brated by inserting measured volumes of Hg vapor at known temperatures. The sensitivity per measurement is ± 0.02 ng of Hg for one standard deviation, or about ± 0.05 ng of Hg per cubic meter of air for natural background measurements and approximately ± 1 percent for all measurements.

Mercury concentrations significantly higher than those in the natural environment have been measured in the home, office, and laboratory environments. The Hg concentration in the confined atmosphere of homes and offices is dependent upon the type of paint used and the length of time that has elapsed since the room was painted. Mercury concentrations in homes 3 years after painting with latex-base interior paint containing diphenyl mercury dodecenyl succinate to prevent fungus growth (Hg compounds dissociate to release elemental Hg) have averaged 0.07 $\mu g/m^3$. Wood-paneled and nonpainted rooms exhibit much lower Hg concentrations. Doctors' and dentists' examination and treatment rooms show Hg concentrations greater than 5 $\mu g/m^3$, an indication that the cleanup of spilled Hg was incomplete. Table 1 indicates the concentrations of Hg in the atmosphere in various locations.

ROBERT S. FOOTE

GeoSensors Inc.,
9731 Denton Drive,
Dallas, Texas 75220

References

1. *Fed. Regist.* **36** (No. 157), 15104 (1971).
2. "Threshold limit values of airborne contaminants and physical agents with intended changes adopted by the American Conference of Governmental Industrial Hygienists" (American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1971).
3. *Fed. Regist.* **36** (No. 235), 23239 (1971).
4. A. C. Stern, Ed., *Air Pollution* (Academic Press, New York, 1968).

10 January 1972; revised 22 May 1972

■

Atmospheric Sulfur: Its Effect on the Chemical Weathering of New England

Abstract. *The present acidity and sulfur content of the upland streams of New England can be accounted for on the basis of the rainout and washout of sulfuric acid from the atmosphere. In spite of this excess acid flux over the New England landscape, the rate of cationic denudation of upland watersheds is relatively low.*

The Northeast for some time has been characterized by an excess deposition of sulfur from the atmosphere (*1*–*3*). This sulfur originates largely from the combustion of fossil fuels (New England is immediately downwind from the major industrial centers of the United States) (Fig. 1). However, in the United States the extent and consequences of this form of pollution on the environment have only recently begun to be appreciated (*4*). In this connection a study of the effects of atmospheric sulfur on the chemistry of surface waters in the Northeast has been in progress since 1963 at the Hubbard Brook Experimental Forest in New Hampshire (*5*).

The rain and snow incident at Hubbard Brook (1963–1969) contained, on the average, 3.1 mg/liter of sulfate with an associated *p*H of 4.1. The *p*H values of individual weekly samples, however, have been as low as 3.0. Pearson and Fisher (*2*) have found that, over a 3-year period, rain and snow in the Northeast contain, on the average, 4.3 mg/liter of sulfate with an associated *p*H of 4.4. Contemporary precipitation, therefore, over much of New England is pervaded by 3 to 4 mg/liter of sulfate, mostly in the form of H_2SO_4, which is sufficient to lower the *p*H of ambient rain and snow to about 4.1 to 4.4. By comparison, geologically normal precipitation, that is, pure rainwater saturated with CO_2 at normal pressure, is much less acid, having a *p*H of only 5.7.

Table 1. Composition of the surface waters of the North Atlantic slope (in milligrams per liter) (*6*).

Component	Hubbard Brook (6-year average)	Maritime Provinces (average of 19 lakes)	New England (average of 66 tributary streams)	World average stream water
HCO_3	*	1.3	17	58.4
SO_4	6.40	5.8	6.9	11.2
Cl	0.64	6.4	2.8	7.8
NO_3	1.14		0.8	1.0
Ca	1.58	1.7	5.7	15.0
Mg	0.39	2.7	1.2	4.1
Na	0.92	4.2	2.6	6.3
K	0.23	2.5	0.7	2.3
Al or Fe†	0.24		0.2	0.7
SiO_2	4.16		4.6	13.1
Total	16.15	> 24.6	42.5	120
	*p*H 5.15		*p*H 6.7	*p*H ≃ 7

* Not detectable, on the average. † Hubbard Brook water contains aluminum and no iron; New England water and world stream water contain iron and no aluminum.

Table 1 gives data (6-year weighted averages) on the stream water chemistry in the Hubbard Brook area; also included are comparative average data on the river water of the world. The absence of bicarbonate in Hubbard Brook stream water is conspicuous and significant. The dominant anion in the Hubbard Brook stream water is sulfate; by contrast, the dominant anion in the rivers of the world is bicarbonate (*6*). Table 1 also gives the average composition of 66 nominally unpolluted tributary streams in New England. These streams drain a rather homogeneous terrain composed of igneous and metamorphic rocks with few limestones. Collectively, these waters show a rather constant sulfate content of about 5 to 7 mg/liter. These data also suggest a systematic increase in the bicarbonate content as the stream size increases.

If typical precipitation over the Northeast contains 3 to 4 mg/liter of sulfate and if a typical value for evapotranspiration over the same area is 50 percent (*7*), then the net precipitation disposed over this landscape should contain 6 to 8 mg/liter of sulfate, the amount actually observed in the upland waters of this region (Table 1). Thus, these data suggest that the present rate of sulfur rainout and washout from the atmosphere is sufficient to account for the present sulfate content of surface waters in New England, as Pearson and Fisher have also surmised (*2*).

In the incongruent solution of rocks and minerals by rainwater, that is, chemical weathering, hydrogen ion is the most important active agent. It is thought that over most of the world today and perhaps everywhere in the geologic past, carbonic acid has been the dominant source for the hydrogen ion (*8*). The interjection of a strong mineral acid such as H_2SO_4 or HNO_3 into a carbonic acid system would shift the equilibrium in the direction of the dissociation of carbonic acid into molecular water and CO_2. In natural water systems whose *p*H is sufficiently lowered by such strong acids, the presence of ionized carbonic acid would then be effectively precluded. As a consequence, the acidity of contemporary rain over the Northeast would be controlled not by carbonate equilibria but rather by the rainout and washout of strong acids such as H_2SO_4 from the atmosphere. Similarly, the acidity of upland stream water may also be attributed to strong mineral acids, despite the presence of heavy, organic-rich (CO_2-rich) soils which characterize much of the region. For example, the data from the past 8 years for the Hubbard Brook watersheds have shown that, as H_2SO_4 enters the system from the atmosphere, comparable amounts of metallic sulfates leave the system dissolved in the runoff (*5*). Bicarbonate ion is conspicuously absent in this system (Table 1).

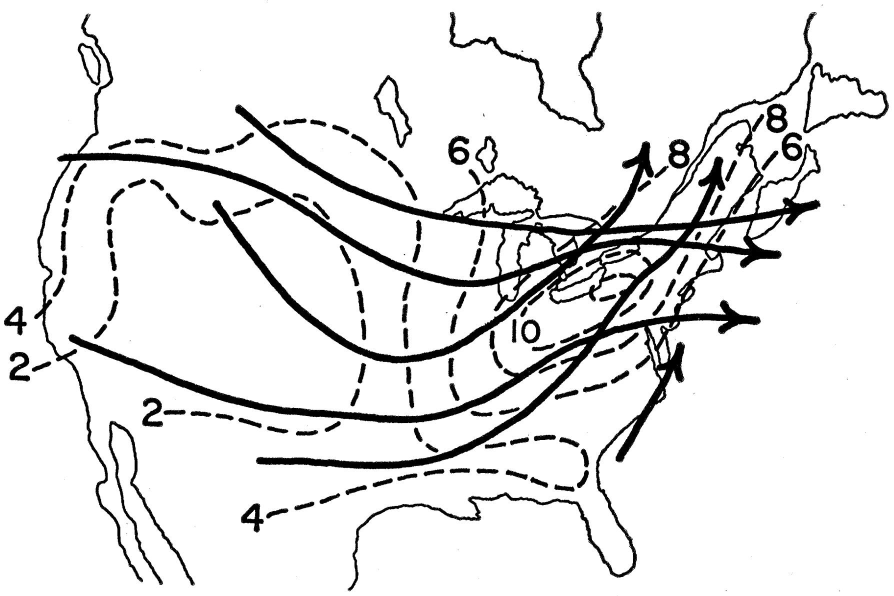

Fig. 1. Most common trajectories of cyclonic storms across the United States (solid lines) and sulfur deposition in excess of marine contributions across the United States (dashed lines) (in units of kilograms of sulfur deposited per hectare per year). If one allows for the complete oxidation and hydrolysis of sulfur, 1 kg of sulfur deposited per hectare per year implies 6.3 meq of H_2SO_4 per square meter per year. [Adapted from data compiled by Eriksson (*3*) and Visher (*14*)]

Simple mass action considerations lead one to expect that weathering rates at *p*H 4.0 (initial conditions at Hubbard Brook) should proceed faster than at *p*H 5.7 (rainwater at normal CO_2 pressure). It is perplexing, therefore, that, on the time and spatial scale of the Hubbard Brook watersheds, weathering reactions are relatively incomplete with the *p*H of runoff water still quite acid (*p*H 5.15). The incomplete nature of the weathering reaction is further suggested by the low rate of cationic denudation observed in the Hubbard Brook watersheds, being 90 meq m^{-2} $year^{-1}$ as compared to 220 meq m^{-2} $year^{-1}$ for the upper drainage basins of northern New England and 380 meq m^{-2} $year^{-1}$ for North America as a whole (*9*). Upland areas of New England sustain only moderate chemical weathering in spite of the acidification of their waters. New England is thus unlike the northern Cascade Mountains, where carbonation weathering reactions acting on igneous and metamorphic rocks similar to those of New England are decidedly enhanced (930 meq m^{-2} $year^{-1}$) (*10*).

The specific cause for the relatively slow weathering rate at Hubbard Brook is not clear. However, a contributing cause may be the maturity of the soil at Hubbard Brook. In the Cascade Mountain watershed (*10*), metamorphic and igneous rocks comparable to those at Hubbard Brook are being rapidly weathered. This rapid weathering is almost certainly expedited by the fresh rock surfaces that are constantly being created in the alpine-glacial environment and subsequently exposed to water. At Hubbard Brook, in contrast, the rock surfaces and mineral grains are mechanically stable and have long been accessible to water and weathering processes. Consequently, their weathering reactivity has probably been reduced by microscopic coatings of alumina and clay which act as diffusion barriers between weathering solutions and the interior of mineral grains (*11*). In any case, the fact remains that cationic denudation of the upland areas of New England, as exemplified by the Hubbard Brook area, does not appear to be unduly accelerated at the present time as a result of the artificial acidification of its waters (*5*). For example, the complete neutralization of 1 m of unbuffered rain (*p*H 4.0) over this area per year can account for 100 meq m^{-2} $year^{-1}$ of cationic denudation, comparable to the amount actually measured at Hubbard Brook. On the other hand, 100 meq m^{-2} $year^{-1}$ is less than half of the rate realized on a larger scale for New England (220 meq m^{-2} $year^{-1}$) and decidedly less than the regional rate (680 meq m^{-2} $year^{-1}$) calculated for the whole of the Northeast (*12*). Evidently, carbonation weathering reactions or congruent solution of minerals, or both, are realized on a regional scale and are the primary processes responsible for most of the observed cationic denudation.

Acidified rain and stream water have also been observed in Scandinavia since World War II. In addition to the effect that atmospheric sulfur may have on cationic denudation, regional changes in soil chemistry, forest growth, and aquatic life have also been demonstrated (*13*). In view of the inequities in the deposition of atmospheric sulfur over the continental United States (Fig. 1), such changes may also be prevalent in the Northeast.

Most geochemists use the carbonic acid system as a model for the analysis of chemical weathering reactions and activity (*8*). However, there are large regions of the earth today where carbonation reactions no longer predominate. Rather, H_2SO_4 from atmospheric pollution may control the geochemical processes in such regions, and the consequences of such a change in the weathering regime cannot be predicted with certainty by recourse to the contemporary literature. New studies are required to fully reveal the mechanisms and rates of chemical weathering in aqueous systems dominated by sulfuric acid.

NOYE M. JOHNSON
ROBERT C. REYNOLDS
Department of Earth Sciences,
Dartmouth College,
Hanover, New Hampshire 03755
GENE E. LIKENS
Section of Ecology and Systematics,
Cornell University,
Ithaca, New York 14850

References and Notes

1. C. E. Junge and R. J. Werby, *J. Meteorol.* **15**, 417 (1958); D. W. Fisher, A. W. Gambell, G. E. Likens, F. H. Bormann, *Water Resourc. Res.* **4**, 1115 (1968).
2. F. J. Pearson and D. W. Fisher, *U.S. Geol. Surv. Water Supply Pap. 1535-P* (1971).
3. E. Eriksson, *Tellus* **12**, 13 (1960).
4. P. H. Abelson, *Trans. Amer. Geophys. Union* **52**, 124 (1971); W. W. Kellogg, R. D. Cadle, E. R. Allen, A. L. Lazrus, E. A. Martell, *Science* **175**, 587 (1972); G. E. Likens, F. H. Bormann, N. M. Johnson, *Environment* **14** (No. 2), 33 (1972).
5. G. E. Likens and F. H. Bormann, in *Ecosystem, Structure and Function*, J. Wiens, Ed. (Oregon State Univ. Press, Corvallis, 1972), pp. 25–67; N. M. Johnson, G. E. Likens, F. H. Bormann, R. Pierce, *Geochim. Cosmochim. Acta* **32**, 531 (1968).
6. Data for Hubbard Brook are taken from (*5*); data for the 19 lakes in the Maritime Provinces are taken fr[illegible] E. Gorham [*Limnol. Oceanogr.* **2**, 12 (1957)]; data on the 66 streams in New England are taken from S. K. Love, Ed. [*U.S. Geol. Surv. Water Supply Pap. 1350* (1958); *U.S. Geol. Surv. Water Supply Pap. 1400* (1959); *U.S. Geol. Surv. Water Supply Pap. 1520* (1960)]; data on world stream water are from D. A. Livingstone [*U.S. Geol. Surv. Prof. Pap. 440-G* (1963)].
7. H. W. Lull, *Forest Atlas of the Northeast* (Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Upper Darby, Pa., 1968).
8. R. M. Garrels and F. T. Mackenzie, *Evolution of Sedimentary Rocks* (Norton, New York, 1971).
9. The value for Hubbard Brook is from the data cited in (*5*). The value for New England is calculated from the chloride-corrected cation sum (440 μeq/liter) in Table 1 representing 66 tributary streams and on the assumption that the average runoff for northern New England is 50 cm (from *7*). Data for North America are calculated from the data of Livingstone (*6*).
10. R. C. Reynolds and N. M. Johnson, *Geochim. Cosmochim. Acta* **36**, 537 (1972).
11. R. Wollast, *ibid.* **31**, 635 (1967).
12. The value for the cationic denudation of the North Atlantic slope of North America (680 meq m^{-2} $year^{-1}$, chloride-corrected) is calculated from the data of Livingston (*6*). Livingstone, however, used data on the chemistry of the Hudson River to represent this region, and the Hudson, unlike northern New England, drains large areas of sedimentary rocks.
13. S. Oden and T. Ahl, *Forsürningen av skandinaviska vatten, Ymer. Aarsbok* (Svenska Saellskapet foer Antropologii och Geografi, Stockholm, 1970), pp. 103–122; B. Lundholm, in *Global Effects of Environmental Pollution*, S. F. Singer, Ed. (Springer-Verlag, New York, 1970), pp. 195–201.
14. S. S. Visher, *Climatic Atlas of the United States* (Harvard Univ. Press, Cambridge, Mass., 1954).
15. This is contribution number 58 in the study of the Hubbard Brook ecosystem. The Hubbard Brook Experimental Forest is operated and maintained by the Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Upper Darby, Pa.

10 April 1972; revised 29 May 1972 ■

World Dynamics: A Note

Abstract. *The results of Forrester's world model are shown to be very sensitive to changes in assumptions.*

In *World Dynamics* (*1*) Forrester presents a simple simulation model of the world. This model consists of five first-order differential equations in five very highly aggregated state variables. For example, the variable NR is defined as "natural resources." He also includes some auxiliary variables that indicate performance; these he calls "quality of life." Forrester performs several simulations and, based on the behavior of the quality of life in these simulations, makes several quite provocative policy recommendations.

For most of the scientific community, modeling the world with only five state variables is a dubious project. Recommending policies based on such a simple, operationally vague model is doubly suspect. Forrester argues that his simulations are not at all dubious, and that since decisions are being made on the basis of simpler and fuzzier verbal models, decision-making can only be improved by using computer simulation. In this report I argue that this assertion is only true if the computer simulation is insensitive to different sets of plausible assumptions and I will show that the *World Dynamics* model does not demonstrate such insensitivity.

World Dynamics has been received very critically. Several reviews have taken Forrester to task for doing bad science. For example, Shubik (*2*) wrote ". . . the book is blatant and insensitive advocacy for unsubstantiated model building on a very large scale. . . . What is this book for? Its behavioral-scientific content is virtually zero. . . . None of his (Forrester's) book has any empirical content, yet the operation of all his models calls for large numerical inputs." These sorts of criticisms miss their mark; Forrester is not trying to do behavioral science. He has a less ambitious goal, to improve on the verbal and mental models that are now in use. And he would argue that computer models are always better than verbal or mental ones. His argument can be condensed into the following propositions:

1) People are quite good at perceiving relationships between various components of the world system.

2) People are not very good at deducing the whole system consequences of these individual relationships.

3) It is quite easy to use computer simulation to accurately deduce the consequences of any set of relationships. Therefore, verbal models or mental images are necessarily inferior to mathematical models.

4) Policy decisions are presently being based on nonmathematical models. Therefore policy can certainly be improved by reexpressing these vague models in a more exacting systems dynamics formalism.

It seems relevant to ask whether this conclusion is true. Does the simple translation of a verbal model into Dynamo improve its predictive ability?

Imagine, for a moment, one of Forrester's social dynamicists entering the political arena. There he would find decisions being based on an array of vague, hard to verify, mental models founded upon conflicting assumptions, and reaching different conclusions. As a first step the social dynamicist could reexpress each of the different mental models as a different simulation of his model. But unless all these simulations show substantially the same results, the dynamicist has done little to improve the lot of the decision makers. Instead of being faced with an array of unverified mental models, he is confronted with an equal number of conflicting computer simulations. To be of use then, the social dynamicist would have to go to a more sophisticated, complicated model whose components can be independently verified in some way.

Let's apply this test to the model in *World Dynamics*. Roughly there exist two ideological poles in the controversy about the future of the world.

1) The Malthusian view. The adherents of this view argue that the earth is endowed with some fixed, finite amount of resources. We only have so much agricultural land, so much petroleum, and so on. Further, Malthusians argue that anything that makes life better, be it better nutrition or increasing material standards of living, leaves birth rates constant and lowers death rates. New technology in this view can only temporarily alleviate shortages; population must inevitably overtake any increases in productivity. Eventually an equilibrium between high death rate and high birth rate is reached. This view is more completely expressed and defended in much of the conservation literature.

2) The technological-optimist view. The adherents of this view argue that there are no foreseeable limits on production of goods. Any particular scarcity will be eliminated by substitution technology. Further, the increasing stock of technology is seen to increase productivity and thus increase the standard of living. Increasing the standard of living is then supposed to produce lower birth rates. Eventually society is