

Chapter 4
The Pollutants of Concern

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The Pollutants of Concern

This chapter: 1) provides estimates of pollutant emissions, 2) describes current geographic patterns of *emitted* pollutants, and concentrations and deposition of *transformed* pollutants, and 3) analyzes the *patterns and processes* of pollutant transport and transformation. The pollutants of concern and their transformation products are:

- sulfur dioxide—both as sulfur dioxide gas and as the transformation product, sulfate;
- nitrogen oxides—as a gas, as the transformation product, nitrate, and as a precursor of ozone; and
- reactive hydrocarbons—as precursors of ozone.

OTA has assembled estimates of current emissions and historical and projected emissions trends for these three pollutants. Projections of sulfur dioxide and nitrogen oxides emissions are provided for the United States overall, for the Eastern 31-State region, and by major producing sector. The

chapter examines future utility emissions of sulfur dioxide in greater detail.

To show where these emissions originate, current emissions levels are described in a series of maps. The chapter then presents maps of measured **deposition levels** for acidity and sulfate, and **air concentrations** for ozone and airborne sulfate. These maps can be used to compare the *origins* of the three emitted pollutants to the eventual *destinations* of the transformed pollutants on which the assessment focuses.

Finally, the chapter presents model-based estimates of the regional *transport* of sulfur oxides—the most abundant acid-producing pollutant, and the pollutant for which the greatest amount of information about transport, transformation, and deposition patterns is available. In addition, the section briefly describes the chemical processes that **transform** the three emitted pollutants, to aid in understanding how changes in emissions levels might affect resulting levels of transported pollutants.

EMISSIONS

Current and Historical

In the United States during 1980 approximately 26 million tons of sulfur dioxide, 21 million tons of nitrogen oxides, and about 24 to 28 million tons of hydrocarbons (volatile organic carbon) were emitted by manmade sources. Of this total, about 22 million tons of sulfur dioxide, 14 million tons of nitrogen oxides, and about 19 to 20 million tons of hydrocarbons were emitted in the 31 States east of or bordering the Mississippi River. For the Nation overall, the major sources of sulfur dioxide emissions—about 90 to 95 percent of the total—are electric-generating utilities, industrial boilers, and industrial processes. Similarly, three sectors—utilities, mobile sources, and industry—produce more than 95 percent of the country's manmade nitrogen oxides emissions. Mobile sources and industrial processes produce about 80 to 85 percent

of U.S. hydrocarbon emissions, while the remainder comes from a wide variety of sources.

Table 1 presents current (1980) estimated emissions of sulfur dioxide, nitrogen oxides, and hydrocarbons for each of the 50 States. ¹To place the current level of emissions into historical perspective, table 2 shows estimated total U.S. and Eastern 31-State emissions of sulfur dioxide and nitrogen oxides, and estimated total U.S. hydrocarbon emissions, for selected years between 1940 and 1980. Between 1940 and 1970, nationwide sulfur dioxide emissions increased by roughly 50 percent, from about 19 million to 30 million tons per year. From

¹Estimates are from *Emissions, Costs, and Engineering Assessment*, Work Group 3B, United States-Canada Memorandum of Intent on Transboundary Air Pollution, June 15, 1982. Tables 3 and 4 compare the 50-State and Eastern 31-State region totals, by utility and industrial sector, with other estimates of sulfur dioxide and nitrogen oxides emissions.

Table 1.—1980 Total Emissions of Sulfur Dioxide, Nitrogen Oxides, and Hydrocarbons in the United States (1,000 tons/year)

State	S ₀ 2	NO x	HC	State	S ₀ 2	NO x	HC
Alabama	760	450	530	Montana	160	120	160
Alaska	20	55	50	Nebraska	75	190	200
Arizona	900	260	250	Nevada	240	80	70
Arkansas	100	220	270	New Hampshire	90	60	100
California	445	1,220	2,550	New Jersey	280	400	810
Colorado	130	275	360	New Mexico	270	290	195
Connecticut	70	135	370	New York	950	680	1,250
Delaware	110	50	70	North Carolina	600	540	680
District of Columbia	15	20	35	North Dakota	100	120	70
Florida	1,100	650	880	Ohio	2,650	1,140	1,280
Georgia	840	490	580	Oklahoma	120	520	460
Hawaii	60	45	75	Oregon	60	200	330
Idaho	50	80	170	Pennsylvania	2,020	1,040	1,360
Illinois	1,470	1,000	1,200	Rhode Island	15	40	120
Indiana	2,000	770	700	South Carolina	330	200	550
Iowa	330	320	300	South Dakota	40	90	110
Kansas	220	440	350	Tennessee	1,100	520	580
Kentucky	1,120	530	430	Texas	1,270	2,540	3,400
Louisiana	300	930	790	Utah	70	190	160
Maine	100	60	120	Vermont	7	25	45
Maryland	340	250	370	Virginia	360	400	530
Massachusetts	340	250	600	Washington	270	290	500
Michigan	900	690	1,100	West Virginia	1,100	450	150
Minnesota	260	370	500	Wisconsin	640	420	530
Mississippi	280	280	330	Wyoming	180	260	110
Missouri	1,300	570	690	U.S. total	26,500	21,220	28,350

SOURCE: Emissions, Costs and Engineering Assessment, Work Group 3B, United States-Canada Memorandum of Intent on Transboundary Air Pollution, June 15, 1982

Table 2.—Historical Trends in Sulfur Dioxide, Nitrogen Oxides, and Hydrocarbon Emissions (millions of tons)

Year	Sulfur dioxide		Nitrogen oxides		Hydrocarbons
	National ^{ab}	Eastern 31 States ^c	National ^{ah}	Eastern 31 States ^b	National ^a
1940	19.1	—	7.2	—	15.3
1950	18.1-21.6	14.6	7.4-10.3	5.4	19.3
1955	17.7	14.3	8.5	6.4	—
1960	21.2-22.2	18.9	11.5-14.0	8.5	23.8
1965	26.7	22.8	14.2	10.4	—
1970	28.7-30.8	24.0	17.7-20.4	12.4	29.8
1975	27.3-28.2	23.4	19.3-21.6	13.3	25.1
1980	25.2-26.1	21.2	21.0-22.8	13.9	24.0-28.3 ^c

SOURCES: National Air Pollution Emission Estimates, 1940-1980, U.S. Environmental Protection Agency, January 1982, EPA-450M-82-001.

^a"Historic Emissions of Sulfur and Nitrogen Oxides in the United States from 1900 to 1980," G. Gschwandtner, et al., 1980. Draft reports to EPA from Pacific Environmental Services, Inc.^cEmissions Costs and Engineering Assessment, Work Group 3B, United States-Canada Memorandum of Intent on Transboundary Air Pollution, June 15, 1982

1970 to 1980 emissions totals show a decline from about 30 million to 26 million tons per year, and from about 24 million to 21 to 22 million tons for the Eastern 31-State region. Estimates are available for pre-1940 emissions levels, but these are based on incomplete data. These data suggest that throughout the period 1920-40, nationwide sulfur dioxide emissions averaged roughly 17 million tons per year.² Appendix A presents historical emissions estimates in greater detail.

Over the period 1940-80, nitrogen oxides emissions grew much more rapidly than sulfur dioxide—virtually tripling—but have declined slightly from 1978 to 1980. Hydrocarbon emissions are estimated to have doubled, from about 15 million tons in 1940 to about 30 million tons per year in 1970. From 1970 to 1980, hydrocarbon emissions declined—according to various estimates, to about 24 to 28 million tons per year.³

Future Emissions Under Current Laws and Regulations

Assuming that current air pollution laws and regulations remain unchanged, future emissions of both sulfur dioxide and nitrogen oxides will depend primarily on three factors:

- future demand for energy, including energy for electricity generation, industrial fuel use, and automobiles;
- the type of energy used to meet future demand, for example, the extent of such non-fossil energy use as nuclear and hydropower, and less polluting fuels such as natural gas; and
- the rate at which existing pollution sources—both stationary sources and highway vehicles—are replaced with newer sources more tightly controlled under the Clean Air Act.

²“Historic Emissions of Sulfur and Nitrogen Oxides in the United States From 1900 to 1980,” G. Gschwandtner, et al., 1983. Draft report to EPA from Pacific Environmental Services, Inc.

³Hydrocarbon emissions are difficult to estimate, in part because a major source of the ir product ion is the evaporation of chemical solvents. As shown in tables 1 and 2, the 24-million-ton estimate is derived from U.S. Environmental Protection Agency, *National Air Pollutant Emission Estimates, 1940-1980*, while the 28-million-ton figure is from the U.S.-Canada MOI, Work Group 3B, *Emissions, Costs and Engineering Assessment*.

Each of these factors is, of course, uncertain, but analysts can estimate pollutant emissions that would result from plausible future trends. The first three parts of this section will present several projections of future sulfur dioxide, nitrogen oxides, and hydrocarbon emissions over the next two to three decades. The fourth part will discuss how these factors, as well as further emission controls, affect future sulfur dioxide emissions from the *utility* sector.

Sulfur Dioxide Emissions

Table 3 presents various projections of sulfur dioxide emissions through the year 2010. For the United States as a whole, sulfur dioxide emissions are projected to increase over 1980 levels by 10 to 25 percent by 2000, and by 20 to 30 percent by 2010. The greatest projected rate of increase is in the industrial sector—25 to 40 percent by 2000.

Within the 31 Eastern States, the industrial sector is again projected to account for the fastest growth in emissions. By 2000, total sulfur dioxide emissions are projected to increase by 10 to 30 percent, while emissions from the industrial sector alone increase between 50 to 90 percent. By 2010, total emissions are projected to increase by about 15 to 25 percent over 1980 levels. These projections assume that rising oil and natural gas prices will cause many current users of these cleaner fuels to switch to coal. Utility emissions are forecast to increase slightly through about 2000 and then to begin declining slightly. Because of the growth increase projected for the industrial sector, utility emissions will drop from about 75 percent of the total in 1980 to about 60 to 65 percent of the total by 2010.

Nitrogen Oxides Emissions

While mobile sources are currently the single largest nitrogen oxides-producing sector, by 2010 rapid growth in emissions from the utility sector is expected to make utilities the single largest source of nitrogen oxides. Table 4 presents various projections of nitrogen oxides emissions for utilities, mobile sources, and industry.

For the United States, nitrogen oxides emissions by 2000 are expected to increase over 1980 levels by about 25 percent; by 2010, emissions are forecast

Table 3.—Projected Sulfur Dioxide Emissions (million tons/year)

	United States							Eastern 31 States						
	1980	1985	1990	1995	2000	2005	2010	1980	1985	1990	1995	2000	2005	2010
Total:								Total						
MOI ¹	26.5	—	25.3	—	29.3	—	—	MOI ¹	21.8	—	21.4	—	24.3	—
EE1 ^{2a}	27.3	26.9	27.2	29.4	31.1	—	33.4	EE1 ^{2a}	21.7	21.2	21.6	23.5	23.9	—
EE1^{2b}	27.3	28.7	29.4	32.0	34.6	—	35.0	EE1^{2b}	21.7	23.5	24.2	26.6	27.9	—
Utility:								utility:						
MOI ¹	17.3	—	17.5	—	17.9	—	—	MOI ¹	16.0	—	15.9	—	16.1	—
EE1 ^{2a}	17.5	17.6	17.9	18.6	18.2	—	18.2	EE1 ^{2a}	16.2	15.05	15.7	15.9	15.1	—
EE1 ^{2b}	17.5	19.3	20.1	21.2	21.6	—	19.8	EE1 ^{2b}	16.2	17.8	18.3	19.0	19.1	—
EPA ³	17.4	18.8	20.0	20.2	19.6	—	18.7	EPA ³	16.2	17.1	17.9	18.0	17.1	—
NWF ⁴	—	—	19.6	—	21.0	—	—	NWF ⁴	—	—	17.8	—	18.1	—
								EEI ⁵	—	—	18.3	—	—	—
Industry:								Industry:						
MOI ¹	7.4	—	5.9	—	9.3	—	—	MOI ¹	4.4	—	4.1	—	6.7	—
EEI ^{2c}	7.5	7.4	7.2	8.6	10.5	—	12.2	EEI ^{2c}	3.8	4.2	4.4	6.3	7.2	—
								EEI ⁵	—	—	4.4	—	—	—

Sources of estimates:

- MOI—Emissions, Costs and Engineering Assessment, Work Group 3B, United States-Canada Memorandum of Intent on Transboundary Air Pollution, June 15, 1982.
- EEI—"Summary of Forecasted Emissions of Sulfur Dioxide and Nitrogen Oxides in the United States Over the 1980 to 2010 Period," prepared by ICF Inc. and National Economic Research Associates for the Edison Electric Institute and Utility Air Regulatory Group, April 1982.
 - 2a—National Economic Research Associates (NERA) estimate.
 - 2b—ICF Inc. estimate.
 - 2c—Joint NERA/ICF estimate.
- EPA—Personal communication from J. Austin, EPA. Projections prepared for EPA by ICF Inc., using assumptions stated in "Analysis of a 10 Million Ton Reduction in Emissions From Existing Utility Powerplants," ICF Inc., June 1982.
- NWF—"Cost and Coal Production Effects of Reducing Utility Sulfur Dioxide Emissions," prepared for National Wildlife Federation and National Clean Air Coalition by ICF Inc., Nov. 14, 1981.
- EEI—"January 25, 1982 Preliminary ICF Analysis of the Mitchell Bill Prepared for the Edison Electric Institute," Edison Electric Institute letter, Feb. 8, 1982.

Table 4.—Projected Nitrogen Oxides Emissions (million tons/year)

	United States							Eastern 31 States						
	1980	1985	1990	1995	2000	2005	2010	1980	1985	1990	1995	2000	2005	2010
Total:								Total:						
MOI ¹	21.2	—	21.2	—	26.6	—	—	MOI ¹	14.0	—	15.0	—	18.5	—
EEI ^{2a}	21.0	22.2	22.3	23.9	26.2	—	32.8	EEI ^{2a}	14.9	15.6	15.6	16.4	17.7	—
EEI^{2b}	21.0	21.7	22.3	24.0	26.5	—	31.8	EEI^{2b}	14.9	15.5	15.8	16.8	18.4	—
Utility:								Utility:						
MOI ¹	6.4	—	7.5	—	9.6	—	—	MOI ¹	4.8	—	5.7	—	6.9	—
EEI ^{2a}	7.2	8.8	9.3	10.2	11.1	—	14.8	EEI ^{2a}	5.4	6.5	6.8	7.2	7.6	—
EEI ^{2b}	7.2	8.3	9.3	10.3	11.4	—	13.8	EEI ^{2b}	5.4	6.4	7.0	7.6	8.3	—
								EEI ³	—	—	6.2	—	—	—
Industry:								Industry:						
MOI ¹	4.6	—	4.2	—	5.6	—	—	MOI ¹	2.4	—	3.0	—	3.7	—
EEI ^{2c}	3.5	3.7	4.2	4.7	5.3	—	6.0	EEI ^{2c}	2.3	2.5	2.8	3.2	3.7	—
								EEI ³	—	—	2.6	—	—	—
Mobile:								Mobile:						
MOI ¹	9.4	—	8.6	—	10.7	—	—	MOI ¹	6.2	—	5.8	—	7.3	—
EEI ^{2c}	9.4	8.9	8.2	8.4	9.2	—	11.5	EEI ^{2c}	6.5	6.0	5.5	5.5	6.0	—

Sources of estimates:

- MOI—Emissions, Costs and Engineering Assessment, Work Group 3B, United States-Canada Memorandum of Intent on Transboundary Air Pollution, June 15, 1982.
- EEI—"Summary of Forecasted Emissions of Sulfur Dioxide and Nitrogen Oxides in the United States Over the 1980 to 2010 Period," prepared by ICF Inc. and National Economic Research Associates for the Edison Electric Institute and Utility Air Regulatory Group, April 1982.
 - 2a—National Economic Research Associates (NERA) estimate.
 - 2b—ICF Inc. estimate.
 - 2c—Joint NERA/ICF estimate.
- EEI—"January 25, 1982 Preliminary ICF Analysis of the Mitchell Bill Prepared for the Edison Electric Institute," Edison Electric Institute letter, Feb. 8, 1982.

to increase by about 50 to 55 percent. The utility sector is projected to account for most of this increase (about 60 to 75 percent). For the 31 Eastern States, nitrogen oxides emissions are projected to increase by about 20 to 30 percent by 2000, and by about 45 percent by 2010.

Hydrocarbon Emissions

Reliable quantitative estimates of future hydrocarbon emissions are not available at this time. However, in general, hydrocarbon emissions are projected to decline somewhat from 1980 levels, and then to remain relatively constant. Petroleum refining and storage is the only major source of hydrocarbons projected to significantly increase emissions through 2000; expected improvements in abatement practices and potential shifts away from liquid hydrocarbon fuels toward coal use might partially or completely offset such increases.⁴ Emissions from industrial processes—a major source of hydrocarbons—depend heavily on the specific process in use, making these emissions very difficult to estimate.

Utility Sulfur Dioxide Emissions in the 31 Eastern States

As demonstrated by the variations among the projections presented in tables 3 and 4, forecasting pollutant emissions is not an exact science. Emissions scenarios depend on numerous assumptions about future economic conditions. For example, projections of rapid growth of sulfur dioxide emissions from the industrial sector assume increased industrial output, along with a change from oil use to coal. The range of the projections reflects different plausible assumptions about future rates of industrial growth and the relative future price of oil and coal.

OTA used a simple projection model to examine how various factors affect forecasts of utility sulfur dioxide emissions in the Eastern half of the country. The major factors affecting utility emissions are: 1) demand for electricity (for this analysis, OTA assumes growth to be 2.5 percent per year, with a range of 2.0 to 3.0 percent per year); and 2) retirement age of existing plants (for this analysis,

OTA assumes the useful life of a plant to be 50 years, with a range of 40 to 60 years). Other factors include reliance on nonfossil energy sources (assumed to provide the same proportion of electricity generation as in 1980), emission rates from new sources regulated under the New Source Performance Standards (NSPS) (assumed to average 0.6 lb sulfur dioxide per million Btu), and reductions required to comply with State Implementation Plans (SIPS) (assumed to be about 1 million tons of sulfur dioxide; possible SIP relaxations might reduce this amount).

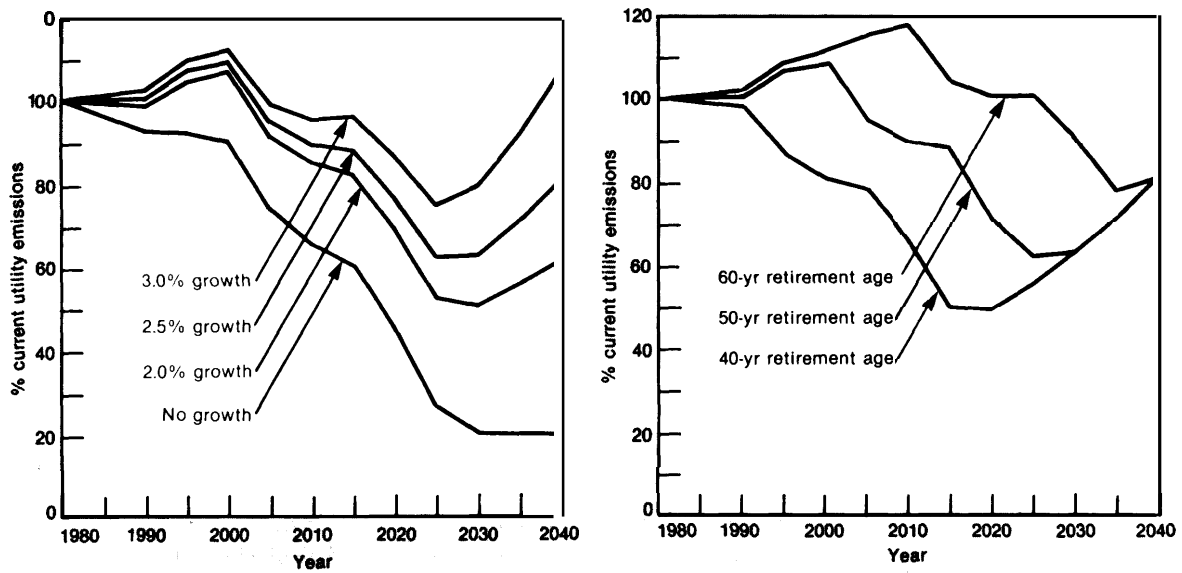
Figure 11 shows how these factors affect emissions forecasts, using a 60-year forecast period to allow for replacement of all utility plants operating in 1980. Figure 11A illustrates the sensitivity of emissions forecasts to demand for electricity. The lowest curve shows emissions in the unlikely event that no growth in demand occurs. Under such a scenario, emissions would decline to 20 percent of the current 16 million tons of utility sulfur dioxide emissions when all existing sources are replaced by new sources regulated under NSPS.

Existing facilities are assumed to retire after 50 years of service. Assuming an increase in demand for electricity ranging from 2 to 3 percent per year, emissions will increase to 7 to 11 percent above current levels by 2000, decline to about 50 to 75 percent of current levels by 2025 to 2030, and then begin to climb again. However, as figure 11 B shows, these trends are extremely sensitive to the average life of existing sources, assumed to be 50 years for the estimates presented above. Figure 11 B illustrates emissions trends assuming 2.5 percent *growth* per year, but varying the average retirement age of existing utility plants. A 40-year retirement age would cause emissions to decline steadily to about 50 percent of current levels by 2015 to 2020, and subsequently rise. If the useful life of existing plants is extended to 60 years, emissions might rise to about 20 percent above current levels by 2010, decline to about 80 percent of current amounts by 2030, and then begin to rise again.

Figure 11 C shows the effect of limiting allowable emission rates now, as opposed to waiting for NSPS-regulated new sources to replace existing utilities. The distance between the “base case” curve (no change in current laws and regulations) and the “emissions rate limitation curves repre-

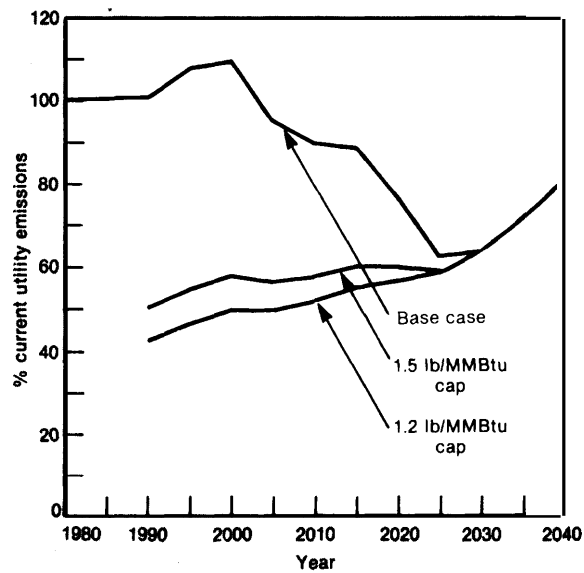
⁴*Environmental Outlook 1980*, U.S. Environmental Protection Agency, July 1980, EPA-600/18-80-003.

Figure 11.—Forecasts of Utility Sulfur Dioxide Emissions for the Eastern 31-State Region of the United States



A: Estimated emissions as a function of growth electricity demand (50-yr retirement age assumed)

B: Estimated emissions as a function of retirement age of electric utilities (2.5%/yr growth assumed)



C: Estimated emissions as a function of allowable emission rates (50-yr retirement age, 2.5%/yr growth assumed)

SOURCE: Office of Technology Assessment

sents the difference in emissions at any point in time. A 1.5 lb sulfur dioxide per million Btu 'emissions cap' on all Eastern utility sources by 1990 would reduce emissions to about 50 percent of current levels. Emissions would then increase to about 60 percent of current levels by 2025 and (after all existing sources retired) follow the same growth trend as the base case by 2030. Under a 1.2 lb per million Btu cap by 1990, emissions would decrease to 40 percent of current emissions by 1990, and then rise to about 60 percent of current levels by 2025. Assuming a shorter retirement age would, of course, decrease the length of time during which

the base case and the emissions cap scenarios substantially differed, and a longer retirement age would increase that time.

The range of projections from the simple model discussed above agrees reasonably well with the more sophisticated projections presented earlier in this section. Projections beyond 2000 to 2010 are presented to illustrate how emissions levels might respond to plausible changes in electricity demand and utility operating procedures, but should not be considered accurate forecasts, as many other factors may change over so long a time.

PATTERNS OF POLLUTANT EMISSIONS, AIR CONCENTRATIONS, AND DEPOSITION

Geographical Emissions Patterns

Figures 12, 13, and 14 display maps of emissions densities (in tons per square mile per year) for sulfur dioxide, nitrogen oxides, and reactive hydrocarbons, respectively. For all three pollutants, emissions densities are generally greater in the East than in the West.

Geographical Patterns of Deposition and Air Concentrations for Transformed Pollutants

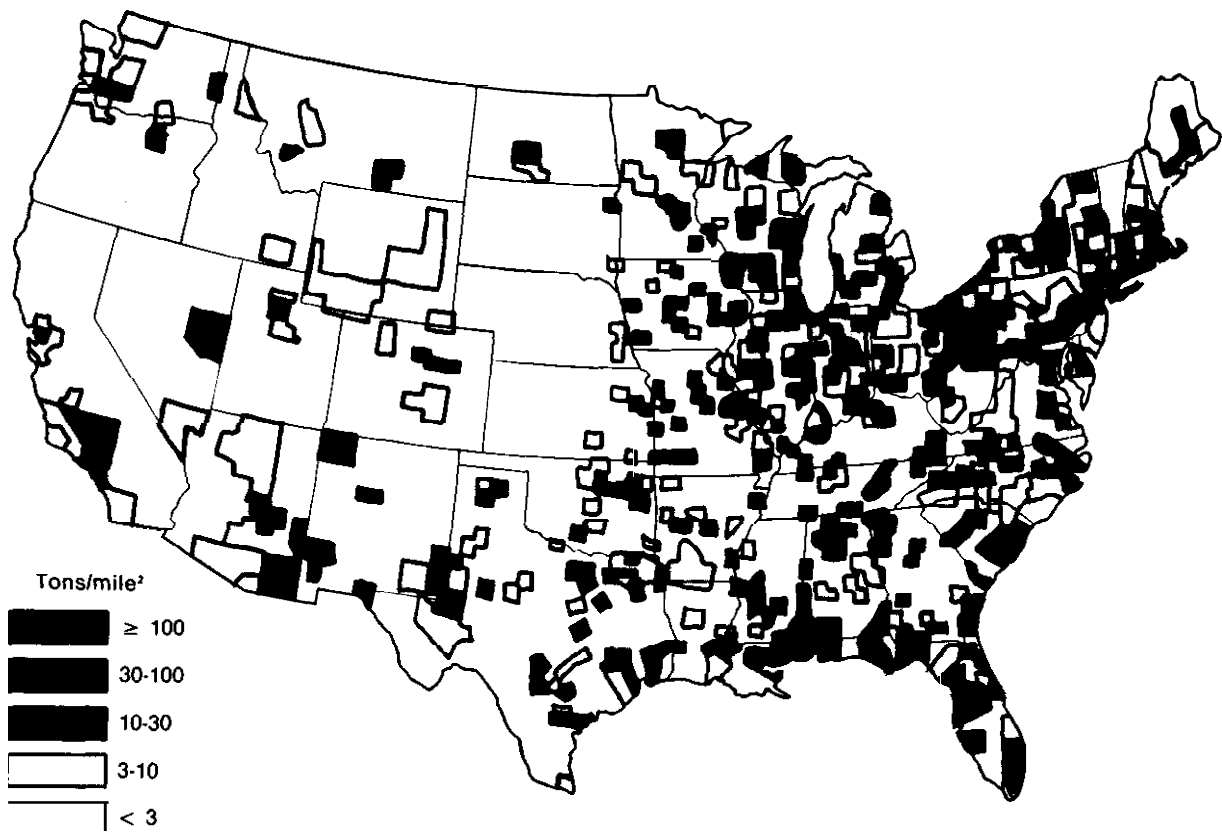
Figures 15 through 18 display maps of deposition levels for acidity and sulfate in precipitation, and air concentrations for airborne sulfate and ozone—each of which is a major determinant of potential damage from transported air pollutants. Patterns of rainfall acidity and sulfate deposition, and airborne sulfate concentrations, are similar over the Eastern United States. The regional distribution of ozone differs substantially from the other three.

The best information available on patterns of acidic deposition comes from monitoring networks that collect rainfall samples. Though only about *half* of all acid deposition over the Eastern United States

comes from precipitation, dry deposition of gaseous and particulate pollutants is not extensively monitored. Figure 15 shows average annual precipitation acidity (measured as pH*) throughout North America during 1980. Figure 16 shows the geographical patterns of wet-deposited sulfate. The highest deposition rates center around eastern Ohio, western Pennsylvania, and northern West Virginia. A band surrounding this area—from the Atlantic Ocean west to the Mississippi River, and from southern Ontario to northern Mississippi, Alabama, and Georgia—receives from 50 to 80 percent of these peak deposition rates. The data used to construct this map are from 1980; deposition will vary from year to year at any given location, but the broad pattern will probably remain quite similar.

Figure 17 displays airborne sulfate concentrations in rural and remote areas, illustrating large-scale, regional patterns. The highest concentrations occur in a broad band covering the Midwest and Middle Atlantic States.

*Acidity is measured in pH units. Decreasing pH corresponds to increasing acidity. The pH scale is not linear; compared to a pH of 6, pH 5 is 10 times more acid, pH 4 is 100 times more acid, and so on.

Figure 12.—Sulfur Dioxide Emissions Density (tons/mile², 1980)

SOURCE Environmental Protection Agency, based on data from National Emission Data System

Patterns of ozone concentration are also available from monitoring data, Figure 18 displays growing-season average ozone concentrations, after eliminating local-scale variations due to urban influences. In the Eastern United States, peak values for ozone are found further south than for acid dep-

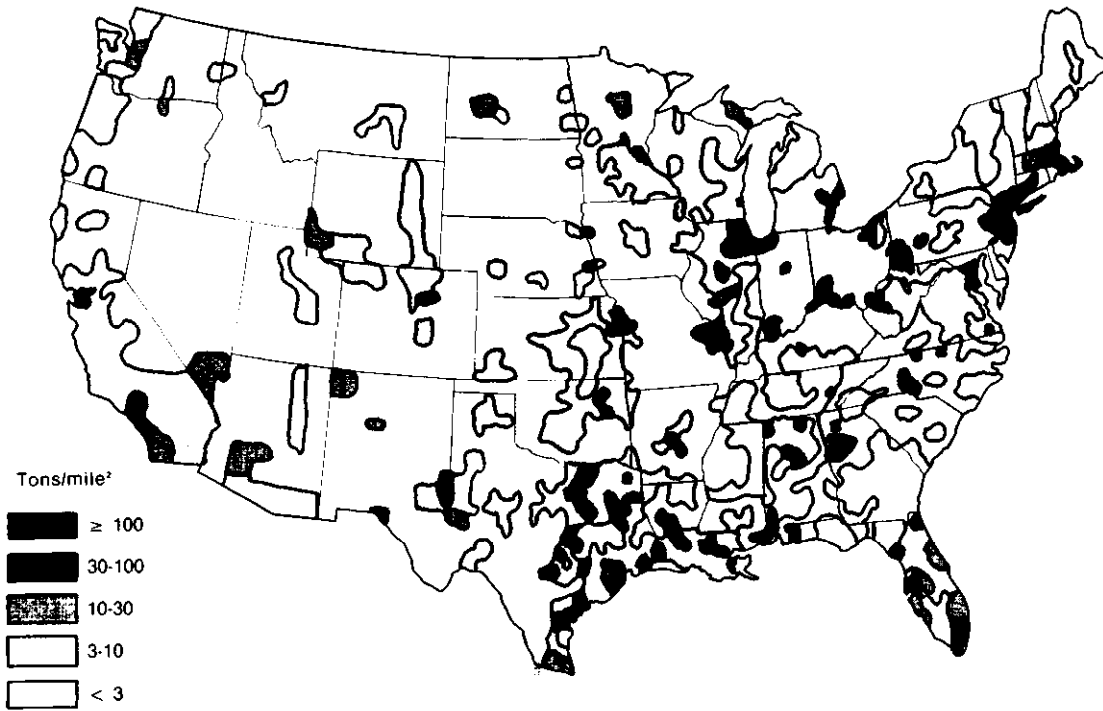
osition, centering on North and South Carolina. A band of elevated ozone extends from the Mid-Great Plains States to the east coast, as far north as central Indiana and south to the central Gulf Coast States.

THE REGIONAL PATTERNS OF SULFUR OXIDES TRANSPORT

How pollutant emissions from a particular region (or group of regions) affect ambient air quality and pollutant deposition at some other location is a major controversy in the long-range transport debate. Emitted pollutants are transformed, transported, and deposited through a complex chain of chemical and physical processes.

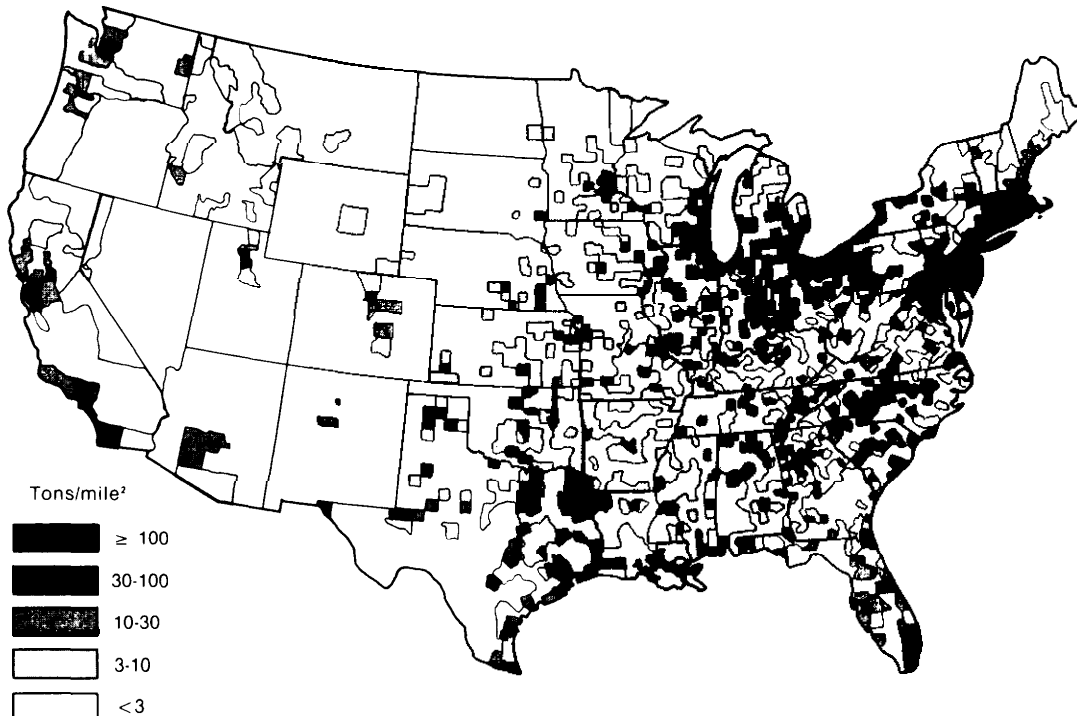
Figure 19 schematically illustrates the gradual transformation and deposition of sulfur pollution as an air mass travels downwind over several days. Sulfur pollution can be deposited in both its emitted form, sulfur dioxide (lighter shading), and as sulfate (darker shading), after being chemically transformed in the atmosphere. Both forms can be de-

Figure 13.—Nitrogen Oxide Emissions Density (tons/mile²)



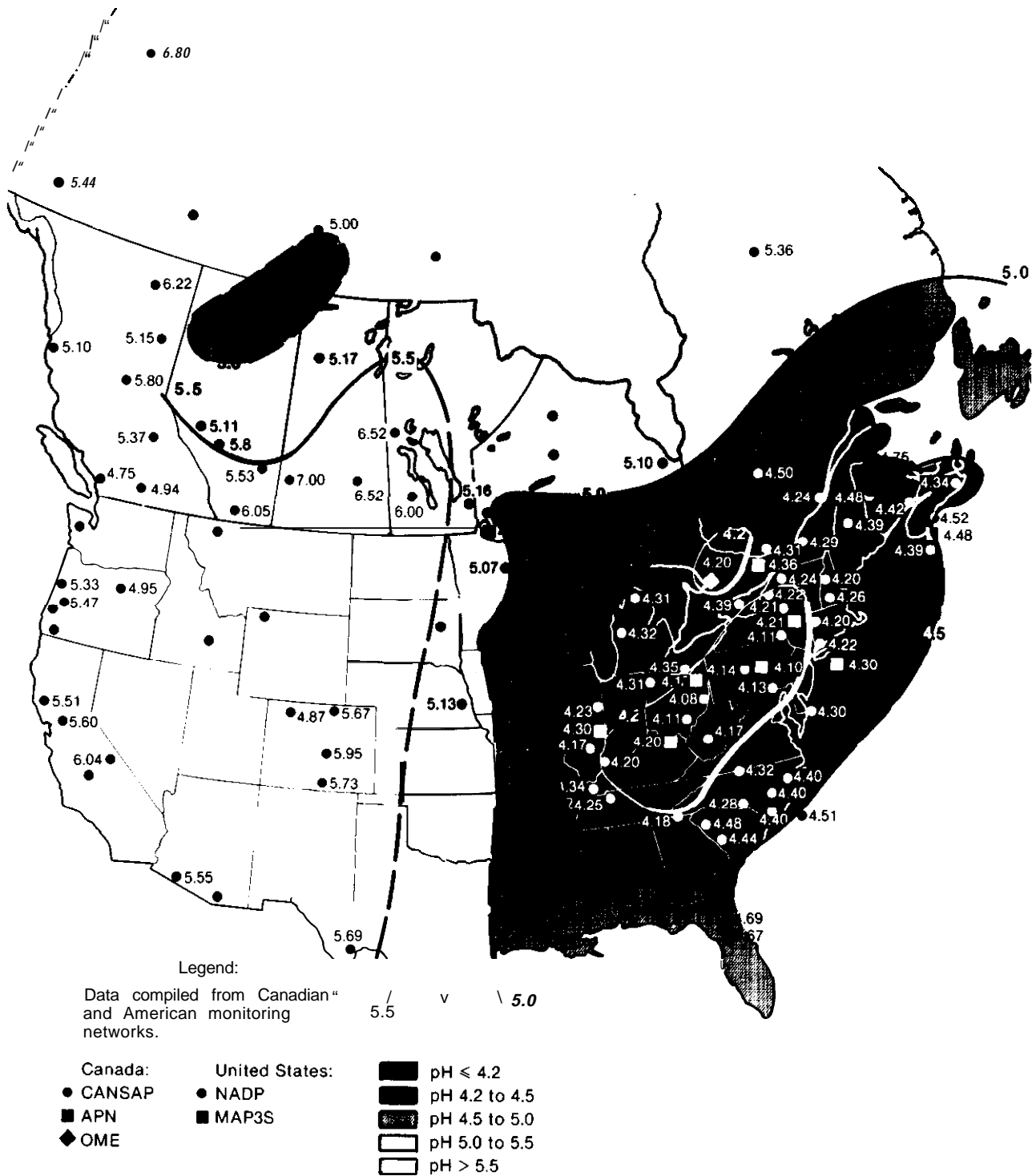
SOURCE Environmental Protection Agency, based on data from National Emission Data System

Figure 14.—Hydrocarbon Emissions Density (tons/mile²)



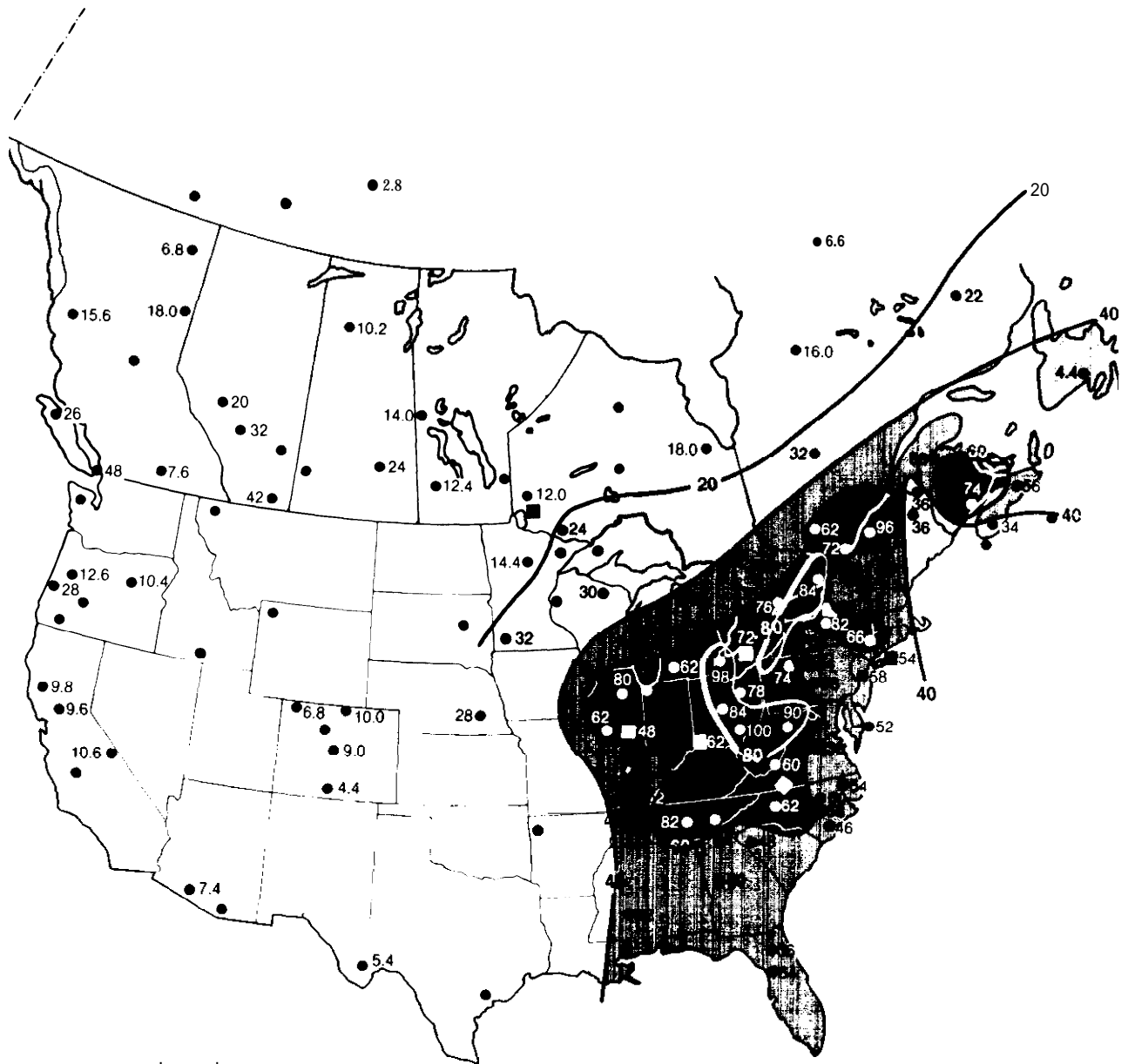
SOURCE Environmental Protection Agency, based on data from National Emission Data System

Figure 15.—Precipitation Acidity—Annual Average pH for 1980, Weighted by Precipitation Amount



SOURCE: Impact Assessment, Work Group 1, United States-Canada Memorandum of Intent on Transboundary Air Pollution, final report, January 1983

Figure 16.—Sulfate in Precipitation, 1980 (annual deposition in milliequivalents/meter²)



Legend:

Data compiled from Canadian and American monitoring networks.

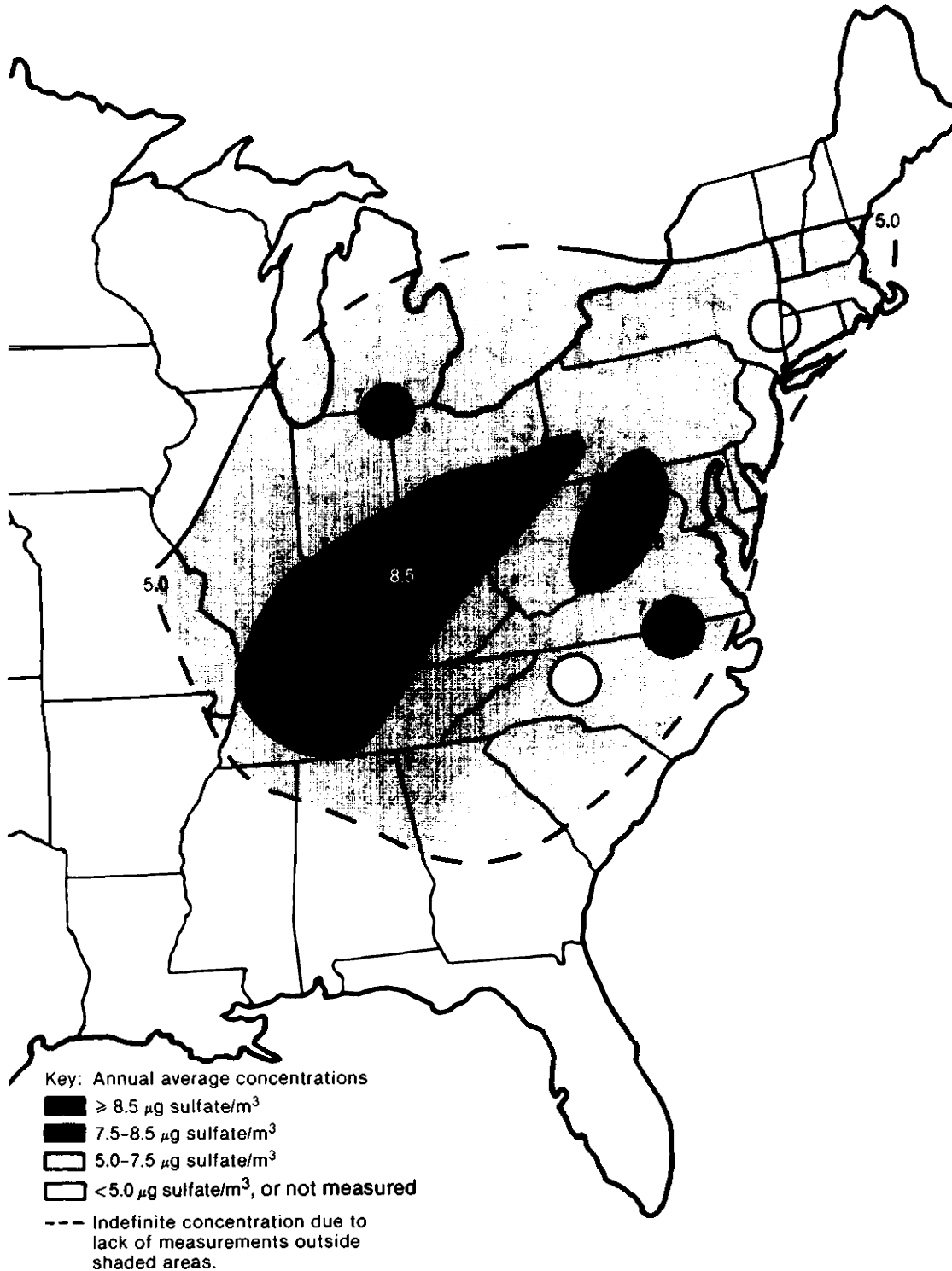
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|--|--------------------------|
| | > 80 meq/m ² |
| | 60-80 meq/m ² |
| | 40-60 meq/m ² |
| | 20-40 meq/m ² |
| | < 20 meq/m ² |

1 milliequivalent/meter² = 0.48 kilograms/hectare

SOURCE: *Impact Assessment*, Work Group 1, United States-Canada Memorandum of Intent on Transboundary Air Pollution, final report, January 1983.

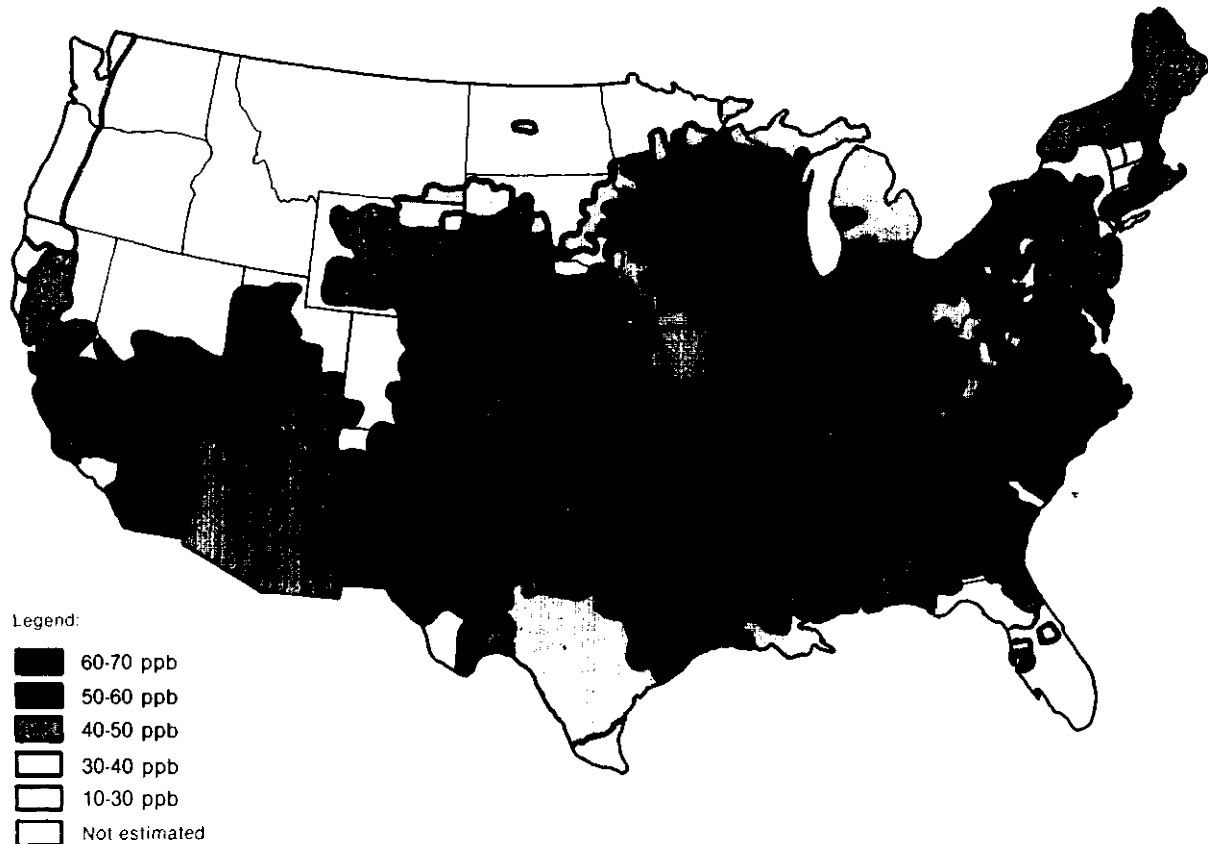
Figure 17.—Airborne Sulfate—Annual Average Concentration for 1977-78 (micrograms/meter³)



NOTE: Contours are based on data collected during selected months to represent seasonal averages between August 1977 and June 1978 at SURE II stations.

SOURCE: B. L. Neimann, "Data Bases for Regional Air Pollution Modeling," presented at the EPA Regional Air Pollution Modeling Workshop, Port Deposit, Md., October 1979.

Figure 18.—Ozone Concentration—Daytime, Growing Season Average for 1978
(parts per billion, June to September daily 7-hr average)



SOURCE: J. Reagan, personal communication, Environmental Protection Agency, 1983.

posited 'wet' (i.e., by removal from the air during periodic precipitation events) and 'dry' (by the slow, continuous removal of gaseous and particulate sulfur oxides).

As distance from the emission source increases, the relative amount of sulfur deposited in each of these forms changes. Dry deposition predominates close to the emission source; wet deposition predominates in distant areas. Most scientists estimate that these two processes deposit about *equal* amounts of sulfur when *averaged annually over the Eastern United States*. Both wet and dry deposition contribute to the *total* acidity received by ecosystems.

Computer models of pollution transport attempt to describe this process mathematically. Transport models are currently the only practical procedure

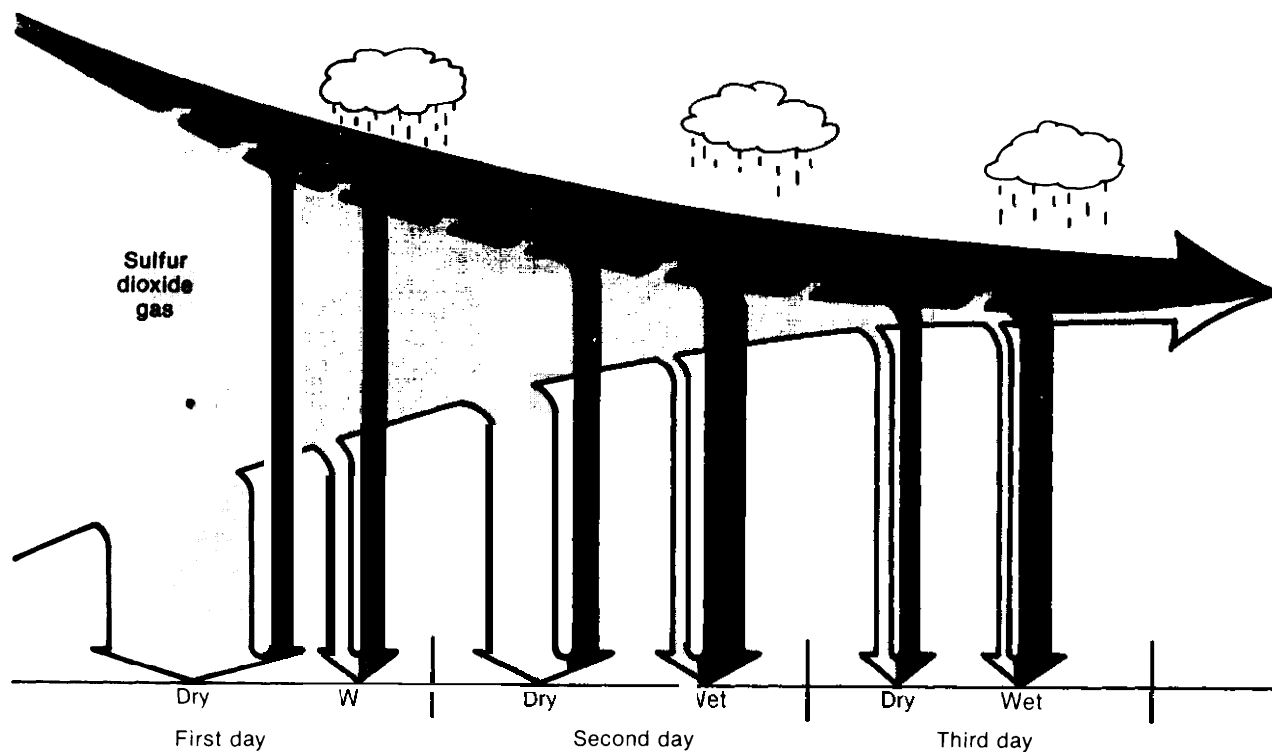
available to estimate the relationship between areas of origin and areas of deposition. * Transport models for sulfur oxides have been available for several years, though their accuracy is still a subject of scientific debate. Appendix C discusses the strengths and weaknesses of these models. Preliminary models of nitrogen oxides transport are just now being developed.

The model results are best used to estimate one region's *relative* contribution to deposition in another, rather than for projecting the magnitude of deposition quantitatively. The discussion that fol-

*Newly developed tracer techniques may provide additional information on pollution transport. The U.S. and Canadian Governments are jointly conducting the "cross-Appalachian tracer experiment" (CAPTEX), using a chemical called perfluorocarbon to trace the flow of acidic pollutants from sources in Ohio and Ontario.

Figure 19.—The Effects of Time and Distance on Conversion and Deposition of Sulfur Pollution

Sulfur can be deposited in both its emitted form, sulfur dioxide (lighter shading), and as sulfate (darker shading), after being chemically transformed in the atmosphere. Both compounds can be deposited in either dry or wet form. The relative amount of sulfur deposited in these forms varies with distance from emission sources. Dry deposition predominates in areas close to emission sources. Wet deposition is responsible for a larger percentage of pollutant load in areas distant from source regions.



SOURCE Office of Technology Assessment

lows characterizes current patterns of sulfur oxide transport, but should not be considered a quantitative description.

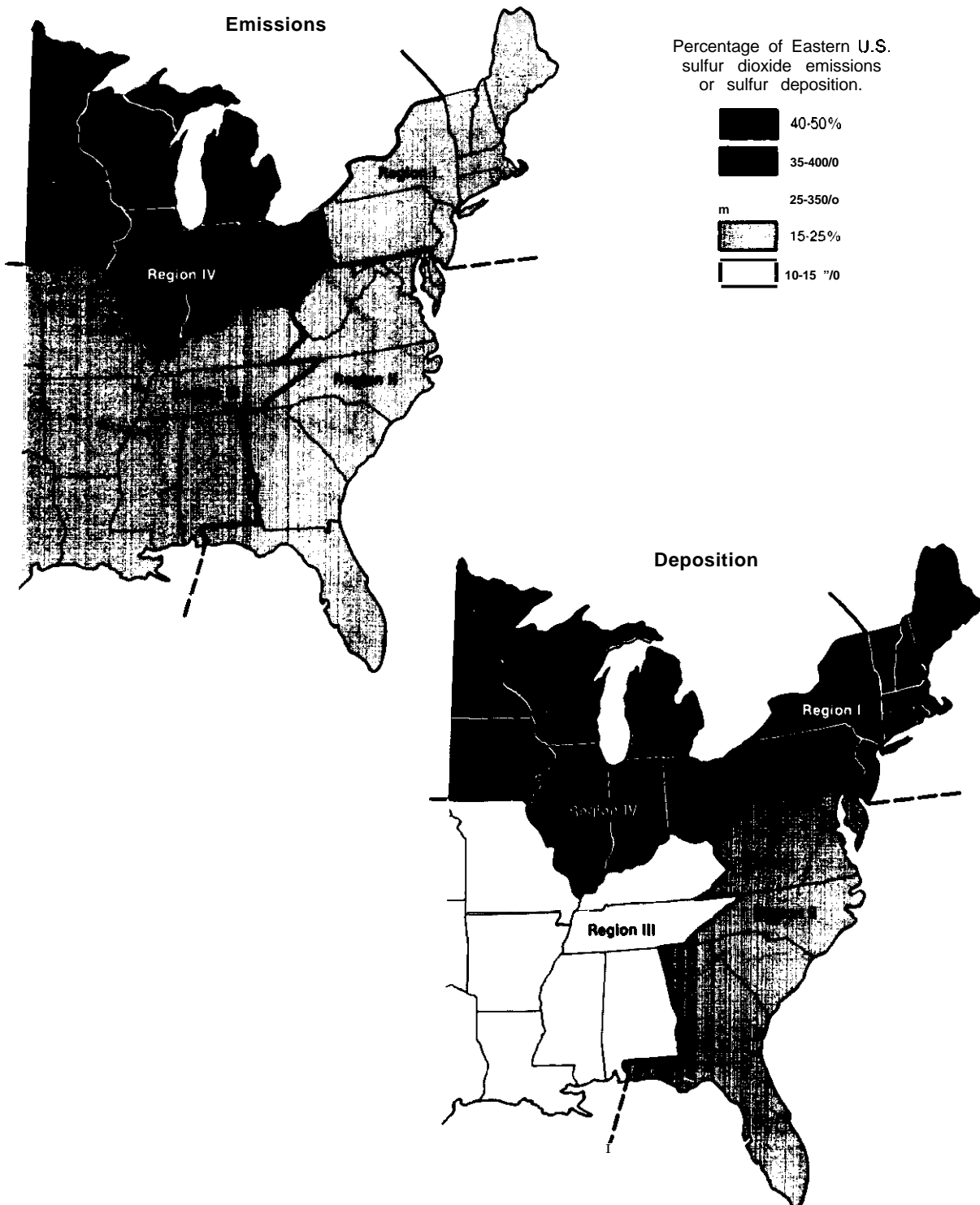
The results of transport models suggest that pollutants travel from one region to another, in all directions, with greater movements of pollutants from west to east and from south to north than in other directions. In addition, while pollutants can travel long distances, emissions *within* a region contribute a large share to total deposition in that region.

To illustrate these points, Eastern North America can be divided into four regions as shown in figure 20. These regions were chosen to intersect at the area of peak wet sulfur deposition in 1980, to minimize deposition biases for any one region. Figure

20 also displays the percentage of sulfur dioxide emitted in each region, and model-based estimates of the percentage of *total* (wet plus dry) sulfur deposited. Sulfur dioxide emissions are roughly comparable in the northeastern region (I), southeastern region (II), and southwestern region (III). Emissions in the northwestern region (IV) are over twice the amount of any of the other regions. Total sulfur *deposition* is lowest in the southern regions (II and III) and highest in the northern regions (I and IV).

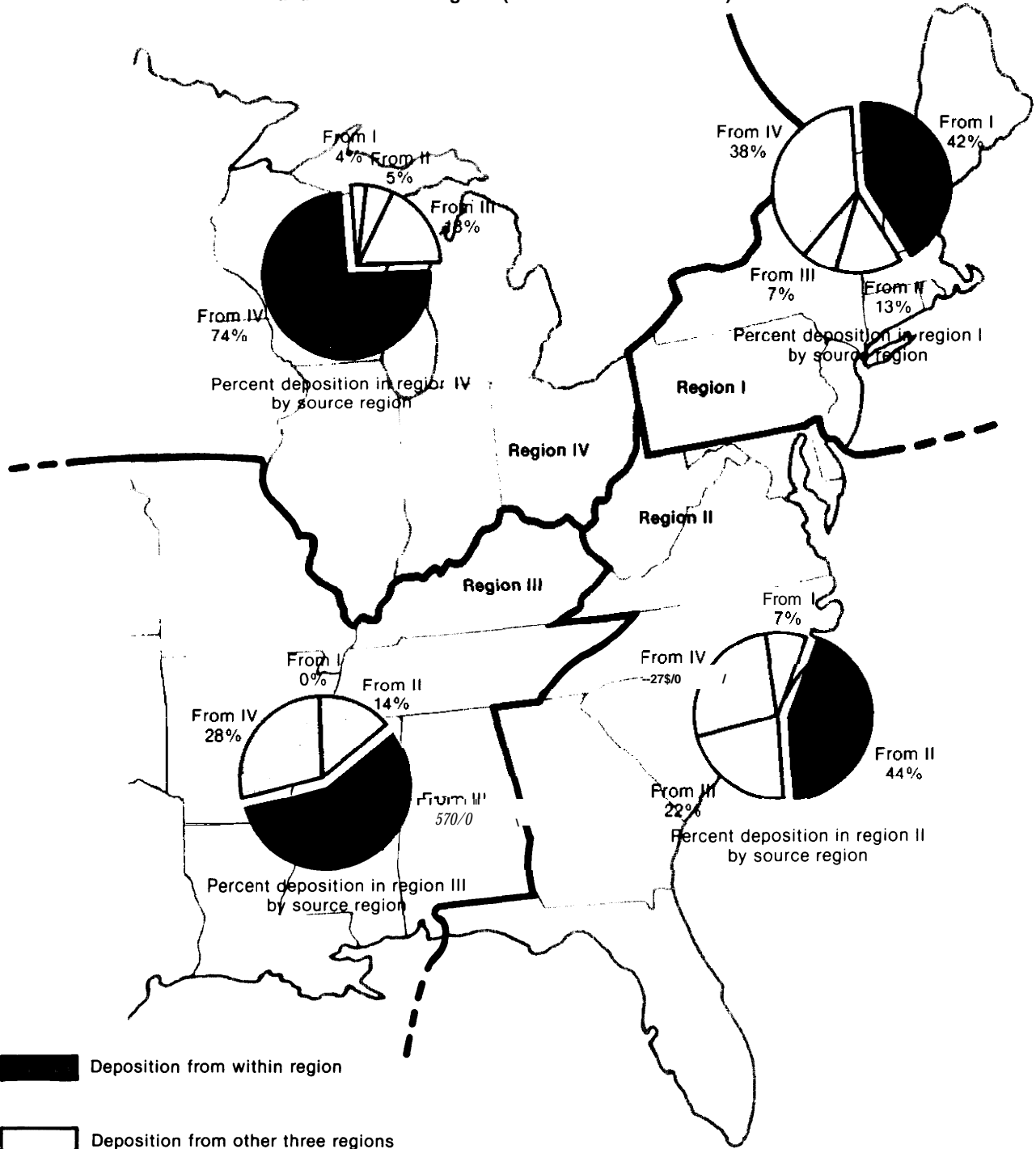
Figure 21 presents model-based estimates of how much deposition in each region originates from *within* its borders, and from each of the other regions. For example, the pie chart in the upper right shows that, of the total sulfur deposited in

Figure 20.—1979 Sulfur Dioxide Emissions and Estimated Sulfur Deposition—Percent Contributed and Received in Four Subregions Covering the Eastern Half of the United States



SOURCE: J. Shannon, personal communication, Argonne National Laboratory and E. H. Pechan & Associates, Inc., 1982.

Figure 21.—Percent of Sulfur Deposition Estimated To Originate From Within Each Region and From Other Regions (winter and summer 1979)



SOURCE: J. Shannon, personal communication, Argonne National Laboratory and E. H. Pechan & Associates, Inc., 1982.

region I (northeastern), approximately 40 percent originates within its own borders, about 40 percent comes from region IV (northwestern), and about 20 percent from the other two regions combined.

When regions as large as these are analyzed, each contributes as much or more to its own deposition as any other single region contributes to it. However, because all regions contribute to deposition in all other regions, a large percentage of deposition in any given region (in some cases over 50 percent) comes from outside. The greatest amounts of interregional transport follow the direction of prevailing winds—generally west to east and south to north.

While the analysis above indicates the magnitude and direction of interregional transport, it does not show the average distances sulfur pollutants can travel. Figure 22 displays model-based estimates of the *percentage of deposition due to long-distance transport*, arbitrarily defined as greater than 500 km (300 miles). A 500-km radius circle is shown to illustrate the scale of transport being discussed. Because wet deposition predominates in remote areas and dry deposition predominates close to emission sources, the two processes are illustrated separately.

In general, long-distance transport accounts for a greater percentage of wet deposition than of dry deposition. Throughout the Midwest and Central Atlantic States, about 30 to 50 percent of the wet deposition originates from emissions greater than 500 km away, as compared to 10 to 30 percent for dry deposition. Throughout New York and New England, long-distance pollutant transport contributes 50 to 80 percent of the wet deposition and 30 to 60 percent of the dry deposition. Over much of the South, most of the deposition originates from sources within 500 km—about 10 to 30 percent of both wet and dry deposition is due to long-distance transport.

These results are model-based simulations of the 1980 summer season. The percentages will vary for other seasons and years, but the broad patterns should be similar.

The accuracy of pollution transport models, which use detailed emissions data and sophisticated meteorology, is a subject of scientific debate.

Measured levels of wet sulfur deposition for 1980 agree fairly closely with OTA's model-based calculations, averaging over large regions on an annual basis. Dry deposition is not monitored routinely enough to compare with model estimates. The model does not include nitrogen oxides, the other major contributor to acid deposition, nor does it portray the complex chemistry involving other atmospheric pollutants.

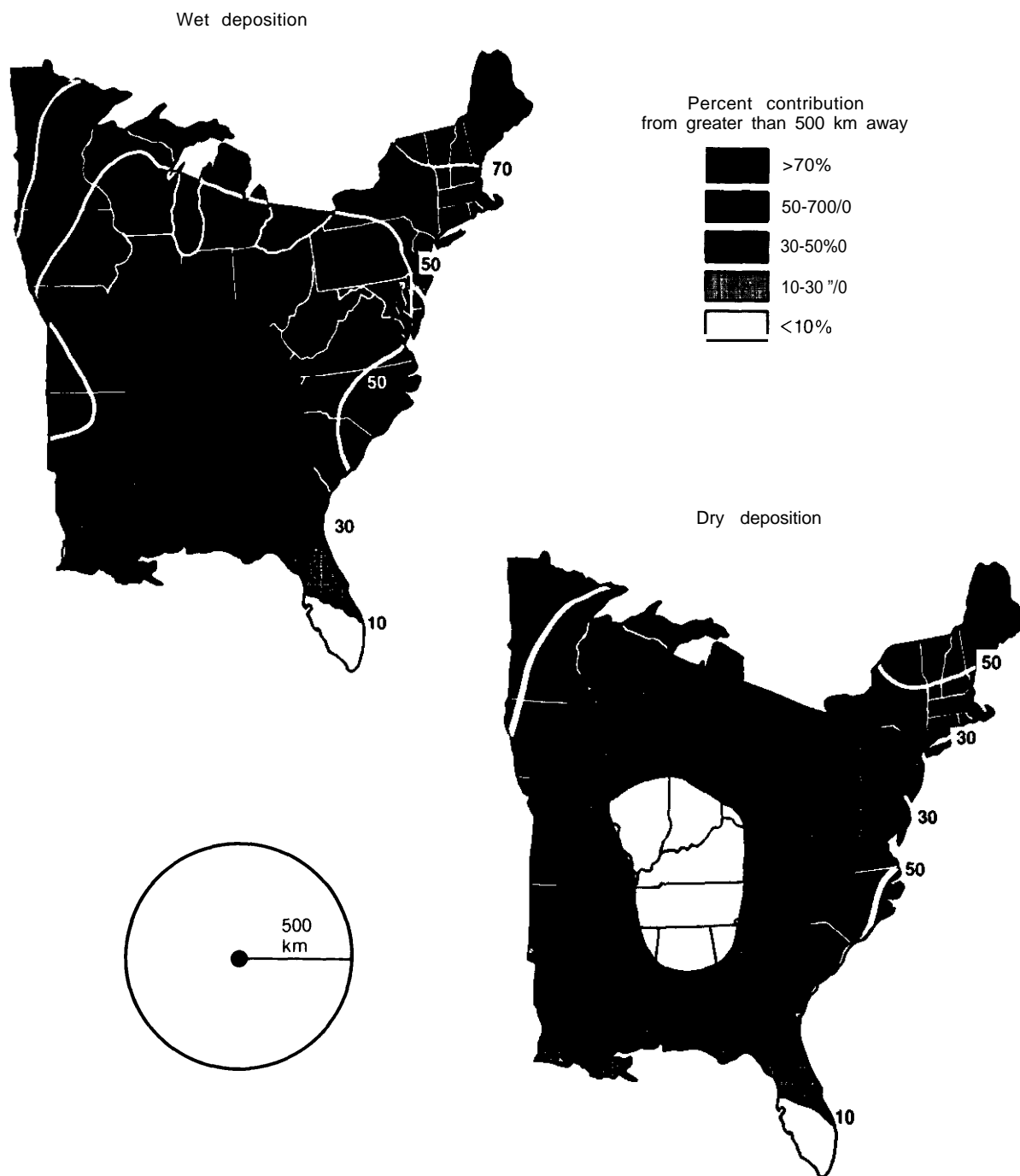
The chemical reactions that produce acid deposition involve a mix of pollutants present in gas form, dissolved in liquids (e. g., in clouds), and adhering to particles. Sulfur dioxide, nitrogen oxides, and hydrocarbons undergo transformations that may follow many complex chemical pathways. The sequence actually followed depends on concentrations of other chemicals that may inhibit, compete with, or enhance production and deposition of acidity. The same chemicals that transform or 'oxidize' sulfur dioxide and nitrogen oxides to acid are also essential for forming ozone. In addition, the physical characteristics of the atmosphere—windspeed, sunlight intensity, and rainfall frequency—affect these transformations.

Predicting quantities of deposition at a *specific* time and place is not yet possible, and may not be for many years. Making such predictions would require detailed information on the current concentrations of sulfur dioxide, nitrogen oxides, and hydrocarbons, as well as on the history of the air mass, including the frequency and amounts of fresh pollutant inputs, the frequency and duration of recent rainfall events, and other specific chemical and physical information.

However, current understanding of the various chemical and physical processes involved permits scientists to characterize very generally over large spatial scales, and seasonal time scales—the effects of reducing emitted quantities of various pollutants. The deposition changes that would result from reducing emissions of sulfur dioxide, nitrogen oxides, and hydrocarbons are discussed in appendix C, and are summarized briefly below:

- Reducing sulfur dioxide emissions will reduce the total amount of acid formed in the atmosphere, *if* levels of nitrogen oxides and hydrocarbons remain constant, and chemical reactions are not limited by a shortage of ox-

Figure 22.—Estimated Percentage of Sulfur Deposition From Emissions Over 500 km (300 miles) Away (summer 1980)



idizing agents. Furthermore, given these conditions, a decrease in sulfur dioxide emissions should decrease total sulfur deposition by an approximately equal proportion. *Where* deposition will decrease can only be estimated on a regional scale.

- Decreasing nitrogen oxides emissions—while holding hydrocarbon emissions constant—would decrease the amount of ozone produced over a large region, as well as the amount of nitric acid ultimately deposited. The total amount of sulfur deposited would probably not be affected, although the conversion of sulfur dioxide to sulfate might accelerate somewhat, affecting the regional distribution of deposition.
- Reducing hydrocarbon emissions can decrease the production of ozone, and of some key chemicals responsible for transforming sulfur dioxide and nitrogen oxides to acids. This would slow the production of sulfuric and nitric acids, again altering the patterns of deposition, but probably would not affect total *amounts* of deposition.

If current regulations remain unchanged, sulfur dioxide emissions are projected to remain about constant or increase slightly, hydrocarbon emissions to remain about constant, and nitrogen oxides emissions to increase. Local acid deposition due to nitric acid would probably increase. The amount of total sulfur deposited might remain about constant, but reactions involving increased nitrogen oxides emissions might cause the geographic patterns of sulfur deposition to change.

Given the complexities of atmospheric chemistry, and inherent meteorological variability, as well as the need to develop detailed emissions inventories (especially for nitrogen oxides and hydrocarbons), it is unlikely that a definitive model linking particular sources to specific receptors will be developed in the next decade. Policy decisions to control or not to control precursor emissions will have to be made without the benefit of such precise information.