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# Acid Rain

*In recent decades the acidity of rain and snow has increased sharply over wide areas. The principal cause is the release of sulfur and nitrogen oxides by the burning of fossil fuels*

by Gene E. Likens, Richard F. Wright, James N. Galloway and Thomas J. Butler

Measurements of the acidity of rain and snow reveal that in parts of the eastern U.S. and of western Europe precipitation has changed from a nearly neutral solution 200 years ago to a dilute solution of sulfuric and nitric acids today. In the most extreme example yet recorded—a storm in Scotland in 1974—the rain was the acidic equivalent of vinegar ( $\text{pH}$  2.4). The main reason for this trend is the rise in the emission of sulfur and nitrogen oxides to the atmosphere accompanying the rise in the burning of fossil fuels. Partly because acid precipitation has a variety of harmful effects on plant and animal life, efforts have been made to curb the emission of such oxides. Notwithstanding these efforts the level of emissions is expected to rise further under the present policy of turning increasingly to coal as a source of energy. At the very least the prospect suggests that a more substantial effort should be made to determine more precisely the effects of acid precipitation; it might also suggest a more vigorous exploration of ways to reduce the release of both sulfur and nitrogen oxides into the atmosphere.

Acidity in a solution such as rain is synonymous with the presence of hydrogen ions ( $\text{H}^+$ ). A common measure of acidity is  $\text{pH}$ , which is defined as the negative logarithm of the hydrogen-ion concentration. The  $\text{pH}$  scale ranges from 0 to 14, with a value of 7 representing a solution that is neutral, values below 7 indicating greater acidity and values above 7 indicating greater alkalinity. One should bear in mind that the  $\text{pH}$  scale is logarithmic, so that solutions of  $\text{pH}$  6, 5 and 4 contain respectively one, 10 and 100 microequivalents of acidity ( $\text{H}^+$ ) per liter (abbreviated  $\mu\text{eq/l}$ ).

What determines the chemistry of

rain and snow? The water comes from evaporation and transpiration (water vapor lost by plants) and is essentially distilled, or pure. Once the vapor reaches the atmosphere, however, it condenses on solid particles and soon reaches equilibrium with atmospheric gases. One of the gases is carbon dioxide ( $\text{CO}_2$ ), and as carbon dioxide dissolves in the water carbonic acid ( $\text{H}_2\text{CO}_3$ ) forms. Carbonic acid, being a weak acid, dissociates only slightly in distilled water, yielding hydrogen ions and bicarbonate ions ( $\text{HCO}_3^-$ ). At normal concentrations and pressures of carbon dioxide in the atmosphere the  $\text{pH}$  of rain and snow would be 5.6.

Other substances reaching the atmosphere tend to shift the  $\text{pH}$  one way or the other. For example, small amounts of dust and debris are swept from the ground into the atmosphere by the wind. Soil particles are usually slightly basic, or alkaline, in distilled water and release into solution base cations (positive ions) such as calcium, magnesium, potassium and sodium ( $\text{Ca}^{++}$ ,  $\text{Mg}^{++}$ ,  $\text{K}^+$  and  $\text{Na}^+$ ), with bicarbonate usually the corresponding anion, or negative ion. Ammonia gas in the atmosphere originates largely from the decay of organic matter. The ammonium ion ( $\text{NH}_4^+$ ) in rain and snow tends to increase the  $\text{pH}$ . In coastal areas sea spray may contribute significantly to the chemistry of precipitation. Here the important ions added are the ones most abundant in seawater, namely the cations  $\text{Na}^+$  and  $\text{Mg}^{++}$  (sodium and magnesium), the anion  $\text{Cl}^-$  (chloride) and to a lesser extent cations of calcium and potassium ( $\text{Ca}^{++}$ ,  $\text{K}^+$ ) and anions of sulfate ( $\text{SO}_4^{--}$ ).

Gases such as sulfur dioxide ( $\text{SO}_2$ ) and hydrogen sulfide ( $\text{H}_2\text{S}$ ), which come from volcanoes and from other natural sources, can also alter the chemistry of

precipitation locally. Sulfur dioxide and hydrogen sulfide are oxidized and hydrolyzed in the atmosphere to sulfuric acid. Nitrogen oxides are similarly converted into nitric acid. If these acids are present in significant quantities, they can acidify precipitation to below  $\text{pH}$  5.6.

The chemistry of natural precipitation, then, depends on the relative amounts of these various substances in the atmosphere. The precipitation in coastal areas can be generally characterized as very dilute seawater if winds are toward the shore. In areas with high winds and sparse vegetation, such as deserts, the precipitation may contain relatively large amounts of base cations. Precipitation in regions with calcareous soils often contains calcium and bicarbonate, presumably as a result of the incorporation of dust, and the  $\text{pH}$  of rain and snow is usually well above 6.

The  $\text{pH}$  of precipitation that fell before the Industrial Revolution and has been preserved in glaciers and continental ice sheets is generally found to be above 5. Swiss workers in Greenland recently measured the  $\text{pH}$  of ice that had originated as snow some 180 years ago; it had a  $\text{pH}$  ranging from 6 to 7.6.

Human activities have significantly changed this picture on a continental scale and perhaps a global one. Large quantities of sulfur and nitrogen oxides are emitted into the atmosphere by the combustion of fossil fuels and the smelting of sulfide ores, particularly in the heavily industrialized and urbanized North Temperate Zone. These oxides are converted into strong acids (sulfuric and nitric) in the atmosphere and fall to the ground in rain and snow. Strong acids dissociate completely in dilute aqueous solutions and lower the  $\text{pH}$  to less than 5.6. The definition of acid precipi-

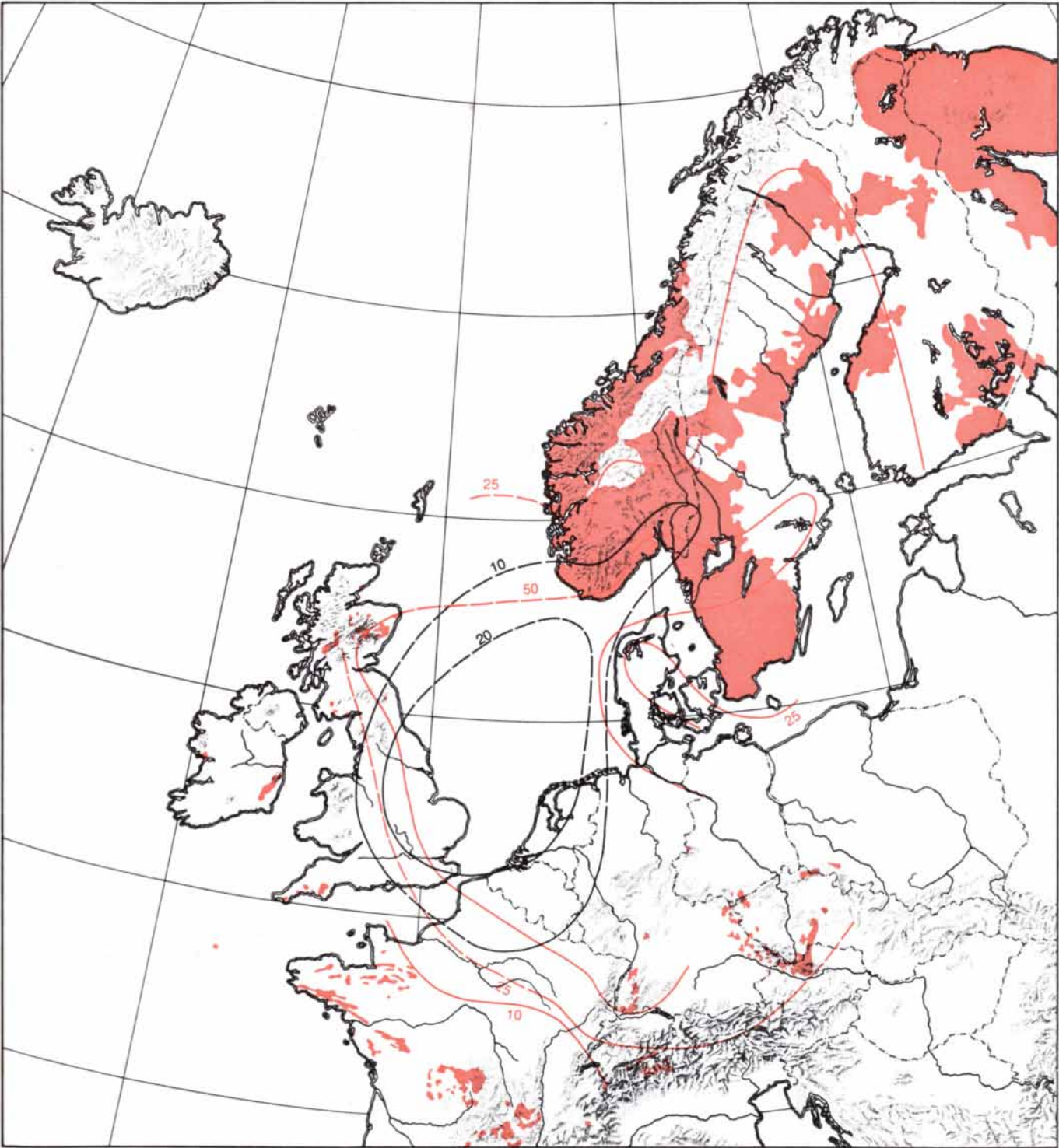
tation is rain and snow at a pH below that value.

An irony in this matter is that the trend toward building taller stacks to relieve local pollution problems has turned the local problems into regional ones. In 1955 only two stacks in the U.S.

were higher than about 180 meters; now essentially all stacks being built are taller than that. By 1975 at least 15 stacks taller than 300 meters had been built in the world. In the United Kingdom tall stacks were an integral part of measures employed to reduce the severity of smog

in London after episodes of life-threatening pollution in the 1950's.

The copper-nickel smelter in Sudbury, Ont., has a superstack more than 400 meters tall. Some 1 percent of the total annual emissions of sulfur throughout the world (from both natural sour-



**ACID PRECIPITATION** in northwestern Europe is compared for 1956 (black) and 1974 (color). Acidity (the concentration of hydrogen ions in rain and snow) is shown by the numbers on the curving isolines; the larger the number, the higher the concentration of acid. The two sets of isoline numbers are based on volume-weighted, average

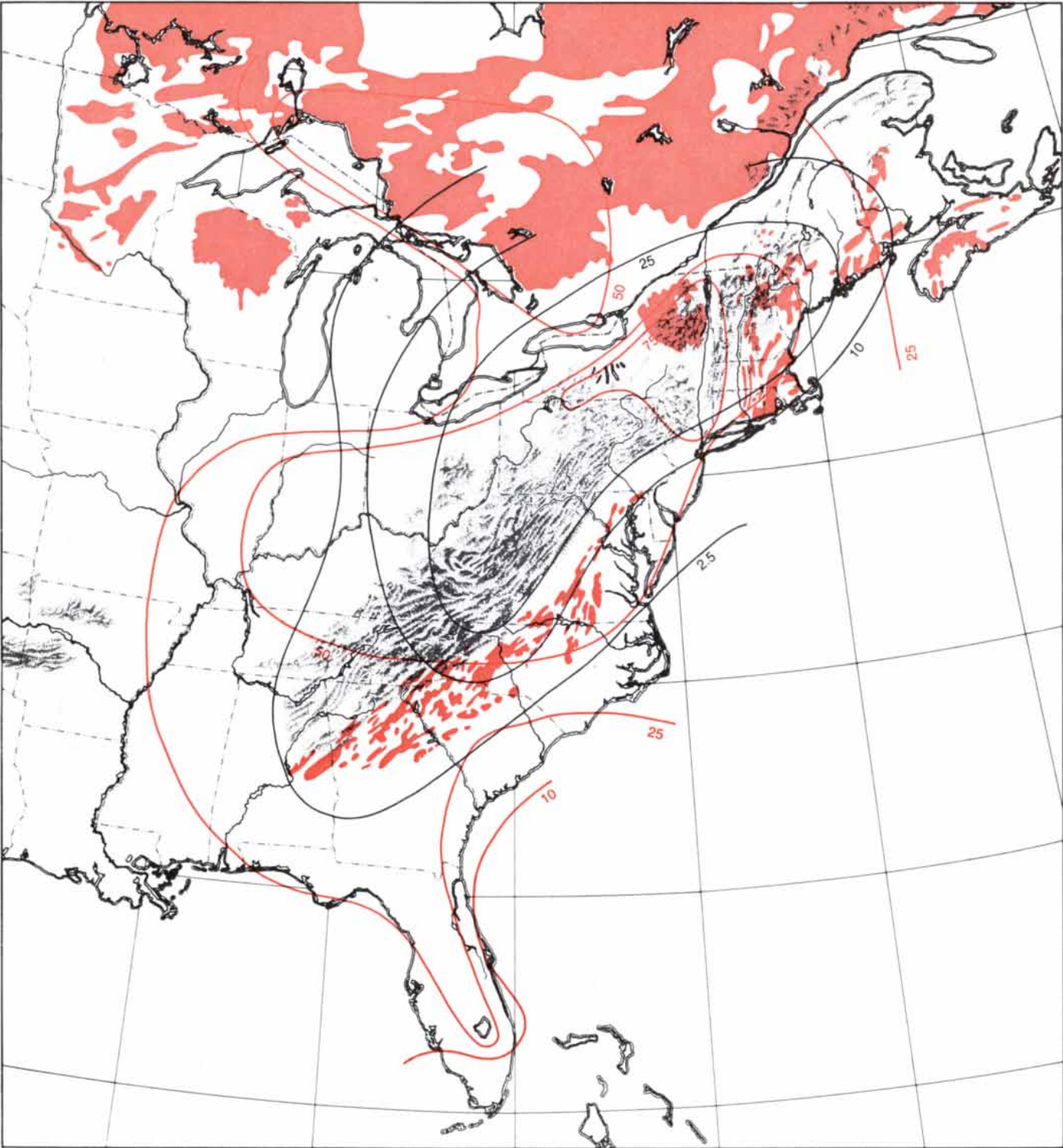
concentrations of hydrogen ions in terms of microequivalents per liter of precipitation. The colored areas of the map indicate areas that are more susceptible to acid rain and snow because of the geology of their bedrock. In general they are areas with highly siliceous types of bedrock, among them granite, quartzite and quartz sandstone.



ces and human activity) come from this one smelter complex. During the past decade the annual emissions of sulfur from Sudbury have about equaled the amount thought to have been emitted by all the volcanoes of the world. It is beyond argument that such pol-

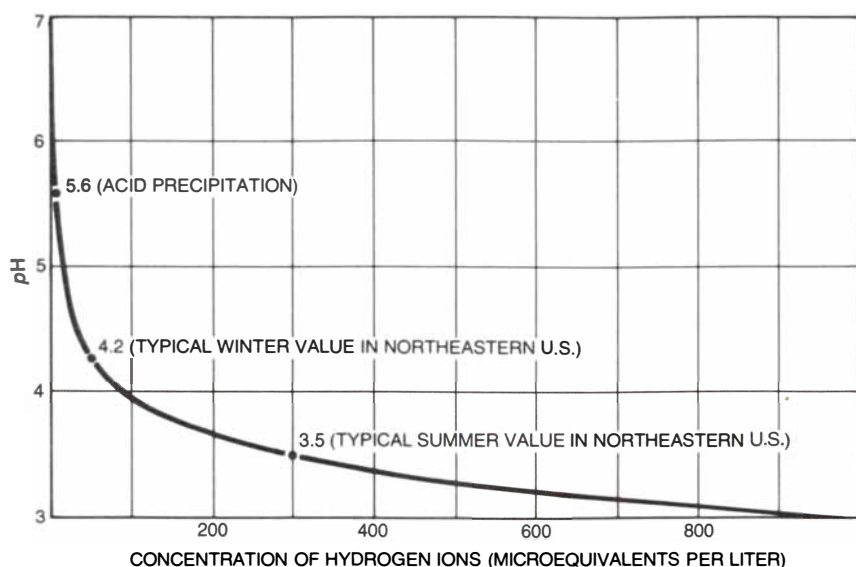
lutants are transported over long distances through the atmosphere. Studies of the deposition of sulfur, lead and other materials on the Greenland ice cap and in other remote places demonstrate such mechanisms of dispersal. What is a matter of sometimes heated discus-

sion, particularly when it is alleged that pollution is crossing a political boundary, is the proportion of pollutants that can be attributed to remote sources. On an annual basis rain and snow over large regions of the world are now from five to 30 times more acid than the low-

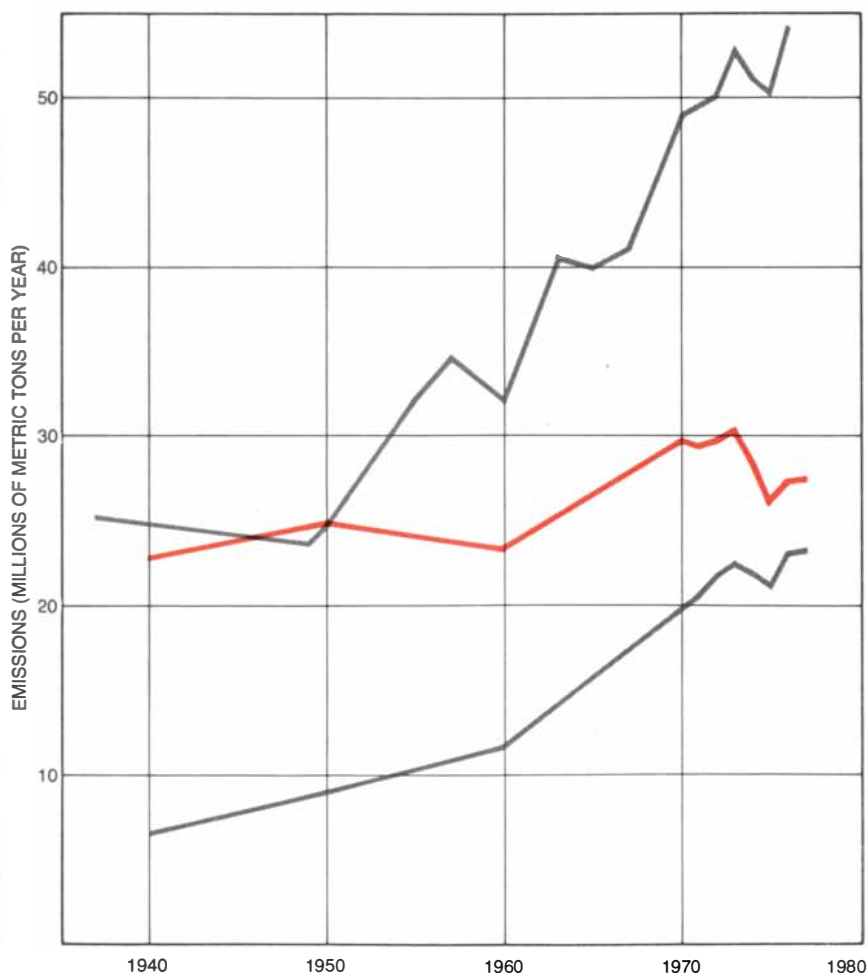


**SPREAD OF ACID RAIN** in eastern North America is depicted for 1955-56 (*black*) and 1975-76 (*color*) with data for the isolines based on the concentration of hydrogen ions in microequivalents per liter. The quality of the data for North America is variable and the sampling methods employed for the two periods represented on this

map were somewhat different, but the general pattern and trend are clear. Areas sensitive to acid rain and snow are also shown. Similar areas are found farther north in Canada and in the Rocky Mountains. They have a low ability to neutralize acids. Values higher than 2.5 microequivalents per liter (*pH* 5.6) are defined as acid precipitation.



**ACID CONCENTRATION** is measured by  $pH$ , which is the negative logarithm of the hydrogen-ion concentration, and more directly by the concentration of hydrogen ions expressed in microequivalents per liter. The relation between the two measures is depicted here for aqueous solutions. Since the  $pH$  scale is logarithmic,  $pH$  6 is 10 times and  $pH$  5 is 100 times more acidic than  $pH$  7. Ten times more hydrogen ions are required to shift from  $pH$  5 to 4 than from 6 to 5.



**RISE IN EMISSIONS** of sulfur and nitrogen oxides is charted. The curves reflect increases due to human activity, namely the burning of fossil fuels and the smelting of ores. From bottom to top the curves respectively trace the rise of nitrogen oxides in the U.S., sulfur dioxides in the U.S. and sulfur dioxides in Europe, excluding the U.S.S.R. Sulfur and nitrogen may be converted into strong acids in precipitation. The increase of acids parallels the rise in emissions.

est value expected ( $pH$  5.6) for unpolluted atmospheres. The rain of individual storms can be from several hundred to several thousand times more acid than expected. Concern over the environmental effects of acid precipitation has led to major research efforts in Sweden, Norway, the U.S. and Canada.

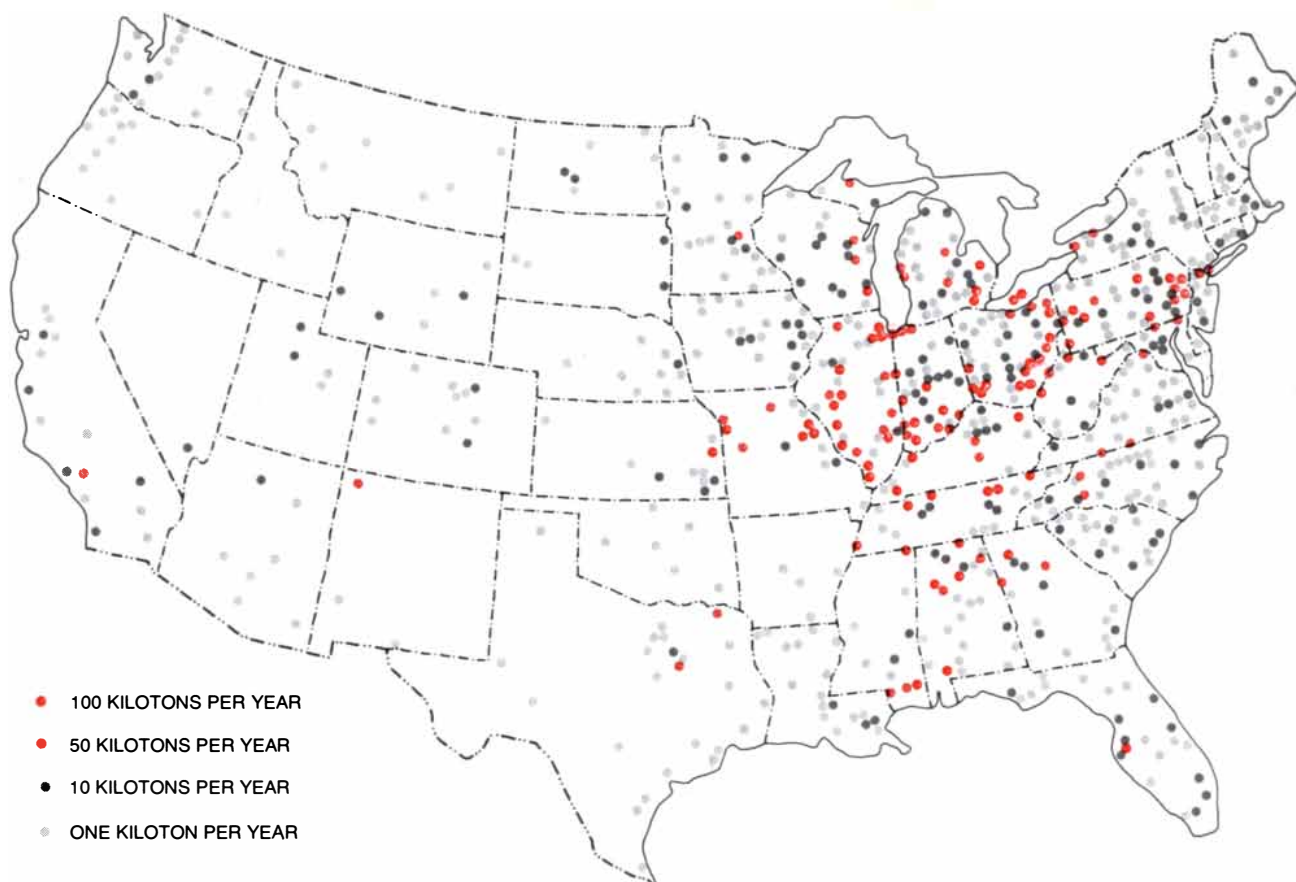
Acid precipitation has been known for many decades in the vicinity of large cities and industrial plants such as smelters, but the phenomenon is now much more widespread. In large areas of the eastern U.S., southeastern Canada and western Europe the annual average  $pH$  of precipitation ranges from about 4 to 4.5. Since the data are fuller for Europe than for North America, we shall discuss Europe first.

The discovery that precipitation in large regions of Europe had become decidedly acidic followed the establishment in the 1950's of the European Atmospheric Chemistry Network (also known as the IMI Network, for the International Meteorological Institute in Stockholm). At times the network encompassed up to 175 stations in northern and western Europe, from which monthly samples of bulk precipitation (a method of collecting with sampling apparatus that is always open) were analyzed for the concentration of 11 major ions. Although many of the stations are no longer in operation, the data provide a record for the  $pH$  of precipitation on a regional scale in Europe more than 20 years ago.

In 1968 Svante Odén of Sweden pointed out that precipitation in Europe had clearly become more acidic since the network was established. Maps of volume-weighted mean annual  $pH$  in precipitation showed that a central region of high acidity ( $pH$  4 to 4.5) had spread from the area of Belgium, the Netherlands and Luxembourg in the late 1950's to most of Germany, northern France, the eastern British Isles and southern Scandinavia by the late 1960's.

The Organization for Economic Cooperation and Development (OECD) recently concluded a three-year study that gives a more detailed picture of the present acidity of precipitation in Europe. The results of the study appear in *Long-Range Transport of Air Pollutants, Measurements and Findings*, a summary of the daily sampling done at 67 stations from 1973 to 1975 as part of the OECD project. The resulting map shows that acid precipitation has continued to spread and today encompasses nearly all of northwestern Europe. (The situation in eastern Europe is unclear for lack of long-term data; clarification may be at hand from data from a new network for precipitation chemistry initiated by the United Nations' Economic Commission for Europe.)

The lowest  $pH$  value reported for an individual storm in Europe up to now is



**PATTERN OF EMISSIONS of sulfur dioxide in the U.S. in 1975 is plotted on the basis of data obtained by Brookhaven National Labo-**

**ratory. The plots indicate the areas where emissions are concentrated because of the activity of generating stations and industrial plants.**

2.4 on April 10, 1974, at Pitlochry, Scotland. In the same month values of 2.7 and 3.5 were reported respectively on the west coast of Norway and at a remote station in Iceland. The lowest annual  $pH$  yet recorded is 3.78 in 1967 at De Bilt in the Netherlands.

At some stations the increase in the annual concentration of hydrogen ions in precipitation since 1955–56 has been about tenfold. This increase in acidity is matched by increases in the concentrations of sulfate and nitrate over the past 20 years. In northern Europe the excess sulfate concentration (in excess of contributions of sea salt) rose markedly from 1955 to about 1963 and has remained virtually constant since then; overall the rise from 1955 to 1975 was about 2 percent per year. The concentration of nitrate in precipitation has increased quite steadily since 1955 at the rate of about 4 percent per year. Both increases parallel rises in the emission of sulfur and nitrogen oxides from the combustion of fossil fuels.

Emissions of sulfur dioxide in Europe were estimated at about 25 million metric tons of sulfur in 1973. A map showing the regional sources was prepared as part of the OECD study; it revealed regions with particularly high emissions in

central Britain, the Ruhr area of West Germany, the coal areas of southern East Germany, southern Poland and Czechoslovakia. It is estimated that human activity accounts for about 90 percent of the sulfur emissions.

It is also estimated that the annual anthropogenic emissions of nitrogen oxides from the 11 OECD countries of Europe totaled about two million metric tons of nitrogen in 1973. The OECD study indicated that these emissions almost doubled from 1959 to 1973. A similar trend might be expected for eastern Europe. In addition biological processes supply oxides of nitrogen to the atmosphere, but the magnitude and significance of these emissions are not known.

The general pattern of the deposition of acid in European rain and snow reflects the long-range transport of air pollutants from the sources of emission. The  $pH$  of precipitation is generally lowest near the sources and increases with distance. The normal flow of air from southwest to northeast results in an asymmetrical pattern, with acid precipitation reaching far up into northern Scandinavia. Swedish investigators have calculated that more than 70 percent of the sulfur in the atmosphere over southern Sweden is from human activity, and 77 percent of it is believed to

originate from sources outside Sweden.

The gradient of acidity is accentuated in mountainous areas that are generally downwind of urban and industrial sources. Mountains enhance precipitation, which continuously removes pollutants from passing masses of air. This situation is found in southernmost Norway, where air masses from the major source areas in the British Isles and central Europe travel many hundreds of kilometers over the North Sea and over land areas of relatively low relief before most of the pollutants are removed in the precipitation over a belt from 100 to 200 kilometers wide along the mountainous Norwegian coast. By the time the air masses have passed over mountainous areas with an elevation of 1,000 meters or so the  $pH$  of the precipitation has changed from an average of 4.2 at the coast to 4.6 or 4.7, representing a decrease in the concentration of hydrogen ions from about 60 microequivalents per liter to about 20.

Since mountains enhance precipitation, their windward flanks receive large amounts of acid. Data from the OECD project show that the annual deposition of acid in rain and snow in 1974 was highest along the mountain slopes of southernmost Norway, southern Germany and Switzerland. Values ranging



from 88 milliequivalents per square meter per year to 120 were observed in those areas.

Dry deposition of sulfur dioxide gas and particulate sulfate also represents the deposition of an equivalent amount of hydrogen ions. Data from the OECD study show maximum values of dry deposition of 10 grams of sulfur per square meter per year in central Europe, or four times the deposition rate by rain and snow, with rates decreasing rapidly with increasing distance from the emission sources to values of about .1 gram in northern Scandinavia. Wet deposition of sulfate in rain and snow begins at three grams of sulfur per square meter per year near the major sources and decreases less rapidly to .5 gram in northern Scandinavia. Dry deposition of sulfur is therefore the dominant mode near the emission sources, whereas wet deposition dominates in remote areas of northern Europe.

The record of changes in precipitation chemistry over North America is much less clear. No monitoring network has been maintained from the 1950's to the present. Even today the monitoring that is done is not sufficient to give a detailed picture.

It is known that before about 1930 relatively large amounts of bicarbonate were found in samples of precipitation

in Virginia, Tennessee and New York. Although no determinations of pH were made, the presence of bicarbonate in the samples shows that they could not have had a pH of less than 5.6. The earliest measurement of precipitation pH in the U.S. that we know of was made during a rainstorm in Maine in 1939 by Henry G. Houghton of the Massachusetts Institute of Technology. He obtained a value of 5.9.

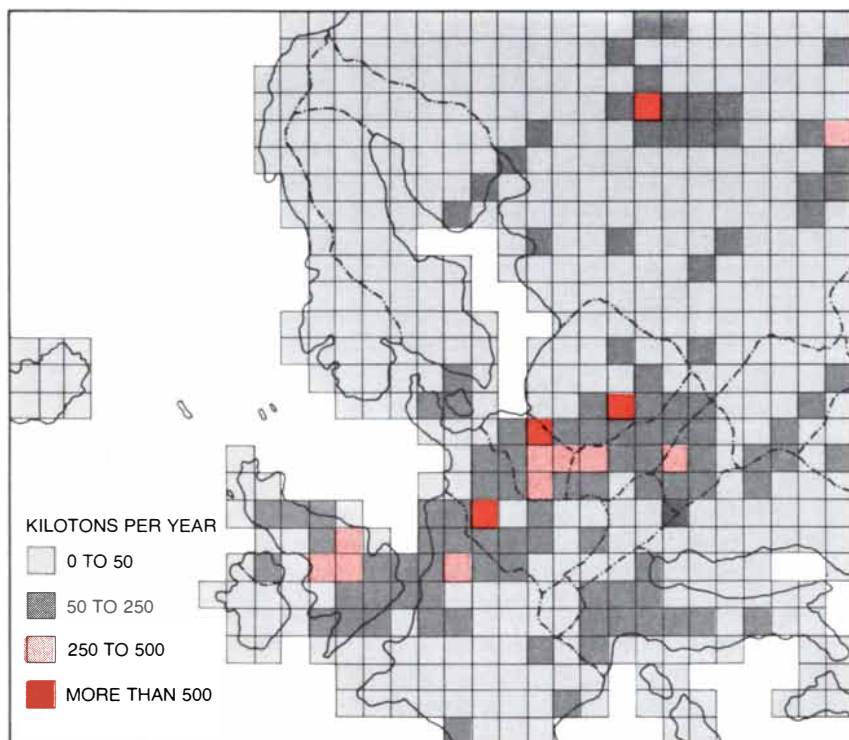
If accurate chemical data are available and the hydrogen-ion concentration is more than about three micro-equivalents per liter, reliable pH values can be calculated from a detailed chemical analysis of dilute aqueous solutions. Such chemical data were collected for precipitation at 24 sites in the eastern U.S. in 1955-56 by C. E. Junge of the Air Force Cambridge Research Laboratory. The data have been employed to calculate the pH distribution at the time. Although the density of sampling points was low, the general pattern is quite clear: a large area of the northeastern U.S. was receiving acid precipitation by 1955.

From 1959 through 1966 the U.S. Public Health Service and then the National Center for Atmospheric Research operated a sampling network for precipitation chemistry throughout the 48 contiguous states of the U.S. During the latter part of the period (1964-66) some

30 stations, 17 of them east of the Mississippi, collected monthly samples of rain and snow with automatic samplers that were open only during precipitation. The majority of the stations west of the Mississippi consistently showed monthly pH values above 5.6; most commonly the values were above 6.5. East of the Mississippi the precipitation was much more acidic. Notwithstanding the paucity of the data from this now discontinued network, the general pattern was quite obvious: areas of acid precipitation were widespread in the eastern U.S., with the most acidic rain and snow falling on New England, New York and Pennsylvania.

Even today there is no high-density, synoptic coverage of the chemistry of precipitation in North America. The situation may soon improve, however, because both the U.S. and Canada have started long-term programs for measuring the composition of atmospheric deposition. The Canadian Network for Sampling Precipitation (CANSAP) began operating in 1976 and the U.S. National Atmospheric Deposition Program (NADP) was initiated in 1978.

In an effort to obtain synoptic data on the current pH of precipitation in the eastern U.S. we personally communicated with all the individuals, groups and state and Federal agencies we knew to be studying precipitation chemistry. Although the density of sampling points is still low (46 stations east of the Mississippi, 19 more in Canada), it is much higher than it was in 1955-56 or 1964-66. The data reveal a southward and westward extension of the area receiving acid precipitation and an intensification of acidity in the Northeast and Southeast since 1955. (We wish to acknowledge in this context the contributions from Gerald M. Aubertin and J. Currier of data for West Virginia; Patrick L. Brezonik for Gainesville, Fla.; T. Burton for Tallahassee, Fla.; D. Charles for Ray Brook, N.Y.; K. G. Dickson for the Lake Okechobee area in Florida; M. J. Duever for Corkscrew Swamp in Florida; the Environmental Data and Information Service for Caribou, Me., Wake County and Macon County in North Carolina, Lauderdale County in Mississippi, Salem, Ill., and Atlantic County in New Jersey; Donald F. Gatz for Urbana, Ill.; Bruce L. Haines for Athens, Ga.; Evelyn B. Haines for Sapelo Island, Ga.; G. S. Henderson for Oak Ridge, Tenn.; Jay S. Jacobson for Yonkers, N.Y.; K. Kuntz for Ontario; J. G. McColl and David F. Grigal for Minnesota; J. M. Miller for Washington, D.C.; M. P. Olson for Ontario and Sable Island in Canada; Rosa de Pena for State College, Pa.; C. J. Richardson for Michigan; W. T. Swank for Asheville, N.C.; the U.S. Geological Survey for sites in the Northeast, and Herbert L. Vol-



**EMISSION PATTERN** of sulfur dioxide for Europe in 1973 is plotted in terms of thousands of tons of sulfur per year. The map is based not on particular "hot spots," as the companion map of the U.S. is, but on a grid that divides Europe into squares about 127 kilometers on a side.

chok for Argonne, Ill., New York, N.Y., Chester, N.J., and Woods Hole, Mass.)

It is worth noting that the most rapid increase in precipitation acidity over the past two decades has been in the Southeast. (The trend is more apparent than it is in the Northeast because a smaller amount of acid is required to cause a change of pH from, say, 6 to 5 than from 5 to 4.) In the same period the Southeast has had a large expansion of the urban and industrial activities that give rise to emissions of sulfur and nitrogen.

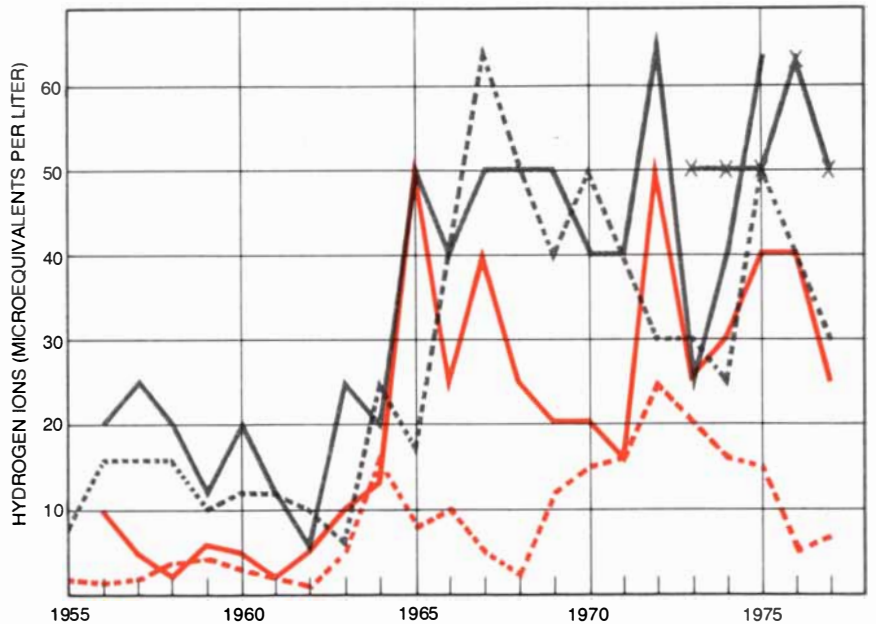
As in Europe, nitrate concentrations in precipitation have increased several-fold in the northeastern U.S. during the past decade or so. Although sulfuric acid is the dominant acid in acid precipitation, nitric acid appears to be contributing about 30 percent (and an increasing proportion) of the hydrogen ions in acid precipitation.

Measurements of the dry deposition of sulfur in the U.S. and Canada are highly scattered. A recent report by the National Academy of Sciences on sulfur oxides suggests that the dry deposition of sulfur is approximately equal to the wet deposition in the eastern U.S.

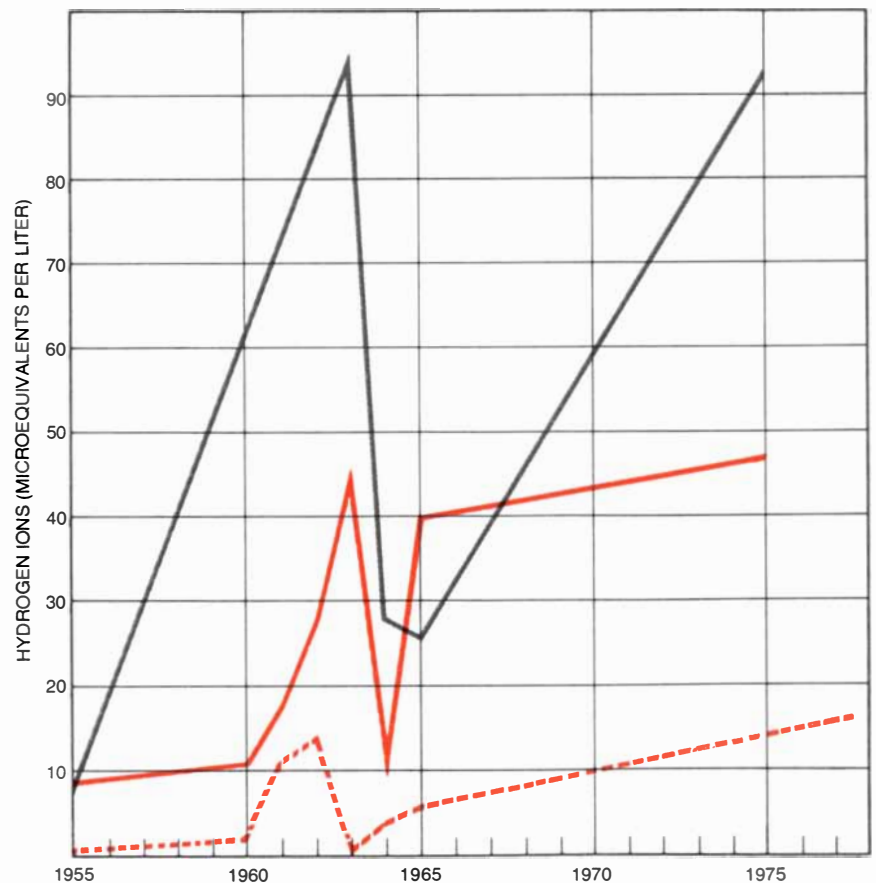
Since there are large sources of emissions in the middle-western U.S. and the general flow of air is from west to east, it is understandable that acid precipitation is a phenomenon of eastern North America. The phenomenon could become national, however, in view of the planned increases in the combustion of fossil fuels in the western regions of the continent.

What effect has the increased acidity had on the environment? The question has not been fully answered, but certain freshwater ecosystems seem to be particularly sensitive to inputs of acid. Such ecosystems are generally in areas underlain by highly siliceous types of bedrock such as granite, some gneisses, quartzite and quartz sandstone. These rock types are highly resistant to dissolution through weathering, with the result that surface waters in such areas contain very low concentrations of ions derived from weathering. Characteristically such soft waters have a low buffering capacity (a low ability to neutralize additions of acids or alkalis). Hence when acid precipitation falls on such an area, the acids are not fully neutralized in the terrestrial watershed or catchment, and so streams and lakes become acidified.

Bedrock geology therefore provides a rough indication of the location of such sensitive areas. Maps of the bedrock, however, do not take into account the mineralogy of overlying, unconsolidated deposits such as glacial till, glaciofluvial materials and marine sand, which may have been transported far from their source and may have a mineralogy



**ACIDITY OF RAIN AND SNOW** in recent years is charted for Lista in Norway (solid gray), Ås in Norway (broken gray), Kise in Norway (solid color) and Kiruna in Sweden (broken color). The acidity is expressed in terms of the annual volume-weighted concentration of hydrogen ions in microequivalents per liter. Most of the data come from samples collected by the European Atmospheric Chemistry Network. The additional curve for Lista from 1973 to 1977 reflects data from the Organization for Economic Cooperation and Development (OECD).



**LOCAL TRENDS** in acid rain and snow are depicted for Washington, D.C. (solid gray), Nantucket, Mass. (solid color), and Tampa, Fla. (broken color). The 1977 value for Florida is from Bradenton and the 1975-76 value for Massachusetts is from Woods Hole; each place is within about 40 kilometers of the original sampling site. Ranges shown for two periods in Washington represent values from different sampling stations in or adjacent to the metropolitan area.



	UNPOLLUTED INLAND (NORTHERN SWEDEN) 1956 pH 5.4	UNPOLLUTED COASTAL (WESTERN IRELAND) 1967 pH 5.8	POLLUTED INLAND (SOUTHERN NORWAY) 1974-75 pH 4.32	POLLUTED COASTAL (SOUTHERN NORWAY) 1972 pH 4.15	POLLUTED INLAND (NEW HAMPSHIRE) 1973-74 pH 3.94
HYDROGEN (H <sup>+</sup> )	4	1.6	48	71	114
SODIUM (Na <sup>+</sup> )	7	930	9	480	6
POTASSIUM (K <sup>+</sup> )	3	24	3	15	2
CALCIUM (Ca <sup>++</sup> )	35	76	8	45	10
MAGNESIUM (Mg <sup>++</sup> )	8	216	4	132	32
AMMONIUM (NH <sub>4</sub> <sup>+</sup> )	0	1	21	48	22
BICARBONATE (HCO <sub>3</sub> <sup>-</sup> )	6	21	0	0	0
CHLORINE (Cl <sup>-</sup> )	10	1,026	11	574	12
SULFATE (SO <sub>4</sub> <sup>--</sup> )	29	131	52	164	110
NITRATE (NO <sub>3</sub> <sup>-</sup> )	0	1	26	54	50
TOTAL CATIONS	57	1,249	93	791	164
TOTAL ANIONS	45	1,179	89	792	172

**CHEMISTRY OF PRECIPITATION** is portrayed for five areas in terms of the concentration (in microequivalents per liter) of 10 ions. Positive ions are cations, negative ones anions. Hydrogen, sulfate, ni-

trate and chloride contribute to acidity (as when hydrogen and sulfate combine to form sulfuric acid); the other ions tend to neutralize an aqueous solution. In coastal areas seawater contributes many ions.

quite different from that of the bedrock. Local variations in the chemistry of surface waters then may result from differences in these two geological substrates, in soil type and in vegetation.

Areas of highly siliceous bedrock are widespread on the Precambrian Fennoscandian Shield in Scandinavia, the Canadian Shield, the Rockies, New England, the Adirondacks, the Appalachians and smaller areas elsewhere. Fresh waters acidified to below pH 5 as a result of acid precipitation are found in southern Norway, southern Sweden, Britain, the Netherlands, East Germany, Nova Scotia, Ontario, northern New England, the Adirondacks and Florida. One clear effect has been on the fish populations, which have been virtually wiped out or severely reduced in acidified lakes in some of these regions.

For example, in southern Norway the acidification of thousands of freshwater lakes and streams has affected fish populations in an area of 33,000 square kilometers. In addition several other ecological changes have been observed as a result of the acid stress in such lakes. The rate of decomposition of organic matter is slowed, presumably because of changes in the predominance of bacteria and fungi. Bacteria, which are efficient decomposers, generally do worse in an acid environment. Changes occur at all

levels of the food web: phytoplankton, zooplankton and fishes, all of which decrease in number of species. Even the behavior of organisms may change because of changes in their environment.

The distribution of acid lakes is congruent with the distribution of acid precipitation. Further evidence of the impact of acid precipitation is that acid fresh waters are normally not found in regions that would be sensitive to acid (being nutrient-poor and poorly buffered) but lie outside the regions of highly acid precipitation. These observations lead to the conclusion that both the amount of acid in precipitation and the geological characteristics of the area are important in determining the sensitivity of fresh waters to acid precipitation.

Working with water-chemistry data from more than 1,000 lakes in Norway, Arne Henriksen of the Norwegian Institute for Water Research has recently developed an empirical relation by which the sensitivity of a given freshwater system to inputs of acid precipitation can be estimated. For example, he predicts that a calcium bicarbonate soft-water lake of the kind found by the thousands in North America and northern Europe with about 80 microequivalents per liter of bicarbonate (corresponding to about 1.7 milligrams of calcium per liter and a pH of about 6.5) will lose its bicarbonate

buffer to the point where the pH drops below 5 and fish are eliminated if the long-term average pH of precipitation is below about 4.3. It would take precipitation even less acidic to give rise to similar conditions in lakes with originally lower concentrations of bicarbonate.

Summer rains are appreciably acid in large areas of North America and Europe, particularly the first part of a rainstorm. They are certainly within the range of acidity where laboratory studies indicate that harmful effects could be expected on growing vegetation if it were exposed and sensitive. It is difficult, however, to isolate the effects of one environmental stress from all the others affecting vegetation, and so the overall effect of acid precipitation on plants has to be regarded as ambiguous in the light of the present state of knowledge.

A natural ecosystem is extremely complex, with numerous interactions at all levels of organization. Evaluating the effects of acid precipitation on such a system is difficult and expensive. The social, economic and political aspects of acid precipitation are particularly vexing because air, rain and snow are not confined by political boundaries. For example, Norway is now completing a \$10-million study of the effects of acid precipitation on its forests and lakes. In the U.S. a recent report by the National

Atmospheric Deposition Program to the President's Council on Environmental Quality (CEQ) concluded that a program of research costing \$9 million per year will be necessary to evaluate the phenomenon of acid precipitation and its effects.

It seems unlikely that the combustion of fossil fuels will decline in the industrialized countries over the next 30 years or so. It is more likely to increase because of the increased reliance on coal as a replacement for oil. The question of the broad environmental effects must be faced. In the U.S. the President's Committee on Health and Environmental Effects of Increased Coal Utilization has identified acid precipitation as one of the two major global environmental problems, the other being the increased emissions of carbon dioxide with their potential effects on climate.

In the U.S. the Environmental Protection Agency (EPA) has ruled that from 70 to 90 percent of the gaseous sulfur must be removed from the emissions of all new coal-based power plants. Old plants remain largely uncontrolled. The control in new plants would be achieved by the installation of scrubbers: flue-gas desulfurization units.

Even so, the EPA predicts that emissions of sulfur dioxide by utilities, which are by far the largest single source in the U.S., will rise from 18.6 million metric tons in 1975 to between 20.5 (with conservation and the best available controls) and 23.8 million (under existing regulations) in 1995. Although such projections are dependent on a variety of known and unknown factors and hence are tenuous, with increased emissions of sulfur dioxide (and nitrogen oxides) it can generally be expected that the deposition of hydrogen ions with precipitation will increase.

The installation of scrubbers is expensive, but the environmental costs of inadequately controlled emissions are also large. Many costs are hidden, particularly the ones associated with the synergistic effects of the stresses that acid puts on organisms (for example, increasing their susceptibility to pathogens and predators). The easy solutions, such as burning low-sulfur coal and oil, have already been applied in the control of emissions in some areas. Nevertheless, in some areas the pH of rain and snow has already been pushed through the "easy" part of the scale (from 7 to 4). Reductions in acidity will now be more difficult and far costlier to effect. Ultimately the solution to the acid-precipitation problem lies in the decrease in emissions of sulfur and nitrogen oxides to the atmosphere. This objective can be achieved with a combination of improved control technology and the conservation of fuel.



**TALL STACKS** of the generating station of the Tennessee Valley Authority in Cumberland City, Tenn., reach a height of 305 meters (1,000 feet). They typify a widespread trend to build taller stacks to reduce the concentration of sulfur and nitrogen oxides near the ground, since that is where the Environmental Protection Agency (EPA) and similar state agencies make measurements of such concentrations. By putting the oxides higher into the atmosphere, however, the stacks cause them to be carried farther, turning a local problem into a regional one.