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Appendix X

MODELING PAPERS

PART 1—MEASURING THE ECONOMIC IMPACT OF WEATHER AND WEATHER MODIFICATION: A REVIEW OF TECHNIQUES OF ANALYSIS

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During the past few years there has been an increasing demand for improved techniques for measuring the impacts of weather and climate on economic activities. This demand stems in part from mounting losses of property and income which result from extreme weather events, in part from man's increasing use of the atmosphere as a transportation route, and in part from his increasing ability to modify the weather. Each year in the United States, for example, losses from tornadoes are estimated to be in excess of $250 million, losses from hurricanes in excess of $200 million, and those from floods over $290 million.[1] Large losses also result from lightning and hail—and from less extreme weather variations.

Part of these losses might be eliminated if improvements were made to existing weather information and forecasting systems.[2] Costly delays in air transportation which result from adverse weather might be reduced if better weather information were available or if weather could be altered.[3] Various other economic activities might also benefit from advances in the field of weather forecasting and modification.

Thus far, however, specific relationships between the weather and various economic activities have been explored only to a limited extent. Most of the research effort in this connection has been devoted to advancing knowledge about the impact of weather on agriculture,[4] and to a lesser extent on transportation [5] and the construction industry.[6] Little is known about the impact of weather on such economic activities as manufacturing or the service trades. Even in those activities in which a good deal of work has been done, knowledge of overall impacts is imperfect. In agriculture, for example, we have some indication of the effects of a particular weather variable on a particular crop in a particular region. But we still lack knowledge of how a given variable affects all crops in a given region, or of how each weather variable affects different crops in a given region. We can determine to some extent how a wet summer affects corn production in Iowa, but estimates of the overall impact on the Iowa economy are fairly crude. Estimates of impacts of particular weather events on the national economy border on guesswork.

Now that weather modification seems capable of achievement, it is imperative that much better estimates of the overall impact of weather on economic activity be obtained. Such estimates are needed because weather modification has differential effects on economic activities. Some activities may gain from a given weather change, but others may lose. Moreover, weather modification is but one of several possible adjustments to the weather. Estimates of overall weather impacts would be helpful in determining which alternative adjustment is most efficient. Would it be best to accept the weather as given and try to reschedule an activity (as in postponing planting or harvesting)—or try to insulate against weather effects (as in using air conditioning or drought-resistant crops)? Or would it be more efficient to try to alter the processes which produce the weather?

Possible Techniques of Analysis

One of the major topics of discussion at the Symposium on the Economic and Social Aspects of Weather Modification, held at the National Center for Atmospheric Research in 1965, was the problem of identifying and measuring the economic impacts of weather variations. Several tools of analysis which might be developed for this purpose were considered.[7]

Ackerman, for example, proposed the development of an Ideal Weather Model.[8] Such a model would identify and measure variations of actual weather conditions from conditions considered ideal for the pursuit of different economic activities, and would express the importance of these variations in economic terms. Development of such a model would require: (1) determination of the requirements of each activity for temperature, precipitation, and wind in terms of volume and timing; (2) assessment of the economic costs of variations in different weather parameters to particular economic activities; and (3) development of some means to trace the impact of a given weather variation through the economic system. Ackerman noted that considerable research is required before such a model can be applied. In particular, he emphasized the need to determine the weather requirements of various activities and the costs of weather changes to them. He suggested, however, that once these problems are solved, recent developments in applied economics, regional science, and computer science will facilitate the identification and measurement of weather impacts in various sectors of the economy.

The Symposium group considered several techniques that have been developed in recent years for analyzing economic systems, both at the regional level and national level. These techniques include: input-output analysis, simulation, linear programming, and regression analysis. In most cases to date, these tools have been applied without considering the climatic factors which may affect an economy: most econometric models have been based on the non-meteorological aspects of an economy. Even a casual look at the economy of most areas, however, reveals that climatic factors cannot be ignored. Hence, existing techniques for economic analysis must be assessed with caution. Generally, substantial modifications will be required before these techniques can be used for evaluating the real impacts of weather and climate on economic activities.

Input-Output Analysis

One technique that can be used to assess the real economic impacts of weather and climate is input-output analysis,[9] known also as interindustry economics. This method is concerned with quantitative analysis of the interdependence of producing and consuming units in a modern economy.[10] In particular, input-output analysis permits study of the interrelations among producers as buyers of each other's outputs, as users of scarce resources, and a sellers to final consumers. Once the linkages among various industries are known, it is possible to trace the impacts of a change in output of one industry on other industries in an economy.

A number of sophisticated models based on input-output concepts have been developed for analyzing economic changes in particular regions.[11] Attempts have also been made to develop a model of the United States economy using this technique.[12] However, most input-output studies do not take account of climatic factors.

Typical of non-climatic econometric models is the Arizona input-output model.[13] In considering the agricultural processing sector, this study shows that to produce a dollar's worth of agricultural products, it takes roughly 31 cents of input from the livestock sector, five cents of input from the crop sector, eight cents from trade and transportation, and so on. Inputs from rainfall, temperature, sunshine, wind, etc., however, are not considered.

Another study makes some attempt to assess the value of water to the Arizona economy.[14] For example, it reveals that of the 5.0 million acre-feet of water consumed in 1958, 1.5 million acre-feet were consumed by cotton, 1.4 million by food and feed grains, 1.3 million by forage crops, and so on. A subsequent analysis of these data indicates that the direct and indirect requirement to fill an order for an additional $1,000 of final demand varies from 65.0 acre-feet for the food and feed grains sector, to 0.03 acre-feet for the trade, transportation and services sector. The indirect economic effect of water is demonstrated in the poultry and eggs sector, which ranks 22d out of 24 in its direct water coefficient, but 3d out of 24 in its direct and indirect coefficient. It takes nearly 21 acre-feet of water usage in the State's agricultural industries to produce $1,000 of poultry products for the consumer. The explanation for the apparently high total is that poultry and eggs require large amounts of agricultural crop inputs, particularly food and feed grains, which are themselves large consumers of water. Here again the values of rainfall, temperature, and sunshine are not considered. If, however, these climatic factors were incorporated into econometric models of the type developed for Arizona, the impacts of changes in these weather parameters on the economy of a region could then be studied.

Variations in weather can obviously result in changes in the production functions of various activities. Given a change in the production function of one activity, input-output analysis can make it possible to determine the impacts of that change on other activities too. An increase of precipitation at a particular time, for example, may permit a significant increase in agricultural output. This in turn will increase the demand in the agricultural sector for inputs from other sectors. Increased output in the agricultural sector, however, does not necessarily imply that there will be increased outputs in all other sectors. Some economic activities may experience substantial gains, but others may suffer declines in the demand for their outputs. Input-output analysis therefore can provide a useful means of identifying which activities may gain and which may lose as a result of given weather variations.

Simulation

If it were possible to have a scale model of the economy, complete in every detail, one could alter one variable in the system and then observe what changes took place in other parts of it. Unfortunately, such scale models are not possible, partly because economic systems are not composed of physical mechanisms that can be scaled down, and partly because of the complexity of the systems. To overcome these problems, simulation models have been developed.[15] These use computer programs instead of physical models to represent the parts of the system and the interactions among the parts. Simulation models incorporate the variables that are believed to be the most important, and can then be used to determine the effects of a change in a particular variable on the system as a whole. The use of such models has increased considerably with advances in computer science and technology.

Simulation techniques offer useful possibilities for examining an economic system and the effects of weather and climate on its activities and on the system as a whole. One recent attempt to assess economic impacts of weather by simulation was made by McQuigg and Thompson.[16] They suggested that relations between weather events, non-weather events, man's function as a decisionmaker, and the economic outcome of an enterprise may be represented by an equation of the form

$$E=f(W,N,A)+u,$$

where E = economic outcome; $W=(w_1, w_2, \ldots, w_n)$, some actual weather events; $N=(n_1, n_2, \ldots, n_k)$, some actual non-weather events; $A=(a_1, a_2, \ldots, a_l)$, a subset of alternatives based on information supplied to the decisionmaker; and u = a "disturbance" factor, which is random and normally distributed.

Using this equation, a simulation model was developed, based on real economic data from an important weather-sensitive enterprise—the management of the flow of natural gas to a city during the winter. While the results of the simulation model analysis were being studied, a basic concept began to emerge: that improvements in the accuracy of weather information may allow the manager of a weather-sensitive process to make "better" and hence more valuable decisions, *provided he has a sufficiently precise rational method of translating weather information into operational terms.* It became apparent that the value of weather information and the use to which it is put depend on a much more detailed knowledge of weather impacts on weather-sensitive activities than is available at the present time.[17]

Simulation techniques may also be usefully applied to the evaluation of weather modification programs, which have characteristics similar to activities that have already been successfully subjected to analysis by simulation, such as transportation systems and environmental health. Simulation techniques for analyzing water resource programs,[18] particularly those which have evolved from the Harvard Water Program,[19] also show promise for applications to the analysis of weather modification programs.

Linear Programming

A relatively new contribution to the field of interindustry economics is the technique of activity analysis or linear programming, developed first by Dantzig and Koopmans.[20] Most applications of this technique have been to problems of single plants or firms, but the method itself is also useful for industry-wide and interindustry analysis.

Basically, activity analysis is a method of analyzing any economic transformation in terms of elementary units called activities. It provides the conceptual framework for the mathematical technique of linear programming, which can be used to determine optimum solutions to various kinds of allocation problems. This technique requires that the relationships among relevant variables be expressed in linear mathematical form. These expressions, together with appropriate constraints, make up a set of equations that have many solutions. The purpose of linear programming is to identify a particular combination of variables that will produce optimum results.

One example of linear programming is the PARM system. This programming model is built up of basic variables called activities, which are represented in the computation system by time-phased vectors grouped in tables. The maximum size of these tables is limited by the available computer memory, the prototype model having 983 such activity vectors. Wood suggests that regional applications would use a supplementary model adjoined to the national model.[21] Applying the regional model in any time period would assume prior application of the national model to that time period. The regional model, like the national model, would be applied first to the period immediately following the historical data, and then successively to subsequent periods, if desired. In this way the data computed for

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each time period would be added to the historical time series and used in the computation of the next period.

Regression Analysis

Regression analysis is also a valuable tool in many kinds of investigations, and particularly appropriate in studies of the effects of climatic variations on aspects of consumption and production. Until recently, multiple regression techniques could only be applied when the number of independent variables was relatively small. Today, however, with electronic computers, regression analyses with 10, 20, 30, or even more independent variables can be processed very quickly. Consequently, the "choice" of independent (climatic) variables is not as critical as it once was.

Regression techniques can usefully be applied to analyzing impacts of weather and climate on economic activities. For example, a regression model was recently developed to assess the effects of significant climatic variations on agricultural production in New Zealand, and their ultimate impacts on agricultural income.[22] With modifications, this model could be applied to the study of climatic impacts on agricultural production in other countries as well. Regression techniques could also be used to trace impacts of weather changes on other aspects of the economy.[23]

Potential Applications of Analytical Techniques

Thus far, applications of the various analytical techniques just described to the evaluation of weather impacts and weather modification programs have been more a matter of discussion than of accomplishment. Advantages and disadvantages of using these analytical tools for such evaluation have not been reviewed in detail. Neither has sufficient attention been given to the problem of what types of data or research are required before these techniques can be used successfully. Kuh, for example, states that "the quality of most available statistics is weak * * *. In many areas of research, computing capability and theory of estimation and behaviour have clearly outstripped the ability of our statistical agencies to produce pertinent data for testing and estimation, even though matters are constantly improving." [24] Clearly, research is needed to select useful data which can be expressed in quantifiable terms; to determine relationships between weather variations and weather-sensitive activities; and to direct imaginative efforts towards developing and adapting techniques for measuring impacts of weather and climate on various economic activities.

The papers which follow this introduction represent attempts to overcome some of the deficiencies in the field. Langford discusses in detail the possibilities of applying one particular technique, input-output analysis, to studies of economic impacts of weather and climate; and he notes the types of information that would be required for such efforts. He suggests that regional economic models, such as the one developed in the Philadelphia Region Input-Output Study, could be adapted to incorporate weather as a factor which influences the production functions of industries included in the input-output tables. He notes, however, that although it may be possible to use this method to determine impacts within a given region, substantial difficulties may be encountered in attempts to apply it for assessing inter-regional impacts.

In a second paper Hufschmidt, Fiering, and Sherwani discuss the possibilities of adapting water-resource system simulation models for use in measuring physical and economic impacts of weather forecasting and weather modification programs. Drawing on the experience gained in the Harvard Water Program, and noting the special problems raised by changes in natural streamflow patterns, they conclude that it would be possible to apply simulation techniques to the analysis of weather modification and weather forecasting programs. They note, however, that several sub-models would need to be developed for this purpose, including sub-models for providing information on streamflow-runoff relationships, flood probabilities, and the economic impacts of changes caused by alterations in normal weather patterns.

In a third paper, McQuigg describes a specific example of a simulation model that can be useful in studying economic impacts of weather modification. The physical process chosen for simulation was the deliberate creation of contrail cirrus clouds. To determine whether or not modification was needed, the simulation model used as basic input data the 20-year record of observed upper air temperatures in the area, together with records of daily maximum and minimum surface temperatures, precipitation, and percent possible sunshine. The model produced a useful modified series of temperature values, with components of variance that could be attributed to changes in the amount of cloudiness claimed. The modified temperature series provided reasonable estimates of the changes that could be expected if summer cirrus clouds over Missouri were modified by creation of a sufficient number of contrails. A natural extension of this work is to apply the model to simulation experiments involving the effects of temperature modification on electric power demand, dairy production, crop production, and other weather-sensitive activities.

The authors of these papers seem to agree that the various methods reviewed can be applied to the evaluation of weather modification programs. They point out, however, that in many cases, data must be gathered and research undertaken in order to improve the usefulness of analytical techniques. In particular, studies are required to determine the sensitivity of various economic activities to changes in different weather parameters. Studies are also needed to determine the ways in which weather information is used. What kinds of information tend to promote action to deal with weather events, and what types tend to promote no action? We need to know how people perceive the weather, and alternative adjustments to it. We need to know how much weather change is required before people will respond and whether reactions to planned changes differ from those to natural variations. At present our knowledge of these matters is quite limited. Further work is needed to develop and refine the conceptual bases of models for analyzing the economic merits of weather modification programs. Parallel work in empirical studies is also urgently required. Model building needs to be accompanied, for example, by studies of the weather requirements of various industries and regions, and by studies of the factors which seem to condition human responses to the weather.

FOOTNOTES

1. Environmental Science Services Administration, *A Proposed Nationwide Natural Disaster Warning System,* Washington, D.C., 1965, pp. 25–37.
2. See U.S. Committee on Government Operations, *Government Weather Programs,* U.S. Government Printing Office, Washington, D.C., 1965.
3. See W. Boynton Beckwith, "Impacts of Weather on the Airline Industry: The Value of Fog Dispersal Programs," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification,* University of Chicago, Department of Geography Research Series No. 105, Chicago, Ill., 1966, pp. 195–208; and U.S. Senate Committee on Commerce, *Weather Modification and Control,* U.S. Government Printing Office, Washington, D.C., 1966.
4. The literature on the impacts of weather on agriculture is voluminous Recent contributions which review some of this work include John W. Kirkbride and Harry C. Trelogan, "Weather and Crop Production," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification,* University of Chicago, Department of Geography Research Series No. 100, Chicago, Ill., 1965, pp. 159–168. See also Emery N. Castle and Herbert Stoevener, "The Economic Evaluation of Weather Modification with Particular Reference to Agriculture," in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification,* op. cit., pp. 141–158; Zvi Griliches, "Estimates of the Aggregate U.S. Farm Supply Function," *Journal of Farm Economics,* vol. 42, May 1960, pp. 282–293; Louis M. Thompson, *An Evaluation of Weather Factors in the Production of Corn,* Iowa State University Press, Ames, Iowa, 1962; and Earl O. Heady and J. L. Dillon, *Agricultural Production Functions,* Iowa State University Press, Ames, Iowa, 1961.
5. See, for example, E. Bollay and Associates, Inc., *Economic Impact of Weather Information on Aviation Operations,* final report to the Federal Aviation Agency, Washington, D.C., 1962; U.S. Weather Bureau, *A Preliminary Analysis of the Effects of Weather on Airport Traffic Flows, Airport Capacity and Acceptance Rates,* a report prepared by the Federal Aviation Agency, Washington, D.C., 1961; and E. J. Weigman, *Analysis of Wind and Weather Factors on the New York-London Air Route for Peak Traffic Day of August 22, 1962,* Stanford Research Institute, Menlo Park, Calif., 1962.
6. One excellent study is J. A. Russo et al., *The Operational and Economic Impact of Weather on the Construction Industry,* The Travelers Research Center, Inc., Hartford, Conn., 1965.
7. See, for example, Edward A. Ackerman, "Economic Analysis of Weather: An Ideal Weather Pattern Model"; W. L. Garrison, "Evaluation of Consequences of Modifications to Weather and Climate"; James R. Hibbs, "Evaluation of Weather and Climate by Socio-Economic Sensitivity Indices"; Ivars Gutmanis and Lester Goldner, "Evaluation of Benefit-Cost Analysis as Applied to Weather and Climate Modification"; Leslie Curry, "Seasonal Programming and Bayesian Assessment of Atmospheric Resources"; and Emery N. Castle and Herbert H. Stoevener, "The Economic Evaluation of Weather Modification with Particular Reference to Agriculture"—all in W. R. D. Sewell, ed., *Human Dimensions of Weather Modification,* op. cit., pp. 61–76, 77–90, 91–110, 111–126, 127–140, and 141–158, respectively.

8. See Edward A. Ackerman, op. cit.

9. The technique of input-output analysis was conceived by Leontief. See W. W. Leontief, *The Structure of the American Economy,* Oxford University Press, Oxford, England, 1951. An excellent summary of concepts and applications of the technique appears in W. W. Leontief, "The Structure of Development," in *Technology and Economic Development,* Pelican Books, London, England, 1963, pp. 129–148. See also Walter Isard et al., *Methods of Regional Analysis,* John Wiley and Sons, Inc., New York, N.Y., 1960.

10. H. B. Chenery and P. G. Clark, *Interindustry Economics,* John Wiley and Sons, Inc., New York, N.Y., 1959.

11. See, for example, Walter Isard, Thomas W Langford, Jr., and Eliahu Romanoff, *Working Papers, Philadelphia Regional Input-Output Study,* Regional Science Research Institute, Philadelphia, Pennsylvania, December, 1966; F. T. Moore and J. Paterson, "Regional Analysis: An Inter-Industry Model of Utah," *Review of Economics and Statistics,* vol. 37, November 1955, pp. 368–383; and C. M. Tieart, *Markets for California Products,* California Development Agency, Sacramento, Calif., 1962.

12. See Gary Fromm and Lawrence R. Klein, "The New National Econometric Model: Its Application," *American Economic Review,* vol. 55, No. 2, May 1965, pp. 348–369. See also Morris R. Goldman et al., "The Inter-Industry Structure of the United States: A Report on the 1958 Input-Output Study," *Survey of Current Business,* U.S. Department of Commerce, Office of Business Economics, Washington, D.C., November 1964.

13. W. E. Martin and L. G. Bower, "Input-Output Analysis: An Arizona Model," *Arizona Review,* vol. 16, No. 2, February 1967, pp. 1–5.

14. W. E. Martin and L. G. Bower, "Patterns of Water Use in the Arizona Economy," *Arizona Review,* vol. 15, No. 12, 1966, pp. 1–6.

15. An excellent review of the concepts and applications of simulation techniques appears in Guy H. Orcutt, "Simulation of Economic Systems," *American Economic Review,* December 1960, pp. 893–907.

16. J. D. McQuigg and R. G. Thompson, "Economic Value of Improved Methods of Translating Weather Information into Operational Terms," *Monthly Weather Review,* vol. 94, 1966, pp. 83–87.

17. A similar point is made in J. A. Russo, "The Economic Impact of Weather on the Construction Industry of the United States," *Bulletin of the American Meteorological Society,* vol. 47, 1966, pp. 967–972.

18. Applications of simulation techniques in water-resource system design are described in Maynard M. Hufschmidt and Myron B. Fiering, *Simulation Techniques for Design of Water-Resource Systems,* Harvard University Press, Cambridge, Mass., 1966. See also Arthur Maass et al., *Design of Water Resource Systems,* Harvard University Press, Cambridge, Mass., 1962.

19. The Harvard Water Program is described in Maynard M. Hufschmidt, "The Harvard Program: A Summing Up," in Allen V. Kneese and Stephen C. Smith, eds., *Water Research,* Johns Hopkins Press, Baltimore, Md., 1966, pp. 441–455.

20. T. C. Koopmans, *Activity Analysis of Production and Allocation,* Cowles Commission Monograph No. 13, John Wiley and Sons, Inc., New York, N.Y., 1951.

21. M. K. Wood, "PARM—An Economic Programming Model," *Management Science,* vol. 11, 1965, pp. 619–680.

22. W. J. Maunder, "The Effect of Climatic Variations on Some Aspects of Agricultural Production in New Zealand and an Assessment of their Significance on the National Agricultural Income," unpublished Ph. D. dissertation, University of Otago, New Zealand, 1965.

23. W. J. Maunder, "Effect of Significant Climatic Factors on Agricultural Production and Incomes: A New Zealand Example," *Monthly Weather Review,* vol. 96, 1968 (in press); "An Agroclimatological Model," *Science Record,* vol. 16, 1966, pp. 78–80; and "Climatic Variations and Agricultural Production in New Zealand," *New Zealand Geographer,* vol. 22, 1966, pp. 55–69.
24. E. Kuh, "Econometric Models: Is a New Age Dawning?" *American Economic Review,* vol. 55, 1965, pp. 362–369.