Abstract

Meteorological services are expected to function as forecasting agencies, but much of the existing data collection network appears to exist in order to provide a data base for scientific studies. A better definition of the goals of a meteorological service should result in greater management and administrative efficiency, and we offer suggestions as to the means of achieving this within a systems analytic framework.

1. Introduction

Most professional meteorologists work in institutions that encompass both public service and scientific research roles. As a result, meteorologists seem to group themselves around one of two central attitudes, namely:

1) That meteorology is an exact physical science that aims at explaining features of the atmosphere. This leads to research and development policies that stress sound theory and assume that public services will be improved by way of understanding atmospheric processes better. This results in tactics whereby problems are solved by breaking them down into smaller and smaller components until a level of simplicity is reached such that each part can be solved by acceptable scientific methods. This is known as the reductionist approach.

2) That meteorology is a public service and that this is more important than its scientific method. The accuracy of forecasts, for example, becomes more important than the method of achieving them. The end is more important than the means, while the reverse is true of the alternative position.

The ideal meteorological service would be one that successfully combines the two attitudes, but for 30 years the reductionist philosophy has dominated. This has had two results:

1) Reputable meteorological journals seldom publish papers that deal with services. Published papers are expected to contain sound theory or original technical content. This precludes publication of material that might improve forecasting while not contributing to explanation.

2) There is little public discussion of management and policy in meteorology. Current interest in the economic value of services is narrowed because discussion is limited to the dominant philosophy.

In order to illustrate this bias, we have extracted and classified a sample of papers published recently in four journals that we consider most likely to discuss forecasting and policy. The results in Table 1 show that, in this sample of published articles, more than half (55%) dealt with "science." The classification definitions used are as follows:

*Science*: concerned with theory and pursuit of knowledge for its own sake.

*Forecasting*: concerned with developing or improving forecasting tools.

*Policy*: dealing with scientific or service policy problems.

*Other*: covering mainly history, climatology, and instruments.

The regular report features in the *WMO Bulletin* were excluded. Some of these might be classified as policy documents, but they report rather than discuss policy decisions. *Weather* provides the bulk of the "other" classification, which reflects that journal's bias towards less numerate meteorologists. Perhaps the statistics most clearly demonstrating the wide acceptance of the present methodological way of thinking (i.e., the paradigm) are those that show that only 12% of papers deal with forecasting and less than 4% with policy issues. If all meteorological journals had been sampled, the percentages would have been much smaller. It is significant that this bias was not as clear before the mid-1950s, and there is evidence that it may already be changing—the
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has recently instituted a new section called "Focus on Forecasting," and a new American magazine called The National Weather Digest has appeared and has been devoted exclusively to forecasting.

Despite some notable exceptions (for example, Sutton, 1954; and Tucker, 1976), meteorologists fail to display insight or perspective on where their discipline lies in the philosophy of either science or management; yet this perspective must be developed and discussed if the discipline is to move forward with its dual scientific and public roles. In order to stimulate discussion, we suggest an alternative scientific and management method within a complete philosophical framework. This systems approach has been defined in many ways. We stress two aspects: First, the philosophy is holistic rather than reductionist—whole units are treated as more than the sum of their individual parts. Second, the product of a process is considered more important than the process itself, which simply should be as efficient as possible. Such assumptions may result in radically different attitudes towards both the management and the science of meteorology (Young, 1978).

2. Systems and services

a. Reductionist management

Many meteorological services have physical scientists in senior management positions, but there is little public discussion on how scientific attitudes influence managerial style. A reductionist philosophy tends towards "technocratic" decision-making (Frenkkel and Goodall, 1978). This is because it is believed fundamentally that a correct decision can be made on the basis of sufficient information. Reaching the correct decision simply depends upon the user having identified the problem clearly and asking the correctly framed question. This might be, for example, a request for a particular set of climate statistics. Unfortunately, many decision makers actually use a trial and error, or incremental, approach to a goal, feeling forward slowly among uncertainties. Technocratic responses from meteorological services in reply to incremental questions from the public creates a communication gap that is very difficult to bridge. Many management journals reflect problems of this kind. As examples, Cox (1977) examines constraints to technocratic decision-making, and Hirschman and Lindblom (1962) advocate a systems framework and deny that public policy problems can be solved by better understanding!

b. Service goals

If a systems approach is carried into public service meteorology, the first question raised is, "What are the goals of a meteorological service?" The real answers to this question would be imprecise. Frequently users do not seem to have a clear idea of what service they want. Unfortunately, imprecise demands from users have been interpreted by professional meteorologists as an indication that users do not know what they want. It may be more truthful to suggest that meteorologists are sometimes ignorant of how administrators and managers use information and how difficult it may be to phrase a precise question in ignorance of the kinds of answers that are possible. Another question that meteorologists might address themselves to is how to give reasonable answers to problems if they cannot perceive the questions that could be asked. In forecasting, such a failure of perception can lead to a forecaster's view of what is required of him being at variance with actual requirements, and his forecasting method could change as a result. Mason (1979) has indicated that different measurement criteria of a forecaster's skill can be optimized in different ways. As an extreme example, if a forecaster knows that he will be judged according to one set of criteria, then his best strategy may be to issue the climatological means as his forecast; a different set of criteria could lead to a best strategy in which he forecasts tomorrow's weather as being identical to today's. In practice, the individual and the meteorological community as a whole perform according to such preconceived and internalized criteria.

In order to bring public questions and attitudes to a clearly articulated state, service structures must allow for close interaction. There should be feedback into meteorological institutions so that responses to user queries can slowly, but in a controlled manner, approach the poorly articulated goals of information users more closely. In practical terms, this means interaction and a flexible organization structure that encourages this process to develop.

c. Efficiency

It is possible to talk about the efficient provision of a service only if the goal is defined clearly. Economic methods can be one way of identifying efficiency, at least in relation to costs. On a broader front, efficiency in the production of services might be approached through alternative scientific methods (discussed later) and through alternative methods of staff training and variation in career structures. For example, given difficulties of question articulation, a staff trained in more pragmatic methods or in descriptive disciplines might be better able to act as an interface between scientists and service consumers. The contemporary bias in meteorology towards a particular type of science, organization, and professional could be subject to radical rethinking. Currently, services seem to be characterized by poorly defined goals achieved with precise and expensive measurement methods, a production structure that would be questioned in any economic management context.

d. Public services

Examples from a range of meteorological services show various balances between the precision of questions asked by users and the types of service provided. Frenkkel and Goodall (1978) divide meteorological users into four groups 1) laymen, 2) operational managers, 3) planners, and 4) national policymakers. They see the problem of weather forecasting as one of providing a suitable model for the tactical decisions made by groups 1) and 2) and for the strategic decisions made by groups 3) and 4). The most successful interactions be-
tween forecaster and customer occur with those in group 2). Perhaps the happiest examples are in the field of aviation meteorology, where statements are clearly defined, often by international agreement, and are put in a codified form acceptable to suppliers and users. Thus, statements of runway conditions and terminal field forecasts leave little scope for comment and can be criticized only in terms of accuracy. Forecasting for the general public provides an example in which goals are poorly defined. General forecasting will remain contentious as long as it remains a service for such varied interests. Climatological data services are a case in which flexibility in data and question processing is important while interaction between questioner and climatologist comes closer and closer to identifying the right question and the correct data to answer it. All too often climatological inquiries are met by technocratic responses from monolithic structures that are concerned with efficient cataloguing of data rather than with identifying methods of answering questions. An interesting practical ramification of systems thinking is that, if users had to pay for climatological services, they would spend more of their own time clarifying both problems and questions before entering into a dialog.

Agricultural meteorology is an example where a systems approach could yield benefits. The basic problem has been failure to identify realistic goals for agricultural services—perhaps goals have been identified at only such a general level that all the problems of public forecasting apply. The result has been acrimonious public debate, an example being Russel (1976), and service recommendations (WMO, 1963), which consider the economics of services but not the institutional aspects that would allow the professional meteorologist to interact with the agricultural community. While interaction occurs at the research level, notably in plant physiology and micrometeorological studies, it is less evident at other levels. Inflexible approaches to instrumentation, inflexible bureaucratic structures that make short-period station operation difficult, insistence on high-precision measurements: all hinder contributions to agricultural development programs. A philosophy that stresses high precision in order to obtain better physical explanation may be inefficient in situations where low precision or even relative data may be enough to help the decision maker.

3. Systems and science

There is a seductive beauty in the equations of fluid dynamics and most physical scientists are imbued with the idea that beauty and scientific truth are related (Chandrasekhar, 1979). It is easy to understand the enthusiasm with which the first numerical weather forecasts were greeted and seen as harbingers of an age to come. There is no doubt that there have been great improvements in numerical weather prediction during the past 20 years, but there is a growing debate as to whether numerical weather prediction has led to a significant improvement in forecasting during the past five years. Writers such as Shuman (1978) and Charba and Klein (1980) see a continued improvement, whereas others, such as Robinson (1978) and Ramage (1976, 1978), express serious reservations. This debate does not deny that the task of parameterization within numerical models has led to a greater physical understanding of the behavior of the atmosphere. What it does query is the effectiveness of large-scale numerical weather prediction models as an adjunct to forecasting, and whether the benefits to be gained by these models may not have reached an asymptotic plateau so that a new approach may be necessary to obtain further improvements in forecasting.

a. Reductionist science

The present system of numerical weather prediction (Gilchrist, 1979) relies on five equations. Three of these are subsumed into the components of the Navier-Stokes equation, which describes the motion of a gaseous fluid, and the remaining two equations represent the conservation of mass and energy, respectively.

The first difficulty arises when one tries to formulate these equations properly. What terms should stay in and what terms should stay out? Some terms can be omitted because their effect is small, but other terms—such as atmospheric compressibility—must be omitted because their effect will come to dominate the result, even though their meteorological import is nil. In the energy equation, the simplest model would treat the atmosphere as an ideal gas. Unfortunately, this would eliminate any possibility of rainfall since an ideal gas never condenses. A practical model really does need to have clouds incorporated, but in the tropics this raises further difficulties. Much of the heat supplied to the tropical atmosphere occurs when monsoonal cumulus clouds condense their water vapor. Each individual cloud is an important source of heat, yet the clouds themselves are found to form clusters, and these clusters together make up the monsoon. The difficulty is that a model at any one scale of size needs to incorporate phenomena at a smaller scale, which in turn requires modeling at an even smaller scale, and so on.

Secondly, there is no mathematical method capable of an analytical solution of the set of nonlinear partial differential equations of second order. One resorts to numerical methods of solution and the numerical methods can introduce instabilities (Haltiner, 1971; Beer, 1974) or spurious diffusion (Molenkamp, 1968). Once these effects are recognized they can be corrected, but there is no certainty that all numerical weather prediction models are free of such errors.

The atmosphere is a complex environmental system that nevertheless seems to display a certain regularity in its behavior, and it is instructive to examine the literature on the modeling of environmental systems in order to see whether new insights can be gleaned from it. In many cases the lack of success of complex environmental models can be attributed in part to the "badly defined" nature of such systems, and it is only recently that there have been attempts to construct a theoretical framework and modeling methodology for such badly defined systems (Young, 1978).

b. Stochastic and systems methods: The example of hydrology

The dynamic equations of hydrology consist of the equations of mass conservation and the St. Venant equations (the hy-
dromological equivalent of the Navier-Stokes equation), and numerical solutions to these are still being developed. The obvious nature of the hydrological inputs (rainfall, groundwater) and outputs (discharge), and their confinement to well-defined streams and rivers, led to the application of deterministic (Thomann, 1972) and stochastic (Kashyap and Rao, 1976; Lawrance and Kottegoda, 1977) systems techniques to hydrological questions. Presumably, the engineering background of the typical hydrologist was also a factor in the ready acceptance of this technique. Basically, it became apparent that much of the behavior of rivers and streams could be modeled in holistic terms whereby the river was compartmentalized into a number of reaches with an input, an output, and a system equation characterizing each reach.

Though there are many exceptions, we feel it would be fair to say that the goal of a hydrological model was seen as the provision of a method that was capable of successful prediction. In both hydrology and fluvial geomorphology (Smart, 1979) there has been a 20-year running controversy over the relative merits of deterministic models, which are based on the laws of physics, and stochastic models, which attempt to incorporate the inherent randomness of geophysical flows.

We find it a most intriguing sociological observation that with a few exceptions—the most notable being the Techniques Development Laboratory of the National Oceanic and Atmospheric Administration (NOAA) (Klein and Glahn, 1974)—the meteorological community has not found itself in a similar argument. There has been a strong belief that whereas climate is a statistical concept and may need to be modeled as such. The problem, then, is to define the time scale involved in a numerical weather forecast. Gilchrist (1979) shows that the theoretical limit for a deterministic weather forecast is about 15 days, though in most realistic circumstances the actual limit is closer to a few days.

In order to see if stochastic modeling, per se, could be of use in weather forecasting, we used data from two Australian Territories in the Indian Ocean—Christmas Island and Cocos Island—and used the CAPTAIN (Young and Jakeman, 1979) package of programs in order to find the best transfer function linking inputs and outputs. The results are summarized in Table 2, where the modeling skill, S, is defined as

\[ S = 1 - \frac{\sum (x_k - \hat{x}_k)^2}{\sum x_k^2} \]  

where \( x_k \) is the observed value of an output variable and \( \hat{x}_k \) is its modeled value.

It is interesting to note that the skill values for the models, based on single station daily data, are within much the same range (0.4–0.7) as the skill values of Barnett and Hasselmann (1979) for stochastic climate modeling based on large-scale time and space averaging of the data.

Though the skill values indicate that it may be possible to construct an adequate stochastic model relating variables between two stations, the long-term predictability of a purely stochastic model seems limited. To examine this, we fitted the most common such model—an autoregressive moving average (ARMA) model (Box and Jenkins, 1976; Balestri et al., 1978) to the daily Christmas Island pressure data \( (p_1, p_2, p_3, \ldots, p_k, \ldots) \), treated as a time series

| Table 2. Sample results from stochastic forecasting methods. |
|----------------------------------|----------|----------------|
| **Input** | **Output** | **Skill** |
| \( T_x \) | \( T_c \) | 0.35 Daily 1200 LT |
| \( T_x \) | \( T_c \) | 0.44 1200 LT every fourth day |
| \( T_x \) | \( T_c \) | 0.78 20-day average |
| \( p_x \) | \( p_c \) | 0.50 Based on daily 1200 LT readings |
| \( p_x \) | \( p_c \) | 0.73 Daily, 1200 LT |
| \( u_c \) | \( u_c \) | 0.06 Daily, 1200 LT |

\( T = \) temperature, \( p = \) pressure, \( \rho = \) density, \( u = \) meridional wind; subscript \( x \) denotes Christmas Island, \( c \) denotes Cocos Island.

\( (P_1, P_2, P_3, \ldots, P_k, P_{k+1}) \) after it had been differenced in order to remove the long period climatic trends. The ARMA model does not have a deterministic input, but is excited by purely random inputs, and nowadays there is a sophisticated methodology of recursive adaptive prediction for such models (e.g., Mendel and Fu, 1970). The resultant simple ARMA model is:

\[ P_k = p_{k+1} - p_k \]  

\[ P_k = \left( \frac{1 + 0.05z^{-1} - 0.09z^{-2} - 0.06z^{-3} - 0.12z^{-4}}{1 + 0.176z^{-1} + 0.21z^{-2} + 0.13z^{-3} - 0.07z^{-4}} \right) e_k \]  

where \( e_k \) is Gaussian random noise and \( z^{-1} \) represents the backward shift operator such that the pressure difference at time \( k \), \( P_k \), is

\[ P_k = z^{-1} P_{k+1} \]

The impulse response of the model to Eq. (3) (i.e., its response to a sudden step in the pressure field) is illustrated in Fig. 1. The model has effectively lost predictive capability after five days. This is also indicated in the power spectrum of the model of Eq. (3), which is depicted in Fig. 2. The dynamics of the system are controlled by periodicities in the four-to-five day range and the differencing has eliminated the longer-term behavior. The existence of strong periodicities in this range in the tropical troposphere is well known, and we find it of interest to note the control that these dynamics have on the statistically determined model.

We are thus led to echo Davis (1977) in noting that a combined statistical–dynamic model is liable to have considerably greater prediction skill than could be obtained from either purely statistical or purely dynamical approaches alone. In addition, a computer run of a meteorological general circulation model is a costly process. The number of computations involved requires extremely long processor times on very large machines. By contrast, the statistical models are normally very cheap and very fast to run. If a dynamic-statistical hybrid model can be constructed in which the statistical part successfully eliminates a large portion of the forward integrations of the dynamic part, then there would be a significant economical advantage.

The most successful hybrid approach to date appears to be the use of Model Output Statistics (MOS) from the Tech-
niques Development Laboratory of NOAA (Klein and Glahn, 1974; Zurndorfer et al., 1979). The MOS method involves matching observations of local weather with output from numerical models. Forecast equations then are determined by statistical techniques, so that the bias and inaccuracy of numerical models, as well as the local climatology, can be taken into account by the forecast system. We would envisage that the next stage in dynamic-statistical hybridization would consist of a feedback loop that would allow the parameters of the dynamic model to be updated so as to reduce the statistical uncertainties of the statistical model.

It may be argued that transfer function modeling is most appropriate in forecasting problems where dynamic modeling is impossible and we do not know how to construct the model because our understanding of the processes is inadequate. An interesting example of such a problem is Findlater’s (1977) description of a statistical relationship between low-level mean winds over east Africa and West Indian rainfall one year later. In this case Findlater was able to suggest causal hypotheses, including the influences of ocean currents and sea surface temperatures, but it was clearly impossible to construct a mechanistic-dynamic model. Again, a simple input-output model was predicated and again CAPTAIN was used to fit a linear model to some of Findlater’s published results. The model took the form:

$$R_k = \frac{(46.6z^{-1} - 64.2z^{-2})}{z^{-1} - 0.83z^{-2}} W_k + \text{noise}$$

where $W_k$ is the overlapped mean wind index of Findlater’s Appendix II and $R_k$ is the deviation from the mean of the overlapped average rainfall of Bombay, Kolhapur, and Poona given in the same appendix. The time unit for the backward shift operator $z^{-1}$ is a year. Output data and the model fit are shown with means removed in Fig. 3, and the skill score is 0.77. Such a simple model, linking the mean July wind index with smoothed rainfall from three stations in western India one year later, would be quite impossible to construct without generalizing a simple transfer function.

Although this discussion has centered on weather forecasting, the method could be used in other fields of applied meteorology. Crop-yield forecasting would be an obvious possibility, and Steele and Jakeman (1980) have successfully used it in air pollution modeling.

4. Conclusions: Beyond costs and benefits

It is interesting to consider the ramifications of an alternative philosophy on, for example, meteorological services in developing countries. In many countries in the tropics, numerical modeling is unlikely, for theoretical and practical reasons, to become an important aid to forecasting in the near future. Few of these countries need be committed to a partic-
ular form of science, and thus can examine alternatives. Instead of examining costs of services in terms of poorly measured user benefits (Bernard, 1975; Sah, 1979), the important question surrounds the cost of a whole approach as opposed to its alternatives.

Sometimes scientists do not appreciate the close relationship between their science and Western culture. For alternative viewpoints, Barnes (1973) looks at similarities between science and magic and Beer (1978) examines the conflict between science, technology, and non-Western culture. Other aspects are discussed by Hills (1979). Factors such as the high cost of overprecise measurement and the loss of employment with automation then fall into a wider perspective. Basic questions are unanswered at present: First, is reductionist science more efficient than alternatives? Second, if it is, is it more expensive? A multiple preference situation emerges, where the factors to be weighed are scientific knowledge, applied information value, efficiency, and cost. Limiting discussion to costs and benefits identifies only two accessible elements. In a wider perspective, other factors may be more important.

References


