	33699	35354	31814	28505	25823	54567	50667	52163	51576	51750	51993	51308
NH	5279	5336	5577	5482	5454	49283	44196	87316	88842	88448	88438	88454
NJ	14469	14760	14884	15306	15266	93626	88448	87655	87930	88057	86129	85589
NY	141121	139837	135708	149353	146203	237229	206849	203301	218443	216385	213388	208364
RI	1719	1845	1704	1407	987	2251	2097	2286	2389	2376	2393	2382
VT	1413	1315	1264	1313	1398	5302	6217	7090	7684	7814	7717	7719
Total	**255584**	**258208**	**249760**	**261079**	**255082**	**498804**	**453294**	**495333**	**512728**	**509935**	**504599**	**506387**

Because of the large step-wise increase in industrial emissions between 1989 and 1990, we are cautious about correlating total SO_2 emission trends with sulfate deposition using the total state SO_2 emission inventories from the NET Viewer.

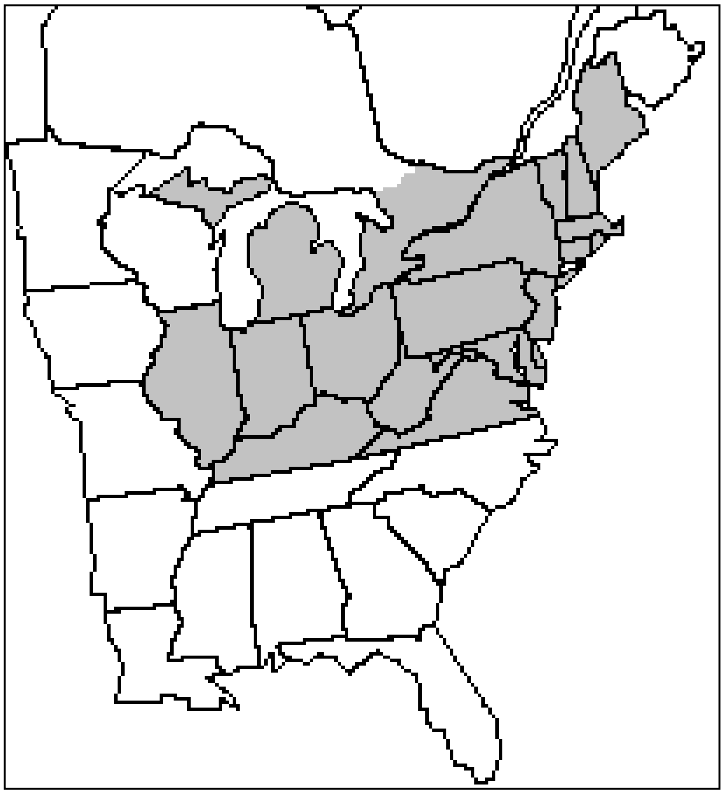
As an alternative to using total state-level SO_2 emissions from the EPA NET Viewer, we look only at fossil fuel power plant SO_2 emissions on the assumption that much of the change in SO_2 emissions is due to reductions at power plants. Industrial sources are a relatively smaller portion of the overall change, so are assumed to be relatively constant over the time period of interest. This appears to be justified in looking at U.S. national trends in SO_2 emissions over the period from 1980 to 1997 (U.S. EPA, 1998b). From 1980 to 1997, total U.S. SO_2 emissions decreased from 25,905,000 tons to 20,369,000 tons; a reduction of 21%. Of the 5,536,000 tons reduced, fossil fuel power plants accounted for 4,387,000 tons, or about 80% of the total reduction.

II. Methodology

We use two general approaches in assessing emission trends with changes in acidic deposition. Both methods focus primarily on the correlation between sulfate deposition and SO_2 emissions because they changed noticeably over the period from 1980 to 1998. We only looked at trends in NO_X emissions and nitrate deposition without evaluating a correlation between the two because the trends show little change over the 1980 to 1998 period. For reasons discussed below, we also had less information on the geographical scope of a NO_X source region that potentially contributes to nitrate deposition in the Maine area, unlike the situation with SO_2 emissions.

The first approach correlating sulfate deposition with SO_2 emissions follows the method used by Husain et al. (1998). This approach looks at the correlation of annual precipitation-weighted sulfate concentrations or total sulfate deposition with annual SO_2 emissions from a particular region. The second approach is similar to that of Shannon (1999) in which annual sulfate precipitation-weighted concentrations and total sulfate deposition are scaled to a mean of unity, averaged together (the scaling procedure creates unitless values), then correlated with a regional SO_2 emission trend.

In both approaches, we estimated the geographical scope of the SO_2 source region that may influence downwind sulfate deposition in Maine and the greater New England region. To do this, we used results from the Regional Acid Deposition Model (RADM), as presented in the U.S. EPA report "Acid Deposition Standard Feasibility Study Report to Congress" (U.S. EPA, 1995). Appendix C of the report presents maps of 53 subregions in the eastern United States generated by using the Tagged Species Engineering Model in the RADM modeling system (McHenry et al., 1992). The Tagged Species Model estimates distances over which an SO_2 emissions source region can have an influence on downwind sulfate deposition. The RADM model "tagged" SO_2 emissions from power plants and large industrial sources in 53 separate subregions of the eastern United States. For each subregion, the model simulated SO_2 emissions in 1985 and projected for 2010 after implementation of Title IV of the Clean Air Act, and then tracked the SO_2 and its chemical transformations during downwind transport and ultimate deposition. From the deposition contribution plots of Appendix C, we identified the following states and province as containing sources that contribute some level of sulfate deposition in the New England region: Connecticut, Delaware, District of Columbia, Illinois, Indiana, Kentucky, Maine, Maryland, Massachusetts, Michigan, New Hampshire, New Jersey, New York, Ohio, Ontario, Pennsylvania, Rhode Island, Vermont, Virginia, and West Virginia (see Map 1). We note that the work of Shannon (1999) also used a regional modeling approach to identify source and receptor regions in evaluating sulfate deposition trends.



Map 1. SO_2 source region (shaded) for deposition trends analyses in Maine and New England.

In looking at downwind sulfate deposition, we varied the size of the receptor region. We initially looked at individual NADP deposition monitoring sites in Maine, as well as deposition averaged over four combined Maine sites. We also looked at sulfate deposition averaged from two NADP sites – one located at Bridgton in western Maine, and one at Hubbard Brook in central New Hampshire. We considered these two sites as the most geographically proximate to the Maine lakes being studied in the lake chemistry portion of this project (separate report). There may, however, be significant site-to-site variation in deposition fluxes within a given region, so that an individual monitoring site, or pair of sites, will not adequately represent regional deposition (Holland et al., 1999; Lovett et al., 1999; Shannon, 1999). Therefore, we also looked at receptor areas expanded in a step-wise fashion that included NADP monitoring sites in Maine, New Hampshire, Vermont, and Massachusetts (ten sites in all).

The usual caveat applies in assessing a correlation. A strong correlation between emission and deposition trends does not necessarily imply a cause-and-effect relationship. The difficulty is that SO_2 emissions from power plants are decreasing across much of the eastern United States. Any deposition decrease in Maine and greater New England could be positively correlated with any decrease in SO_2 emissions no matter where it occurs in the eastern United States. Therefore, the RADM modeling results are used to better refine the scale of the potential source region. Determining which upwind areas, based on the RADM results, contain sources contributing to downwind deposition provides an objective rationale for narrowing the geographical scope of the potential source region. While not completely conclusive, it provides a basis for believing a positive correlation between SO_2 emissions and sulfate deposition in the Maine and greater New England region will be more than coincidental.

III. Results

First approach

The first approach we take in evaluating emissions-related deposition is to plot NADP deposition data directly against source region SO_2 emissions. This is the approach of Husain et al. (1998) for a site at Whiteface Mountain in New York's Adirondack Mountains. While we looked at trend correlations from individual sites in Maine, and a small group of sites in Maine and New Hampshire, we decided that a larger number of NADP sites were more appropriate for analyses of emission-related deposition trends. Several studies suggest that a regional average of a number of monitoring sites is preferable because spatial variability in a receptor region may mask trends if using a single site or a small cluster of sites. Spatial variability may arise from climatological factors such as changes in the frequency and intensity of wind and precipitation patterns from one year to the next across deposition monitoring sites (Venkatram et al., 1990; Renne et al., 1991, Shannon, 1999).

On an annual basis, both the sulfate precipitation-weighted mean concentrations and total sulfate deposition have decreased in the greater New England region since 1980 (Figures 4 and 5).

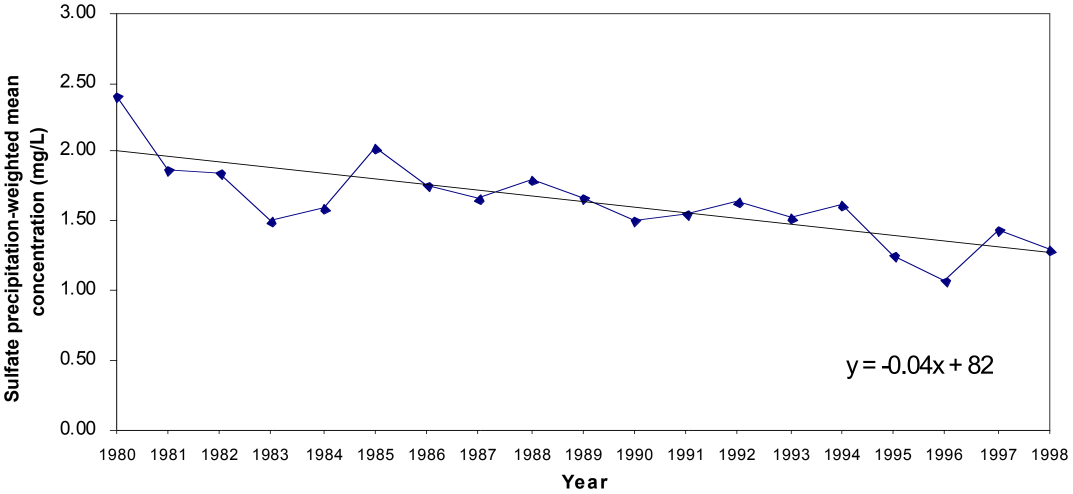


Figure 4. Sulfate precipitation-weighted mean concentration (mg/L) trend in the New England region from 1980 to 1998.

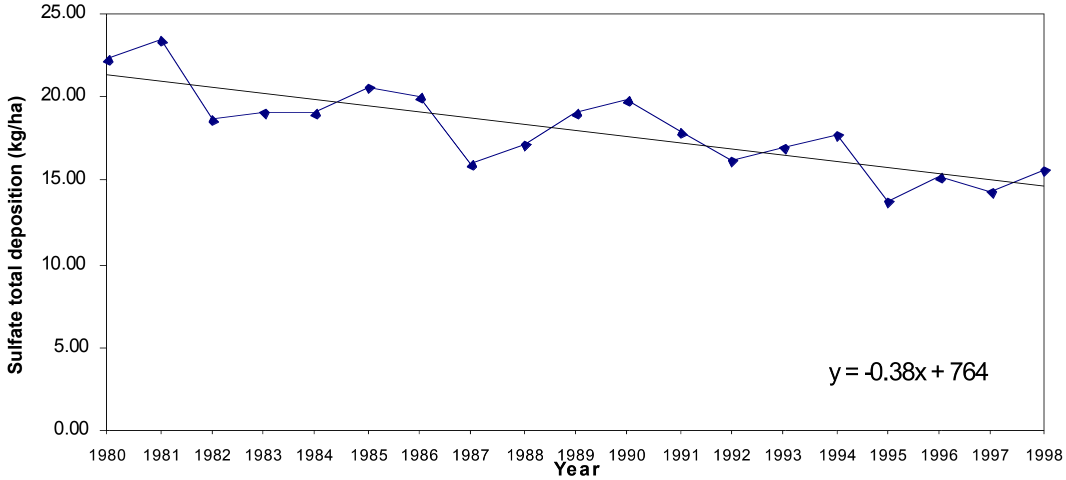


Figure 5. Sulfate total deposition (kg/ha) trend in the New England region from 1980 to 1998.

The following figures investigate how the SO_2 emission trend correlates with sulfate deposition in downwind receptor regions of increasing size. We present plots of the SO_2 emissions-related correlation with sulfate deposition averaged over the following site groupings:

- Individual NADP monitoring sites in Maine,
- A combination of the Bridgton, Maine and Hubbard Brook, New Hampshire NADP sites,
- A combination of all Maine NADP sites (4 total),
- A combination of all Maine and New Hampshire NADP sites (five total),

- A combination of all Maine, New Hampshire, and Vermont NADP sites (seven total),
- A combination of all NADP sites in Maine, New Hampshire, Vermont, and Massachusetts (ten total).

We present plots for both sulfate precipitation-weighted mean concentrations (mg/L) and total deposition (kg/ha).

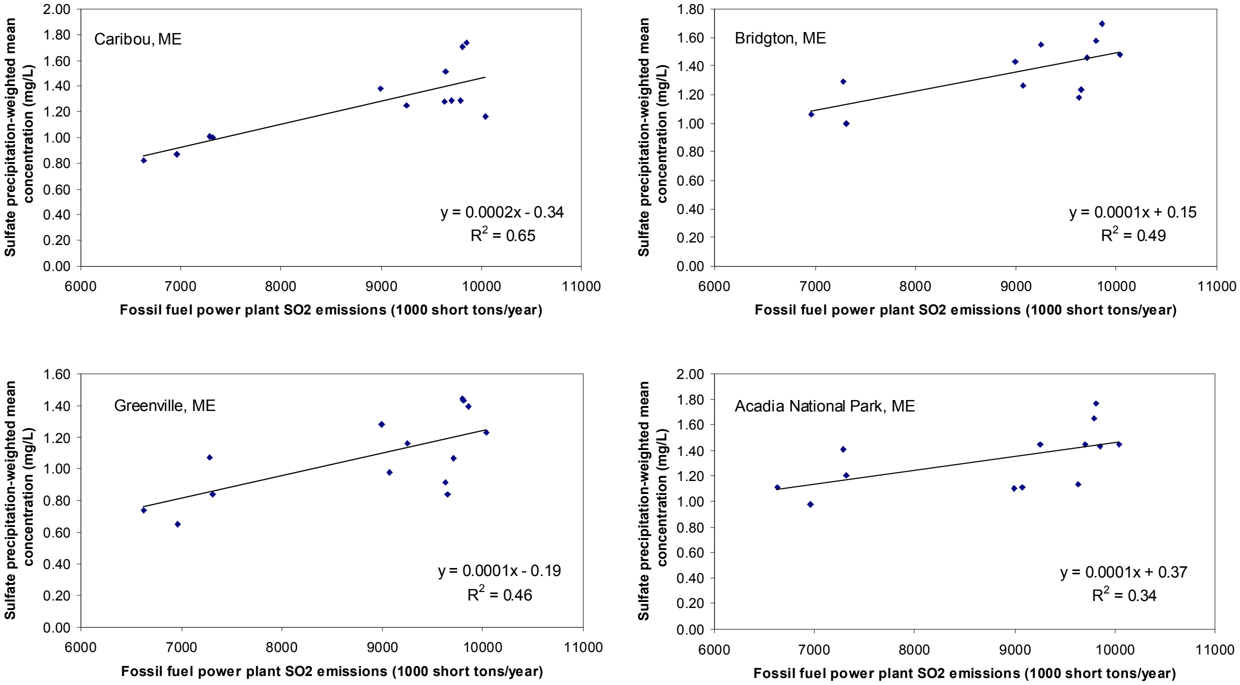


Figure 6. Emissions-related correlation of sulfate precipitation-weighted mean concentrations (mg/L) at four individual NADP sites in Maine from 1985 to 1998.

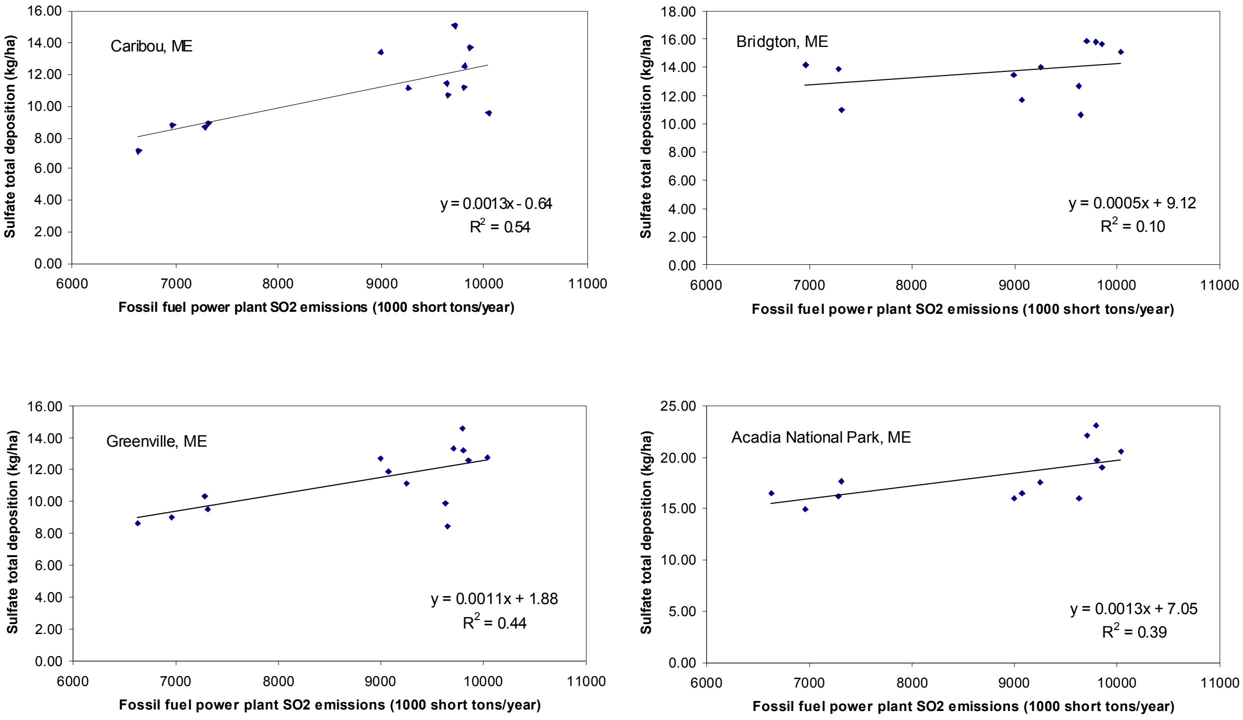


Figure 7. Emissions-related correlation of sulfate total deposition (kg/ha) at four individual NADP sites in Maine from 1985 to 1998.

In general, most of the above plots indicate a modest degree of positive correlation between SO_2 emissions and sulfate deposition at individual NADP monitoring sites in Maine. There is some degree of variability in the correlation coefficients in the figures, particularly among the total deposition (kg/ha) plots (R^2 ranges from 0.01 to 0.51). With the exception of the Acadia National Park site, the correlation coefficient is greater in the plots for the precipitation-weighted mean concentrations than for total deposition.

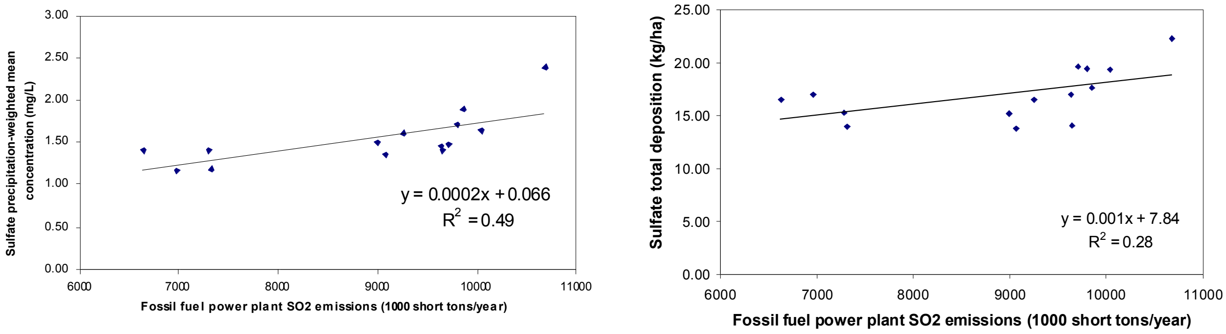


Figure 8. Emissions-related correlation of sulfate precipitation-weighted mean concentration (left) and total deposition (right) averaged over the combined Hubbard Brook, NH and Bridgton, ME NADP sites from 1980 to 1998.

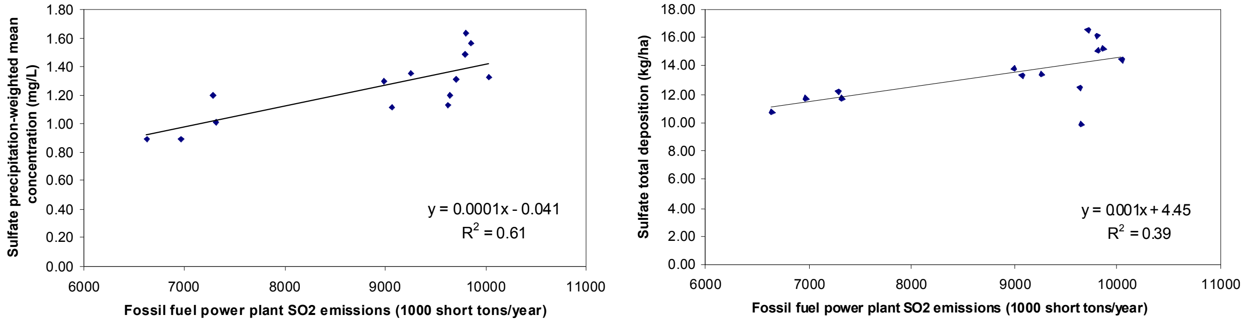


Figure 9. Emissions-related correlation of sulfate precipitation-weighted mean concentration (left) and total deposition (right) averaged over four Maine NADP sites from 1985 to 1998.

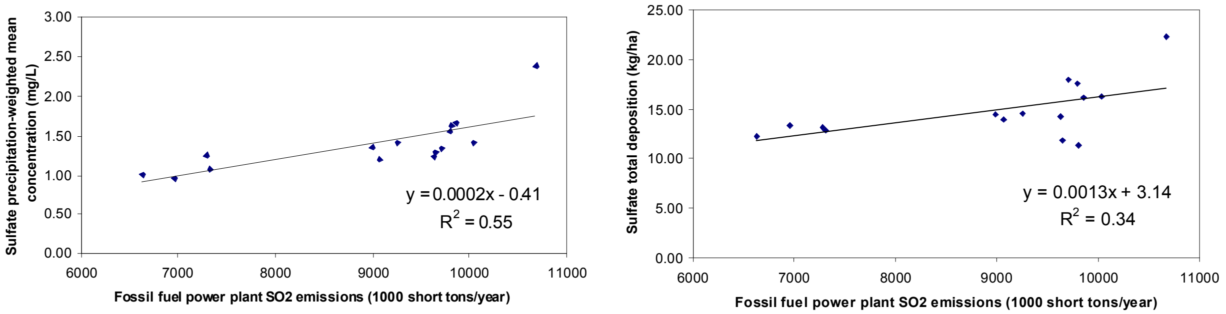


Figure 10. Emissions-related correlation of sulfate precipitation-weighted mean concentration (left) and total deposition (right) averaged over four Maine and one New Hampshire NADP sites from 1980 to 1998.

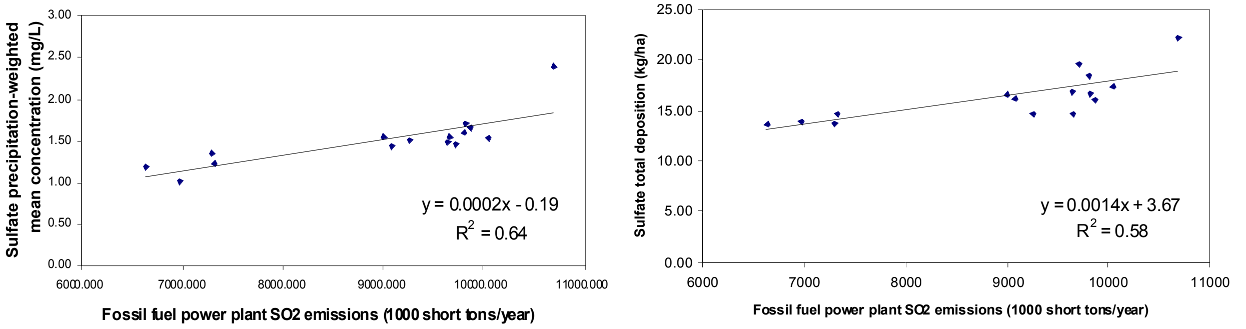


Figure 11. Emissions-related correlation of sulfate precipitation-weighted mean concentration (left) and total deposition (right) averaged over four Maine, one New Hampshire, and two Vermont NADP sites from 1980 to 1998.

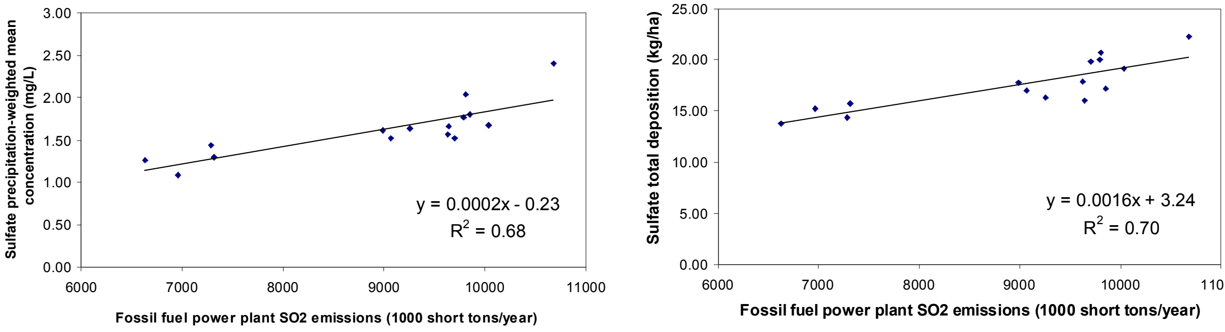


Figure 12. Emissions-related correlation of sulfate precipitation-weighted mean concentration (left) and total deposition (right) averaged over four Maine, one New Hampshire, two Vermont, and three Massachusetts NADP sites from 1980 to 1998.

As a general observation, the positive correlation coefficient in the above plots tends to increase with the increasing number of NADP sites. There is a small decrease, however, in the correlation coefficient when we group the Hubbard Brook, New Hampshire site with the four Maine sites (Figures 9 and 10). The reason may be due to the limited amount of NADP data for 1980. Only the Hubbard Brook site met the NADP-recommended completeness criteria for 1980. Observed deposition at the Hubbard Brook site is generally larger than the annual regional average for the years that have data from the other sites. Therefore, using only 1980 Hubbard Brook data may overstate deposition across the New England region in 1980 and likely affect the correlation coefficient relative to the Maine-only plots where 1980 data are absent. This is suggested in Figure 10 by the data point on the right side of each plot well above the correlation line, which corresponds to the 1980 sulfate deposition at the Hubbard Brook site.

Another general observation from the correlation plots is a greater positive correlation coefficient for the precipitation-weighted mean concentration relative to the total deposition plots. The only exception (aside from the Acadia site mentioned previously) is in Figure 12 where the Massachusetts NADP sites are included. We note, however, that in the second approach used to evaluate the emissions-related correlation, the combined precipitation-weighted mean concentration and total deposition data (scaled to a mean of unity) have a greater positive correlation coefficient than either of the data sets plotted separately (discussed below).

Second approach

We evaluated acidic deposition trends in which we scaled the annual precipitation-weighted mean concentrations and total sulfate deposition to a mean of unity for the period 1980-1997. This is the approach used by Shannon (1999) in evaluating emission-related sulfate deposition trends from 1980 to 1995, although we identified the source region using RADM modeling results rather than using Shannon's modeling approach and focused on annual emissions-related deposition trends rather than using seasonal data. We also extended the trend analysis to include deposition data from 1996 to 1998, as well as data from more NADP monitoring sites in 1995 than used by Shannon. Even with these differences, our updated results for the emissions-related sulfate deposition trends during 1980-1998 are consistent with Shannon's work for the 1980-1995 period.

We used the same New England geographical region for the receptor area as used by Shannon. The receptor region includes deposition data from NADP sites in Maine, Massachusetts, New Hampshire, and Vermont. As with Shannon (1999), we use both annual precipitation-weighted mean concentrations and total deposition data from NADP. Differences in year-to-year precipitation amounts may affect the precipitation concentrations and the total deposition amounts in opposite ways. A relatively high rainfall year could result in higher total acidic deposition amounts, but the precipitation-weighted mean concentrations could be lower due to the effect of dilution as rain more frequently washes out sulfates and nitrates in the air. By scaling both the precipitation-weighted mean concentrations and total deposition to a mean of unity, we are able to average the pair of unitless values for each year to reduce the effect of year-to-year climatological variability.

The procedure for scaling NADP annual deposition data to a mean of unity is described by Shannon, and we briefly summarize the steps here.

- We adjusted the NADP annual sulfate and nitrate precipitation-weighted mean concentrations and total deposition data for the years preceding 1994 according to the NADP recommended adjustments described earlier. We omitted data from specific monitoring sites for any year not meeting the completeness criteria recommended by NADP.
- We scaled the adjusted NADP annual data from each station to a temporal mean of unity by dividing the adjusted data by the average of the annual data for all years meeting the completeness criteria at each station.
- We arithmetically averaged the scaled NADP data from all stations in the New England region for each year.
- We divided the 18 sets of annual precipitation-weighted mean concentrations and total deposition data by their corresponding averages. Shannon performed this step because the regional averaging of incomplete scaled station values can produce regional trends whose mean differs slightly from unity due to different numbers of individual stations contributing to each yearly regional value.
- We averaged the scaled precipitation-weighted mean concentrations with the scaled total deposition values for each year to produce the unitless scaled values used in the emissions-related trend analysis (called "CONCDEP" by Shannon).

Nitrate deposition trend in New England

Applying the approach of Shannon (1999) to nitrate deposition, we scaled annual nitrate precipitation-weighted mean concentrations and total deposition to a mean of unity. Plotting the scaled annual nitrate deposition over time suggests little change in nitrate deposition in the New England region (Figure 13).

A straight-line fit of the annual scaled deposition data indicates no significant increase or decrease in nitrate deposition over the period from 1980 to 1998 in the New England region. The greater year-to-year variability in the earlier years could be a reflection of the fewer NADP sites with complete deposition data relative to the later years (see Table 2), or may indicate greater year-to-year climatological variability not captured by averaging the scaled precipitation-weighted mean concentrations with the total deposition data.

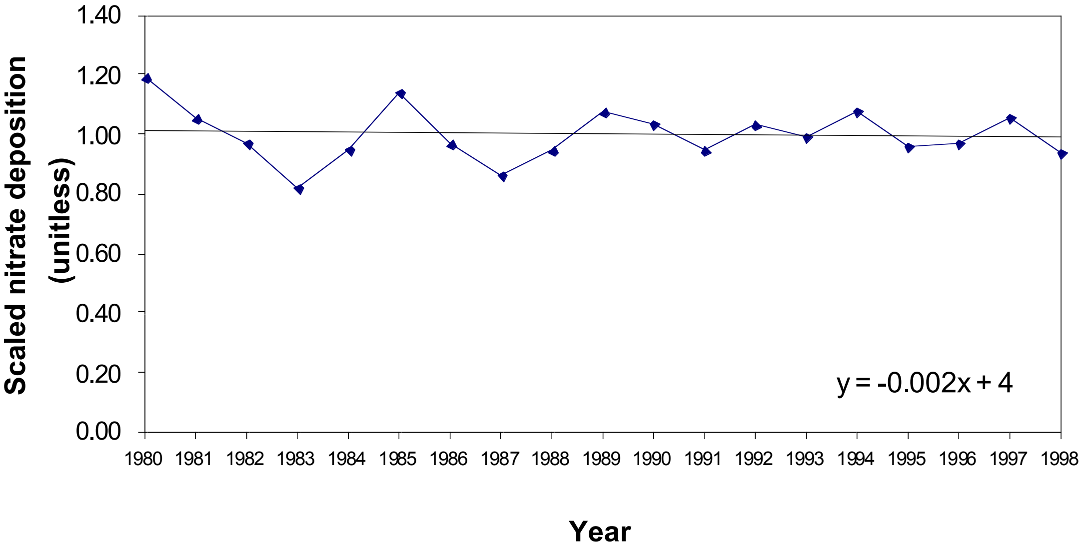


Figure 13. Plot of annual scaled nitrate deposition in the New England region from 1980 to 1998.

The lack of a significant nitrate deposition trend is consistent with the findings of Holland et al. (1999) who looked at atmospheric nitrogen concentrations at 34 rural sites in the eastern United States from 1989 to 1995.

Figure 14 is a plot of the total nitrogen oxides (NO_X) emissions from the upwind source region identified in this study. Based on state-level total NO_X emissions data from the EPA NET Viewer (1998), the figure indicates the absence of a significant increasing or decreasing NO_X emission trend over the period from 1985 to 1996. This assumes the NO_X source region coincides with the SO_2 source region identified from the RADM results, but transport distances may differ between nitrates and sulfates. The NO_X source region for downwind nitrate deposition will only be reasonable for this qualitative comparison if NO_X transformation processes and nitrate deposition occur on a similar transport scale as SO_2 chemistry and sulfate deposition. In any case, NO_X emission trends in general have not changed drastically across much of the eastern United States regardless of the size of the upwind source region. On a national level, emissions of NO_X decreased only 5% from 1980 to 1997 (U.S. EPA, 1998b).

While the annual nitrate deposition and NO_X emission trends do not clearly demonstrate an increase or decrease, the data establish a baseline from which we should be able to assess future trends and any correlation between the two. The Ozone Transport Commission (OTC) Phase II NO_X reductions began in many areas of the Northeast during the summer of 1999, with further reductions planned for Phase III in 2003. While currently stayed by a federal court, additional NO_X reductions in 22 eastern states could occur at some point in the future under EPA's "NO_X SIP Call" (Federal Register, 1998). In the absence of the NO_X SIP Call, a group of state petitions filed under §126 of the Clean Air Act (42 U.S.C. § 7426) may result in NO_X reductions from major stationary sources (mostly power plants) in a smaller region than that covered by the NO_X SIP Call. If any of these NO_X reductions occur, they should affect nitrate deposition in parts of the eastern United States. Changes in deposition may be more pronounced on a seasonal basis, however, since the programs currently require reductions only during the ozone season (May-September). More modest annual NO_X reductions should occur under Title IV (acid rain provisions) of the Clean Air Act. It will be important to keep the current NADP monitoring network in place in order to assess the future nitrate deposition trends.

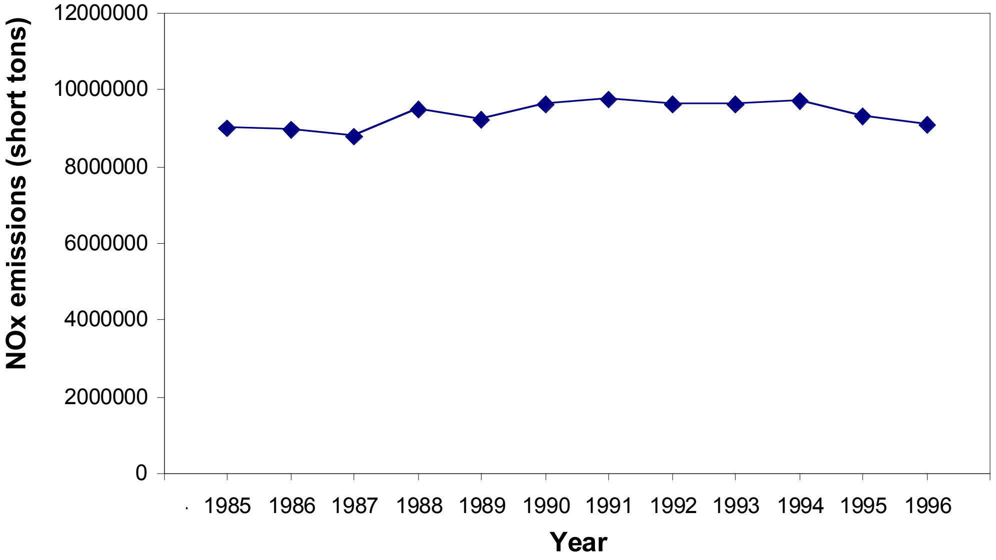


Figure 14. Trend in total NO_X emissions from CT, DE, DC, IL, IN, KY, ME, MD, MA, MI, NH, NJ, NY, OH, PA, RI, VT, VA, and WV during 1985-1996.

Sulfate deposition trend in Maine and greater New England

As in the nitrate deposition approach described above, we scaled annual sulfate precipitation-weighted mean concentrations and total deposition to a mean of unity (Shannon, 1999). Unlike the nitrate deposition trend in New England, the plot of the scaled sulfate deposition shows a decreasing trend over time since 1980 (Figure 15). This is in agreement with the results of Shannon (1999) for the New England region.

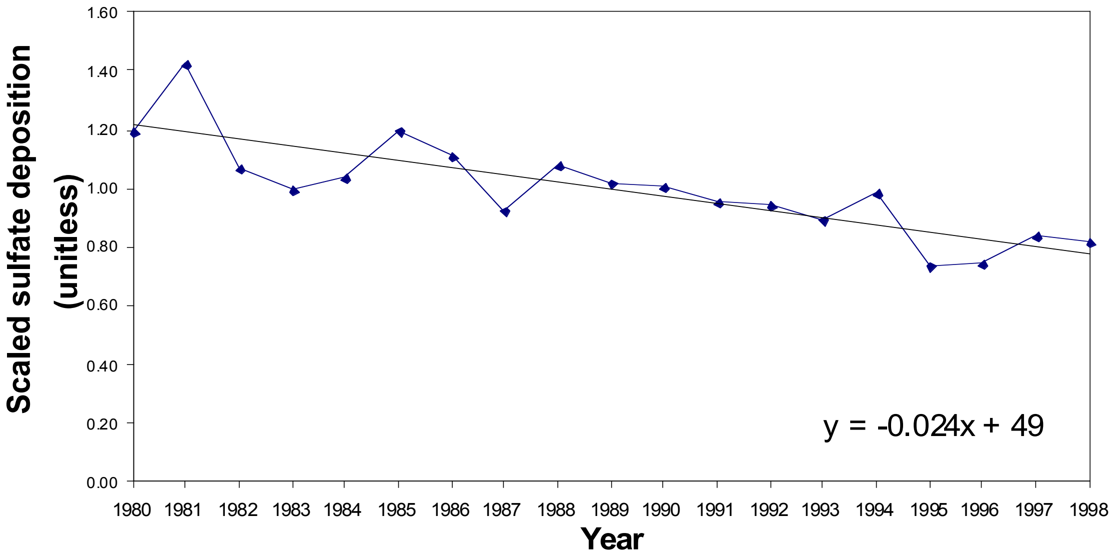


Figure 15. Scaled sulfate deposition (unitless) trend in New England region for 1980-1998.

The scaled precipitation-weighted mean concentration and total deposition trends, when plotted separately rather than averaged as in Figure 15, are both decreasing as well with similar negative slopes (plots not shown here). For the scaled precipitation-weighted mean concentration trend, $m = -0.026\ \text{year}^{-1}$. For the scaled total deposition annual trend, $m = -0.023\ \text{year}^{-1}$.

A plot of SO_2 emissions from fossil fuel power plants in the source region identified by the RADM results also show a decreasing trend over the same time period (Figure 16). Shannon (1999) noted in his study that the SO_2 annual emission trend appears to have a less steep negative slope than the scaled sulfate deposition trend from 1980 to 1995, and has less year-to-year variability. The less steep slope could imply that sulfate deposition is decreasing more rapidly than SO_2 emissions, but Shannon suggested possible areas of uncertainty in deposition and emissions data gathering over the years that may prevent drawing such a conclusion. As also recognized by Shannon, we believe that changes have occurred in the way SO_2 emissions have been reported, as reflected in large single-year SO_2 emission jumps for individual states in the EPA NET Viewer (1997). Therefore, we hesitate to place much significance on any possible differences in the steepness of the deposition and emission trend slopes.

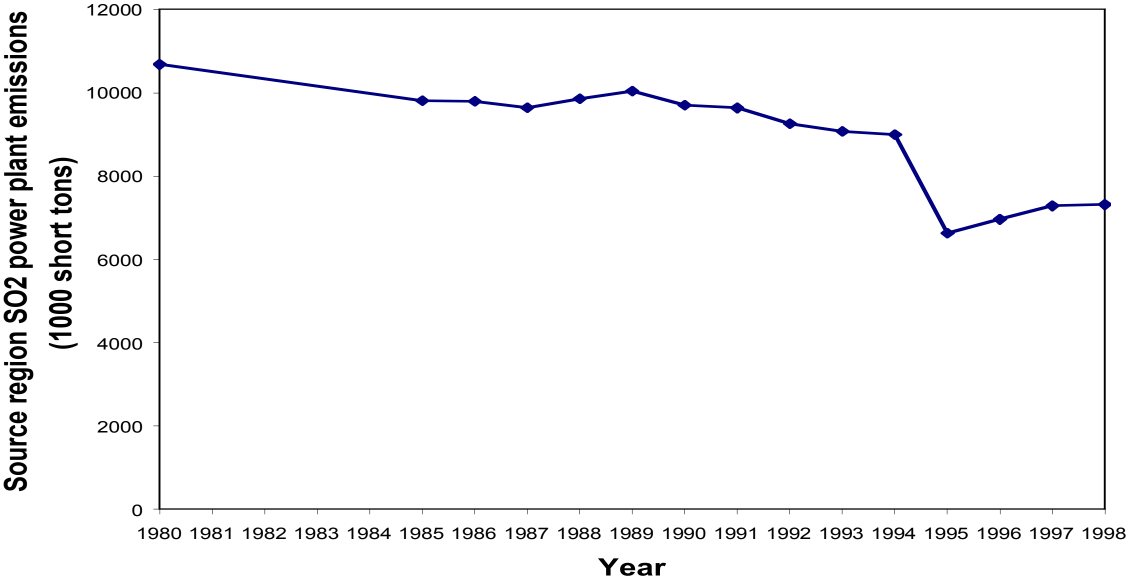


Figure 16. Trend in SO_2 emissions over the 1980-1998 period from fossil fuel power plants in CT, DE, DC, IL, IN, KY, ME, MD, MA, MI, NH, NJ, NY, OH, PA, RI, VT, VA, WV and Ontario.

The SO_2 emissions from fossil fuel power plants increased after 1995 following a sharp drop. The drop in 1995 is due to reductions required by the acid rain provisions of the 1990 Clean Air Act Amendments (Title IV). While the scaled deposition trend is more variable from year-to-year, an increase in sulfate deposition appears to coincide with the increase in SO_2 emissions after 1995.

Figure 17 presents a plot of the emissions-related correlation with the scaled sulfate deposition. The trend in sulfate deposition in the New England region appears well-correlated with fossil fuel SO_2 emissions in the source region identified from the RADM modeling results ($R^2 = 0.78$).

The results are consistent with previous trend analyses by Holland et al. (1999) and Shannon (1999).

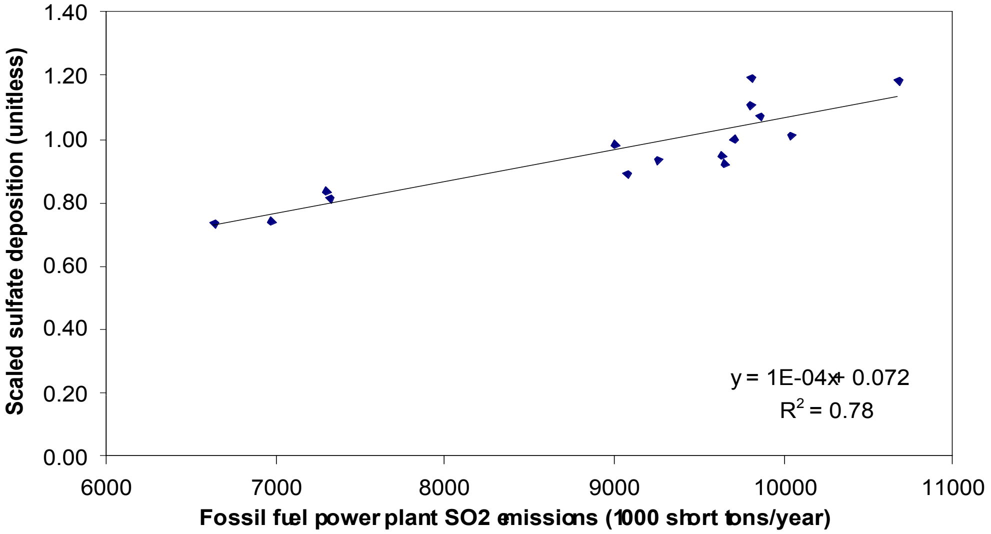


Figure 17. Fossil fuel power plant SO_2 emissions correlation with the combined sulfate precipitation-weighted and total deposition scaled to a mean of unity in the New England region from 1980 to 1998.

For comparison, we plotted the emissions-related correlation of the average scaled precipitation-weighted and total sulfate data using total state-level SO_2 emissions given in the EPA NET Viewer (1997) for 1985 to 1996 (Figure 18). This is to compare the correlation using only fossil fuel power plant emissions in Figure 17 with total state-level SO_2 emissions as given in the EPA NET Viewer.

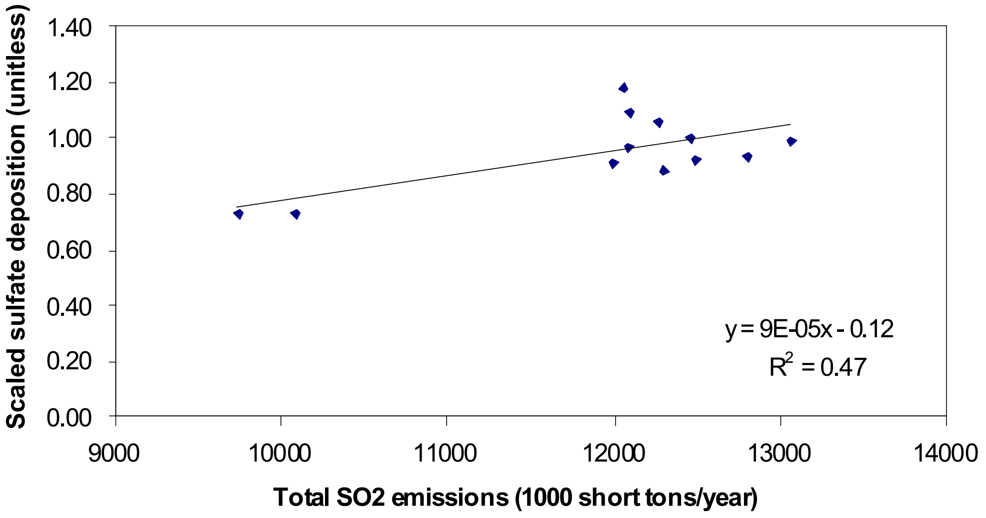


Figure 18. State-level SO_2 emissions correlation with the combined sulfate precipitation-weighted and total deposition scaled to a mean of unity in the New England region from 1985 to 1996. SO_2 emissions data are from the EPA NET Viewer, 1985-1996 (1997).

Using emissions data from the EPA NET Viewer results in a somewhat weaker emissions-related correlation with sulfate deposition than derived from the power plant-only correlation of

Figure 17. Of course, Figure 17 includes data for 1980, 1997 and 1998 not used in Figure 18 (data for 1981-1984 are not used in either plot). Re-plotting the data of Figure 17 after omitting the 1980, 1997 and 1998 data reduces the correlation coefficient slightly ($R^2 = 0.072$), so the difference with the correlation coefficient of Figure 18 remains large. For the reasons discussed previously, we have some concerns about the year-to-year consistency in the total SO_2 emissions data of the EPA NET Viewer that complicate their use for evaluating the emissions-related correlation with sulfate deposition over the 1985-1996 time period.

We also plotted the scaled NADP data for the precipitation-weighted mean concentrations and the total wet deposition separately, rather than averaged together as in Figure 17. The emissions-related correlation coefficients of the separate plots are comparable (shown in Figures 19 and 20), albeit a little lower, than the combined scaled data plotted in Figure 17. The stronger correlation using the combined scaled data suggests that the Shannon procedure helps account for year-to-year climatological variations not fully captured using the precipitation-weighted mean concentration or total wet deposition data separately.

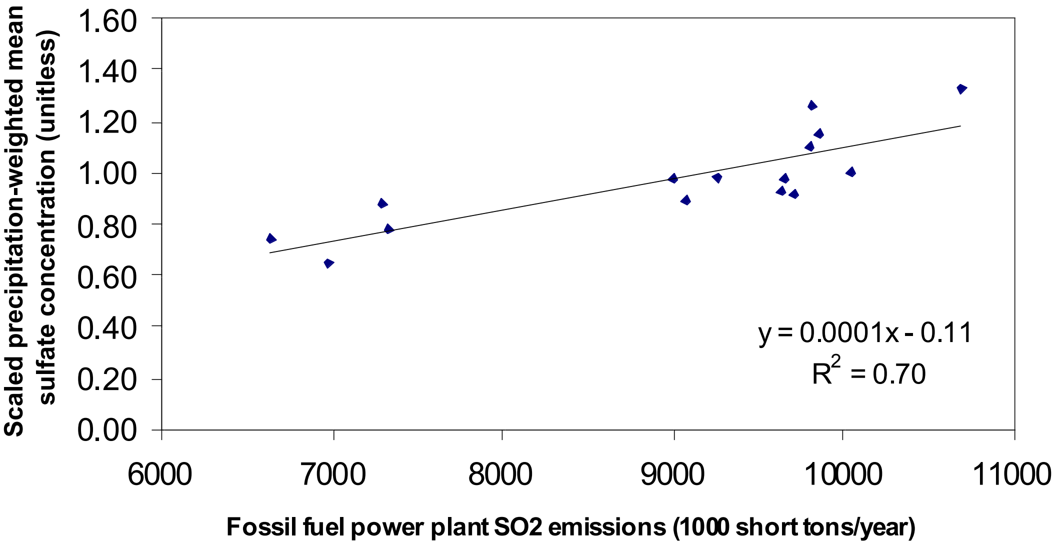


Figure 19. Emissions-related correlation of precipitation-weighted mean sulfate concentrations scaled to a mean of unity in the New England region from 1980 to 1998.

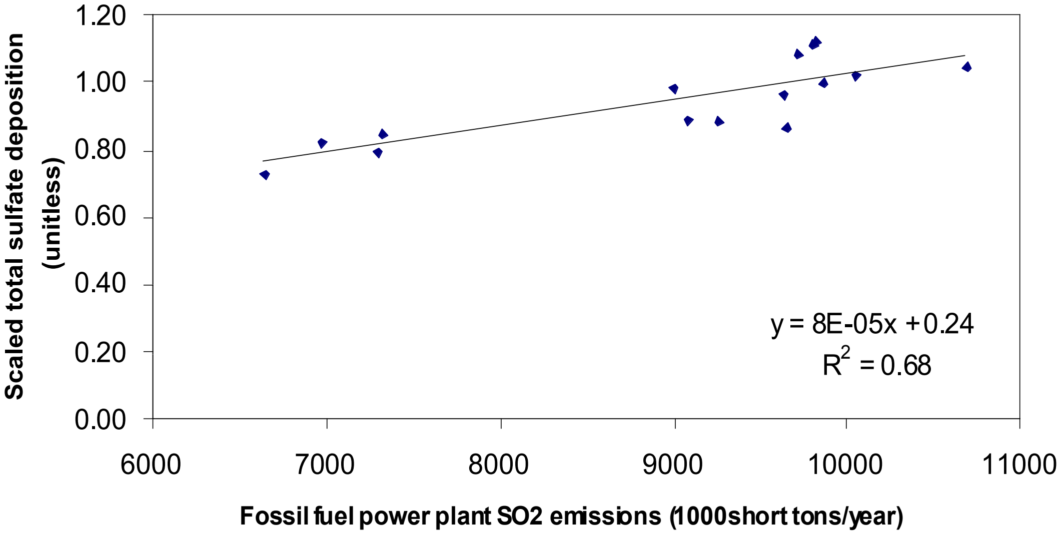


Figure 20. Emissions-related correlation of total wet deposition scaled to a mean of unity in the New England region from 1980 to 1998.

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