ECONOMIC VALUE OF IMPROVED METHODS OF TRANSLATING WEATHER INFORMATION INTO OPERATIONAL TERMS [1]

JAMES D. McQUIGG [2] AND RUSSELL G. THOMPSON
University of Missouri, Columbia, Mo.

ABSTRACT

A number of investigators have advanced the thesis that weather information has (or accrues) economic value because it makes possible "better" management decisions in a weather-sensitive process. A simulation model approach is used to modify this thesis, and to illustrate the necessity for the decision-maker to have a sufficiently precise method for translating weather information into operational terms.

1. INTRODUCTION

There are at least two reasons why attempts are being made to measure (or make reasonable estimates of) the economic value of weather information.

First, some meteorologists believe that the managers of many enterprises have not realized the potential value of recent developments in meteorology. Hallanger [4] pointed this out at a meeting of the National Industrial Conference Board in 1962. White [18] characterizes the improvements in atmospheric science in recent years as a "quiet revolution" in which even seemingly limited scientific victories can mean huge economic gains for business and government.

Second, modern tools and skilled manpower which are required for operation of a national weather service require expenditure of sizable amounts of public funds which must be justified in the budgeting process of our government. A recent U.S. Department of Commerce report [16] to the Interdepartmental Committee on Atmospheric Sciences describes some of the problems encountered in the allocation of public funds to present and future governmental programs in the atmospheric sciences.

A number of investigators, such as Demsetz [2], Gleeson [3], McQuigg [7], Moody [8], Murphy [9], Rapp and Huschke [10], Nelson and Winter [11], Thompson [14], Thompson and Brier [15], and White [18] have advanced the seemingly reasonable thesis that weather information has (or accrues) economic value because it makes possible "better" management decisions during the operation of a weather-sensitive process. It has been especially difficult to compute, or make reasonable estimates of, the increased economic value that might result from improvements in the accuracy of weather information. Reasons for this difficulty include: (1) A dearth of real economic data from weather-sensitive processes. (2) The expense, danger, or undesirability of conducting actual experiments in which the accuracy of weather information used by a decision-maker is deliberately varied.

The simulation model analysis which follows is believed worthy of being reported because it is based on real economic data from an important weather-sensitive enterprise, i.e., management of the flow of natural gas to a city in the winter. In addition, while the results of the simulation model analysis were being studied, a basic concept began to emerge which has not been emphasized by most previous investigators. This concept can be stated very simply as follows:

"Improvements in the accuracy of weather information may allow the manager of a weather-sensitive process to make 'better' (hence more valuable) decisions, *provided he has a sufficiently precise rational method for translating weather information into operational terms.*" This concept will be discussed at greater length in a later section.

2. THE GENERAL MODEL

Relations between weather events, non-weather events, man's function as a decision-maker, and the economic outcome of an enterprise may be represented by the schematic outline in figure 1. In this figure, solid lines represent relationships between actual events and the process which is being managed. Dotted lines represent the production and use of information. Collection, analysis, and transmission of information have an effect on the economic outcome only through their influence on the decision process.

In mathematical terms, consider the weather-sensitive process of figure 1. The economic outcome, π, may be expressed as:

$$\pi = f(W, O, A^*) + u, \qquad (1)$$

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[2] Missouri State Climatologist, Environmental Science Services Administration, Columbia, Mo.

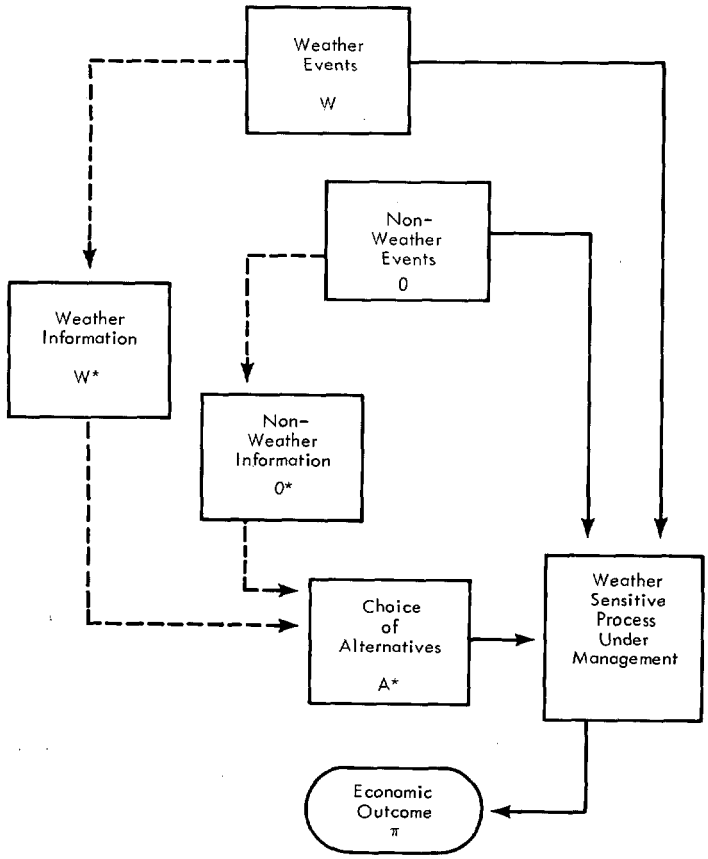

FIGURE 1.—Schematic outline of relations between weather events, non-weather events, the choice of alternatives by management, and the economic outcome of an enterprise.

where $W=(w_1, w_2, \ldots, w_n)$, some actual weather events, $O=(o_1, o_2, \ldots, o_k)$, some actual "non-weather" events, $A^*=(a_1, a_2, \ldots, a_i)$, a subset of alternatives chosen by the manager, with the * notation indicating that the choice was based on information supplied to the decision-maker. The term u represents a "disturbance" factor, which is random and normally distributed with $\bar{u}=0$, and $\sigma_u=\Phi$.

This is to say that the economic outcome of the enterprise is related to some actual weather events, some actual non-weather events, and to the particular choice of alternatives that is made by the decision-maker. The term, u, is included to point out the fact that the relationship between π and (W, O, A^*) is almost never known exactly.

By now the reader may be asking, "How do the sets W^*, O^* have any effect on π?" This can be answered by considering the decision process. At the time the choice of alternatives is being made, the decision-maker does not know the actual values of W, O that will occur, nor does he know the exact value of u. He evaluates the following

$$\pi^*=f(W^*, O^*, A) \tag{2}$$

for each possible alternative, choosing A^*, a subset of A, in some rational manner such that π^* will come as close as possible to being consistent with his long-term strategy. (One such rational strategy would be to attempt to maximize expected profit.) If W^*, O^* were always exactly right, and if $\sigma_u=0$, the decision-maker would have perfect knowledge, and could arrive at some "best" economic outcome, denoted by π_{MAX}. Most of the time in actual practice there are errors in information and $\sigma_u \neq 0$. The difference $(\pi_{MAX}-\pi)$ is related *both* to the accuracy of information considered by the decision-maker and to the distribution of the disturbance term, u. The example which follows will illustrate this point.

3. AN EXAMPLE OF SIMULATION MODEL ANALYSIS

Management of the flow of natural gas through the distribution system of a company serving a city is a weather-sensitive process [1]. This was chosen to serve as an example of simulation model analysis for several reasons:

(1) The mathematical relationship between daily natural gas demand and ambient temperature can be expressed in simple linear form.

(2) Enough regression analysis has been done on actual data to provide realistic estimates of the regression coefficients and of the variance of the "disturbance" term, σ_u^2.

(3) The set of alternatives open to management can be defined, and a rational basis exists for choosing alternatives, i.e., minimization of costs.

The pipeline serving a certain local gas company has many other customers. The amount of gas that can be pumped through the pipeline under various pressures is limited. A simplifying assumption is made that the local gas distribution system in this simulation model has no storage facilities, and that it has an agreement with the pipeline serving it that calls for "penalty" payments proportional to demand over a given amount on any given day. Wastie [17] describes such a rate structure. In order to keep from paying the "penalty" rate during periods of heavy demand for gas the local company has negotiated agreements with certain users which allow service to these users to be curtailed, with a few hours, notice.

A further simplifying assumption is made that the manager has only one time, i.e., the beginning of each day, to choose one of the two possible alternatives open to him. These are:

a_1=order no curtailment of service to local users.

a_2=order curtailment of service to some local users to (it is hoped) avoid paying the penalty rate.

One of two possible losses may occur on any particular day if the manager chooses the wrong alternative:

(1) He may order no curtailment of service when it turns out that he should have, which results in penalty payments.

(2) He may order curtailment when it turns out that he did not need to, thus losing sales that his company could have made.

4. THE SPECIFIC MODEL

The set of non-weather events is considered fixed in this application of the model. Rates for gas purchased from the pipeline and sold to local users are fixed either by contract or government regulation. The number of customers is known. (For simplicity, this number is considered fixed in this application.) Previous regression analysis [6] showed clearly that variation in demand was closely related to variation in temperature.

The reader should be aware that the model that is described in detail in the following paragraphs is believed to be realistic, but simple (unsophisticated). It is deliberately expressed in simple terms to emphasize an important point. In actual practice, a consultant meteorologist and the management of a weather-sensitive enterprise might wish to test several more sophisticated decision models.

Let Y_p be the level of demand above which the penalty rate applies, Y_i^* the decision-maker's estimate of demand, and C_i the amount of curtailment ordered for a certain day. There are two alternatives:

$$\text{If } (Y_i^* > Y_p),\ C_i = Y_i^* - Y_p$$

$$\text{If } (Y_i^* < Y_p),\ C_i = 0$$

A series of daily observed values of the number of heating degree days (base 65° F.) for December through March for 30 winters in Columbia, Mo., was used in two ways in the model.

First, several series of "forecasts," each with a given distribution of errors, were generated in the following manner: If X_i is the observed value of heating degree days for a particular day, a "forecast" value X_i^* was generated as $X_i^* = X_i + e_i$, with the property that e_i could be considered as drawn at random from a normally distributed sample in which $\bar{e}=0$, and $\sigma_e = \theta$. This was accomplished for several values of θ by a technique based on work reported by Marsaglia et al. [5] and Rotenberg [12]. For a particular value of θ, and a particular day,

$$Y_i^* = A + BX_i^*, \tag{3}$$

in which A, B are linear regression coefficients, and where the values $A=4157.0$ and $B=248.11$ were used in this application. A is in units of thousands of cubic feet of gas and B is in units of thousands of cubic feet of gas per heating degree day. From this computation of Y_i^*, the choice concerning C_i was made, as described above.

Second, several series of "observed" levels of demand Y_i were computed, to simulate several levels of precision of the linear regression relationship. For a particular day, Y_i was computed as

$$Y_i = A + BX_i - C_i + u_i \tag{4}$$

in which A, B are defined as before, X_i is the *observed* number of heating degree days, and C_i is the level of curtailment ordered. The term u_i can be thought of as being drawn at random from a normally distributed sample of values with the property that $\bar{u}=\theta$ and $\sigma_u = \Phi$.

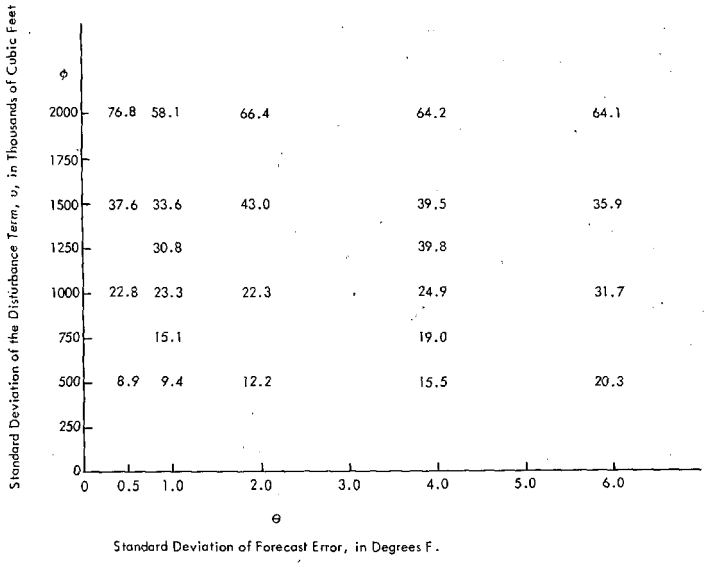

FIGURE 2.—Data in body of graph are average annual loss function values, in millions of cubic feet of natural gas.

Formula (4) illustrates that the amount of gas demanded for a particular day is influenced by the weather that actually occurs (represented by X_i), by the decision made by the manager (represented by C_i), and by some random events (represented by u_i). For a given pair of (θ, Φ), the amount of penalty sales is computed as

$$(Y_{PEN})_i = Y_i - Y_p \tag{5}$$

where $(Y_{PEN})_i = 0$ in case $Y_i < Y_p$. If $C_i > 0$, *and* $Y_i < Y_p$, the amount of lost sales is computed as

$$(Y_L)_i = Y_p - Y_i \tag{6}$$

It is assumed that one unit of penalty sales costs 10 times the value of a unit of lost sales. A value of the "loss function," L_i, is then computed as

$$L_i = (Y_L)_i + 10(Y_{PEN})_i \tag{7}$$

An average annual loss function value computed for various pairs of (θ, ϕ) is presented in figure 2. These can readily be converted into terms of money by multiplying by the proper price.

There are several refinements that may be added to this admittedly simple model. It is possible to modify the level of estimated demand Y_i^*, above which curtailment is ordered. Many local gas companies have storage facilities, into which they divert gas during comparatively warm periods and from which it can be drawn during periods of heavy demand. Sliepcevich [13] describes still

another method of taking care of heavy demand for gas during very cold periods through transport of liquefied natural gas.

The same basic decision problem exists in each of these more sophisticated models. It is necessary to estimate the demand for gas several hours in advance, and then choose one of several alternatives which it is hoped will result in the most favorable economic response.

5. RESULTS OF APPLICATION OF THE SIMULATION MODEL

Annual average loss function values, expressed in terms of millions of cubic feet of natural gas, are plotted in figure 2. In order to help the reader "calibrate" himself, the average daily natural gas demand is close to 14.5 million cubic feet for Columbia, Mo. The reader should be aware that had the model been applied to a different subset of random normal numbers (with the same statistical properties, but appearing in different order) there would be some relatively small differences in the average annual loss function values plotted in figure 2.

Some interesting patterns emerge in this figure. First, there is a reasonably consistent increase in the values in the body of the figure from left to right in the lower portion of the graph, where $\phi<1000$. The reader is reminded that this represents the situation in which the decision-maker is using a reasonably precise expression to translate weather information into operational terms. (The regression analysis of Columbia data by McQuigg and Thompson [6] produced values of ϕ in the 700–1000 range.) As one studies the upper region of figure 2, where $\phi>1500$, it is apparent that there is no consistent change in the average value of the loss function as θ increases or decreases. Putting this another way, a manager using an imprecise relationship to translate weather information into estimates of gas demand could not discriminate between degree-day forecasts that were almost perfect and those that were very poor.

It is also interesting to note that there is a reasonably consistent change in the average annual loss function values as ϕ changes from large to smaller values, given a certain value of θ. This suggests the possibility that efforts to increase the precision of the relationship used by the decision-maker will "pay off", even though the forecasts used may be of only comparatively poor accuracy.

This interpretation of results is based on one admittedly simple (but realistic) model, applied to a comparatively long period of weather records. If these results are typical of other weather-sensitive decision problems, one should not be surprised to find some managers unenthusiastic about the potential value of weather information. This would be especially true if they had been unwilling to allocate some of their own resources to develop reasonably precise relationships, or to develop rational decision patterns, or if they were dealing in an area where there were no consistent relationships between weather events and their enterprises.

6. GENERAL CONCLUSIONS

It has been shown that a simulation model approach can be used to estimate marginal changes in the value of improvements in weather information. It would be presumptuous to claim that similar results would be obtained from application of this approach to all kinds of weather-sensitive decisions. However, there are many decision problems that resemble the one used in this paper. The idea of a level of activity above (or below) which some "penalty" is exacted, is common to many enterprises. Flooding does not occur until some particular water level is exceeded; freezing does not occur until some temperature is reached; a structure is not damaged until a certain wind speed is exceeded, etc.

It does seem reasonable to claim that improvements in the accuracy of weather information will result in increased economic returns to individual decision-makers, if:

(1) Alternatives, or choices of action are open to the decision-maker, and a difference in economic consequences exists between at least two combinations of weather events and alternatives.

(2) The decision-maker has knowledge of a sufficiently precise relationship between weather events and the events under his control to allow him to translate weather information into economically meaningful terms, which in turn lead him to a rational choice of alternatives.

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