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WEATHER INFORMATION: ITS USES, ACTUAL AND POTENTIAL

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SANTA MONICA • CALIFORNIA

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PREFACE

This report represents The RAND Corporation's portion of a study conducted by the U.S. Weather Bureau to determine the impact of research in the atmospheric sciences on the social and economic activities of the nation. The study was initiated at the request of the Interdepartmental Committee on Atmospheric Sciences (ICAS). The RAND work was performed under Contract Cwb-10772 with the Weather Bureau.

The original request was for a study that would compare the benefits to be derived from atmospheric research with the cost of proposed research. This report, however, is devoted largely to a discussion of the benefit to be derived from improved weather information.

The thesis is advanced that weather information has value principally because it leads many people and organizations to make the decisions that counter the deleterious effects of weather. This hypothesis is then used both to explicate the difficulties of evaluating atmospheric research in economic terms and to suggest techniques for improving weather information and estimating the value of weather information thus improved.

NONTECHNICAL SUMMARY

Asked to do so by the Chief of the U.S. Weather Bureau, RAND has taken a hard look at ways and means to foresee what a planned piece of meteorological research will be worth to man, to the world of trade, and to the state.

The search led first to the men in all walks of life whose choice of action rests on their own views of what weather will do to them and to whatever they may value. The man who lacks access to weather forecasts but whose values are affected by the weather has little choice but to base his decisions as though what has occurred in the past will occur again. When this assumption is wrong, his loss may be great or his gains small, so he adopts a conservative posture, which may cut his losses, but can rarely help him pyramid his gains.

A man who knows what weather is coming part of the time can calculate his risks more closely, can occasionally take risks knowing that part of the time they will pay off. What he gains when he acts on his foreknowledge measures the worth of forecasts to him.

No daily forecast of the weather is right every day. But one who must lean on forecasts need not always act as though they were always true. By analysing the costs, losses, and gains that result from each possible course of action open to him under conditions of each kind of weather that affects him, and by weighting this according to the percentage of times the daily forecast is right, he can fix on an optimum course of action for every type of weather forecast (not of weather itself) that will make his long-term loss small and his long-term gains large.

A person or group that specializes in this comparing of weather and actions, and weighting the results by the probability of correct forecasts is called in this report a weather advisor.

Surely there are few such weather analyses being made today, and there may be none. Yet any assessment of the worth of weather forecasts -- or of the improvement of such forecasts -- can only come from the amassing of the findings of thousands of such studies, each

applied to some small segment of the economy or society. It is here urged that the function of the weather advisor be developed -- not only because of the immediate gain for individual users of the weather-advisor function, but also as a first step toward learning what our investments in meteorological knowledge are really worth.

There are a few warnings to be noted. First, if every farmer at one time took advantage of improved weather forecasts, the resulting glut of crops might create a general loss. It is impossible to foresee in how many activities other than farming this might apply. Second, no one can rationally assess the value of the lives and health that are preserved by weather forecasts or improvements in the forecasts. Third, no one can fully estimate the secondary gains to any initial benefit; the fact that a trucker delivers his freight on time and in good condition means savings to his customer as well as to him. Fourth, no one can truly estimate the worth of many public operations that may be considerably enhanced by foreknowledge of the weather; e.g., the worth of delivering the mail or of keeping city traffic moving during a storm.

Finally, although through the efforts of the hypothesized weather advisor it may be possible someday to make an after-the-fact crude estimate of the total worth of an improvement in weather information, it must be remembered that research is notably an activity that results in the unforeseen, the unforeseen being benefits as expected, no benefits, or benefits that fall in an unexpected quarter.

ACKNOWLEDGMENT

Although this report represents efforts of RAND and reflects the point of view of the authors, it was done in close cooperation with a study group within the Weather Bureau and with the counsel of the Steering Committee appointed by the National Academy of Sciences and the Chief of the Weather Bureau. The authors are greatly indebted to all the members of both of these groups for the assistance they have provided; the close working arrangements preclude the assignment of specific ideas to specific individuals.

R. R. Nelson and T. K. Glennan, Jr., economists with The RAND Corporation, provided much material for this report. Their broad experience with applications of decision theory within the field of economics and their understanding of the problems of evaluating research were invaluable.

The study of the two-route problem presented as Appendix C was made by Conway Leovy with the assistance of E. S. Batten.

CONTENTS

I. ORIGIN AND APPROACH

In reviewing the research programs of all federal agencies in the atmospheric sciences, the Interdepartmental Committee on Atmospheric Sciences (ICAS) recognized eight major objectives of federal meteorological research. One of these major objectives is:(1)

> "To improve the means of description and the prediction of the weather for social and economic purposes."

The chairman of ICAS requested that the Department of Commerce Member have made an analysis "...to determine the benefits to be derived and the costs of meeting this objective...." In order to proceed with such a study, it is expedient to formulate a series of questions which will highlight some of the difficulties which are not apparent in the initial statement of the problem.

In the following paragraphs we will present the series of questions this report attempts to answer. We believe that they are in such sequence that the answer to one depends on the answers to all those preceding. The brief answer which follows each question in this section serves as a guide to its treatment in subsequent sections of the report.

Perhaps the first question to be asked is, "How can descriptions and predictions of the weather be of social or economic benefit?" The first reaction most people have when pressed with this question is to suggest that forecasts prevent weather-caused disasters. A little reflection leads to the realization that, unless some action is taken, no amount of description or prediction will prevent weather-caused disasters.

The benefits to be derived from prediction and description of the weather are the benefits of having information upon which a course of action can be based. Since the information content is the source of the benefit, we choose to consolidate prediction and description into a single term -- weather information. Weather information can

be a history of past observations, a description of the current state of the atmosphere or a prediction of its future state.

The conclusion that weather information is useful because it leads to better decisions led us naturally to a survey of decision makers. A cursory examination indicates that they are many and that they have a variety of problems. Furthermore, there is a strong suggestion that, because of conflicting interests, benefits to one may work to the detriment of another. Because of the number of decision makers, the variety of their problems, and the fact that their benefits are not necessarily additive, it was concluded that a rigorous analysis of the benefit of weather information is infeasible.

We felt that if any progress were to be made on the problem of estimating the usefulness of weather information, it would be necessary to investigate more thoroughly these same decision makers — the real users of weather information. Our second question is, therefore, "Who uses the information and to what kind of problems is it applied?" Only by searching out the individual users of weather information and analysing their problems, the weather effects that create these problems, and the possible courses of action that these users can take, can we estimate the need for weather service and its possible benefits.

The logical third question is: "How can research be planned in such a way as to improve prediction and description?" If we accept the thesis that the value of weather information derives from its use in determining a course of action, then its value will increase as the use of the information leads to more frequent choices of the proper course of action. It should be noted that the increase in value or utility of better information comes from its usefulness in making a choice, not from improvement of the information *per se*.

It is important, therefore, that the quality of, and improvements in, weather information be judged by the effect it has on the consumer of the information and not by some arbitrary standards of accuracy and efficiency that merely appear reasonable within the structure of a weather service.

The fourth question, which summarizes the problem is, "How can the cost of a research project be compared with the benefit which

will be derived from it?" We note that the total cost and benefit of improving weather service involves too many imponderables to be subjected to a rigorous cost--benefit analysis. We suggest specific research that will lead to better utilization of present service by the users; this same research will also provide estimates of the value of weather service. An outline of a crude, simple technique for estimating the value of improved information is suggested.

II. WEATHER INFORMATION AND DECISIONS

DECISION MODELS

We will accept as axiomatic the idea that weather information has value only insofar as it is used to decide on a favorable course of action. In order to investigate the ramifications of this idea and to study the value that weather information may have, it is useful to have some sort of model of the decision process. Such models have been proposed by Thompson,[2] Gringorten,[3] Nelson and Winter,[4] and several others. We will reproduce here the simplified arguments following Nelson and Winter for the most simple of all possible decision processes.

Our purpose in reviewing the decision process is not to provide a means for evaluating the weather service or the weather information put out by the weather service, but rather to show something of how the decision process works.

It is highly unlikely that anyone currently using weather information, even though he might do so successfully, could set down all of the parameters necessary for making a rigorous evaluation. Nevertheless, whether the process is a rigorous, quantitative, mathematical one or a subjective analysis in the mind of some decision maker, the basic principles of the mathematical model will hold. The difference lies in the rigor with which the process is carried out.

A Simple Model

We will, therefore, first derive the rigorous procedure for a decision maker who has two courses of action, one which would be better in one weather state, and one which would be better in another. We shall then show how this simple model needs to be made more complex in order to fit the real world, and incidentally, try to indicate how the subjective decision maker proceeds along the lines of this model.

We take a decision maker who has two alternate methods of doing a given task. One method is more advantageous in one weather condition; the other is better for another condition. For example, in the Los Angeles trucker's problem analysed by Nelson and Winter,[(4)] the cargo can go uncovered if rain is absent or very light, but if heavy rain occurs, the cargo must be covered with a tarpaulin. There are costs and losses associated with these actions and with subsequent weather conditions that can best be visualized with the aid of a matrix, Fig. 1(a). Here a_1 and a_2 are the alternative actions, w_1, and w_2 are the two different weather states.

The C_{ij} indicates the cost or loss that occurs as the decision maker chooses his action and as a weather state follows.

Assume that action a_1 is better if weather state w_1 occurs, and that action a_2 is better if weather state w_2 occurs. In this instance C_{11} and C_{22} would be maximum gains or minimum losses and C_{21} and C_{12} would be minimum gains or maximum losses. Where the decision maker correctly matches the action to the weather state there is a maximum gain or a minimum loss. Where the decision maker incorrectly matches the action to the weather state there is a minimum gain or a maximum loss.

Consider the case of the trucker. Here w_1 represents less than 0.15" of rain, w_2 more than 0.15" of rain, whereas a_1 represents not covering the trucks, and a_2 represents covering them. Now C_{11} is the cost or loss if rain is absent or light and the trucks are not covered; it is zero in this example. The cost of covering the trucks, C_{21}, is given as \$20. The loss to the trucker through cargo damage if the cargo is not covered and rain occurs, is C_{12}; it is estimated at \$500 for the trucker. Again, C_{22} is the cost of covering the trucks, \$20; the subsequent weather does not vary this cost.

Now suppose a decision maker knows that the weather state w_1 occurs P_1 fraction of the time, and weather state w_2 occurs $P_2 = (1-P_1)$ fraction of the time. If the decision maker has no other information he may decide to take action a_1 always or take action a_2 always. His climatologically expected costs for each decision if he always takes action a_1 are:

$$\bar{C}_1(c) = P_1C_{11} + P_2C_{12} \quad .$$

His expected costs if he takes action a_2 are:

$$\bar{C}_2(c) = P_1C_{21} + P_2C_{22} \quad .$$

For the Los Angeles trucker in the rainy season, $P_2 = 0.09$ and $P_1 = 0.91$. His expected costs if he never covers the cargo are, therefore:

$$\bar{C}_1(c) = 0.91 \times 0 + 0.09 \times 500 = \$45 \text{ per shipment,}$$

and if he always covers the cargo, they are:

$$\bar{C}_2(c) = 0.91 \times 20 + 0.09 \times 20 = \$20 \text{ per shipment.}$$

In the absence of more precise information, the trucker's only rational decision is always to cover the trucks in the rainy season and accept a cost of \$20 per truck in preference to an expected loss of \$45 per truck.

Now suppose the decision maker had perfect information. He would always take action a_1 when w_1 occurred and action a_2 when w_2 occurred. Then his perfect-prediction-based expected cost would be

$$\bar{C}(p) = P_1 \times C_{11} + P_2 \times C_{22} \quad .$$

For the trucker, the expected cost would be

$$\bar{C}(p) = 0.91 \times 0 + 0.09 \times 20 = \$1.80 \text{ per shipment,}$$

a saving of \$18.20 per shipment over the best decision based on climatology.

In actual practice the decision maker would not be able to get perfect forecasts, but he could get forecasts that might be better than climatology. Such an imperfect information system can be represented by Fig. 1(b).

Weather state	Cost for action vs. weather state	
	Action, a_1	Action, a_2
w_1	C_{11}	C_{21}
w_2	C_{12}	C_{22}

(a)

Weather state	Joint probabilities		Total
	Information, I_1	Information, I_2	
w_1	$\pi_1\pi_{11}$	$\pi_2\pi_{21}$	P_1
w_2	$\pi_1\pi_{12}$	$\pi_2\pi_{22}$	P_2
Total	π_1	π_2	1.0

$$1.0 = \pi_1 + \pi_2 = \pi_{11} + \pi_{12} = \pi_{21} + \pi_{22} + P_1 + P_2$$

(b)

Fig. 1 Simple decision--information system

In this contingency table the w_j indicate the weather states as before, and the I_i represent the information given to the decision maker as to what weather state to expect. The column headed "Total" contains the climatological probability of the occurrence of each weather state, P_1 and P_2. The row labeled "Total" shows the relative frequency, π_1 and π_2, with which the information is given that the weather will be in either state. The π_{ij} are the conditional probabilities that weather state w_j will occur if information I_i is given, and of course, $\pi_1\pi_{11}$ is the joint probability that both I_1 and w_1 occur.

It should be noted that the P_j are fixed by the climatology but that the π_i can be modified by the person giving the information. It should also be noted that, once the π_i are fixed, a single π_{ij} will completely determine the remainder of the entries in the matrix. Once the relative frequency of giving the information that the weather will be in state 1 is decided, and the appropriate values of the π_{ij} are determined from some forecasting system, the cost to the decision maker with this kind of information can be calculated as

$$C(I) = \pi_1(\pi_{11}C_{11} + \pi_{12}C_{12}) + \pi_2(\pi_{21}C_{21} + \pi_{22}C_{22}) \quad .$$

Returning to the problem of the trucker, let us assume that, on 18 out of 100 days, he receives information that more than 0.15 inches of rain will fall; i.e., π_2 is 0.18. Of these 18 days, rain actually occurs only seven times; so $\pi_{22} = 0.39$. From the relation among the variables in the contingency table we find

$$\begin{array}{lll} \pi_{11} = 0.98 & \pi_{21} = 0.61 & P_1 = 0.91 \\ \pi_{12} = 0.02 & \pi_{22} = 0.39 & P_2 = 0.09 \\ \pi_1 = 0.82 & \pi_2 = 0.18 & \end{array}$$

The trucker's costs are then reduced to

$$C(I) = 0.82\ (0.98 \times 0 + 0.02 \times 500) + 0.18\ (0.61 \times 20 + 0.39 \times 20)$$

$$= \$11.80 \text{ per shipment,}$$

a saving of $8.20 over his best decision from climatology, but still $10.00 higher than his costs if the information were perfect.

We might note at this point that, for categorical forecasts, it is possible to make an evaluation of the increase of value of timely information over climatology, but it is not possible to determine the nature of those forecasts that would be most valuable to the decision maker. If the forecasts were expressed in some manner that would permit the calculation of π_{ij} as a function of π_i, it would be possible to choose that distribution of the information which minimized the loss or maximized the gain of the user. Note that the forecasts that result in the maximum gain to the user are not necessarily those that are most frequently correct. Probability forecasts are the most direct method of supplying this additional information.

Complicating Factors

Let us consider some of the factors that make an actual decision process more complex than this simple model. The first point that must be considered is that decisions are not independent events; they must be made sequentially, and a decision at one point in time is dependent on preceding decisions and subsequent alternatives. This means that the elements of the process, the a_j, w_j, I_1, and C_{ij} are not fixed numbers but are functions of what has gone before and what may follow.

In the example that has been used to demonstrate the technique, it might be noted that the value of all cargoes is not likely to be the same. Some cargoes may be damaged by lesser amounts of rain while others might be able to withstand more rain without damage. Bulky cargoes may require more labor to cover than compact loads. It is apparent, from even this simple and relatively straightforward example, that our model does not conform strictly to reality.

Consider as another example, the decision to irrigate or not to irrigate a certain crop. The dividing line between w_1 and w_2 keeps shifting day-to-day as the state of the crop and the condition

of the fields affect the quantity of rain required to benefit the crop significantly. Costs and losses depend on the cost of water, the condition of the fields, and the state of the crop. As the season progresses, the resulting matrix changes daily. A decision based on these factors on one day will not hold for long because of the constant change in the crops. The decision process must be constantly repeated and future decisions are dependent on current decisions. The farmer who makes the decision to turn on the water has subjectively, and perhaps unconsciously, taken some or all of these complexities into account.

In many walks of life and in many operations, decision makers have imperfect information about what the weather is or will be and imperfect information about the relative costs of various actions. The fact that many of the variables of the problem are unknown does not necessarily render the model useless. One should perhaps construct a probabilistic model in order to take into account the imperfectly known factors. But it is a step in the right direction just to approach any problem of supplying weather information, knowing that there is a decision to be made, that the decision is sensitive to the weather information supplied, and that the value of the resulting action is sensitive to the actual weather, which may or may not correspond to the weather information.

In order to show how a rigorous approach can make a dollar-and-cent estimate for weather information, we have appended to this report a few analyses that are as realistic as we could make them. These are examples only. Any attempt to evaluate the usefulness of weather information to the whole of the economy, or the whole of our society, is fraught with problems which grow more complex as more and more segments of our society are considered. In order to focus attention on these mounting complexities we will give a brief survey of decision makers who must base their decisions on the type of weather expected.

DECISION MAKERS

The three main socio-economic components of a nation are also our three main sets of weather-service users: People, Government, and Business. The first two are acknowledged direct consumers of national weather service; the last is a voracious consumer of weather information, but the information channels are often not direct from the national service.

People

The Federal Government has assumed the responsibility for providing People -- the general public -- with information that will help them cope with the extremes of weather and to better order their daily lives.

People are motivated to employ weather information in a very personal and individual way -- to save their lives, protect their property, save time, maintain health, be more comfortable, have more fun. People are highly flexible economic units, much more so than units of either government or business. They can more often afford to "wait and see" before deciding a course of action. In fact, it is a general rule that People react to weather itself rather than to information about it.

In a fully qualitative way (for there are no data on which to base this), Fig. 2 indicates the extent to which People make and act on beneficial decisions, either in response to weather-service information or in reaction to weather, according to a scale of potential weather effects. Let's say, for the moment, that this is a valid characterization. We can also arbitrarily indicate a level where the resulting activity is economically and socially "significant." The solid curve in Fig. 2(a) is meant to show that "most" (more than 80%) of the people will be able to and will take some beneficial action based on a <u>forecast</u> of weather that threatens serious, negative ("disastrous") consequences. Also it represents a much smaller "significant," number of people making some beneficial decision based on a <u>forecast</u> of "obstructive" weather (weather that would cost them some loss of time and, possibly, minor property damage).

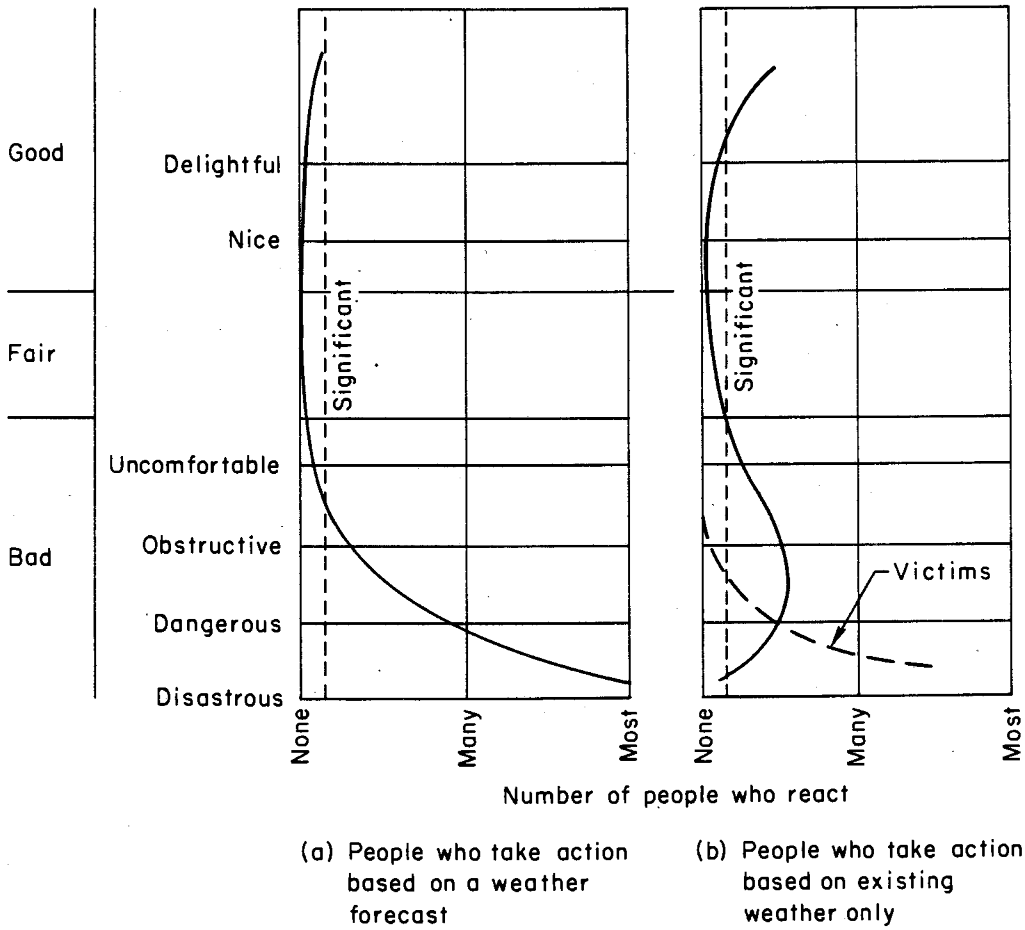

Fig. 2 Variation in number of people who react to weather as a function of weather extremes

Forecasts of less ominous weather, says the curve in Fig. 2(a), cause little direct action by all but an insignificant portion of the populace. (This is not to say that people do nothing whatever as a result of forecasts of fair weather. To predictions of nonextreme weather, people respond by pursuing whatever courses are normal considering the climatology of the region.)

The solid curve in Fig. 2(b) purports to show the number of people who react beneficially to weather as it occurs. It indicates that when "disastrous" weather (hurricane, flood, etc.) occurs, there is scarcely a significant number of people, who have not taken prior action, who can still choose among beneficial actions. (The dashed curve on the right, labeled "victims," is included to show that as weather worsens, latitude for action lessens, and the term "beneficial" becomes synonymous with "necessary.") The solid curve, 2(b), also shows that a more-than-significant portion of the public can await the arrival of "dangerous" weather (heavy snow, ice storms, etc.), or "obstructive" weather (lighter snow, rain, etc.), and "uncomfortable" weather and still choose a beneficial action; and it suggests that the arrival of "delightful" weather elicits favorable actions in a "significant" number of people. Thus, although forecasts of much better or slightly worse than normal weather may not greatly benefit the public *per se*, such forecasts may be cast as predictions of public behavior and do serve those who rely on public behavior for their livelihood.

Although the arbitrary placement of "significance" as used in Fig. 2 can and should be argued, and the "activity" curves could be reshaped within limits, we believe that Fig. 2 represents reality quite well. People benefit from weather service when that service helps them protect lives and property and save appreciable time, because People attach great importance to these things. When weather does not threaten these values, or when warnings cannot be made available, insignificant service is rendered. Furthermore, the real but less pressing benefits of enhanced convenience, comfort, peace-of-mind, and recreation defy quantification even of the vaguest sort.

Although People, the general public, are the major beneficiaries of the federal weather service, it is impossible to quantify the benefit to the society of the use of weather information by the

individuals in that society. There is no doubt that the dramatic evacuations of storm- and flood-threatened areas or the protective measures to reduce the loss of life and property when tornado warnings are issued, are definite social and economic benefits. But these are only a part of the benefit, and we entertain the suspicion that of the good done by the weather service they may represent only a small fraction.

Government

Weather information is supplied to local, state, and federal authorities who must make weather-sensitive decisions that regulate our society.

If, at any level (federal, state, or local), weather service can help make better use of tax dollars by enabling a government agency to serve the public more effectively or efficiently or both, then that agency is a weather-service user. The public is the beneficiary, but the agency is the user.

In the simplest case, the value of weather information is expressed in dollars saved per unit public service rendered, assuming no change in quality of the particular public service. A more common case, though, is where the quality of an agency's public service is dependent upon use of weather information, where right decisions entail more expensive actions, and where the public benefit, to be balanced against the added costs is largely intangible or so complex as to be indeterminable. What, for example, is the net value of maintaining an adequate flow of traffic throughout a city during and after a heavy snowfall? What is the potential value of smog-free air over the Los Angeles basin?

Table 1 is a basic list of weather-sensitive government services (approximately following an existing USWB system of classifying users). The table indicates the distributions of weather service utility among three levels of government -- national, state, and local -- and among three kinds of application -- operations, planning, and research. This is a qualitative compilation, and serves only to illustrate the magnitude of the governmental aspect of the weather-service benefit problem.

Table 1

QUALITATIVE SUMMARY OF GOVERNMENT UTILIZATION OF WEATHER SERVICE

User Class	Types of Government Service; Agency Responsibilities	Weather Service Used For: O = Operations, P = Planning, R = Research — Nat'l O	Nat'l P	Nat'l R	State O	State P	State R	Local O	Local P	Local R
(3) Preservation and Protection of Public Safety, Health, and Property (Government)	Highway Maintenance				#	#		#	#	
	Surface Traffic Control				#	#		#	#	
	Air Traffic Control	#	#							
	Flood Control	#	#	#	#	#	#	#	#	
	Public Health	#		#	#		#	#		
	Disaster Control and Relief	#	#		#	#		#		
	Fire Protection							#		
	Air Pollution Control		#	#	#	#	#	#	#	#
	Water Pollution Control		#	#	#	#	#	#	#	#
	Radioactive Pollution Control	#	#	#						
	Rescue Service	#	#		#			#		
	Sanitation							#	#	#
	Harbor and Waterway Maintenance	#	#		#	#		#	#	
	Coast and Waterway Patrol	#	#					#	#	
(4) Social and Economic Operational Services (Government)	Postal Service	#	#							
	Urban Transportation*					#		#	#	
	Public Housing		#			#			#	
	Schools							#	#	
(5) Development and Protection of Natural and Economic Resources (Government)	Highway Design and Construction*		#			#		#	#	
	Forest Service	#	#	#	#	#	#			
	Park Service	#	#		#	#		#	#	
	Water Supply*	#	#	#	#	#	#	#	#	
	Power Supply*	#	#							
	Harbor and Waterway Development	#	#		#	#		#	#	
	Agriculture Advisory Service	#	#	#	#	#	#			
	Radio Communication*	#		#						
	Atomic Energy Development*	#	#	#						
	Aero-astronautics Development*	#	#	#						
	Fishery Advisory Service	#		#						
	Soil Conservation Service		#	#		#	#			
	Community Planning								#	
	Survey and Mapping*	#	#		#	#		#		
	Land Management and Reclamation		#			#				

*sometimes non- or quasi-governmental service

The fact that a listing of government agencies and their problems has been attempted should not be taken as an indication that the problem of evaluating the benefits of weather information to government is any simpler than an evaluation of the benefits to people. Usually the decision process is so complicated by factors other than the weather that simple decision models cannot be applied. In addition, the true value is not to the government agency, but to the people it serves, and therefore subject to the same difficulties of quantization.

Business

Weather information is supplied to all segments of business in order that they may optimize their operations and maximize their production.

Weather-service value to Business is directly in terms of dollars -- increased profit -- realizable in a number of different ways: more sales, higher margins, reduced material losses, greater efficiency, lower costs.

A few of these business decisions are amenable to the simple, quantitative analysis presented earlier in this section. We can even foresee improved and more complex methodology that will make economic evaluations for most of the problems listed in Table 2. But even if it were possible to make rigorous analyses for all of the individual decision makers, we would face an impossible task if we tried to estimate the value for an industry as a whole. We show in Appendix B, for example, the value of rainfall forecasts to an individual raisin producer. If all raisin producers utilized these forecasts to the utmost, raisin production would increase and the market for raisins would need to adjust to the increased supply. Furthermore, if all raisin producers tried to protect their product at the same time, the competition for labor might cause an increase in wages that would increase the cost of protection. Although we do not try to present strict economic arguments, we can be fairly sure that the value of improved weather forecasts to an industry is not necessarily the simple sum of the values to each decision maker in that industry.

Table 2

QUALITATIVE SUMMARY OF BUSINESS UTILIZATION OF WEATHER SERVICE

Weather Service Usd For: O = Operations, P = Planning, R = Research

User Class	Types of Business	Most O	Most P	Most R	Some O	Some P	Some R	Few O	Few P	Few R
(6) Land Transport	Truckers	#							#	
	Railroads	#				#				
	Bus Lines	#				#				
	Urban Transit Lines*	#								
	Taxicabs	#								
	Commuter Railroads*	#								
	Airport Bus Lines				#					
	Auto Rental Agencies	#				#				
	Terminal Companies*	#	#							
(7) Air Transport	Airlines (All Types)	#	#							
	Aircraft Charter and Rental Agencies	#	#							
	Terminal Companies*	#	#							
(8) Water Transport	Ocean Freight Lines	#								
	Ocean Passenger Lines	#	#							
	River Freight Lines	#							#	
	Harbor Craft	#								
(9) Construction	Architects--Designers		#				#			
	Cement Contractors	#								
	Earth Movers				#	#				
	Building Contractors				#	#				
	Road Contractors	#	#							
(10) Finance	Casualty Insurance		#	#						
	Agricultural Brokers				#					
	Gamblers (Other)							#		
(12) Water Supply	Local Water Companies*	#	#							
(13) Power and Fuel Supply	Electric Power Companies*	#	#				#			
	Gas Companies*	#	#				#			
	Fuel Oil Companies	#	#							

*Sometimes all- or quasi-governmental business

Weather Service Used For: O = Operations, P = Planning, R = Research

User Class	Types of Business	Most O	Most P	Most R	Some O	Some P	Some R	Few O	Few P	Few R
(14) Merchandising	Department Stores				#				#	
	Caterers							#		
	Lunch Truck Operators							#		
	Bakeries							#		
	Newspaper Distributors	#								
	Advertising Agencies							#	#	
	Door-to-Door Salesmen				#					
	Traveling Salesmen	#				#				
	Roadside Merchants				#				#	
	Agriculture Suppliers		#		#					
	Automotive Suppliers				#	#				
	Recreation Concessionaires (etc.)				#					
(15) Recreation Industry	Ski Resorts	#	#							
	Marina Operators	#	#							
	Beach Resorts	#				#				
	Professional Baseball	#								
	Amusement Parks				#					
	Outdoor Theaters				#	#				
(16) Manufacturing	Shipbuilders	#	#							
	Oil Companies	#	#				#			
	Food Processors		#		#		#			
	Chemical Companies		#	#	#					
	Manufacturers (in General)						#			
(17) Commercial Fishing	Fishing Fleets	#	#							
(18) Agriculture	Farmers (in General)	#	#							
	Ranchers	#				#				
	Greenhousemen	#								
	Nurserymen	#				#				
(19) Forestry and Other Resources	Offshore-Oil Operators	#	#							
	Loggers	#				#				
	Mine and Quarry Operators				#				#	
(20) Communications	Telephone and Land-Line Companies	#	#							
	Radio Stations					#		#		

Similar economic interactions -- some of greater complexity -- would need to be investigated if the value of improved information to several industries needed to be combined. And finally it would be necessary to determine the value to society of the improved efficiency of Business, a basic economic problem that has not been solved.

AGGREGATION OF VALUES

The value of prediction and description of the weather is the aggregate of the value of correct decisions made by a host of decision makers in all segments of our society. The economic evaluation of the most simple individual decision process is a difficult task, and a meaningful aggregation of all these decision values is impossible.

But we do not believe that it is necessary to have a rigorous economic accounting in order to demonstrate the usefulness of weather information and the usefulness of attempts to improve the quantity and quality of that information.

There is the need, therefore, for a new and different framework -- a framework in which weather problems can be classed according to the economic, social, and meteorological requirements of cost-benefit analyses, whether the analyses be rigorous or intuitive. Our approach to devising such a framework is presented in the next section of this report.

III. WEATHER-SERVICE CONSUMERS AND THEIR REQUIREMENTS

The complexity of the weather-service cost-benefit problem lies, as we have seen, mainly in the extreme difficulty in generalizing or aggregating the net values of actions predicated on weather information. There is another complicating factor that has not yet been emphasized: it is the difficulty in defining weather information in such a way that its utility can be determined.

To attack the cost-benefit problem, no matter how qualitative our approach, we must be aware of:

the ways that values are affected by weather;

ameliorating actions, their costs, and the influence of time;

the nature of useful weather information.

Obviously, understanding of the third is dependent on understanding the first two.

We will attempt, in this section, to explicate the nature of useful weather information by taking the suggested route. That is, we will first discuss ways that weather affects the values of users and some of the ramifications in attaching numbers to such values. Next, we will outline the kinds of actions that can be taken and show how the value of actions fluctuates with reliability and timeliness of weather information. We will then discuss the content of useful weather information.

At the end of this section, we summarize the results of a sample analysis of weather-information requirements. The analysis is empirical, but it is incomplete, and the basic data are quite subjective. Nevertheless, gross implications may be valid, and it should be a useful prototype for future work.

WEATHER EFFECTS AND VALUES AFFECTED

Three general classes of weather effects can be defined, each being distinguished by the different manner in which the value of decision makers' products or services can be altered. Weather can influence capital value, operational cost, and potential revenue. In none of these classes is there an inclusive, clear and simple way of determining value.

Weather Influence on Capital Values

"Capital" is defined to include private and public property, commercial products, and the national stock of human life and health. Any of these things can be destroyed, damaged, or even improved, by weather. Value estimations of material goods can be variously made; possibly the most common is to employ such indices as fair market value, resale value, replacement cost, or repair cost. The value of a commercial product is also dependent on its position *en route* from producer to consumer. The value of a publicly consumed resource (water or clean air, for example) is extremely difficult to determine. Possibly, it can be determined only be estimating the total economic and social consequences of a reduced supply. The real value of life and health influenced by a weather event might be estimated by enumerating the directly attributable deaths, percentage of disabilities, and medical costs. This last problem represents the ultimate in social benefit evaluation and cannot be ignored despite the obvious difficulties in quantification.

Weather Influence on Operational Costs

Weather affects many operations. When in the face of a given weather condition an operation must be varied to maximize its effectiveness, it is obvious that the optimum choice among these variations must also be influenced by the weather. The kinds of operation involved are those of government (public service), commerce and industry, public utilities, and the private individual. The value of a threatened loss of effectiveness is seldom easy to determine. In the case of private citizens, individually or collectively, it is their "own time" that is mainly involved, and also their comfort, pleasure, and incidental expenses. Most operations of the government and public utilities are constrained, legally or morally, to a given level of effectiveness despite the weather; n.b., the motto of the U.S. Post Office. On the other side of the ledger, there are budgetary limitations on their choices of operational methods. Commerical and industrial operations lend themselves most readily

to dollar evaluation, but the freer choice of alternatives available in the business world frequently complicates the process.

Weather Influence on Revenues

To analyze problems in the third class of weather effects, we are required to estimate potential changes in revenues due to the influence of weather on the demand for goods or services. (We exclude from this class all the government services that "must" be provided because or in spite of the weather, for example, highway snow removal and traffic control. We might also exclude public utility services, but do not because direct revenues are involved.) In all cases the effect of weather is to alter public behavior in such a way that the user could use foreknowledge of the change in behavior to some advantage. When the effect is to increase demand, and the user takes action to increase his supply, the advantage is two-fold: it is immediately remunerative, and in the long run it results in customer satisfaction. When the demand is decreased by weather, then the advantage lies in a user's ability to reduce costs and lighten the blow.

AMELIORATING ACTIONS, THEIR COSTS, AND THE INFLUENCE OF TIME

In order to compute, in an individual cost--benefit analysis, the total "costs" of actions based on weather information -- e.g., the costs appearing in the cost matrix, Fig. 1(a) -- it is necessary to know the weather-threatened values and the costs of various actions that may be taken to protect against losses in value. The action costs are just as difficult to generalize as the weather-threatened values; but a better appreciation for the differences in costs can be acquired by thinking about the different kinds of actions a user may take. Further insight is gained by considering the critical influence of "lead time," that is, the time interval before a weather effect occurs in which a decision maker must complete his actions.

The Nature of Beneficial Actions

In general, and depending greatly on available lead time, decision makers will first make preparations to optimize their later choice of tactics. Preparatory actions are usually those that require long lead times (ordering supplies) and those that can be done most efficiently at deliberate speeds (preparing a fleet of buses for winter operation; setting out and fueling orchard heaters). Tactics, on the other hand, are defined as those actions which can be avoided until the last possible moment. Many users will have permanent preparations (stocked storm cellars in the Mid-West) or will complete many of the preparatory actions on a routine, seasonal schedule -- betting that their experience (climatology) will enable them to anticipate the need in time and not lead them to do expensive, unnecessary things. This brings up an important rule: The basic, normal set of preparatory actions always available to a decision maker are those dictated by climatology. Thus, a great value in the proper and complete use of adequate climatological information is implied -- though it is not discussed -- in this part of the report. Let us refer to climatologically founded actions as the "routine," and refer only to departures from routine as "actions." Within each of the three classes of weather effects (previous subsection), possible actions are consistent; among the classes, however, they differ somewhat.

Preparatory Actions. In all weather-effect classes, capital, cost, and revenue, the possible preparatory actions are similar. It is a matter of mobilizing beforehand for nonroutine activity, for example: to protect weather-threatened life, health, or property; to perform an operation under adverse weather conditions; or to make sure that the supply of a product or a service is appropriate to the expected demand. To so mobilize, a user may have to order, and obtain, or redistribute stock and supplies and major equipment, prepare equipment for its use, arrange for the augmentation or redistribution of work force, and place his organization on alert. Particularly where operational costs or potential revenues are involved, a key preparatory action is to ensure short-term flexibility.

Tactical Actions. In detail, there are almost as many possible tactical actions as there are weather-service users. Capital in the form of property can be protected by moving it, not moving it, sheltering it, tying it down, or purging aggravating factors; the lives and health of people can be protected by restricting or facilitating their movement into or away from an endangered area, and providing shelter and other survival aid; and both people and (their) property are protected by combatting and containing the adversity and by informing the populace. To optimize revenues and operational costs, the decision maker employs flexibility in adjusting schedules, routes, coverages, equipment, stock, personnel, and -- mainly -- methods of operation to meet the weather-induced threats, difficulties, and demands.

Lead Time Required for Beneficial Actions

The way we view the critical influence of different lead times (times of warning in advance of a weather event) is schematically diagrammed in Fig. 3. In this diagram, time prior to a weather effect is represented along the abscissa, and the net value of actions along the ordinate. It is assumed that the weather information, the forecast, is always of predictable accuracy (e.g., in probabilistic terms) so that the decision maker can objectively decide on a course of action.

Two curves are shown in Fig. 3. The solid curve illustrates the value increase with lead time in the case of a climatologically "normal" (expected) event -- one for which routine (seasonal) preparations have been made. The dashed curve is for an "abnormal" (unexpected) event -- an occurrence exceptionally severe or unseasonal, or both, for which climatological economics would dictate no routine preparations. (The points A, B, C, and D along the abscissa of Fig. 3 will be discussed near the end of Section III.)

The forecast on which these curves are based has a high enough probability of verification that the user does in fact take actions; and the critical probability can vary with lead time. An example can

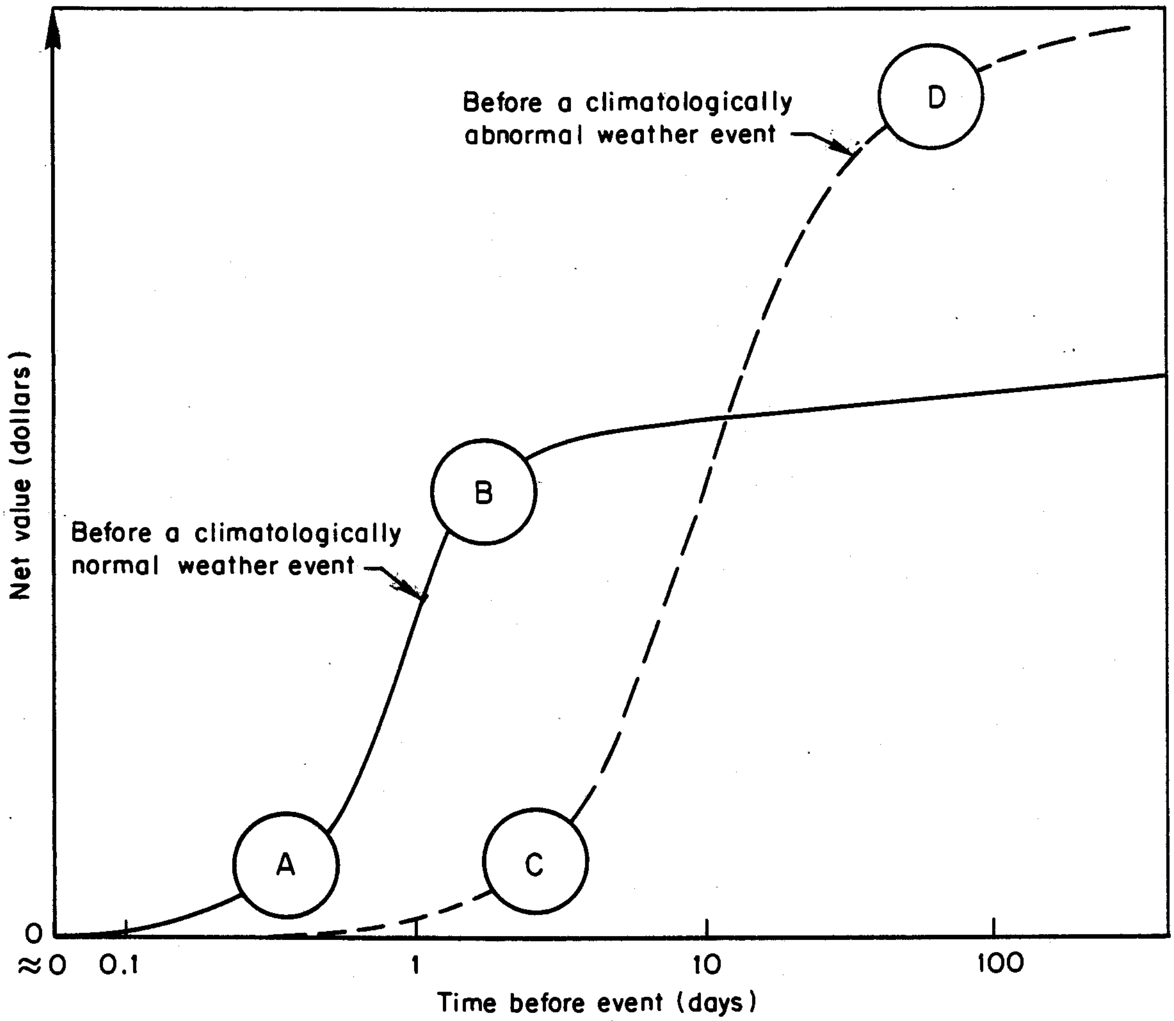

Fig. 3 Schematic of lead-time value for an individual problem and user

illustrate this difficult but important premise: Based on a forecast of rain one day in advance, a user has determined that he profits by expending the costs of protection against rain damage if it rains at least 80% of the time that he has protected. Therefore, if the probability of success of a one-day rain forecast is 80% or higher, he will protect; if less than 80%, he will not. The user's net benefit from the forecast is the value he has protected less the cost of a protection. (For an example, see Appendix B.) When the user has two days warning, he can protect less expensively, more completely or both; therefore, his net potential benefit is greater, and he can afford to protect on the basis of a forecast with a lower probability of success. With only six hours warning, his protective actions are much more costly, less complete, or both, and his potential benefit correspondingly lower, and he can afford to protect only given a forecast of higher than 80% reliability. (Sequential decisions such as these implied in the above example often take the form of "hedging" -- continuously maintaining a protective posture at minimum expenditure.)

The "S" shape of the curves in Fig. 3 is an idealization. In reality, they would probably be more step-like, reflecting the fact that each action or set of actions requires a characteristic period of time for its successful completion. For each weather problem of each user, and in each pertinent climatic regime, such curves could be constructed; and probably no two would be identical.

Thinking of time requirements this way brings up an interesting facet that pervades the whole problem of determining weather-service benefits. Essentially it is this: <u>The lead time vs. reliability function of weather forecasts is part of the experience on which a user bases his routine preparations</u>. For example, a user expects a certain critical weather problem to occur an average of twice a year, but in one year out of three it doesn't occur at all. The set of routine precautions is costly, but is climatologically worth while to take once every season; and the first of the several precautionary steps must be taken five days before the weather problem occurs.

Thus, as the improvement of meteorological techniques causes the lead time of a categorically or statistically "reliable" forecast to increase, the user can eliminate his precautionary steps one at a time, each time reducing the amount and cost of seasonal routine. What were formerly routine now become actions taken only when a forecast so indicates and the costs of those actions no longer accrue annually; actually, in one-third of the years, they will not accrue at all.

THE NATURE OF USEFUL WEATHER INFORMATION

From a user's point of view, we have established that a weather forecast should:

(1) describe the expected state of the atmosphere in enough pertinent detail that the user can correctly anticipate the kind and degree of weather effect and thereby estimate the threatened value;

(2) contain information about the expected reliability of all the elements of the forecast, including the time elements.

The decision maker is practical. He does not ask for a perfect categorical forecast far in advance. He only asks for all of the pertinent meteorological information that the state of the art allows.

The sum of the weather-forecast needs of all users would closely approximate a complete and detailed continuous description of the atmosphere. But an analysis of the total needs would reveal that predictions of certain weather conditions (that is, atmospheric phenomena, critical values of atmospheric variables, and combinations of phenomena and variables) are more frequently needed than others. If the economic and social "value" of weather information could be equated with the frequency of need of this information, the order of "importance" of weather conditions would be established. On a national scale, then, it would be most "useful" to improve the ability to predict most "important" weather conditions.

All users are concerned with certain geographical areas, varying in size from a point to an ocean. When given a weather prediction that pertains to an area that does not coincide exactly

with his own area of interest, a user particularizes the prediction to his own area. If the required spatial resolution is finer than the resolution provided in the forecast, then additional uncertainty is added and the forecast's usefulness is reduced. Thus, the required spatial resolution of the important weather conditions should be analyzed; and it would be "useful" to attempt to resolve the forecasts to meet the needs of the most users.

In the discussion (pp. 24, ff.) of Fig. 3, we brought out the interdependence of the usefulness of a forecast's timeliness and reliability. We indicated that a forecast far in advance can have greater value than a much more reliable forecast that provides little warning time. Two things are suggested by this: all forecasts should include reliability (confidence or probability) statements; and a forecast should be issued as soon as any estimate of its reliability can be made.

In summary, weather information is most useful if it

(1) can be directly related to practical problems,
(2) can be resolved to the user's area of interest,
(3) contains a statement of reliability, and
(4) is issued as soon as an estimate of its reliability is established.

ANALYTICAL SUMMARY OF WEATHER INFORMATION FOR USERS

A sample catalog of weather problems has been compiled. We have assumed that the catalog contains information enough to suggest useful guidelines for judging national weather service in terms of consumer benefits. The catalog itself, and an explanation of its content and format constitute Appendix A; it is the sole basis for the following analysis of beneficial weather information.

The catalog lists weather problems of government agencies and businesses; but not of the general public; each entry is intended to represent a discrete weather problem for which there exists one or more beneficial counteractions. No attempt is made to weight the problems or users according to their contribution to the Gross National Product, their weather "sensitivity," or the like. Consequently, a

problem common to all airlines is considered equal in significance to a problem common to just nonscheduled airlines and to one common to all cranberry growers.

In the analysis below, we are concerned only with problems that can be ameliorated by actions based on weather predictions. Each problem catalogued -- and there may be more than one for a single user -- is paired with a specific "weather effect" of the type discussed earlier in this section (and classified in Table A-2, Appendix A).

It is interesting and pertinent to note the variety of weather effects (and, therefore, weather problems) that is faced by users in a single socio-economic category. Table 3 shows the number of problems from each class of weather effect catalogued versus each category of user. Only agriculture seems convincingly associated with a single type of problem. Also, there appear to be significantly more problems where the effect of weather is to influence capital values than where the effect is on operating costs or expected revenues.

Every "weather effect" is produced by the occurrence of one or more "weather conditions." We have tried to describe and classify weather conditions (Table A-3, Appendix A) in such a way that they can be identified both with effects and predictablity. Forty-nine "simple weather conditions" are listed, and these are grouped according to four weather elements of predominant influence, namely, wind, temperature, precipitation (including lightning), and cloudiness (including fog and humidity). In setting up Table A-3, recurrent sets of simple conditions were combined into nine convenient "compound weather conditions" that describe the weather effects on ground mobility, outdoor activity, and air transport. The rationale for inventing the compound conditions is to provide for a crude index of meteorological complexity to be attached to the weather effects and problems. The catalog lists every weather condition that contributes to every problem. It was suggested that the multiple demand for information about certain types of weather conditions might indicate a relative importance of the conditions. Table 4 is

Table 3

THE NUMBER OF PROBLEMS IN EACH CLASS OF WEATHER EFFECT LISTED IN APPENDIX A FOR EACH CATEGORY OF USER

	Number of cases catalogued in specified weather-effect class											
	1a	1b	1c	1d	2a	2b	2c	2d	3a	3b	3c	3d
Categories of Users	Capital: Value of private or public property affected	Capital: Value of commercial product affected	Capital: Value of public utility affected	Capital: Life and health affected	Costs: Public service affected	Costs: Commercial operations affected	Costs: Public utility affected	Costs: Private operation affected	"Revenues": Public service operation affected	Revenues: Commercial service affected	Revenues: Public utility affected	Revenues: Commercial product affected
GENERAL PUBLIC	?			?				?				
GOVERNMENT												
Public Protection	4			14	6							
Operational Services				1	1							
Resource Protection	4		1	3	5				1		1	
BUSINESS												
Land Transportation	1	2				7	2			2	2	
Air Transportation	1	1				3					1	
Water Transportation	1	2				2						
Construction		2				2						
Water Supply			1								1	
Power and Fuel Supply	1						1				3	
Merchandising		2				1						8
Recreation Industry	1	3								1		
Manufacturing						2						
Commercial Fishing	1	1										
Agriculture	1	12				1						
Resource Industry	1	1		1								
Communications	1						1					
TOTALS	17+	26	2	19+	12	18	4	?	1	3	8	8

Table 4

THE MOST FREQUENTLY TABULATED WEATHER CONDITIONS

IN THE WEATHER PROBLEM CATALOG

a. Simple weather conditions occurring individually and as part of compound weather conditions	Occurrences in Catalog
C6 Surface snow cover	72
A2 Damaging wind and turbulence	68
C5 Surface icing; glaze	51
D4 Surface (horizontal) visibility	39
C4 Damaging hail	29
C1 Rain wetting; soaking	25
C15 Lightning	25
D3 Vertical visibility; ceiling; vis. aloft	24
B4 Extreme cooling ($\lesssim 0^{\circ}F$)	20
C13 Inundation; stream flooding	20
b. Simple weather conditions occurring individually	
A2 Damaging wind and turbulence	29
A6 Wind waves; surf	19
C6 Surface snow cover	18
C1 Rain wetting; soaking	14
C5 Surface icing; glaze	10
C13 Inundation; stream flooding	9
A3 Pollutant concentration; transport	9
B1 Cooling; chilling (relative)	9
C3 Damaging glaze	9
D3 Vertical visibility; ceiling; vis. aloft	8
A1 Upper-wind transport; displacement	8
c. Compound weather conditions	
X3 Hazardous (driving) conditions	13
Z3 Hazardous conditions in flight	11
X2 Obstructive (driving) conditions	10
Z1 Air-terminal operating conditions	7
Y2 Unpleasant (outdoor) conditions	6

a listing of the most frequently tabulated weather conditions in our weather-problem catalog. Part (a) of the table is a ranking of simple weather conditions appearing in the catalog both individually and as part of compound weather conditions; part (b) ranks the simple conditions that appear individually; and part (c) ranks the compound conditions. It probably is significant that precipitation-induced conditions dominate both parts (a) and (b) of the table.

Table 5 shows how the main groups of simple weather conditions are distributed among the weather-effect classes. The simple conditions occurring as part of compound conditions are tabulated separately from those occurring individually. This table seems to provide a helpful revelation. The weather effects that influence capital value (and for which economic data <u>might</u> be the most easily obtained) are produced largely by individually occurring simple weather conditions, the predictions of which are more easily structured and verified than predictions involving compound conditions. By the same reasoning, weather-service benefit to users concerned with effects on operational costs would be harder to evaluate, and the evaluation of benefit deriving from effects on revenues might be very difficult, indeed.

Users are concerned with different regions in space to which they must particularize weather information in order that they may correctly anticipate weather effects. Associated with each simple weather condition in the catalog is an estimate of the spatial resolution that the user requires for that particular problem.

We have also estimated "maximum and minimum beneficial lead times" for predictions of each of the conditions in the catalog. To do so, we considered the choices of actions available to the decision maker to counteract each weather effect produced by each weather condition. We then mentally constructed for each weather condition a set of value versus lead time curves such as those illustrated in Fig. 3 (p. 25), and attempted to characterize each curve by two points in time that bracket the greatest rate of increase in value. The lower point we have called the "minimum beneficial lead time," and the upper point the "maximum beneficial lead time." In Fig. 3, points A and C illustrate the "minimum" and points B and D the "maximum"

Table 5

GROSS DISTRIBUTION OF WEATHER CONDITIONS

AMONG WEATHER EFFECT CLASSES

Weather Condition Group	Simple Weather Conditions	Weather-Effect Class (1) Capital	(2) Costs	(3) Revenue	Total
A. Wind	Single Occurrence	61	18	1	80
	Part of Compound Occurrence	5	15	32	52
	Total	66	33	33	132
B. Temperature	Single Occurrence	35	7	12	54
	Part of Compound Occurrence	2	12	26	40
	Total	37	19	38	94
C. Precipitation and Lightning	Single Occurrence	72	23	10	105
	Part of Compound Occurrence	16	72	100	188
	Total	88	95	110	293
D. Clouds, Fog and Humidity	Single Occurrence	12	13	2	27
	Part of Compound Occurrence	13	32	29	74
	Total	25	45	31	101
Total	Single Occurrence	180	61	25	266
	Part of Compound Occurrence	36	131	187	354
	Total	216	192	212	620

beneficial lead times for climatologically normal and abnormal weather conditions, respectively. Thus, we treat normal and abnormal occurrences of the same weather condition as creating weather problems in different degrees.

Table 6 relates the required spatial resolution to the forecast lead time (the minimum beneficial lead time) for the four groups of simple weather conditions. In this table, all of the simple weather conditions were tabulated without differentiating between their occurrence individually or as part of compound conditions. It is apparent from Table 6 that the required spatial resolution for most of the information is much finer than that which can normally be supplied by the weather service: over 25% of the conditions could advantageously be predicted to a resolution of less than 2 miles; and over 70% require a resolution of less than 10 miles. As for timeliness, to provide "minimum" benefit, about 25% of the conditions should be "reliably" predicted (and the decision makers informed!) from 1 to 3 days in advance, and over 75% of predictions should be known to decision makers from 3 to 9 hours in advance. To provide "maximum" benefit (the tabulation for which is not shown), over 25% of the conditions should be predicted from 3 to 10 days in advance, and about 70% of predictions are needed from 1 to 3 days in advance. (The warning-time requirements are almost certainly biased because of practical limitations in compiling our catalog of weather problems, for the useful time-span of present-day forecasts weighs heavily in the mind of anyone who has dealt in the provision of weather service.)

We repeat that no weather problems of the general public were explicitly considered in this sample analysis. As indicated in Table 3, private individuals are concerned with weather effects of classes (1a), (1d), and (2d), i.e., damage to their property and life and health, and "operational" disruption of their affairs. If general-public problems could be added to the catalog, it is likely that the essential features of the summary tables (4, 5, and 6) would remain unaltered.

Table 6

DISTRIBUTION OF PROBLEMS ACCORDING TO WEATHER CONDITIONS, AND LEAD TIME REQUIREMENTS

Minimum Beneficial Lead Time	Simple Weather Conditions	Required Spatial Resolution (mi) pt. to 2	1.5 to 10	7 to 60	40 to 300	200 to 1000	Total
< 1 hr	Wind	4	8	2	...	...	14
	Temperature	2	...	...	...	...	2
	Precipitation and Lightning	13	6	2	...	...	21
	Clouds, Fog, and Humidity	8	11	2	...	...	21
	Total	27	25	6	...	...	58
1 hr to < 3 hrs	Wind	5	10	5	...	...	20
	Temperature	2	3	...	...	...	5
	Precipitation and Lightning	11	22	7	...	...	50
	Clouds, Fog, and Humidity	2	11	6	...	...	19
	Total	20	46	18	...	...	84
3 hrs to < 9 hrs	Wind	7	20	5	3	...	35
	Temperature	4	11	9	4	...	28
	Precipitation and Lightning	31	48	11	...	...	90
	Clouds, Fog, and Humidity	9	15	4	2	...	30
	Total	51	94	29	9	...	183
9 hrs to < 24 hrs	Wind	6	15	3	2	...	26
	Temperature	9	9	6	2	...	26
	Precipitation and Lightning	31	39	9	...	...	79
	Clouds, Fog, and Humidity	1	9	3	...	...	13
	Total	47	72	21	4	...	144
1 day to < 3 days	Wind	5	10	13	2	...	30
	Temperature	5	8	8	3	...	24
	Precipitation and Lightning	9	18	17	2	...	46
	Clouds, Fog, and Humidity	1	4	13	...	...	18
	Total	20	40	51	7	...	118
3 days to < 10 days	Wind	...	3	1	1	2	7
	Temperature	1	2	4	1	1	9
	Precipitation and Lightning	5	3	3	1	...	12
	Clouds, Fog, and Humidity	...	...	...	...	...	...
	Total	6	8	8	3	3	28
10 days to < 1 mo	Wind	...	...	...	...	...	...
	Temperature	...	...	...	...	...	...
	Precipitation and Lightning	...	...	3	2	...	5
	Clouds, Fog, and Humidity	...	...	...	...	...	...
	Total	...	...	3	2	...	5
Total	Wind	27	66	29	8	2	132
	Temperature	23	33	25	10	1	94
	Precipitation and Lightning	100	136	52	5	...	293
	Clouds, Fog, and Humidity	21	50	28	2	...	101
	Total	171	285	136	25	3	620

SUMMARY

We have attempted, in this section, to show the variety of ways in which weather affects the decision makers who are the consumers of weather information, and to put meteorological requirements into practical perspective. We have suggested that whoever performs cost--benefit studies of weather service must explicitly define: (1) the ways in which weather affects values to the consumer; (2) the functional relationship of net weather-information value to forecast lead time and reliability; and (3) pertinent weather conditions in terms that facilitate the association of weather effects and predictability.

If we were to apply this or a similar approach and successfully produce generalized statements of weather service present and improved, we would still have to face the problem of balancing the costs of weather research against the value gained by improving the weather service.

IV. PLANNING RESEARCH FOR IMPROVED INFORMATION

The preceding estimates, subjective though they be, indicate the types of information (and their time and space scales) that will be of most interest to most users. If we accept the thesis that the present system is socially and economically beneficial because it provides information that leads to good decisions, it follows that a refinement of the information should provide an increment of gain in these benefits. Such refinement could accrue from research and development in atmospheric science. In order to trace the impact of successful research on the information given to the user, it will be necessary to set up a model of a weather-service system and look at the various portions of the system that could be improved.

THE FLOW OF INFORMATION

In the center of Fig. 4 we show the elements of a weather service. The job of the weather service is to collect basic information, and to synthesize it into descriptions of the current weather and descriptions of the climate. The descriptions of the current weather and the knowledge of the climate plus whatever statistical and dynamical means are available, are used to make predictions of the future state of the weather. Thus the weather service puts out descriptions and predictions of broad classes of atmospheric phenomena.

These broad classes of atmospheric phenomena must then be interpreted and transformed into separate bits of specific weather information for each of the individual users as discussed in Section III. This interpretation and transformation is not always done by the same group or organization in the information flow diagram. Sometimes it is clearly the responsibility of the weather service to provide the user directly with the specific information he requires. Sometimes it is obvious that the user can derive from the general descriptions the specific information that he needs. In other cases it might be necessary to have middlemen who would take the basic descriptions put out by the weather service and transform them into the specific information needed by the user.

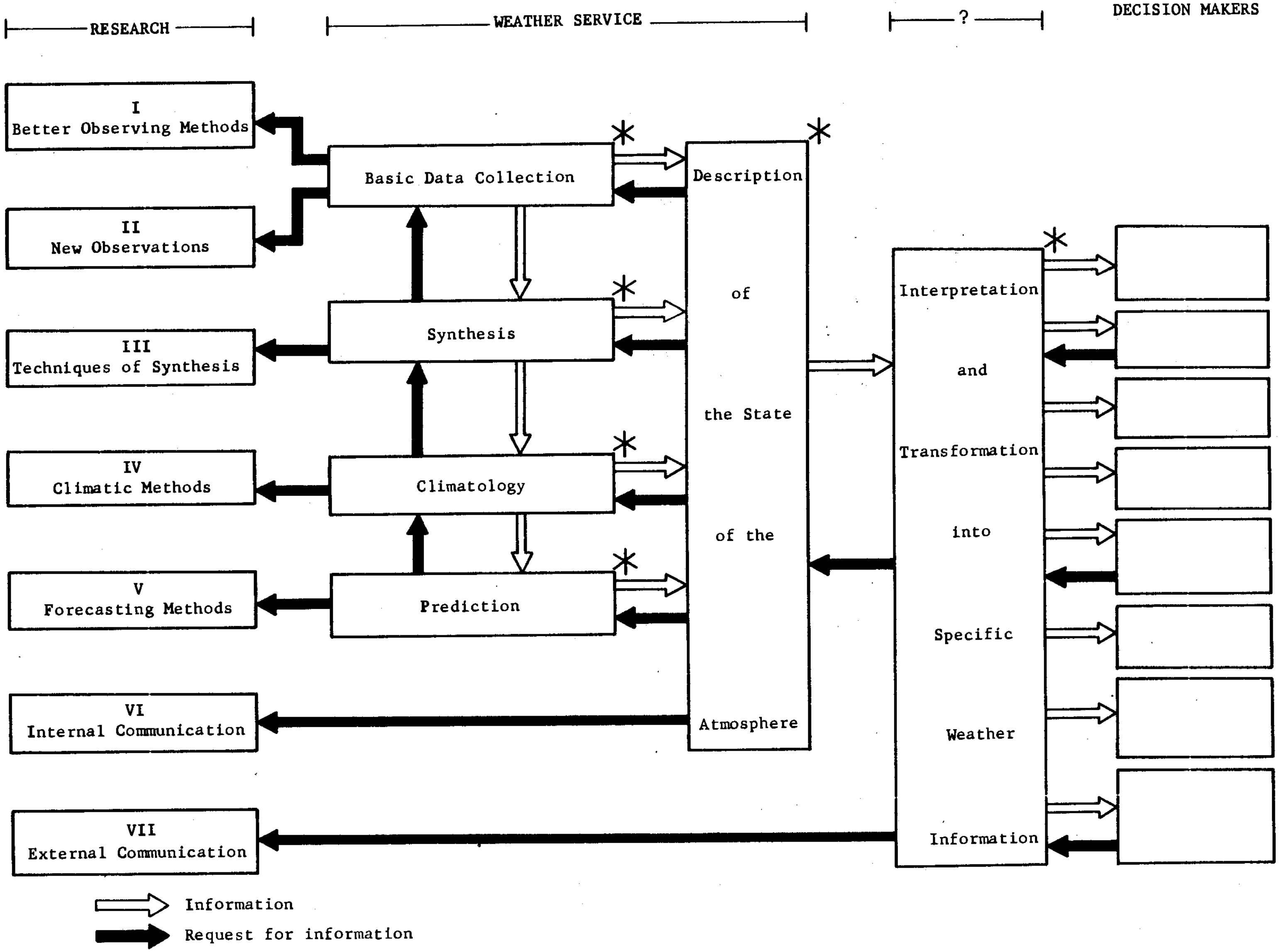

Fig. 4 Schematic of the elements of a weather service

The hollow arrows show the flow of information from basic-data collectors to the many consumers of weather information. Each of these boxes can be considered a point where information is either developed or transformed in some manner that will make it useful to the next succeeding operation.

The ultimate benefit is measured by the value of the information to the decision maker. If we ask how the value of the information may be increased, we must trace backward through this system and look, at each step along the way, for something to improve. The solid arrows indicate the flow of requests for better information; where such improvement can come as a result of research and development, asterisks appear. Listed on the left side of this chart are the seven classes of research and development to which this breakdown leads.

Need for Balanced Effort

With this grouping of research areas in mind, we would like to suggest that there is a need to maintain a program that devotes some resources to each. An effort concentrated on a single research area would not appear to produce the improvement we seek. For example, if a determined effort were made to improve the communications (external communication box) from the weather bureau to the consumers of weather information to the exclusion of other research areas, it would be possible to reap greater benefits from present descriptions of the atmosphere. But as the economy expands, there will be requests for more information, more precise information, and new types of information, and the present state of the art would soon prove inadequate. On the other hand, if resources were lavished on improved observations without due attention to improving the synthesis and interpretation of these observations, only minimal gains could be expected from the direct use of the improved observations as information.

We would, therefore, suggest that any coordinated research program should have sufficient work in each of these seven categories to insure a steady increase in the quality and quantity of information forwarded to decision makers.

Examples

To make this view of the relationship between decision makers' needs, and the objectives of atmospheric research more concrete, we will look at a few examples. Figures 5 and 6 show the same view of the flow of weather information as Fig. 4, but in these two charts, we see (1) the response of research to the individual clients' needs and (2) the benefit to a variety of consumers of the results of the research.

Figure 5 shows the problem of an airline flight dispatcher who must decide whether to proceed with a flight as scheduled, cancel the flight, or invoke some emergency plan designed to minimize the effect of bad weather. The box labeled Decision Maker lists his choices of action, his problem, the weather information he needs, the scale of the weather that concerns him, the lead time of the forecast, and the nonweather information he must also use in the decision-forming process discussed earlier in Section II.

The client's basic need is a good decision. His decisions will be improved by an improvement in the quality of the weather information he receives. But even though the best decision can not be expected, for want of perfect weather information, he can, as was pointed out earlier, be given much useful information.

We have assumed that the decision maker will get his information from a source which we have called the Weather Advisor, the person or organization who interprets and transforms general descriptions and predictions of the state of the atmosphere into specific information for this particular decision maker.

Because this interpretation and transformation may sometimes be done within the weather service, sometimes by the user, and occasionally by a third party between the weather service and the user, we have found it expedient to postulate a "weather advisor" to describe this function. Let us look at the weather advisor's function as he addresses the problem of improving his service. Looking to himself, he may revise the structure of the information he provides his client to maximize the benefit to be derived from any available description.

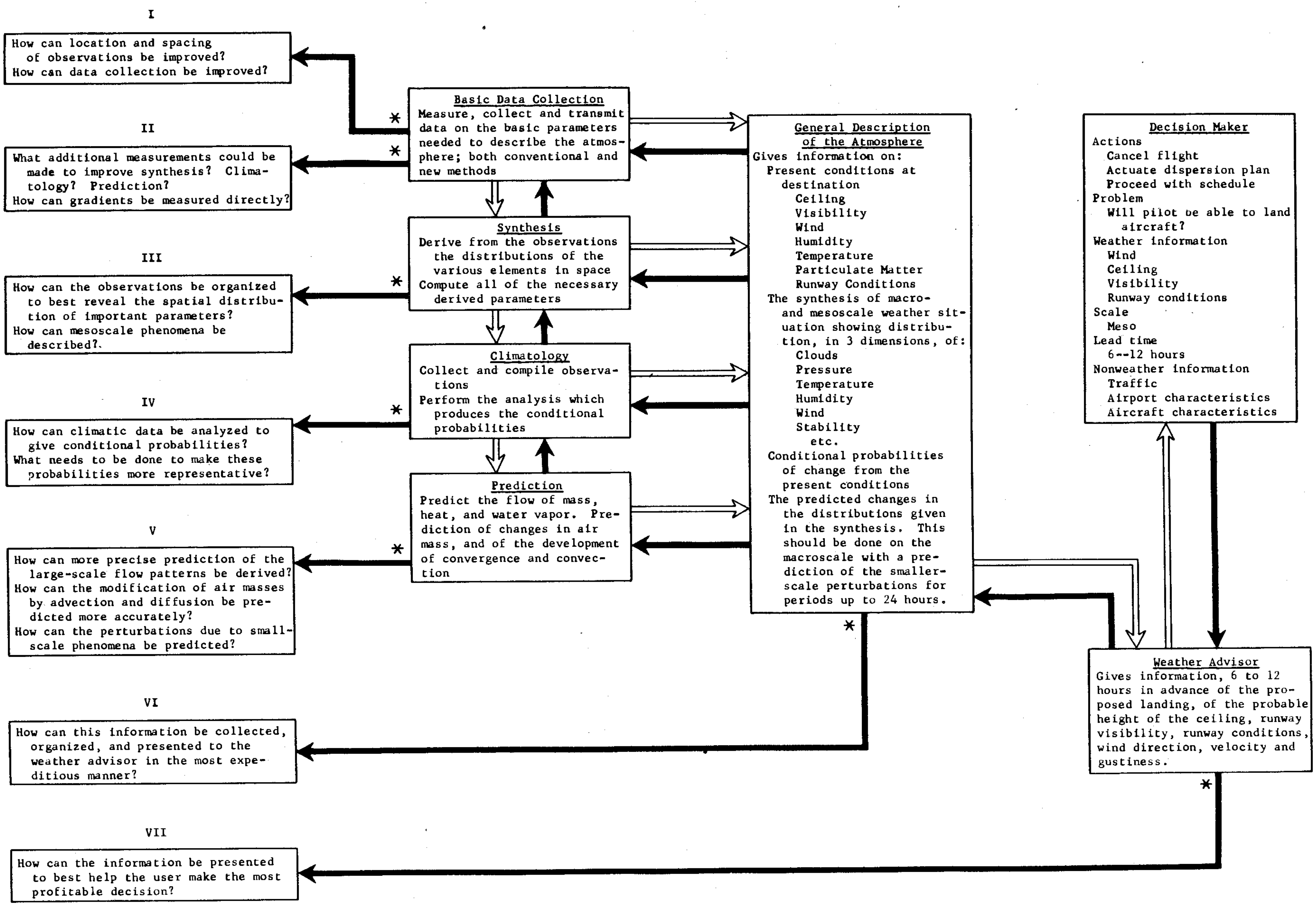

Fig. 5 Research generated by the problems of an airline dispatcher

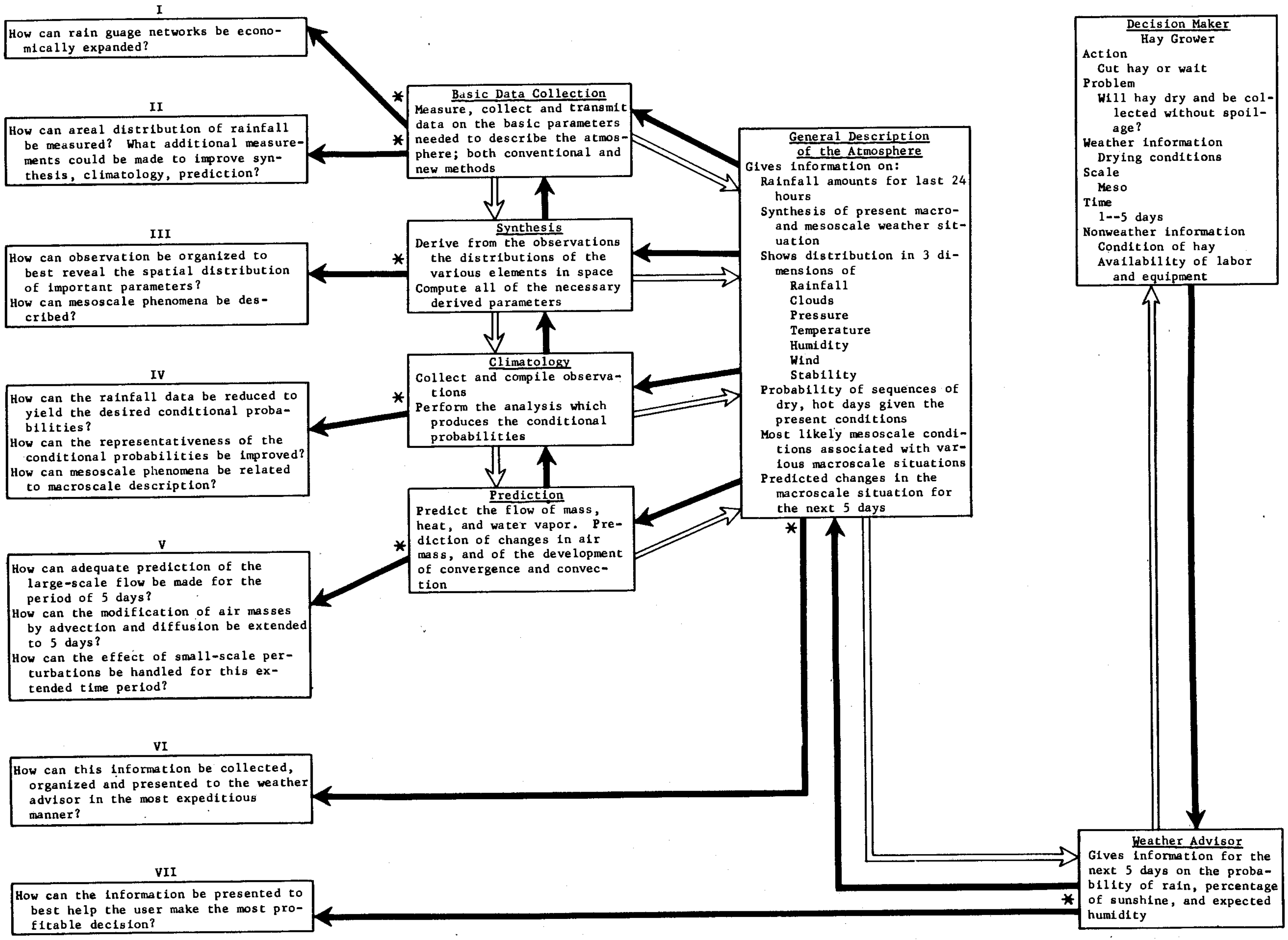

Fig. 6 Research generated by the problems of a hay grower

Looking to his sources, he can request more accurate, better organized information. Note that in the first case, he can himself institute research to improve his product; in the second, he merely forwards a request.

The weather advisor's research problem leads us to box VII. The research required to optimize the structure of the information obviously must have a close bearing on the needs of the individual user. The commercial airlines maintain meteorological departments that perform the function of the weather advisor. They use the output of the national weather service and endeavor to distill from it the information most useful to their employers. But, although they have not yet developed techniques for evaluating the economics of the service or quantifying their information structure, they are becoming more aware of the nature of the decisions that need to be made and are endeavoring to reduce these decisions to a form amenable to mathematical treatment.

Next we look for ways the service can be improved as viewed by those engaged in description and prediction. Looking toward the weather advisor, the descriptions and predictions can be organized and transmitted to him in such a way as to minimize the labor needed to extract the necessary information. Looking toward the data sources, a request can be forwarded for more data or for more accurate data. Note that again, the first step toward improvement is something that can be initiated by the description services (leading to box VI); whereas the second effort involves merely the forwarding of a request for basic meteorological research.

We look next at the column of boxes labeled <u>Basic Data Collection</u>, <u>Synthesis</u>, <u>Climatology</u> and <u>Prediction</u>. The improvement of the information input to the general description of the atmosphere depends on raising the level of technical competence in the fields of (1) observing, and collecting and disseminating basic quantitites; (2) synthesizing these measurements into a unified picture of the state of the atmosphere; (3) deducing from the accumulation of past observations the normal state of the atmosphere and the probabilities of its change from one state to another; and (4) predicting by physical

or statistical means the likely future states of the atmosphere. In each of the boxes in this column, methods of improvement are listed that lead to the kind of questions listed on the left side of the chart (boxes I to V). We also indicate by means of the solid vertical arrows that each of these functions depends on the others.

It is because of this interdependence that the research questions arising in each box are very general.

Although for the airline there is a special need for better observations of ceiling and visibility, the prediction systems may, in addition, require observations of winds aloft to permit prediction of the movement and modification of the air masses wherein these ceilings and visibilities occur.

It is important, therefore, when considering the needs of a specific user, to trace all of the sources of his information. It is important to avoid designing research projects that may, if they succeed, improve some of his information but fail to provide the general descriptions essential to the general improvement of the services he receives.

It is important to note that the flow of requests for improved information which originate at the user and are passed upstream along the information flow channel, do not necessitate a research project for each and every request. As requests for improvement are passed along, they can be collected and organized in such a manner that will keep the research adminstrator appraised of the practical problems encountered in trying to make the best use of weather information. Summaries of requests for information from persons or organizations who have an understanding of both the user's problems and the weather service's capability will be the best possible guide in making decisions on research programs.

Figure 6 shows a similar analysis of the weather-information needs of a farmer who grows hay. In the terms of Section III above, this is a problem of damage and spoilage. The farmer's needs differ from those of the airline dispatcher chiefly in that the farmer needs an earlier warning. The actions the farmer can take require

that his plans be made as much as five days in advance, and he, therefore, needs good predictions for this period.

We note that, in contrast to the case of the airline dispatcher, there is no person or organization to fulfill the role of weather advisor to the hay grower. It is unlikely that the hay grower would be able to make maximum use of improved five-day forecasts if the forecasts were not adapted for him by someone who was familiar with his problem.

Despite the differences in the length of the forecast, much research is common to the needs of the farmer and airline dispatcher. The key to useful forecasts in both instances is the prediction of the movement and character of the air masses in the region under consideration -- and the dynamic processes that will modify these masses.

The improvement in prediction and description that is useful to the airline dispatcher is the first step in the solution of the problem of the farmer. The weather situation that may close an airport tomorrow may be the prelude to a rainy day hundreds of miles away -- three days from now.

The same general truth is illustrated in Fig. 7. Improvements in the general descriptions of weather that are provided to weather advisors, would result in broad benefits to a whole spectrum of clients. Figure 7 illustrates the problem of a contractor who is erecting a building. The long-term predictions that lead to the benefit of the farmer can also be adapted by a weather advisor to answer his client's questions about the mobility of his earth-moving equipment. If the climatological problems of sequences of dry days were solved ("General Description" box in Fig. 6), the scheduling problems of the contractor could be attacked with the same type of study. If good predictions of wind, ceiling, and visibility were available to the airline dispatcher, they could be adapted to help the builder avoid dangerous situations in the framing, siding, and roofing stages of his operation.

Decision Maker

Actions	Problems	Lead Time
Overall plan of attack	How much weather hold-up?	Several months
Excavation scheduling	Can heavy equipment work?	12--36 hours
Pouring concrete	Will the concrete be spoiled?	12--24 hours
Framing, roofing, siding	Can men and equipment work (particularly high above ground)?	12--24 hours

Weather Information	Nonweather Information
Rain Temperature--freezing Wind	Scheduling restraints Supply, equipment, and labor availability

Fig. 7 Structure of the building contractor's weather problem

The Pivotal Role of the "Weather Advisor"

We have repeatedly pointed out the fact that meteorological research that improves the general description of the weather will be useful to a great many users. In each case, however, we have tacitly assumed that some one will adapt the general description to the user's needs. Unless the user's needs are understood and the weather information tailored to his requirements, however, improvements in the general description of the weather will not be reflected in improved social and economic benefits. We feel that the job of the weather advisor and the research on external communications are vital to the application of meteorological research for the benefit of society. In order to see what is involved in research on external communication, we will again use the problem of the raisin producer, a summary of which is appended to this report. We will not follow the actual historical development of this case but will try to indicate how this problem could have been approached.

The first step in the process is to state the problem of the user; in this case his problem is to minimize the loss due to the wetting of the raisins at a critical time during the drying process. The next step is to determine just what weather parameters are critical and what areal resolution is needed for adequate advisories. In the case of the raisin industry it was found that an average of 0.04 inches of rain in an area of the central valley of California about 60 miles long and 20 miles wide would cause widespread damage. Although finer resolution of rainfall quantity appeared to be useful, no attempt to refine the figures was made for this study. (This might be a subject which the weather advisor could further study in order to determine how much more useful resolution could be attained and how the weather service capabilities could be best matched to the user's needs.)

The effect of the weather is not merely the physical effect but also implies an economic loss, thus the "widespread damage" alluded to in the study of the effects of rainfall on the drying raisins was estimated at $200 per ton of dried raisins.

Once the effects are known, it is necessary to determine the actions that could be taken to reduce the damage and to determine

the cost of these actions. In our example the drying grapes are on paper trays which can be rolled and stacked to shed the rain. It should be noted that the available action requires a certain amount of time to complete and that this determines how much in advance the raisin drier needs the warning.

With the above information on the user's problem, the "weather advisor" is in a position to apply the available weather information to the problem. The methodology in this case is that outlined in the first portion of Section II. It should be noted that in order to maximize the benefit to the raisin producer, the weather advisor must be able to determine the frequencies of the prediction errors as a function of the frequency of rain forecasts. He therefore requests that the rain forecasts for the area of his interest be couched in probability terms.* With this type of information he is able to provide the raisin producer with forecasts which will minimize loss.

This outline of the procedure is deceptively simple. The example is a problem that has been solved only because much of the information needed was readily available and because the problem could be reduced to a simple protect--not-protect situation. The analysis of Section III shows that there are not many problems which can be handled in such a straightforward manner. Furthermore a little reflection will disclose the oversimplification of the raisin producers' problem. We have already mentioned the fact that the resolution of the predictions should be made finer, and the original study pointed out that the problem varied considerably depending on how long it took the grapes to ripen. Nevertheless we believe that the raisin producers' problem is a step toward an evaluation of weather information.

SUMMARY OF SECTION IV

We have attempted to elucidate two principles in this section: (1) improvements in the general description of the behavior of the

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*In this instance a forecast system which produced probability forecasts had already been devised.(5)

atmosphere can lead to benefits to many and varied users, and (2) in order that the benefits of these be realized, the weather service must maintain good internal communications and an adequate liaison with the specific users of weather information.

The first principle can simplify the evaluation of research projects in the first five categories at the left of Fig. 4, because it frees such projects from the restraints of serving one specific user. It would be difficult, in view of the users and potential users discussed in Section III, to find improvements in the general description of the atmosphere that would not benefit more than one client. The second principle, on the other hand, is one that demands continuous and diligent study, not only to exploit available weather information to the limit, but particularly to permit a useful assessment of the value of meteorological research.

V. FEASIBILITY OF COST--BENEFIT STUDIES

The value of weather information is the value that accrues to a society because many people, agencies, and organizations can choose an optimum course of action if they know the effect of the weather on their operations, have a choice of beneficial actions and sufficient information about the weather. We have tried to demonstrate, in Section II, how the value to a single decision maker can be estimated, and we have tried to point out the insurmountable difficulties in making such estimates for all decision makers and then aggregating the results.

In view of these difficulties we have sought a framework whereby those facets of the problem that could be analyzed and that information which is available could be used to assist in making reasonable decisions about the kind of research that might be most advantageous for improvement of the weather system. In Section III we discussed the nature of the users' problems and tried to relate them to descriptions of weather conditions that are familiar prediction objectives of meteorologists. In Section IV we attempted to show how users' problems could generate meaningful research problems. We stressed the fact that the basic research problems generated in this way could be useful to a great variety of consumers, but that more effort was needed in order to apply the results of successful basic research to the problems of the users.

The research we have called external communication and have discussed as being a principal duty of the weather advisor is, we believe, the most pressing need revealed in the course of our analysis. A program that would examine a fair sample of users from the work of Section III by the methodology outlined in Section II would serve a threefold purpose. First, it would improve the weather service to those users and to many others; second, it would focus attention on the areas of basic research that would be most beneficial to the economy and society; and third, it would provide the basic data from which rough estimates of the value of weather information could be derived.

Despite the fact that the methodology outlined in Section II does not have universal application, it may be possible to approximate many real problems with sufficient accuracy to make a definite contribution to many a user's application of weather information. Should the model prove inadequate, it is possible that modifications and improvements would produce a model that would permit a realistic analysis. Even if the problem cannot be analysed in a quantitative fashion, the orderly search for the important parameters outlined in Section III should still improve the user's understanding of how weather information can be used subjectively in making his decision.

As more and more user's problems are critically analysed with the view to interpreting the weather the requests for improved information that are passed along through the weather service will be helpful in deciding on the allocation of research effort. A single request for information that would take a large research and development effort to answer would probably go unheeded. If, however, a large number and variety of users needed the same type of information there would be more cause to institute the necessary program. The feedback of requests from the weather advisors will keep the research administrator informed on the needs of the consumers.

After a few years of experience with estimating the value of weather information to individual users, it may be possible to combine the values in a matrix similar to Table 6. Instead of counting the number of problems in each cell of the matrix, however, the crude total dollar benefit could be entered. These totals would need cautious interpretation because of the economic factors, which would indicate that simple summation is not an appropriate way to combine the value to individual users, but at least they might be considered as an index of value.

Having once estimated the value of the present service it would be relatively simple to assume an increase of accuracy and precision of the service represented by each cell in the matrix and to estimate the value of this improved service. In this manner it would be possible to provide an index of the value of an improvement in the general description of the weather as it is represented by

the matrix. The necessary investment of resources to attain this improvement can still be only subjectively estimated on the basis of the outcome of research programs, but the research administrator need no longer consider the applicability of the research to individual users but only to the improvement of the general description of the weather.

Caveat. We do not suggest that even this approximation to a cost--benefit analysis will be easy or inexpensive. We are convinced, however, that research in external communication, by the hypothetical weather advisor, is basic to the attainment of any estimate of the value of weather information. If such research is stimulated and is successful in providing increased utility of the present state of the art of forecasting, then it will provide the necessary background data for an estimate of the value of research in the atmospheric sciences.

Appendix A

COMPILING A WEATHER-PROBLEM CATALOG

PURPOSE AND PRINCIPLES

The weather-problem catalog was inspired by two desires: (1) the desire to be somewhat empirical in this short-term study of the needs of users of a national weather service; and (2) the longer-term desire to experiment with a technique that might be applied toward a continuing and increasingly detailed and valid comparison of the weather-service product and the social and economic requirements for that product.

The desire for empiricism stems from our conviction that the needs of users defy generalization without explicit consideration of many weather problems over a broad spectrum. The desire to experiment with a cataloguing technique stems from our feeling that the evaluation of weather-service benefit should become ever more quantitative in years to come and that the service product and user requirements demand a novel framework for their joint analysis.

This compilation does not list matters of benefit from the use of climatology per se, nor does it consider the possible benefit of weather information to research and development. In other words, it excludes problems of long-term planning and of research support. It concentrates on problems whose solutions may depend on weather forecasts that exceed the accuracy of climatological forecasts.

The objective was to assemble -- quickly -- an experimental catalog large enough to reveal the problems inherent in the organization and analysis of the situations and decisions faced by a wide range of users of weather information. We believe we have succeeded in this. However, there was no attempt to exhaust the field, an attempt costly of time; the catalog, therefore, is not to be considered complete or definitive, but rather, representative.

Expediency mainly dictated our choice of sources. We drew upon the few case studies of weather service utility that had been done at RAND; we consulted with a few "weather advisors," both

private and government-employed; we talked with several users in the nearby business community; and we consulted with the Central Office staff of the U.S. Weather Bureau; but mainly we relied upon our own past personal experiences in dispensing weather information.

METHOD

The following descriptions and tables are needed in order to understand the compilation of the catalog and to interpret the data.

User Categories

Table A-1 lists eighteen categories of users of weather information; it is adapted from a classification system developed by the U.S. Weather Bureau. Table A-1 is, in effect, an outline of the catalog. Specific problems of users in categories 1 and 2, the general public and the scientific community, are not in the catalog, because it is extremely difficult to define a representative selection of discrete segments in either of these categories for which specific problems can be stated. The other 16 categories, however, are used in the catalog, and are numbered in the catalog as in Table A-1.

Each user listed has been chosen, insofar as possible, to represent the largest governmentally or commercially homogeneous group sharing the same weather problem or set of problems.

Weather Problems and Weather Effects

Each weather problem is verbally described, and each different aspect of the problem is keyed to a "weather-effect class." These pairs of problems and effects are the basic building blocks of the catalog.

The weather effect classes and code are given in Table A-2. Each class represents a somewhat different way in which "value" to the user is influenced by the weather.

Table A-1

CATEGORIES OF WEATHER-SERVICE USERS

Category Number	Category
[1]	General Public (Not used in catalog)
[2]	Scientific Community (Not used in catalog)
	Government
(3)	Preservation and Protection of Public Safety, Health and Property
(4)	Social and Economic Operational Services
(5)	Development and Protection of National and Economic Resources
	Business
(6)	Land Transportation
(7)	Air Transportation
(8)	Water Transportation
(9)	Construction
(10)	Water Supply
(11)	Power and Fuel Supply
(12)	Merchandising
(13)	Recreation Industry
(14)	Manufacturing
(15)	Commercial Fishing
(16)	Agriculture
(17)	Forestry and other Resources (Commercial)
(18)	Communications

Table A-2

WEATHER EFFECT CLASSIFICATION

Weather Effect Code	Classification of Weather Effect
Class 1	Weather influences CAPITAL, where that capital consists of:
1a	Private or public property
1b	A commercial product
1c	A public utility product
1d	Human life or health
Class 2	Weather influences COSTS involved in, and the ability to perform:
2a	A public service operation
2b	A commercial service (or industrial) operation
2c	A public utility service operation
2d	A private, noncommercial operation
Class 3	Weather influences REVENUES, and intangible benefits, expected to be derived from:
3a	A public service
3b	A commercial service
3c	A public utility service or product
3d	A commercial product

Weather Conditions

In order to effect a direct transformation between problem solving (the user's responsibility) and weather information (the meteorologist's responsibility), it is necessary to try to describe weather conditions so that users are able to associate the weather conditions quite directly with a specific weather effect.

Table A-3 is our attempt to meet this objective. It lists all of the weather conditions required to produce all of the weather effects contained in the catalog (and also shows how the weather conditions in the catalog are encoded).

In Table A-3 "simple" weather conditions are described in terms of their ability, individually or collectively, to produce effects. They are stated in relative terms, in recognition of the fact that their effects vary in degree with user, with problem, with climate, with antecedent conditions, and with concurrent conditions of other types. For the sake of meteorological analysis, it was advisable to group the "simple" conditions according to whether they are mainly induced by wind, temperature, precipitation (including lightning), or cloudiness (including fog and humidity). Also, recurrent combinations of "simple" conditions are said to be "compound" conditions. In the catalog, every "simple" weather condition is listed even if it occurs as part of a "compound" condition.

Spatial Resolution of Weather Conditions

For each weather condition and for each weather effect that constitutes a problem to him, a decision maker is concerned with a critical distance, area, or volume in space. His space scale of interest may or may not be a function of the space scale of the associated meteorological phenomena. It is the decision makers' requirements for spatial resolution that we have attempted to specify in the catalog.

The spatial resolution scale encoded in the catalog is given in Table A-4. The class intervals overlap, and the logarithms of equivalent measure in each class are approximately equal.

Lead-Time Requirements

For every action that a decision maker may take to ameliorate an anticipated weather problem, a certain amount of time is required. For most problems, a dependent sequence of actions is necessary to optimize the user's benefit from advance weather information. It is self-evident, then, that the greater the lead time, the greater the potential benefit. For practical purposes, however, we have tried to estimate a "minimum beneficial lead time" as the time required to complete those actions that will secure, for the user, a small but significant fraction of the maximum possible benefit afforded by the weather information. Information provided in less than "minimum beneficial lead time" is considered to have no significant value. With increasing lead time, the user is able to perform an increasingly complete sequence of actions and, thereby, progressively secure greater benefits. We have estimated a "maximum beneficial lead time" that will enable the user to complete enough actions to secure most (say 80%) of the benefit from the weather information. In addition (in deference to the usefulness of climatology), we have attempted to estimate, where pertinent, different sets of required lead times for climatologically "normal" and "abnormal" weather conditions.

The lead-time scale employed in the catalog is shown in Table A-5. The logarithms of the time intervals in each class are approximately equal.

It is obvious from the above discussion that the lead times are the most subjective of all the data in the catalog.

Characteristic Actions

The catalog contains a brief description of user actions only to help the reader gain a concrete and specific concept of the problems. The "preparatory" routines are those taken deliberately by a user before action is urgent, to optimize his later choice of tactics. "Tactical" actions are those which can be avoided until the last possible moment. The distinction between the two types is not always clear cut.

Table A-3

WEATHER CONDITION CLASSIFICATION

	"Simple" Weather Conditions	"Compound" Weather Conditions (see Key below)								
		X			Y			Z		
		1	2	3	1	2	3	1	2	3
A. WIND	1. Upper-air transport; displacement								*	
	2. Damaging wind and turbulence	#	#		#	#	#	#	*	*
	3. Pollutant concentration; transport				#					
	4. Particulate transport; drifting	#			#					
	5. Blowing sand and dust	#			#	#				
	6. Wind waves; surf									
	7. Storm surge; enhanced tide									
B. TEMPERATURE	1. Cooling; chilling (relative)				#					
	2. Overcooling (general; unspecified)					#				
	3. Freezing (< 32°F)	#								
	4. Extreme cooling (≈ < 0°F)		#				#			
	5. Warming (relative)				#					
	6. Overheating (general; unspecified)					#				
	7. Extreme heating (≈ > 95°F)	#					#			
	8. Ground temperature									
	9. Ground freeze									
	10. Ground thaw									
	11. Avalanche									
	12. Air density									*
	13. Water surface temperature									
	14. Sea, lake, and river ice									
C. PRECIPITATION (INCLUDING LIGHTNING)	1. Rain wetting; soaking	#			#	#	#			
	2. Rain wash-off; leaching									
	3. Damaging glaze									
	4. Damaging hail	#	#		#	#			*	*
	5. Surface icing; glaze	#	#	#	#	#	#	#		
	6. Surface snow cover	#	#	#	#	#	#	#		
	7. Wetting of surfaces; water film	#	#		#	#				
	8. Flood erosion; washout	#								
	9. Stream flow; flood flow									
	10. Landslide									
	11. Effective runoff									
	12. Ground-water flooding; slush	#			#	#				
	13. Inundation; stream flooding	#	#							
	14. Atmospherics; radio static									
	15. Lightning				#	#	#		*	*
	16. Forest fire danger									
	17. Drought; precipitation shortage									
	18. Water supply shortage									
D. CLOUDINESS (INCLUDING FOG AND HUMIDITY)	1. Low light intensity; dull	#			#					
	2. High light intensity; bright; sunny	#			#					
	3. Vertical visibility; ceiling; vis. aloft							#	*	*
	4. Surface (horizontal) visibility	#	#	#	#	#		#		
	5. Radiation propagation (IR, radio)									
	6. Dryness				#					
	7. Desiccation									
	8. Moistness; mugginess				#					
	9. Damp; foggy; dewy									
	10. Aircraft icing								*	*

*aloft

Key

X. LAND MOBILITY; DRIVING
1. General conditions
2. Obstructive conditions
3. Hazardous conditions

Y. UNSHELTERED ACTIVITY
1. General comfort conditions
2. Unpleasant conditions
3. Very uncomfortable or hazardous conditions or both

Z. AIR TRANSPORTATION
1. Terminal operating conditions
2. General conditions in flight
3. Hazardous conditions in flight

Table A-4

SPACE SCALE OF WEATHER CONDITIONS

Code	Name	Linear Equiv. (mi)	Areal Equiv. (mi^2)	Examples
1	Micro	point--2	point--4	dock, airport, orchard, field, stadium, small farm, RR yard, small lake
2	Micro-Meso	1.5--10	2.5--100	large farm, town, urban center, suburb, harbor, lake
3	Meso	7--60	50--4000	metropolitan area, county, ranch, large lake
4	Meso-Synoptic	40--300	2000--100,000	large county, stream basin, megalopolitan area, state, bay, great lake, forest
5	Synoptic	200--1000	50,000--10^6	large state, region, river basin, sea, gulf
6	Synoptic-Macro	700--5000	(0.5--30) $x10^6$	large region, continent, small ocean
7	Macro	>4000	>$16x10^6$	large continent, hemisphere, ocean, planet

Table A-5

LEAD-TIME SCALE

Code	Lead-Time Class Interval
1	Less than 1 hour
2	1 hour to 3 hours
3	3 hours to 9 hours
4	9 hours to 24 hours
5	1 day to 3 days
6	3 days to 10 days
7	10 days to 1 month
8	1 month to 3 months
9	3 months to 1 year
10	1 year and greater

CATALOG OF WEATHER PROBLEMS

(3) PRESERVATION AND PROTECTION OF PUBLIC SAFETY, HEALTH, AND PROPERTY

(3-1) Highway Maintenance (State, Local)

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Effectively protect roads from weather-caused damage ...	1a++		A2++	2++	3++	5++	...	...	Preparatory
			A4	2	3	5	5++	6++	Order supplies
			B9	2	3	5	...	...	Prepare equipment
			B10	4	4	6	...	...	Alert crews
			B11	1	...	...	5	6	Tactical
			C5	1	3	5	5	7	Plow snow
			C6	2	3	5	5	6	Sand or salt
			C8	1	5	6	6	8	Clear obstacles
			C10	1	...	...	6	8	Sand bag
			C12	1	3	5	...	...	Barricade
			C13	1	...	...	6	8	
... and maintain safe travel conditions...	1d		C5	1	2	3	...	...	
			C6	2	3	5	...	...	
... at minimum cost in face of adverse weather	2a	X3++	C5	1	3	5	...	...	
			C6	2	3	5	4	6	
			D4	2	3	5	...	...	
(3-2) Highway Traffic Control (State, Local)									
Effectively minimize risks of traffic accidents due to weather...	1d	X3	C5	1	2	3	...	...	Preparatory
			C6	2	2	3	...	...	Prepare vehicles
			D4	1	1	3	...	...	Alert personnel
... at minimum cost in face of adverse weather	2a	X3	C5	3	3	4	...	...	Tactical
			C6	3	3	4	4	6	Set emergency patrol
			D4	3	3	4	...	...	Close hazardous areas
									Curtail traffic
									Change speed limits
(3-3) Air Traffic Control (Federal)									
Safely regulate terminal traffic under unfavorable operating conditions	1d	Z1	A2	2	1	2	...	...	Tactical
			B12	1	1	2	...	...	Predict hold time
			C5	1	1	2	...	...	Control stack pattern
			C6	1	1	2	...	...	Control landing rate
			D3	1	1	2	...	...	Close terminal
			D4	1	1	2	...	...	
		Z3	A2*	2	1	2	...	...	
			C4*	1	1	2	...	...	
			C15*	2	1	2	...	...	
			D3*	2	1	2	...	...	
			D10*	2	1	2	...	...	
Maximize general safety of aircraft in flight	1d	Z3	A2*	3	1	3	...	...	Tactical
			C4*	2	1	3	...	...	Advise of hazardous conditions *en route*
			C15*	3	1	3	...	...	
			D3*	3	1	3	...	...	
			D10*	3	1	3	...	...	
(3-4) Flood Control (Federal, State, Local)									
Minimize flood damage to property...	1a		C9	2	...	...	4	6	Preparatory
			C13	2	...	...	3	6	Insure capacity to control
... and minimize hazard to life and health	1d		C13	2	...	...	2	5	Alert system
									Tactical
									Regulate water storage and release
									Warn of flash (and other uncontrollable flooding)

++For Weather Effect, see Table A-2.
For Weather Condition, see Table A-3.
For Spatial Resolution, see Table A-4.
For Beneficial Lead Time, see Table A-5.

*aloft

(3-5) Public Health (Federal, State, Local)

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Protect public against toxic pollutants	1d		A3	3	3	5	4	6	<u>Preparatory</u> Augment supplies and personnel <u>Tactical</u> Warn proper authorities
Protect public from hazards of overexposure	1d		A2	2	2	5	6	7	<u>Tactical</u> Advise public
			A5	3	3	5	6	7	
			B2	4	3	5	5	6	
			B6	4	3	5	5	6	
			C15	2	2	3	...	...	
			D2	3	3	5	...	...	

(3-6) Disaster Control (Federal, State, Local)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize losses of property...	1a		A2	2	...	...	5	7	<u>Preparatory</u> Mobilize forces (relocate, alert, augment, etc.) <u>Tactical</u> Issue warnings Provide shelter Evacuate Survey and rescue
			A5	2	...	...	5	7	
			A7	3	...	...	5	7	
			B11	1	...	...	6	8	
			C9	2	...	...	4	7	
			C10	1	...	...	6	8	
			C13	3	...	...	4	7	
...and life, due to severe weather and its effects...	1d		A2	2	...	...	2	4	
			A5	1	...	...	3	5	
			A7	3	...	...	3	5	
			B11	1	...	...	2	3	
			C9	1	...	...	2	5	
			C10	1	...	...	2	3	
			C13	2	...	...	3	5	
...and do so with maximum effectiveness under unfavorable weather conditions	2a	X3	C5	3	3	4	...	...	
			C6	3	3	4	...	...	
			D4	2	3	4	...	...	
		Z3	A2*	2	1	3	...	...	
			C4*	2	1	3	...	...	
			C15*	2	1	3	...	...	
			D3*	2	1	5	...	...	
			D10*	2	1	3	...	...	

(3-7) Fire Protection (Local)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Maximize efficiency under varying weather conditions	2a		A1	1	1	3	...	...	<u>Preparatory</u> Prepare equipment
			B4	2	...	...	3	5	
			C1	1	1	2	...	...	
			C5	2	3	4	...	...	
			C6	2	3	4	...	...	

(3-8) Air Pollution Control (Local, State)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Efficiently minimize public exposure to smog	1d		A3	3	3	4	5	7	<u>Tactical</u> Regulate pollutant production Advise public

(3-9) Radioactive Pollution Control (Federal)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Efficiently minimize radiation hazard	1d		A3	1	2	3	...	...	<u>Tactical</u> Alter operation and test procedures

(3-10) Water Pollution Control (Federal, State, Local)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Efficiently minimize stream pollution	1d		C9	2	5	6	...	...	<u>Tactical</u> Regulate pollutant release

(3-11) Air-Sea Rescue (Federal, State)

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Anticipate hazards...	1d		A6	4	3	5	...	...	Preparatory
			C6	2	3	5	...	...	Alert forces
			D4	2	3	5	...	...	Tactical
									Warn public
...and perform effectively despite adverse weather	2a		A6	2	3	5	...	...	Vary procedures according to weather
			C6	1	2	4	...	...	
			D1	2	3	5	...	...	
			D2	2	3	5	...	...	
			D4	1	3	4	...	...	
		Z3	A2*	3	2	3	...	...	
			C4*	3	3	3	...	...	
			C15*	3	2	3	...	...	
			D3*	3	2	3	...	...	
			D10*	3	3	3	...	...	

(3-12) Sanitation (Local)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize flood-caused disruption of sanitation system	1d		C12	1	5	7	...	...	Preparatory
			C13	1	5	7	...	...	Protect system
									Prepare emergency measures
									Tactical
									Advise proper authorities

(3-13) Coast and Waterway Patrol (Federal, Local)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Protect small craft against hazard of rough seas...	1d		A6	3	3	5	...	...	Preparatory
									Alert forces
...effectively under difficult operating conditions	2a		A6	2	2	3	...	...	Tactical
									Issue warnings
									Set emergency patrol

(3-14) Harbor and Waterway Maintenance (Federal, State, Local)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize damage to facilities due to high water, current, ice, and wave action	1a		A6	2	3	5	6	8	Preparatory
			A7	2	...	...	5	8	Alert forces
			B14	2	4	5	5	7	Tactical
			C9	2	...	...	4	6	Secure facilities
			C13	2	...	...	4	6	

(4) SOCIAL AND ECONOMIC OPERATIONAL SERVICES

(4-1) Postal Service (Federal)

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
"Complete appointed rounds" with maximum efficiency	2a	X2	A2	2	2	2	...	...	<u>Preparatory</u> Prepare equipment
			B4	3	...	...	3	5	
			C4	2	2	2	...	...	
			C5	2	3	3	...	...	
			C6	2	3	5	5	6	
			C7	2	2	3	...	...	
			C13	1	4	5	...	...	
			D4	2	2	2	...	...	

(4-2) Schools (Local)

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
Minimize weather risks to children <u>en route</u> to and from school	1d	X3	C5	2	2	4	...	...	<u>Preparatory</u> Prepare buses <u>Tactical</u> Close schools
			C6	2	2	4	...	...	
			D4	2	3	4	...	...	

(5) DEVELOPMENT AND PROTECTION OF NATURAL AND ECONOMIC RESOURCES

(5-1) Forest Service (Federal, State, Local)

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
Anticipate lightning-	1a		C15	2	5	6	...	...	<u>Preparatory</u>
caused fires...			C16	2	5	6	6	8	Augment surveillance
...and increase surveillance	2a	Z3	A2*	2	2	4	...	...	Alert fire-fighting
despite adverse weather			C4*	2	2	4	...	...	forces
			C15*	2	2	4	...	...	<u>Tactical</u>
			D3*	2	2	4	...	...	Suppress lightning
			D10*	2	2	4	...	...	
Fight fires effectively	2a		A1	1	2	3	...	...	<u>Tactical</u>
			C1	1	2	3	...	...	Vary fire-fighting plan
		Z3	A2*	2	2	4	...	...	
			C4*	2	2	4	...	...	
			C15*	2	2	4	...	...	
			D3*	2	2	4	...	...	
			D10*	2	2	4	...	...	
Minimize number of fires in	1a		C16	3	5	7	7	9	<u>Preparatory</u>
general									Alter fire detection and
									fighting capacity
									Alert loggers
									<u>Tactical</u>
									Close forests to public
									Shut down logging

(5-2) Park Service (Federal, State, Local)

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
Maximize efficiency in meet-	3a	Y1	A2	3	5	6	...	...	<u>Preparatory</u>
ing variable public volume			A3	3	5	6	...	...	Augment work force
			A4	3	5	6	...	...	
			A5	3	5	7	...	...	
			B1	3	5	7	...	...	
			B5	3	5	6	...	...	
			B13	2	6	7	...	...	
			C1	3	5	7	...	...	
			C4	3	5	6	...	...	
			C5	3	5	7	...	...	
			C6	3	5	7	...	...	
			C7	3	5	6	...	...	
			C12	3	5	7	...	...	
			C15	2	5	6	...	...	
			D1	3	5	6	...	...	
			D2	3	5	6	...	...	
			D4	3	5	6	...	...	
			D6	3	5	6	...	...	
			D8	3	5	6	...	...	
Maintain safety of	1a		A7	2	...	...	6	7	<u>Preparatory</u>
property...			B11	1	4	6	5	7	Prepare equipment
			C10	1	...	...	6	8	Alert personnel
			C16	3	5	6	...	...	<u>Tactical</u>
...and of the public	1d		A7	2	...	...	2	4	Close facilities
			B11	1	...	...	3	5	Secure properties
			C10	1	...	...	3	5	Restrict activity
		X3	C5	2	4	5	...	...	
			C6	2	4	5	...	...	
			D4	2	2	3	...	...	

(5-3) Water Supply (Federal, State, Local)

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Make optimum adjustment between anticipated water supply...	1c		C11	4	5	7	...	...	Tactical
			C18	4	...	...	7	9	Control routing
									Inhibit evaporation
...and demand	3c		C17	4	6	7	7	9	Ration water
									Order cloud-seeding
(5-4) Atomic Energy Development (Federal)									
Effectively protect public from hazard of radioactive pollution...	1d		A3	1	3	5	...	...	Tactical
									Alter operations schedule
...at minimum operating cost	2a		A3	1	2	6	...	...	
(5-5) Aero-Astronautics Development (Federal)									
Minimize hazard to public and private property...	1a		A1*	2	1	5	...	...	Tactical
			A2	1	1	5	5	7	Reschedule test
			A2*	2	1	5	...	...	Alter test procedures
			C3	1	1	5	...	...	Secure facilities
			C4	1	1	2	...	...	
			D3	2	1	5	5	7	
			D5	2	1	5	5	7	
...and life...	1d		A1*	2	1	5	...	...	
			A2*	2	1	5	...	...	
			D3	2	1	5	5	7	
			D5	2	1	5	5	7	
...at minimum cost and loss of effectiveness of vehicle test operations	2a		A1*	2	3	5	...	...	
			A6	3	2	5	...	...	
			C14	3	2	5	...	...	
			D3	1	1	5	...	...	
			D3*	2	2	5	...	...	
			D5	3	2	5	...	...	
(5-6) Survey and Mapping (Federal, State, Local)									
Optimize survey procedures according to weather conditions	2a		A1*	4	3	5	...	...	Preparatory
			A6	4	...	...	6	8	Prepare equipment
			C6	2	5	7	...	...	Tactical
			D1	3	5	6	...	...	Change schedule
			D2	3	5	6	...	...	Alter methods
			D3	2	5	6	...	...	
			D4	1	5	6	...	...	
		Z3	A2*	3	2	5	...	...	
			C4*	3	2	5	...	...	
			C15*	3	2	5	...	...	
			D3*	3	2	5	...	...	
			D10*	3	2	5	...	...	

(6) LAND TRANSPORTATION

(6-1) Truckers

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Safely transport temperature sensitive goods	1b		B2	3	3	6	...	...	Tactical
			B6	3	3	6	...	...	Change equipment
									Change route
									Change schedule
Safely transport rain-sensitive goods	1b		C1	2	3	4	...	...	Tactical
									Install tarps
Minimize delivery costs in face of adverse driving conditions	2b	X2	A2	2	2	4	...	...	Preparatory
			B4	4	...	...	5	6	Prepare equipment
			C4	2	2	4	...	...	Tactical
			C5	3	3	5	...	...	Change route
			C6	3	3	5	4	6	Change schedule
			C7	3	2	4	...	...	
			C13	1	...	...	4	6	
			D4	2	2	4	...	...	

(6-2) Railroads

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize delay due to adverse track conditions	2b		C5	2	4	5	6	7	Preparatory
			C8	1	...	...	5	7	Alert snow-removal crews
			C13	1	...	...	5	6	Tactical
									Dispatch crews
									Change schedule
									Change route
Minimize failure of equipment...	1a		B4	1	4	5	...	...	Preparatory
									Prepare (or change) equipment
...and resulting loss of service due to extreme cold			B4	1	4	5	...	...	Augment yard work force
Maximize service...	2c		B4	3	4	5	...	...	Preparatory
			C6	1	3	4	5	6	Alert crews
									Prepare extra cars
...and revenues of abnormally high commuter trafic	3c	X2	A2	3	4	5	...	...	Tactical
			B4	3	4	5	...	...	Use augmented capacity
			C4	3	4	5	...	...	
			C5	3	4	5	...	...	
			C6	3	4	5	...	...	
			C7	3	4	5	...	...	
			C13	3	4	5	...	...	
			D4	3	4	5	...	...	

(6-3) Bus Lines (Long Distance)

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize costs in face of adverse driving conditions	2b	X2	A2	3	2	5	...	...	Preparatory
			B4	4	3	4	4	6	Prepare for emergencies
			C4	2	2	4	...	...	Tactical
			C5	2	2	5	...	...	Change schedule
			C6	3	3	5	4	6	Change route
			C7	3	3	5	...	...	
			C13	1	2	5	...	...	
			D4	3	2	4	...	...	

(6-4) Metropolitan Transit Lines (Includes Subway, Bus, Streetcar)

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
Maximize service...	2c	X3	C5	2	3	5	...	...	Preparatory
			C6	2	3	5	4	6	Alert personnel
			D4	2	3	5	...	...	Prepare equipment
...and revenues of abnormally high demand	3c	X2	A2	2	4	5	...	...	Tactical
			B4	3	4	5	...	...	Increase schedule
			C4	2	4	5	...	...	
			C5	2	4	5	...	...	
			C6	2	4	5	...	...	
			C7	2	4	5	...	...	
			C13	1	4	5	...	...	
			D4	2	4	5	...	...	
		Y2	A2	2	4	5	...	...	
			A5	2	4	5	...	...	
			B2	3	4	5	...	...	
			B6	3	4	5	...	...	
			C1	2	4	5	...	...	
			C4	2	4	5	...	...	
			C5	1	4	5	...	...	
			C6	2	4	5	...	...	
			C7	2	4	5	...	...	
			C12	1	4	5	...	...	
			C15	2	4	5	...	...	
			D4	2	4	5	...	...	

(6-5) Taxicab Companies

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
Maximize service...	2b	X3	C5	3	3	5	...	...	Preparatory
			C6	3	3	5	4	6	Alert personnel
			D4	2	3	5	...	...	Prepare cabs
...and revenues of abnormally high demand	3b	X2	A2	2	3	4	...	...	Tactical
			B4	3	3	4	...	...	Use augmented capacity
			C4	2	3	4	...	...	
			C5	2	3	4	...	...	
			C6	2	3	4	...	...	
			C7	2	3	4	...	...	
			C13	1	3	4	...	...	
			D4	2	3	4	...	...	
		Y2	A2	2	3	4	...	...	
			A5	2	3	4	...	...	
			B2	3	3	4	...	...	
			B6	3	3	4	...	...	
			C1	2	3	4	...	...	
			C4	2	3	4	...	...	
			C5	1	3	4	...	...	
			C6	2	3	4	...	...	
			C7	2	3	4	...	...	
			C12	1	3	4	...	...	
			C15	2	3	4	...	...	
			D4	2	3	4	...	...	

(6-6) Airport Transport Companies

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
Maximize service...	2b	X3	C5	2	3	4	...	...	Preparatory
			C6	2	3	5	4	6	Alert contract buses
			D4	2	3	4	...	...	Tactical
...and revenues due to abnormally high landing rate of an airport	3b	Z1	A2	1	3	5	...	...	Alter schedule
			B12	1	3	5	...	...	Use contractors
			C5	1	3	5	...	...	
			C6	1	3	5	...	...	
			D3	1	3	5	...	...	
			D4	1	3	5	...	...	

(6-7) Parcel Delivery Service

Problem	Weather Effect	Weather Condition		Spatial Resolution	Beneficial Lead Time				Characteristic Actions
		Compound	Simple		Normal Min	Normal Max	Abnormal Min	Abnormal Max	
Minimize delivery costs in face of adverse driving conditions	2b	X3	C5	2	3	4	...	...	Preparatory
			C6	2	3	4	4	6	Prepare equipment
			D4	2	3	4	...	...	Tactical
									Reschedule deliveries

(7) AIR TRANSPORTATION

(7-1) Airlines

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Pre-flight decision in face of adverse landing conditions at destination (and alternates)	2b	Z1	A2	1	2	4	...	...	<u>Tactical</u> Cancel flight Add fuel Change schedule
			B12	1	2	4	...	...	
			C5	1	2	4	...	...	
			C6	1	2	4	...	...	
			D3	1	2	4	...	...	
			D4	1	2	4	...	...	
In-flight decision in face of adverse landing conditions	2b	Z1	A2	1	1	2	...	...	<u>Tactical</u> Divert Hold
			B12	1	1	2	...	...	
			C5	1	1	2	...	...	
			C6	1	1	2	...	...	
			D3	1	1	2	...	...	
			D4	1	1	2	...	...	
		Z3	A2*	2	1	2	...	...	
			C4*	2	1	2	...	...	
			C15*	2	1	2	...	...	
			D3*	2	1	2	...	...	
			D10*	2	1	2	...	...	
Optimize flight path	2b	Z2	A1*	4	3	4	...	...	<u>Tactical</u> Choose quickest route
			A2*	3	1	4	...	...	
			B12*	4	3	4	...	...	
			C4*	1	1	1	...	...	
			C15*	1	1	1	...	...	
			D3*	4	3	4	...	...	
			D10*	4	3	4	...	...	

(7-2) Light Plane Rental

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize risks to customers and aircraft	1b	Z1	A2	1	1	3	...	...	<u>Tactical</u> Restrict use Recall aircraft
			B12	1	1	3	...	...	
			C5	1	1	3	...	...	
			C6	1	1	3	...	...	
			D3	1	1	3	...	...	
			D4	1	1	3	...	...	
		Z3	A2*	3	2	3	...	...	
			C4*	3	2	3	...	...	
			C15*	3	2	3	...	...	
			D3*	3	2	3	...	...	
			D10*	3	2	3	...	...	

(7-3) Air Terminal Companies

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Maximize efficiency in meeting weather-caused fluctuations in traffic	3c	Z1	A2	1	3	5	...	...	<u>Preparatory</u> Alert personnel <u>Tactical</u> Alter service operations
			B12	1	3	5	...	...	
			C5	1	3	5	...	...	
			C6	1	3	5	...	...	
			D3	1	3	5	...	...	
			D4	1	3	5	...	...	
Maximize landings and take-offs in face of poor runway conditions	1a		C5	1	3	4	4	6	<u>Preparatory</u> Alert work force Prepare equipment <u>Tactical</u> Clear runways
			C6	1	3	4	4	6	

(8) WATER TRANSPORTATION

(8-1) Ocean Shippers

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize time *en route*	2b		A1	5	6	8	...	...	*Tactical*
			A6	5	6	8	...	...	Deviate from great circle (or climatologically "best") route
			B14	5	6	8	...	...	
Safeguard ship...	1a		A6	4	5	6	...	...	*Tactical*
...and cargo against effects of high winds and rough seas	1b		A2	4	4	5	...	...	Extra-secure cargo
			A6	4	4	5	...	...	Change course

(8-2) Longshore Companies

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Safeguard (perishable) cargo during handling in port	1b		A2	2	3	5	...	...	*Tactical*
			B2	2	3	5	...	...	Change schedule
			B6	2	3	5	...	...	Provide protection
			C1	2	3	5	...	...	

(8-3) Riverboat and Barge Operators

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize costs and losses due to adverse navigation conditions	2b		B14	2	...	...	5	7	*Tactical*
			C9	4	...	...	5	7	Change schedule
			D4	3	4	6	...	...	

(9) CONSTRUCTION

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
(9-1) Cement Contractors									
Avoid rain damage to fresh cement	1b		C1	1	3	6	...	...	Tactical Reschedule pouring Provide cover
(9-2) Contractors (in General)									
Minimize costs of effects of inclement weather on outdoor work	2b	Y3	A2 B4 B7 C1 C5 C6 C15	1 2 2 1 1 1 1	4 4 4 4 4 4 2	6 6 6 6 6 6 3	... ...	... ...	Preparatory Alert work force Prepare equipment Tactical Augment work force (advance schedule) Redistribute work force
Minimize costs of protecting exposed work against wetting	1b		C1	1	3	6	...	...	Tactical Temporary cover Permanent cover
(9-3) Earth Movers									
Minimize costs resulting from adverse ground conditions	2b		B9 B10 C6 C12	1 1 1 1	5 5 5 5	7 7 7 7	... ...	... ...	Preparatory Prepare equipment Tactical Reschedule work Alter methods

(10) WATER SUPPLY

(10-1) Local Water Companies

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize costs of extreme shortage...	1c		C11	3	5	7	...	...	<u>Tactical</u>
			C18	3	...	...	7	9	Ration water
...in face of increased demand	3c		C17	3	6	7	7	9	Obtain more water

(11) POWER AND FUEL SUPPLY

(11-1) Electric-Power Companies

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Efficiently meet abnormal demands for power	3c		B1	3	3	4	5	6	Preparatory
			B5	3	3	4	...	...	Prepare standby generators
			D1	3	3	4	...	...	Tactical
									Re-route power
Minimize lightning, ice, and wind damage to lines and equipment...	1a		A2	2	4	5	5	7	Preparatory
			C3	2	1	2	5	7	Prepare emergency equipment
			C15	2	4	5	...	...	Mobilize repair crews
...and minimize costs of doing so under adverse weather conditions	2c		A2	2	4	5	5	7	Tactical
			C3	2	4	5	5	7	Heat lines
			C15	2	3	5	...	...	Dispatch repair crews
		X3	C5	2	4	5	...	...	
			C6	2	4	5	5	7	
			D4	2	4	5	...	...	

(11-2) Gas Companies

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Efficiently meet abnormal demands for gas	3c		B1	3	3	5	6	7	Preparatory: Order and store additional supply; Manufacture and store additional supply. Tactical: Alter distribution

(11-3) Fuel-Oil Distributors

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Efficiently meet abnormal demands for fuel oil	3c		B1	3	5	6	6	8	Preparatory: Order and store additional supply. Tactical: Step up distribution schedule

(12) MERCHANDISING

(12-1) Retail Merchants (in General)

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Maximize sales of "weather goods" on days of high demand	3d		B1	3	5	5	6	8	Preparatory
			B5	3	5	5	...	...	Increase stock
			C1	3	5	5	...	...	Advertise
			C5	3	5	5	...	...	Redistribute stock among
			C6	3	5	5	6	8	outlets (chain stores)
			C7	3	5	5	...	...	
			D2	3	5	5	...	...	

(12-2) Lunch-Truck Operators

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Efficiently meet weather-caused fluctuations in demand	3d		B1	2	4	5	...	...	Preparatory
			B5	2	4	5	...	...	Change type of food
		Y3	A2	2	3	4	...	...	Change quantity available
			B4	2	3	4	...	...	Tactical
			B7	2	3	4	...	...	Change truck locations
			C1	2	3	4	...	...	
			C5	2	3	4	...	...	
			C6	2	3	4	...	...	
			C15	2	3	4	...	...	

(12-3) Bakeries

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize losses due to too-old bread and understocking	3d	X2	A2	2	3	5	...	...	Preparatory
			B4	2	3	5	...	...	Change quantity baked
			C4	1	3	5	...	...	Alter distribution among
			C5	1	3	5	...	...	outlets
			C6	2	3	5	...	...	
			C7	2	3	5	...	...	
			C13	1	3	5	...	...	
			D4	1	3	5	...	...	
		Y3	A2	1	3	5	...	...	
			B4	2	3	5	...	...	
			B7	2	3	5	...	...	
			C1	1	4	5	...	...	
			C5	1	3	5	...	...	
			C6	1	3	5	...	...	
			C15	1	3	5	...	...	

(12-4) Merchants (Roadside and Resort Areas)

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Maximize profits on days of high demand	3d	Y1	A2	3	5	5	...	...	Preparatory
			A3	3	5	6	...	...	Increase stock
			A4	3	5	5	...	...	Augment work force
			A5	3	5	5	...	...	
			B1	3	5	5	...	...	
			B5	3	5	6	...	...	
			B13	2	5	6	...	...	
			C1	2	5	5	...	...	
			C4	2	5	5	...	...	
			C5	3	5	5	...	...	
			C6	3	5	5	...	...	
			C7	3	5	5	...	...	
			C12	2	5	5	...	...	
			C15	2	5	5	...	...	
			D1	3	5	5	...	...	
			D2	3	5	6	...	...	
			D4	3	5	5	...	...	
			D6	3	5	6	...	...	
			D8	3	5	6	...	...	

(12-5) Caterers

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize costs of safe-guarding goods against inclement weather at outdoor functions...	1b		A2	1	3	4	...	...	Preparatory
			C1	1	3	4	...	...	Prepare equipment
									Reassure client
									Tactical
...and maximize revenues	3d		A2	1	3	4	...	...	Put up shelter
			C1	1	3	4	...	...	

(12-6) Merchants (Stores)

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Maximize telephone sales during inclement weather	3d	X2	A2	2	4	5	...	...	Preparatory
			B4	2	4	5	...	...	Advertise
			C4	2	4	5	...	...	Augment phone-order capacity
			C5	2	4	5	...	...	
			C6	2	4	5	...	...	
			C7	2	4	5	...	...	
			C13	2	4	5	...	...	
			D4	2	4	5	...	...	
		Y2	A2	1	4	5	...	...	
			A5	1	4	5	...	...	
			B2	1	4	5	...	...	
			B6	1	4	5	...	...	
			C1	1	4	5	...	...	
			C4	1	4	5	...	...	
			C5	1	4	5	...	...	
			C6	1	4	5	...	...	
			C7	1	4	5	...	...	
			C12	1	4	5	...	...	
			C15	1	4	5	...	...	
			D4	1	4	5	...	...	

(12-7) Newspaper Distributors

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize losses due to wet, home-delivered papers...	1b		C1	2	3	4	...	...	Preparatory
			C5	2	3	4	...	...	Alert personnel
			C6	2	3	4	...	...	Prepare equipment
			C7	2	3	4	...	...	Tactical
			C12	2	3	4	...	...	Advance schedule
...and serve effectively	2b	X3	C5	2	3	4	...	...	Wrap with waxed paper
			C6	2	3	4	...	...	
			D4	2	3	3	...	...	
Efficiently meet weather-caused fluctuations in urban sales pattern	3d	X2	A2	2	2	3	3	4	Tactical
			B4	2	2	3	...	...	Alter distribution among sales points
			C4	2	2	3	...	...	
			C5	2	2	3	3	4	
			C6	2	2	3	3	4	
			C7	2	2	3	...	...	
			C13	2	2	3	3	4	
			D4	2	2	3	...	...	
		Y3	A2	2	2	3	3	4	
			B4	2	2	3	...	...	
			B7	2	2	3	...	...	
			C1	2	2	3	...	...	
			C5	1	2	3	3	4	
			C6	2	2	3	3	4	
			C15	2	2	3	...	...	

(12-8) Door-to-Door Salesmen

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Maximize customer contacts	3d	X2	A2	2	3	4	...	...	Tactical
			B4	2	3	4	...	...	Alter pattern of calls
			C4	1	3	4	...	...	
			C5	1	3	5	...	...	
			C6	2	3	5	...	...	
			C7	2	3	4	...	...	
			C13	1	3	5	...	...	
			D4	1	3	5	...	...	

(13) RECREATION INDUSTRY

(13-1) Ski Slope Operators

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Ensure best possible snow surface	1b		B8	1	4	5	5	7	Tactical
			C6	1	4	5	5	7	Make artificial snow

(13-2) Marina Operators (Non-River)

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize damage due to storm and sea conditions, to private property...	1a		A2	2	3	5	...	...	Preparatory
			A6	2	4	5	...	...	Alert personnel
			A7	2	5	6	...	...	Alert clients
			B14	2	5	6	...	...	Tactical
...and commercial goods and facilities	1b		A2	2	3	5	...	...	Take protective action (varying degrees)
			A5	2	3	5	...	...	
			A7	2	3	5	...	...	
			B14	2	3	5	...	...	

(13-3) Professional Baseball

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize loss and costs due to rain	1b		C1	1	3	3	...	...	Preparatory
									Cover infield
									Tactical
									Cancel game

(13-4) Amusement Park Operators

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Maximize efficiency in adjusting to variable volume of business	3b	Y1	A2	2	4	5	...	...	Preparatory
			A3	2	4	5	...	...	Vary work force
			A4	2	4	5	...	...	Tactical
			A5	2	4	5	...	...	Vary hours of operation
			B1	2	4	5	...	...	
			B5	2	5	5	...	...	
			B13	2	5	5	...	...	
			C1	2	4	5	...	...	
			C4	1	4	5	...	...	
			C5	2	4	5	...	...	
			C6	2	4	5	...	...	
			C7	2	4	5	...	...	
			C12	1	4	5	...	...	
			C15	1	4	5	...	...	
			D1	2	4	5	...	...	
			D2	2	5	5	...	...	
			D4	2	4	5	...	...	
			D6	2	5	5	...	...	
			D8	2	4	5	...	...	

(14) MANUFACTURING

(14-1) Effluent Producers

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
Minimize costs of reducing air pollution	2b		A3	3	5	7	...	...	Tactical Change fuels

(14-2) Shipbuilders

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Beneficial Lead Time Normal Max	Beneficial Lead Time Abnormal Min	Beneficial Lead Time Abnormal Max	Characteristic Actions
Minimize losses due to effects of inclement weather on outdoor work	2b	Y3	A2	1	4	5	...	...	Tactical Reschedule work force
			B4	1	4	5	...	...	
			B7	1	4	5	...	...	
			C1	1	4	5	...	...	
			C5	1	4	5	...	...	
			C6	1	4	5	...	...	
			C15	1	4	5	...	...	

(15) COMMERCIAL FISHING

(15-1) Fishing Fleets

Problem	Weather Effects	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize losses due to storms (at sea or in port)	1a		A5	4	5	6	...	...	Tactical Take refuge
Find fish faster	1b		B13	4	6	7	...	...	Tactical Divert from normal course

(16) AGRICULTURE

(16-1) Citrus Growers

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize losses due to freezing of fruit	1b		B3	1	3	5	5	6	Preparatory Order fuel Prepare equipment Alert work force Tactical Force harvest Start wind machines Start heaters
(16-2) Raisin Producers									
Minimize losses due to rain in drying phase	1b		C1	1	4	5	...	...	Tactical Roll and stack
(16-3) Tobacco Growers									
Minimize costs and losses due to poor natural drying conditions	1b		D9	1	3	5	...	...	Preparatory Prepare equipment Tactical Begin artificial drying
(16-4) Hay Growers									
Avoid losses due to rain during harvest	1b		C1	2	5	6	...	...	Tactical Change harvest schedule
(16-5) Ranchers									
Minimize loss of livestock due to severe winter weather	1b		A2	3	5	6	...	...	Preparatory Obtain supplies Alert work force Tactical Shelter stock Air-drop food
			A4	3	5	6	...	...	
			B4	3	5	6	...	...	
			C6	3	5	6	...	...	
(16-6) Cranberry Growers									
Minimize losses due to frost	1b		B3	1	4	4	...	...	Preparatory Alert work force Tactical Flood bogs Accelerate harvest
(16-7) Greenhousemen									
Minimize damage to structures...	1a		C4	1	3	4	...	...	Tactical Cover glass
...and plants due to hail storms	1b		C4	1	3	4	...	...	
(16-8) Cotton Growers									
Minimize the need to replant	1b		B8	2	5	7	...	...	Tactical Delay planting
(16-9) Beet and Potato Growers									
Minimize losses due to "frozen in" crops	1b		B9	2	5	6	...	...	Preparatory Alert work force Tactical Advance harvest

(16-10) Farmers (General)

Problem	Weather Effect	Weather Condition Compound	Weather Condition Simple	Spatial Resolution	Beneficial Lead Time Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize losses due to late spring frost	1b		B3	2	4	6	6	8	Preparatory Alert work force Prepare equipment Tactical Delay planting Protect crops
Minimize losses due to early fall frosts	1b		B3	2	4	6	...	...	Preparatory Alert work force Prepare equipment Tactical Advance harvest Protect crops
Maximize effectiveness of spraying operations	2b		A1 A3 C2 D9	2 2 2 2	4 4 4 4	6 6 6 6	... ...	... ...	Tactical Change schedule
Minimize costs of irrigation and losses due to lack of water (including desiccation)	1b		C17 D7	2 2	... 2	... 4	6 ...	8 ...	Preparatory Order water Tactical Irrigate

(17) FORESTRY AND OTHER RESOURCES (COMMERCIAL)

(17-1) Offshore Drilling

Problem	Weather Effect	Weather Condition		Spatial Resolution	Beneficial Lead Time				Characteristic Actions
		Compound	Simple		Normal Min	Normal Max	Abnormal Min	Abnormal Max	
Minimize losses due to adverse weather and sea conditions...	1a		A2 A6	1 1	4 4	5 5	5 5	6 6	Preparatory Alert personnel
...and safeguard personnel	1d		A2 A6	1 1	... ...	... ...	5 5	6 6	Tactical Take protective measures (various degrees)

(17-2) Loggers

Problem	Weather Effect	Compound	Simple	Spatial Resolution	Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Balance risk of fire against costs of curtailing operations	1b		C16	3	...	...	6	8	Preparatory Augment personnel and equipment Tactical Increase output

(18) COMMUNICATIONS

(18-1) Telephone Companies

Problem	Weather Effect	Weather Condition: Compound	Weather Condition: Simple	Spatial Resolution	Beneficial Lead Time: Normal Min	Normal Max	Abnormal Min	Abnormal Max	Characteristic Actions
Minimize lightning, ice, and wind damage to lines, equipment...	1a		A2	2	4	5	5	7	<u>Preparatory</u>
			C3	2	4	5	5	7	Prepare emergency equipment
...and service	2c		A2	2	4	5	5	7	Mobilize repair crews
			C3	2	4	5	5	7	Remove contributory factors
		X3	C5	2	4	5	...	...	<u>Tactical</u>
			C6	2	4	5	5	7	Dispatch repair crews
			D4	2	4	5	...	...	

Appendix B

RESUMÉ OF RM-2748-NASA

[This appendix is a summary of the analysis of one of the weather problems of the raisin industry.]

In this report the discussion is confined to the value of having a "protect--don't protect" decision criterion for the raisin-drying operation in California.

The grapes destined to be raisins are customarily dried in the vineyards for 3--4 weeks, commonly between August 20 and October 5. Excellent drying conditions normally prevail until mid-September; thereafter temperatures drop and probability of rain significantly increases. Rains of 0.1 inch usually cause damage, and amounts over 0.25 inch cause widespread damage.

The cost of protecting the grapes is approximately $6.00 a ton. At $200 valuation per ton, the raisins are obviously well worth protecting. With the economic decision criteria of Thompson and Brier[(B-1)*] and the climatic data presented by Jorgensen,[(B-2)] we show that a forecast can be tailored to be of maximum use to the raisin drier in deciding whether to protect his grapes or not.

Near Fresno, the probability of rain is 0.0222 for each day of the period from September 1 through October 20. Using the approximate value 0.0300 for the cost-loss (C/L) ratio and 0.0222 for the climatology for the entire drying period, one would make the decision not to protect the grapes.

Following Nelson and Winter,[(B-3)] we can calculate the cost of not protecting. Assuming that the probability of rain is serially independent, the probability of one rain in 28 days is approximately 0.47. The expected cost of never protecting, therefore, is 0.47 x $200, or $94 a ton. Another way of expressing this expected loss is to note that the raisin crop would be lost 5 years out of 10.

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*References are listed at the end of this resumé.

A margin of \$106 per ton of raisins is rather slim. The costs of raising, picking, drying, collecting, packing, and shipping would leave little profit if added to the \$94 average loss due to rain.

However, again from Jorgensen, there is an increasing probability of rain as the season advances (Fig. B-1). We draw the constant C/L ratio (0.03) across the figure on which we have plotted the increasing probability of rain, and find that the risk exceeds the C/L ratio at September 23. The grower, then, who decides never to protect has a substantial advantage if he starts to dry his grapes early enough to be finished before September 23. From the data given, it is further possible to estimate the expected cost to the producer who never protects as a function of the date he sets the grapes out to dry. Assuming a fixed 4-week drying period, the resulting curve is shown in Fig. B-2.

(It is acknowledged that the sugar content of the grape improves as the season advances, making the crop more valuable, that drying time is a function of temperature and sunshine, and that the climatology cited is incomplete and strictly local.)

The ideal situation for the raisin dryer would be to know exactly when it would rain and protect only then. Then his expected outlay for protection would average only about \$3.70 per ton, and he could defer picking until the grapes were ideal.

* * *

We can, however, with our present knowledge of the weather, tailor forecasts to maximize the benefits to the producer.

If N_r is the number of rain forecasts made by the forecaster, and $N_{nr:r}$ is the number of times during the drying period that no-rain was predicted but it rained, the expected cost to the producer is

$$\hat{C} = 6N_r + 200N_{nr:r}$$

where $\hat{C}$ is the expected cost in dollars per ton when the producer protects each time rain is forecast. We assume that the forecaster's predictions can be ranged in a spectrum, at one end having a

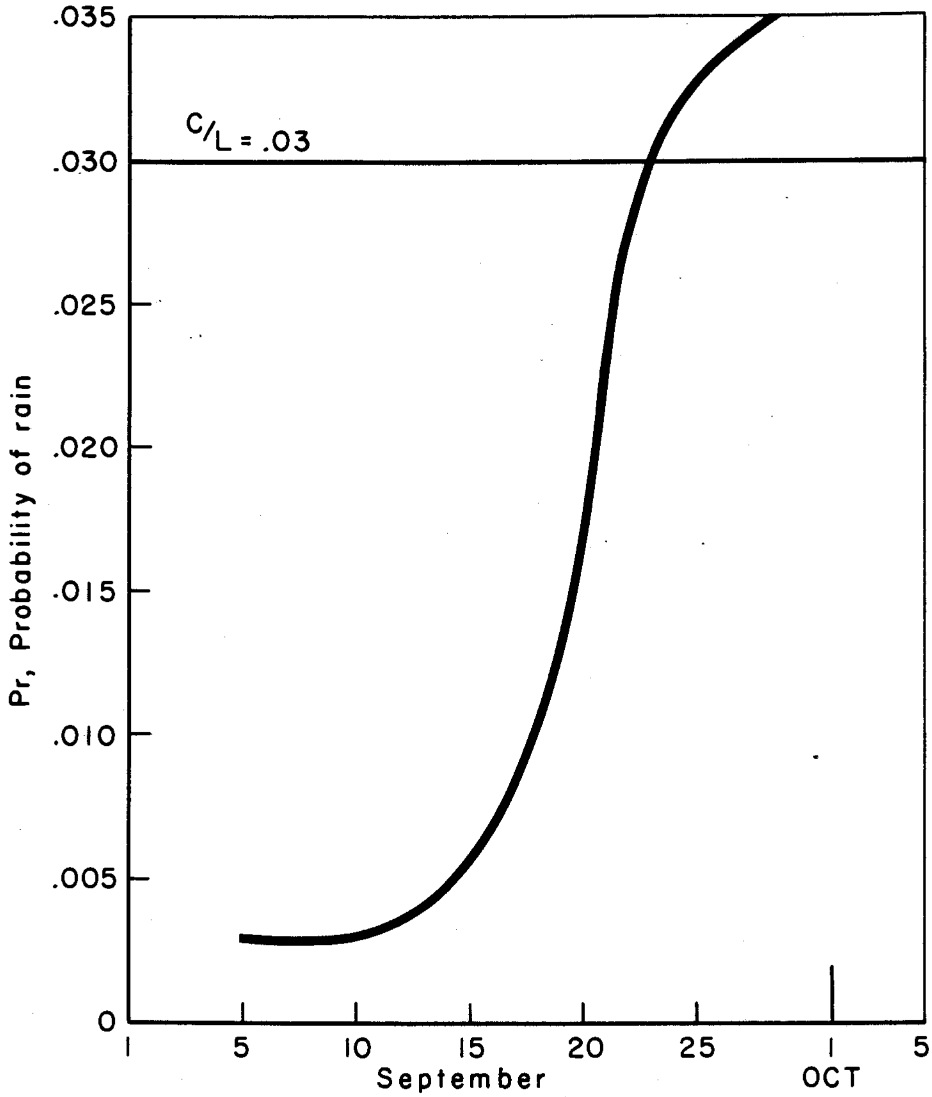

Fig. B-1 Probability of damaging rain on September and October dates at Fresno (1887--1945, after Jorgensen)

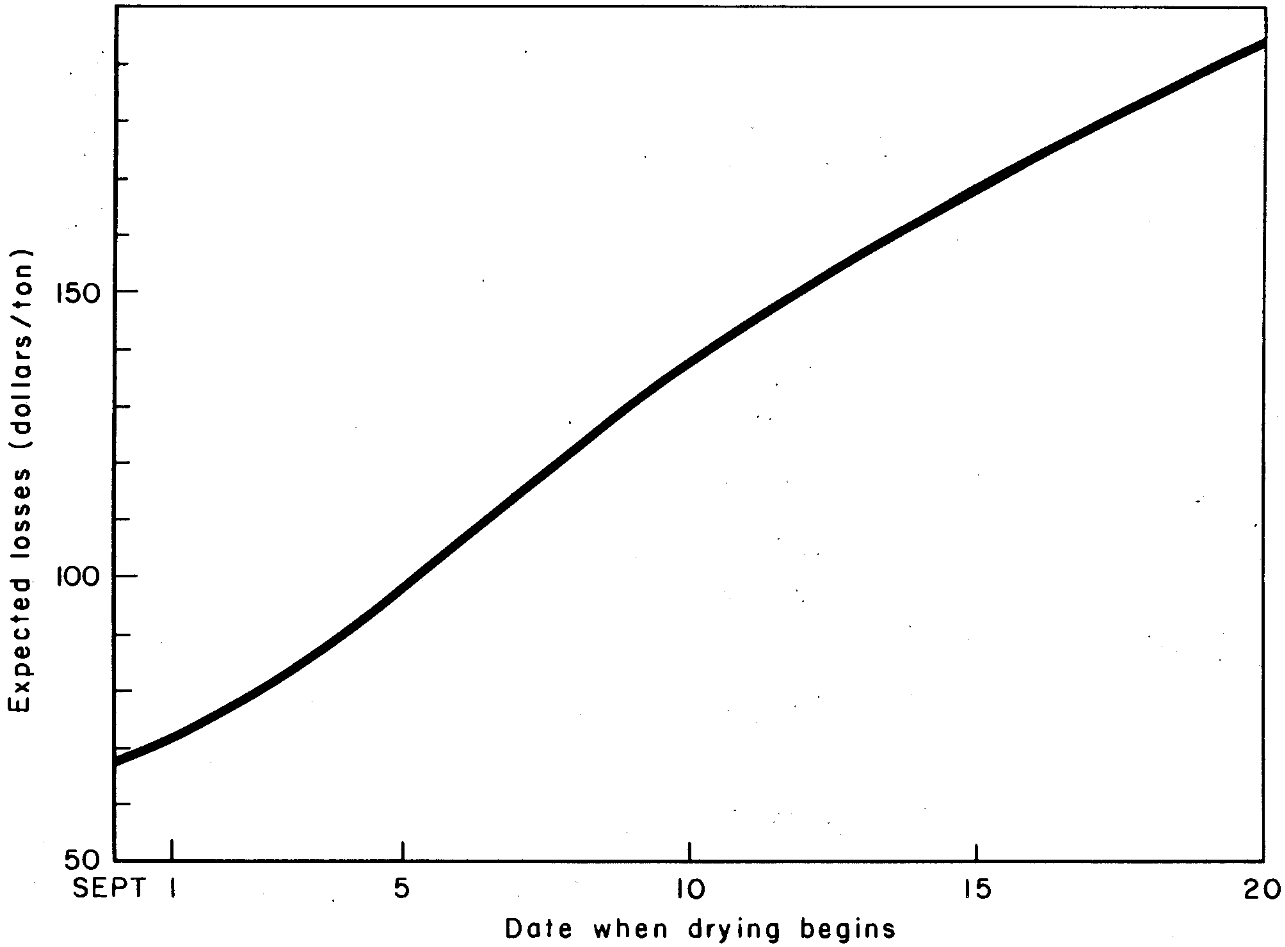

Fig. B-2 Expected losses due to rain as a function of date when drying begins

predominance of correct no-rain forecasts. The forecaster can choose to make more rain forecasts if he wishes to decrease the number of times when he erroneously predicts no-rain. His criterion then is that number of forecasts which make the expected cost a minimum. (Note: this does <u>not</u> maximize the number of correct forecasts.) Many rain forecasts followed by no-rain will result.

Table B-1 shows the data from 585 forecasts in the form of the number of rain and no-rain days accumulated, as a function of Jorgensen's complex variable, W. Jorgensen's data show that out of a total of 534 days when W was less then 50, rain did not occur on 533 days, but did occur on 1 day.

In Table B-2, Column 4 shows the expected cost to the producer who protects whenever the forecaster predicts rain. If the forecaster predicts rain when W is greater than 60, he will expect to get rain following a no-rain prediction on 0.1 day in the 28-day period. But according to Table B-2, the forecaster should predict rain every time the value of W is greater than 30. If the producer then always protects, the expected cost per year will be about $22 per ton. In ten years the grower would protect about 36 times. Of these 36 times, potentially damaging rains would occur on only 6 occasions. The cost over 10 years would be $220 for protecting a ton of raisins every year, a trifle more than had his raisin crop just once been damaged by rain.

* * *

The three necessary elements for such a study are (1) a good grasp of the effect of weather on the operation, (2) climatic information in a form suited to the problem, and (3) an estimate of the economic factors.

> [It should be pointed out that this analysis applies to an individual grower. If one were to try to extend the analysis to the entire industry it would be necessary to look very closely at the effect of optimizing the production of raisins on the changes in the price structure which may be brought about by the change in supply.]

Table B-1

TOTAL NUMBERS OF DAYS OF RAIN AND OF NO-RAIN ACCUMULATED AS A FUNCTION OF W

W	NR, Days of No-Rain	R, Days of Rain	Total
Less than 10	446	0	446
" 20	487	0	487
" 30	510	0	510
" 40	527	1	528
" 50	533	1	534
" 60	543	2	545
" 70	554	2	556
" 80	562	5	567
" 90	569	6	575
" 100	572	13	585

Table B-2

FORECASTS AND EXPECTED COSTS FOR A 28-DAY PERIOD
AS A FUNCTION OF THE W-VALUE SELECTED
AS A CUT-OFF POINT

W-Value Chosen for Cut Point	N_r, Rain Forecasts Expected	$N_{nr:r}$, Rains Occurring When No-Rain is Forecast	$\hat{C}$, Expected Cost if Producer Protects When Rain is Forecast ($)
10	6.65	0	39.90
20	4.69	0	28.14
30	3.59	0	21.54
40	2.73	0.05	26.38
50	2.44	0.07	28.64
60	1.92	0.10	31.52
70	1.39	0.17	42.34
80	0.86	0.25	55.16
90	0.48	0.33	68.88
100	0.00	0.62	124.00

<u>References for Resumé</u>

B-1. Thompson, J. C., and G. W. Brier, "The Economic Utility of Weather Forecasts," <u>Mon. Weather Rev.</u>, Vol. 83, No. 11, November, 1955, pp. 249-254.

B-2. Jorgensen, D. L., "An Objective Method of Forecasting Rain in Central California During the Raisin Drying Season," <u>Mon. Weather Rev.</u>, Vol. 77, No. 2, February, 1949, pp. 31-46.

B-3. Nelson, R. R., and S. G. Winter, <u>Weather Information and Economic Decisions, A Preliminary Report</u>, The RAND Corporation, RM-2620-NASA, August 1, 1960.

Appendix C

THE VALUE OF AVIATION-ROUTE WIND FORECASTS

1. Introduction

The problem of determining the value of a forecasting system has been generally formulated by Nelson and Winter* in terms of the utility or cost of a set of actions depending on a set of weather states, the conditional probabilities of weather states for given forecasts, and the probability distribution of weather forecasts. In the examples they considered, the weather states and courses of action were discrete and finite so that the functional relationship between utility or cost, choice of action, and weather state could be given by a utility matrix. Furthermore, the conditional probability distribution of actual weather for a given forecast could be given by a contingency table, and the distribution of forecasts could be given by a vector.

In a fairly large class of problems, the possible courses of action may be limited to a finite and discrete set while the costs for each course of action are continuously varying functions of continuously varying weather conditions. These characteristics are typical of routing problems in which only a finite number of route choices are available, and in which the time *en route* depends on weather conditions along the route. In the following, the formulation of Nelson and Winter will be modified to deal with these problems under the assumption that cost distributions can be derived from distributions of weather states. (This assumption may be valid, for example, when the pertinent weather states are simply weather-dependent *en route* times, and cost is proportional to time.) The method will then be applied to a highly simplified model of an airline routing problem using the output of the Numerical Weather Prediction unit of the National Meteorological Center as the basis for the forecasting system.

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*Nelson, R. R., and S. G. Winter, *Weather Information and Economic Decisions, A Preliminary Report*, The RAND Corporation, RM-2620-NASA, August 1960.

2. The Two-Route Airline Model

It will be assumed that only two routes are available to choose from and that the variations in *en route* times result only from variations in winds at cruising altitude. The required relations between the statistics of *en route* times and *en route* winds will be derived in the next section.

It is assumed that forecast times and actual times on each of the two routes possess joint normal distributions, $P(t_1, \tau_1)$ and $P(t_2, \tau_2)$ with correlation ρ between actual and forecast times. It is also assumed that the forecasts are unbiased in the sense that means and standard deviations of the forecast times, τ_1, τ_2, are identical to means and standard deviations of the actual times t_1 and t_2. Finally, it is assumed that both actual and forecast times for the two routes are independent, and standard deviations of actual and forecast times are the same on both routes.

The restrictions to two routes, neglect of factors other than wind -- density for example, and the assumption that times on the two routes are independent of each other seriously limit the applicability of the results, but some important features of the route-forecasting problem will be illuminated nevertheless. In addition, more detailed studies along these same lines may be able to remove some of the more serious of these limitations.

The wrong route will be picked if either of the combinations

$$\begin{Bmatrix} \tau_2 > \tau_1 \\ t_2 < t_1 \end{Bmatrix} \quad \text{or} \quad \begin{Bmatrix} \tau_2 < \tau_1 \\ t_2 > t_1 \end{Bmatrix}$$

occur. Then, if c_r is the operating cost per unit time, the expected cost for a single flight (defined relative to the hypothetical perfect forecasting system, I_o) is the cost per unit time multiplied by the actual time difference and the probability of encountering the two actual times all integrated over the possible limits of the actual times. For the two cases under consideration, the expected cost per flight is given by either

$$c_1(I_f) = c_r \int_{-\infty}^{\infty} \int_{-\infty}^{t_2} (t_2 - t_1)\, P_f\, (t_2, t_1 | \tau_2, \tau_1)\, dt_1 dt_2 \quad , \qquad (1)$$

if $\tau_2 < \tau_1$, or

$$c_1(I_f) = c_r \int_{-\infty}^{\infty} \int_{t_2}^{\infty} (t_2 - t_1)\, P_f\, (t_2, t_1 | \tau_2, \tau_1)\, dt_1 dt_2 \quad , \qquad (2)$$

if $\tau_2 > \tau_1$, where the conditional probability function

$$P_f\, (t_2, t_1 | \tau_2, \tau_1) \quad ,$$

is given by

$$P_f(t_2, t_1 | \tau_2, \tau_1) = \frac{1}{2\pi\sigma^2(1-\rho^2)} \exp \left\{ - [2\sigma^2(1-\rho^2)]^{-1} [t_2 - \rho\tau_2 - (1-\rho)\bar{\tau}_2]^2 - [2\sigma^2(1-\rho^2)]^{-1} [t_1 - \rho\tau_1 - (1-\rho)\bar{\tau}_1]^2 \right\} .$$

Here σ is the standard deviation of the actual <u>en route</u> times, which are assumed to be the climatological standard deviations, and $\bar{\tau}_1$, $\bar{\tau}_2$ are the mean values of the forecast <u>en route</u> times, which are assumed to be the same as the climatological values of the actual <u>en route</u> times. The areas in the (t_1, t_2) plane involved in the integrals of Eqs. (1) and (2) are illustrated in Figs. C-1(a) and C-1(b).

If the expected cost per flight is now multiplied by the probability of being given a pair of forecasts, τ_1, τ_2, and this product is integrated over the possible pairs of forecast values, the mean expected cost over many flights is estimated. If c_T is the mean expected cost, it is given by

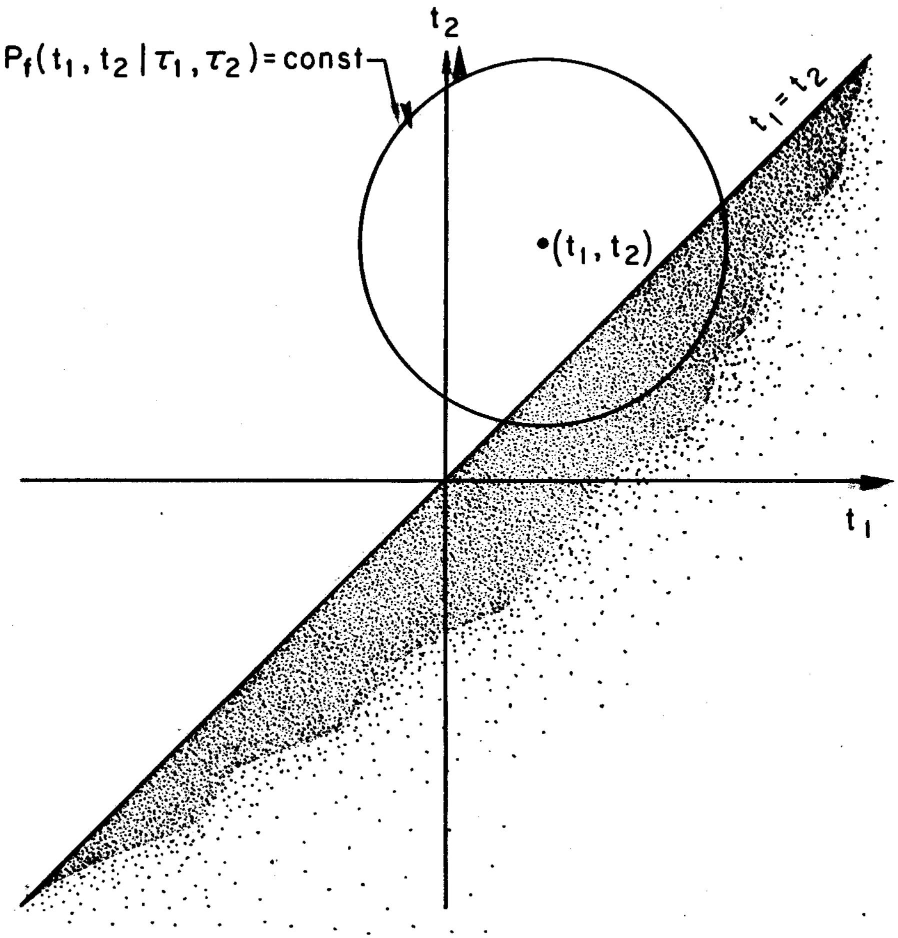

Fig. C-1(a) The shaded area represents the integral in Eq. (1). The point $(\underline{t}_1, t_2)$ is defined by $t_1 = \tau_1 - (1-\rho)(\tau_1 - \bar{\tau}_1)$, $t_2 = \tau_2 - (1-\rho)(\tau_2 - \bar{\tau}_2)$

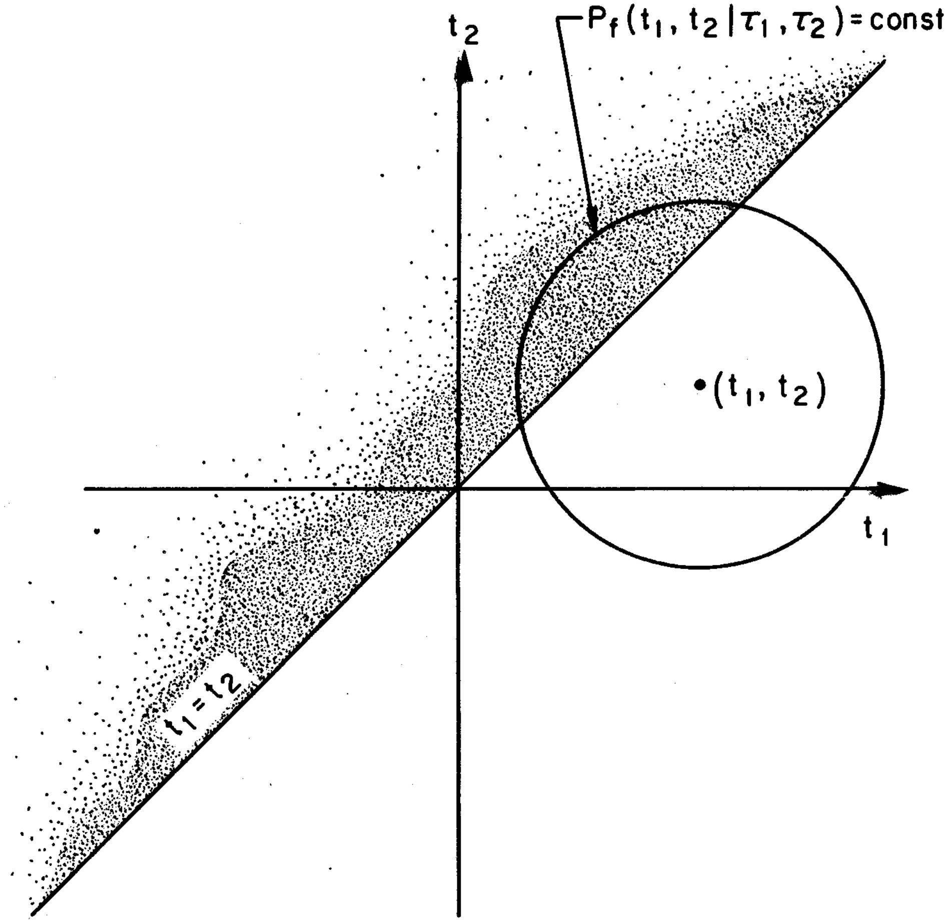

Fig. C-1(b) The shaded area represents the integral in Eq. (2)

$$c_T(I_f) = c_r \left\{ \int_{-\infty}^{\infty} \int_{\tau_2}^{\infty} \pi_f(\tau_2,\tau_1;\bar{\tau}_2,\bar{\tau}_1) \int_{-\infty}^{\infty} \int_{-\infty}^{t_2} (t_2-t_1)\, P_f(t_2,t_1|\tau_2,\tau_1) \right.$$

$$dt_1 dt_2 d\tau_1 d\tau_2 \tag{3}$$

$$\left. - \int_{-\infty}^{\infty} \int_{-\infty}^{\tau_2} \pi_f(\tau_2,\tau_1;\bar{\tau}_2,\bar{\tau}_1) \int_{-\infty}^{\infty} \int_{t_2}^{\infty} (t_2-t_1)\, P_f(t_2,t_1|\tau_2,\tau_1)\, dt_1 dt_2 d\tau_1 d\tau_2 \right\} ,$$

where $\pi_f(\tau_2,\tau_1;\bar{\tau}_2,\bar{\tau}_1)$ is simply the probability density function for the forecast (τ_2,τ_1). Introducing the assumed forms for π_f and P_f into Eq. (3), we obtain

$$c_T\,(I_f) = \frac{c_r}{4\pi^2\sigma^4(1-\rho^2)} \left(\int_{-\infty}^{\infty} \int_{\tau_2}^{\infty} \exp\left\{ -\frac{1}{2}\left[\frac{\tau_2-\bar{\tau}_2}{\sigma}\right]^2 - \frac{1}{2}\left[\frac{\tau_1-\bar{\tau}_1}{\sigma}\right]^2 \right\} \cdot \right.$$

$$\int_{-\infty}^{\infty} \int_{-\infty}^{t_2} (t_2-t_1) \exp\left\{ - [2\sigma^2(1-\rho^2)]^{-1} [t_2-\rho\tau_2-(1-\rho)\bar{\tau}_2]^2 [2\sigma^2(1-\rho^2]^{-1} \right. \tag{4}$$

$$\left. [t_1-\rho\tau_1-(1-\rho)\bar{\tau}_1]^2 \right\} dt_1 dt_2 d\tau_1 d\tau_2 - \int_{-\infty}^{\infty} \int_{-\infty}^{\tau_2} \exp\left\{ -\frac{1}{2}\left[\frac{\tau_2-\bar{\tau}_2}{\sigma}\right]^2 - \frac{1}{2}\left[\frac{\tau_1-\bar{\tau}_1}{\sigma}\right]^2 \right\} \cdot$$

$$\int_{-\infty}^{\infty} \int_{t_2}^{\infty} (t_2-t_1) \exp\left\{ -[2\sigma^2(1-\rho^2)]^{-1} [t_2-\rho\tau_2-(1-\rho)\bar{\tau}_2]^2 - [2\sigma^2(1-\rho^2)]^{-1} [t_1-\rho\tau_1-(1-\rho)\bar{\tau}_1]^2 \right\}$$

$$\left. dt_1 dt_2 d\tau_1 d\tau_2 \right) .$$

The integrals in Eq. (4) can be evaluated with the aid of the transformations:

$$x = t_2-t_1 \qquad u = \tau_2-\tau_1 \qquad \bar{u} = \bar{\tau}_2-\bar{\tau}_1$$
$$y = t_2+t_1 \qquad v = \tau_2+\tau_1 \qquad \bar{v} = \bar{\tau}_2+\bar{\tau}_1 .$$

Then y and v can be integrated out, and

$$c_T = \frac{c_r}{4\pi\sigma^2(1-\rho^2)^{1/2}}\left(\int_{-\infty}^{0} \exp\left\{-\left[\frac{u-\bar{u}}{2\sigma}\right]^2\right\}\int_0^{\infty} x\exp\left\{-[4\sigma^2(1-\rho^2)]^{-1}[x-\rho u-(1-\rho)\bar{u}]^2\right\}dxdu\right.$$
$$\left.-\int_0^{\infty}\exp\left\{-\left[\frac{u-\bar{u}}{2\sigma}\right]^2\right\}\int_{-\infty}^{0} x\exp\left\{-[4\sigma^2(1-\rho^2)]^{-1}[x-\rho u-(1-\rho)\bar{u}]^2\right\}dxdu\right) \quad (5)$$

$$= \frac{c_r}{4\pi\sigma^2(1-\rho^2)^{1/2}}\left(\int_{-\infty}^{0}\int_0^{\infty} x\exp\left\{-[4\sigma^2(1-\rho^2)]^{-1}[(x-\bar{u})^2-2\rho(x-\bar{u})(u-\bar{u})+(u-\bar{u})^2]\right\}dxdu\right.$$

$$\left.-\int_0^{\infty}\int_{-\infty}^{0} x\exp\left\{-[4\sigma^2(1-\rho^2)]^{-1}[(x-\bar{u})^2-2\rho(x-\bar{u})(u-\bar{u})+(u-\bar{u})^2]\right\}dxdu\right) .$$

The integrations given in Eq. (5) in the (x,u) plane are depicted in Fig. C-1(c). Additional transformations of the dummy variables u and x reduce Eq. (5) to

$$c_T = \frac{c_r}{4\pi\sigma^2(1-\rho^2)^{1/2}}\int_0^{\infty}\int_0^{\infty}(x+u)\exp\left\{-[4\sigma^2(1-\rho^2)]^{-1}[(x-\bar{u})^2+2\rho(x-\bar{u})(u+\bar{u})^2]\right\}dxdu .$$

The double integral can be further simplified by non-dimensionalizing x and u. Let

$$\frac{x-\bar{u}}{2\sigma(1-\rho^2)^{1/2}} = z$$

$$\frac{x+\bar{u}}{2\sigma(1-\rho^2)^{1/2}} = w$$

$$\frac{u}{2\sigma} = \bar{w} .$$

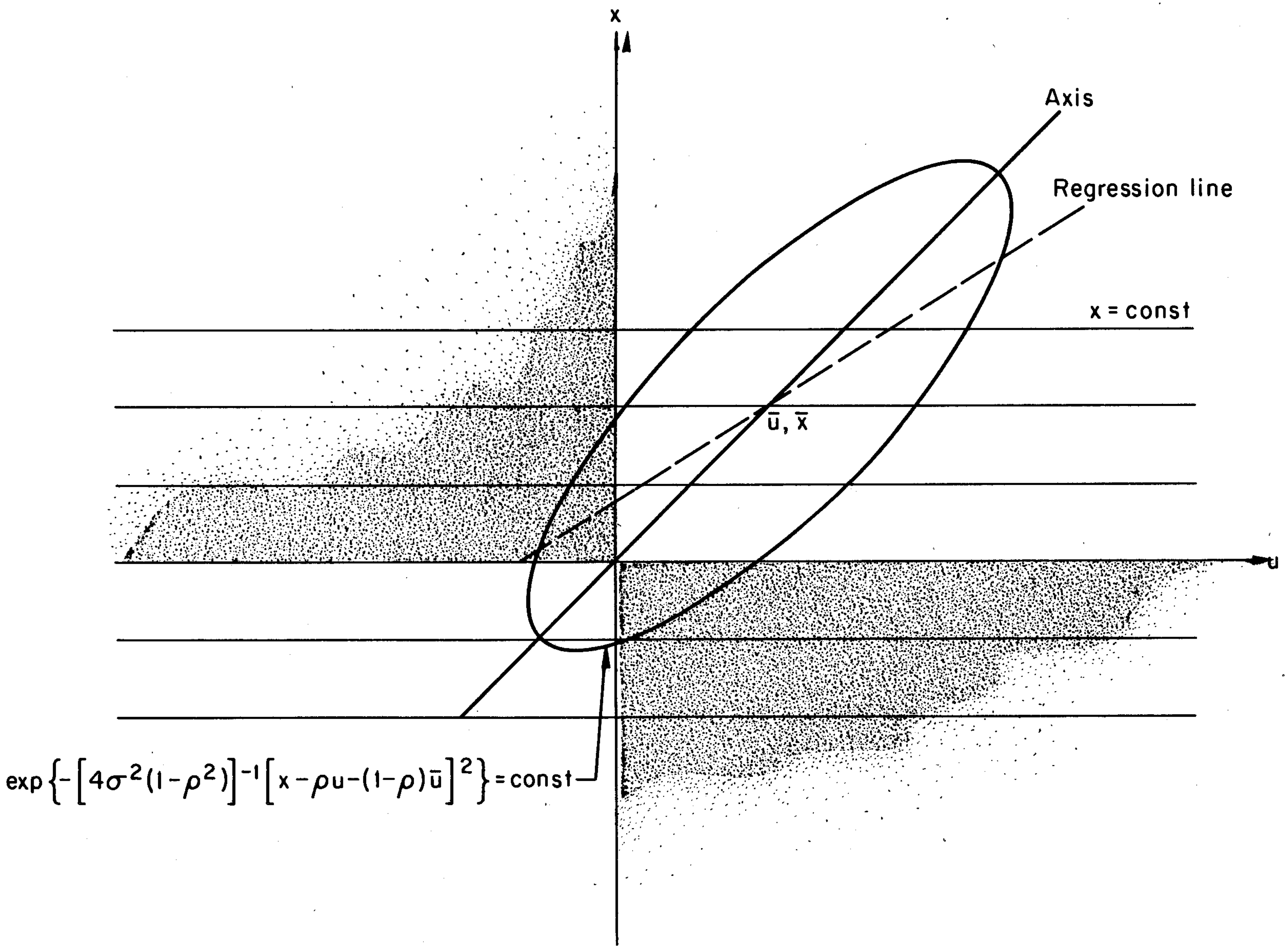

Fig. C-1(c) The shaded areas are the areas involved in the integrals of Eq. (5)

Then

$$c_T = \frac{2\sigma c_r(1-\rho^2)}{\pi} \int_{\frac{\bar{w}}{(1-\rho^2)}}^{\infty} \int_{-\frac{\bar{w}}{(1-\rho^2)}}^{\infty} (z+w) \exp\left[-z^2-2\rho zw-w^2\right] dz dw \quad . \qquad (6)$$

Integration can be carried out in a straightforward way by completing the squares in the integrands. The outer integration makes use of an integration by parts. The result is:

$$c_T = \frac{c_r \sigma}{\sqrt{\pi}} (1-\rho) e^{-\bar{w}^2} \quad . \qquad (7)$$

It will be worthwhile to compare the expected cost of any forecasting system with the expected oost of using only climatological information. In this case, the route with the smaller of $\bar{\tau}_1$ or $\bar{\tau}_2$ would always be the one chosen, and the climatological distribution of forecasts is simply

$$\pi_c(\tau_2,\tau_1;\bar{\tau}_2,\bar{\tau}_1) = \delta(\tau_2 - \bar{\tau}_2)\,\delta(\tau_1 - \bar{\tau}_1) \quad . \qquad (8)$$

It follows from Eqs. (3) and (5) that

$$c_T(I_c) = \frac{c_r}{2\sqrt{\pi\sigma}} \left\{ \int_{-\infty}^{0} \delta(u-\bar{u}) \int_{0}^{\infty} x \exp -\left(\frac{x-u}{4\sigma}\right)^2 dx du \right\}$$

$$= -\frac{c_r}{2\sqrt{\pi\sigma}} \left\{ \int_{0}^{\infty} \delta(u-\bar{u}) \int_{-\infty}^{0} x \exp\left[-\left(\frac{x-u}{4\sigma}\right)^2\right] dx du \right\} , \qquad (9)$$

the first integral applying if $\bar{u} < 0$, the second if $\bar{u} > 0$. These integrals can be evaluated, and the result is

$$c_T(I_c) = \frac{c_r \sigma}{\sqrt{\pi}} \left\{ e^{-\bar{w}^2} - \sqrt{\pi}\,|\bar{w}|\,[1 - \text{erf}\,|\bar{w}|] \right\} , \qquad (10)$$

where erf $(\overline{w})$ is defined by

$$\text{erf}\ (\overline{w}) = \frac{2}{\sqrt{\pi}} \int_0^{\overline{w}} e^{-x^2}\,dx \quad . \tag{11}$$

Figure C-2 shows $c_t[\rho(I_f),\overline{w}]/c_r\sigma$ from Eq. (7). The intersection of the climatology curve, $c_T(I_c,\overline{w})/c_r\sigma$ given by Eq. (10), with the curves of Eq. (7) is shown by the heavy dashed line. Note that for a given value of $\overline{w}$, any forecast must be characterized by a ρ value such that the forecast lies to the left of the climatology curve if the forecast system is to have a lower cost than simply using climatology. This result reflects the fact that any forecasting system must be very good indeed in order to pick out those few occasions when the normally slower route happens to be the fastest. In fact, for a particular forecasting scheme (a particular value of ρ), routes which have a $\overline{w}$ such that $c_T[\rho(I_f)\overline{w}]/c_r\sigma$ falls to the right of the climatology curve should not even be considered as possible alternatives, This result applies to more general cases than the simple two-route model since, for the purpose of selecting potential alternatives for consideration, the comparison between any potential route and the climatologically fastest route reduces to a two-route problem.

3. Statistics of Route Times

Before the results of the last section can be applied, it is necessary to relate certain statistics of en route times to statistics of the en route winds. This problem has been considered by Sawyer,* who presented results in terms of the "equivalent headwind." It is more convenient to work directly with en route times, and we will develop results in those terms, although the approach is essentially that of Sawyer.

Consider a track element of length ds. The increment of time required by an aircraft to traverse the element is

$$dt = \frac{ds}{v(s)} \quad , \tag{12}$$

*Sawyer, J. S., "Equivalent Headwinds, Application of Upper-Wind Statistics to Air-Route Planning," Meteorological Report 6, M.O. 535a, Air Ministry, London, 1950.

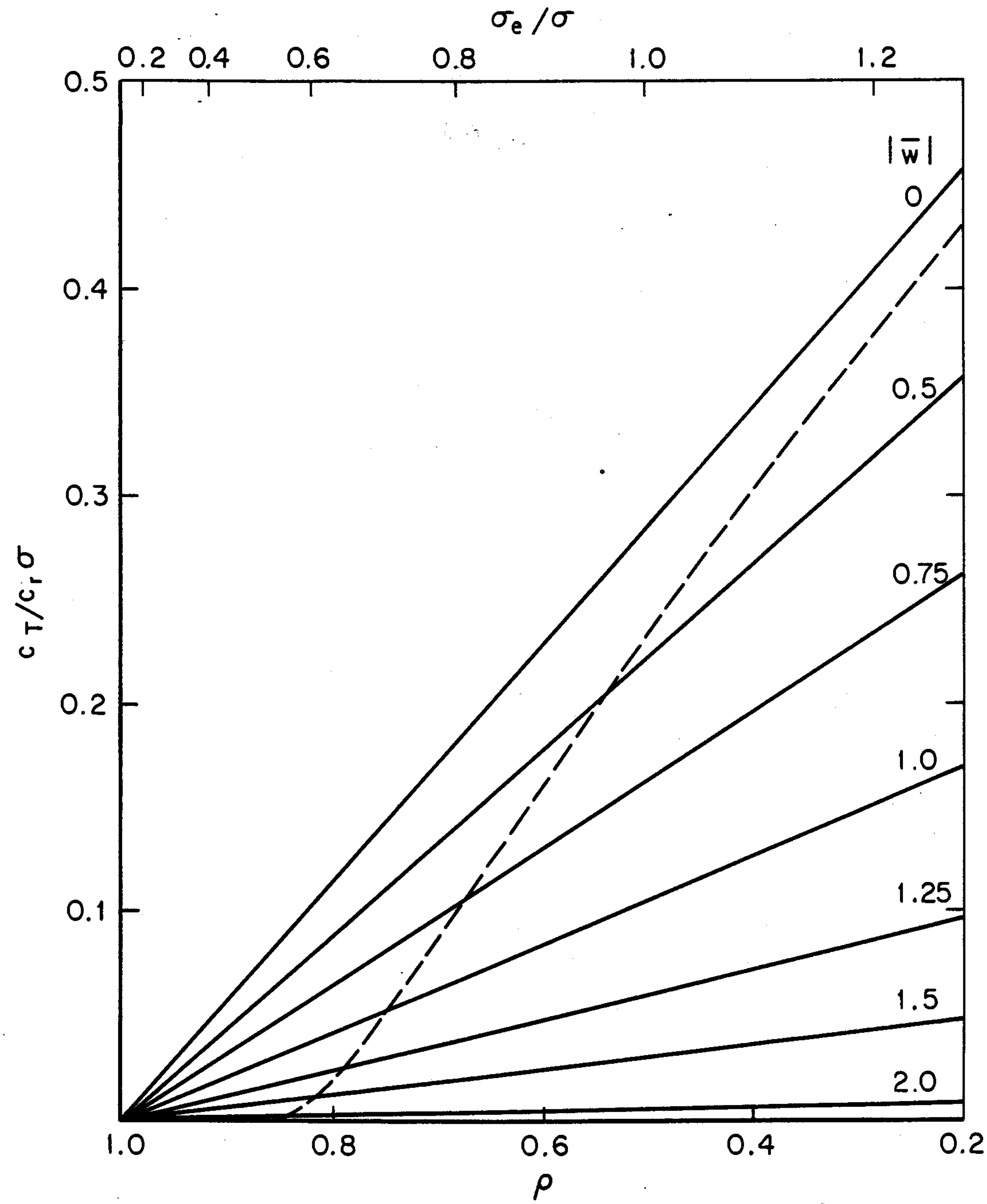

Fig. C-2 $(c_T/c_r\sigma)$ versus ρ or (σ_e/σ) for various values of $|\bar{u}|$. The heavy dashed line represents the relationship between $(c_T/c_r\sigma)$ for climatology and $|\bar{u}|$.

where v(s) is the true ground speed at the point s. To find v(s) in terms of the wind velocity, $\underline{v}_w(s)$ and the true air speed, $v_a(s)$, consider the velocity triangle defined by the vector equation

$$\underline{v}(s) = \underline{v}_a(s) + \underline{v}_w(s) \quad . \tag{13}$$

Let θ be the angle between v and $\underline{v}_w$, and let v_p and v_n be the wind components parallel and normal to the direction of $\underline{v}$ (or $\underline{ds}$). Solving the triangle for v(s), and making use of the fact that

$$\cos\theta = \frac{v_p}{v_w} \quad ,$$

we get

$$v = v_a\left(1 - \frac{v_n^2}{v_a^2}\right)^{1/2} + v_p \doteq v_a\left(1 - \frac{1}{2}\frac{v_n^2}{v_a^2}\right) + v_p \quad , \tag{14}$$

where the convention is made that v_p is positive for a tailwind, negative for a headwind. The third-order terms neglected in the approximation do not introduce an error as large as 1% for jet speed flights. To the same accuracy,

$$\text{dt} \qquad dt \doteq \left[v_a\left(1 - \frac{1}{2}\frac{v_n^2}{v_a^2}\right) + v_p\right]^{-1} ds$$

$$\doteq \frac{ds}{v_a}\left(1 + \frac{1}{2}\frac{v_n^2}{v_a^2} - \frac{v_p}{v_a} + \frac{v_p^2}{v_a^2}\right) \quad ,$$

so that for a flight of length D_o,

$$t(D_o) = \int_0^{D_o} \frac{ds}{v_a}\left(1 + \frac{1}{2}\frac{v_n^2}{v_a^2} - \frac{v_p}{v_a} + \frac{v_p^2}{v_a^2}\right) \quad . \tag{15}$$

To obtain the statistics of t, v_a is assumed to be constant, and fluctuations of the vector wind are assumed to have a circular normal distribution about an ensemble mean. It follows that

$$\overline{t(D_o)} = \int_0^{D_o} \frac{ds}{v_a} \left(1 + \frac{1}{2} \frac{\overline{v_n}^2}{v_a^2} - \frac{\overline{v_p}}{v_a} + \frac{\overline{v_p}^2}{v_a^2} + \frac{3}{4} \frac{\sigma_w^2}{v_a^2} \right) \quad , \tag{16}$$

where $\sigma_w^2 = 2\sigma_n^2 = 2\sigma_p^2$ is the variance of the vector wind, and the bar indicates an ensemble average. It is convenient to define the quantity

$$\psi_w(s) = \left(1 - \frac{v_p}{v_a} + \frac{1}{2} \frac{v_n^2}{v_a^2} + \frac{v_p^2}{v_a^2} \right) . \tag{17}$$

By straightforward manipulation and use of the assumption of a circular normal distribution of winds one obtains the standard deviation of ψ:

$$\sigma_\psi^2(s) = \frac{\sigma_w^2}{2v_a^2} \left(1 - \frac{4\overline{v}_p}{v_a} + \frac{4\overline{v}_p^2}{v_a^2} + \frac{\overline{v}_n^2}{v_a^2} + \frac{3}{4} \frac{\sigma_w^2}{v_a^2} + 2 \frac{\overline{v'^2_n v'^2_p}}{v_a^2 \sigma_w^2} \right)$$

$$\doteq \frac{\sigma_w^2}{2v_a^2} \left(1 - \frac{4\overline{v}_p}{v_a} \right)$$

to first order in (v_w/v_a). Here v'_n and v'_p are deviations from the means. Following Sawyer's procedure, and neglecting the dependence of the statistics of ψ on position, the standard deviation of <u>en route</u> time can be obtained.

$$\sigma^2(D_o) = \frac{2}{v_a^2} \int_0^{D_o} \int_0^{s} \sigma_\psi^2 \, r_\psi (s-x) \, dx\,ds$$

$$\doteq \frac{D_o^2}{v_a^2} \frac{\sigma_w^2}{v_a^2} \left(1 - \frac{4\overline{v}_p}{v_a} \right) \left\{ \frac{1}{D_o^2} \int_0^{D_o} \int_0^{s} r_\psi (s-x) \, dx\,ds \right\} \quad . \tag{18}$$

The quantity

$$r_\psi(s-x) = \frac{\overline{\psi_w'(s)\psi_w'(x)}}{\sigma_\psi^2}$$

is the spatial autocorrelation function of ψ. To first order in (v_w/v_a) it is the same as the autocorrelation function of Sawyer's equivalent headwind. This quantity has been tabulated by Sawyer and found to be reasonably independent of season and location in mid-latitudes. Sawyer's results were therefore used to evaluate the quantity

$$\frac{1}{D_o^2} \int_0^{D_o} \int_0^s r_\psi(s-x)\, dxds.$$

Equation (18) relates the climatological <u>en route</u> time variance to the variance of point winds. An expression is also required for the correlation ρ between observed and forecast <u>en route</u> times. First consider the variance of the difference between forecast and observed <u>en route</u> winds. Let ψ_w' be the fluctuation of ψ_w corresponding to the fluctuation of the observed time, t'. Let ψ_ν' be the corresponding quantity for the fluctuation of the forecast time, τ'. Then

$$(t' - \tau') = \int_0^{D_o} (\psi_w' - \psi_\nu') \frac{ds}{v_a} \quad . \tag{19}$$

Again using Sawyer's method,

$$\overline{(t'-\tau')}^2 = 2 \int_0^{D_o} \int_0^s [\psi_w'(s)\psi_w'(x) + \psi_\nu'(s)\psi_\nu'(x) - \psi_w'(s)\psi_\nu'(x) - \psi_w'(x)\psi_\nu'(s)] \frac{dxds}{v_a^2} \quad .$$

It is assumed that the statistics of observed and forecast winds are identical and that they are independent of s. Then

$$\overline{(t'-\tau')^2} \equiv \sigma_e^2 = 2 \int_0^{D_o} \int_0^s \sigma_w^2 \, r_\psi(s-x)[1-\rho(\psi_w,\psi_\nu)] \frac{dxds}{v_a^2} = 2[1-\rho(\psi_w,\psi_\nu)]\sigma^2 \quad , \qquad (20)$$

from Eq. (18). But to first order in v_w/v_a, fluctuations in ψ_w and ψ_ν are given by fluctuations in observed and forecast tailwinds, v_p and ν_p, so that

$$\rho(\psi_w,\psi_\nu) \approx \rho(v_p,\nu_p) \quad .$$

But since the actual and forecast winds and wind forecasts are assumed to have identical circular normal distribution, their correlation is

$$\rho_w = \rho(v_p,\nu_p) = 1 - \frac{1}{2}\left(\frac{\sigma_{ew}}{\sigma}\right)^2 \quad , \qquad (21)$$

where σ_{ew}^2 is the variance of the vector difference between observed and forecast winds. It follows that, to first order

$$\frac{\sigma_e}{\sigma} = \frac{\sigma_{ew}}{\sigma_w} \equiv s \quad , \qquad (22)$$

and since times are assumed to be normally distributed, the correlation $\rho(t,\tau)$ between observed and forecast enroute times is approximately

$$\rho(t,\tau) = 1 - \frac{1}{2}\left(\frac{\sigma_{ew}}{\sigma_w}\right)^2 \equiv 1 - \frac{1}{2}s^2 \quad . \qquad (23)$$

Substituting Eq. (23) into Eq. (7) we get

$$c_T = \frac{c_r\sigma}{2\sqrt{\pi}} \, s^2 \, e^{-\overline{w}^2} \quad . \qquad (24)$$

We note that the assumption of normal distributions for observed and forecast times cannot be strictly correct since en route times are restricted to positive values. However, to first order the time distributions are determined by the headwind distributions, and these are indeed normal, in most cases, to a high degree of accuracy.

4. Application to a Forecasting System

Using the model described above, a comparison was made of expected costs of using observed winds (persistence) with expected costs based on linear interpolation between observed winds and numerically forecast winds as transmitted on facsimile circuits. Verification data* on both persistence and forecasts at the 300 mb level (approximately 30,000 feet), gives the vector error standard deviation for both persistence and forecast as a function of lag time (time elapsed after observation). These data have been plotted in forecast decay diagrams, Figs. C-3(a) -- C-3(d), for January, April, July, and October, 1962, and for January, 1963.

For persistence, it was assumed that the latest available analyzed 300 mb winds were used as the basis of route selection. Observed or forecast winds were considered to be available if they had been transmitted on Facsimile Service C at least one hour prior to scheduled take-off. The lag time for this forecast was taken to be the time between observation and the scheduled midpoint of the flight. The value σ_w for this forecast was obtained by linear interpolation of σ_w^2 in the appropriate forecast decay diagram. Linear interpolation seems well justified by the nearly linear growth of σ_w^2 in time during the first 36 hours in all months for both persistence and forecasts. The value σ was then obtained from Eq. (18).

For the forecast, it was assumed that the decision was made by linear interpolation between the latest available 300 mb wind analysis and the latest available 24 hour 300 mb wind forecast. The value σ_w^2 for this forecast was obtained by linear interpolation of σ_w^2 in the forecast decay diagram. When an observation was available for a time subsequent to the time on which a forecast map was based (due to delay between analysis and forecast transmissions), σ_w^2 was assumed to lie on the straight line joining $\sigma_w^2 = 0$ at the observation time and the σ_w^2 of the forecast map. The value σ was again obtained from Eq. (18).

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*Provided by Dr. George Cressman of the National Meteorological Center, USWB. Verification is for geostrophic winds.

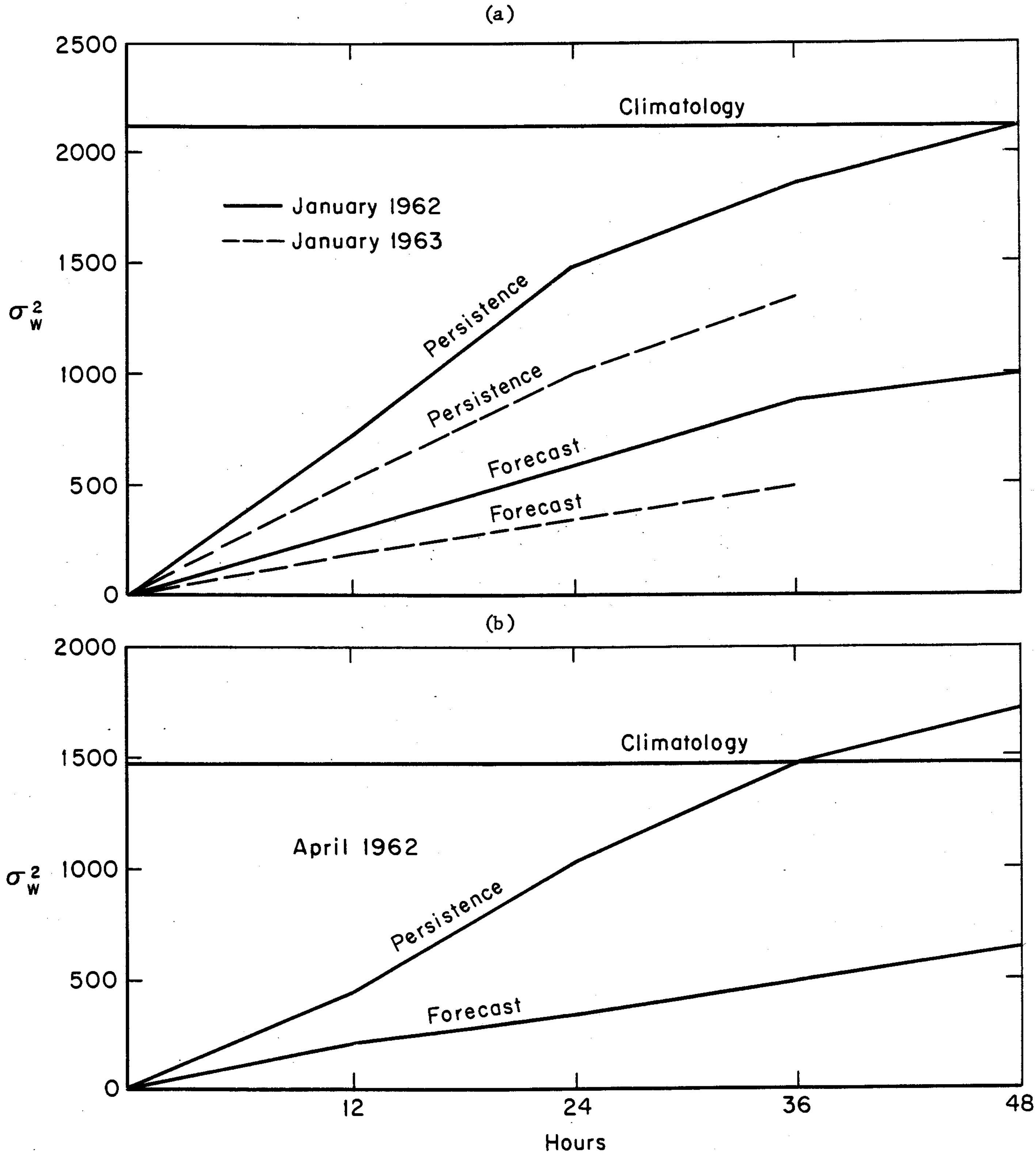

Fig. C-3(a,b) Forecast decay diagram representations of the NWP verification data

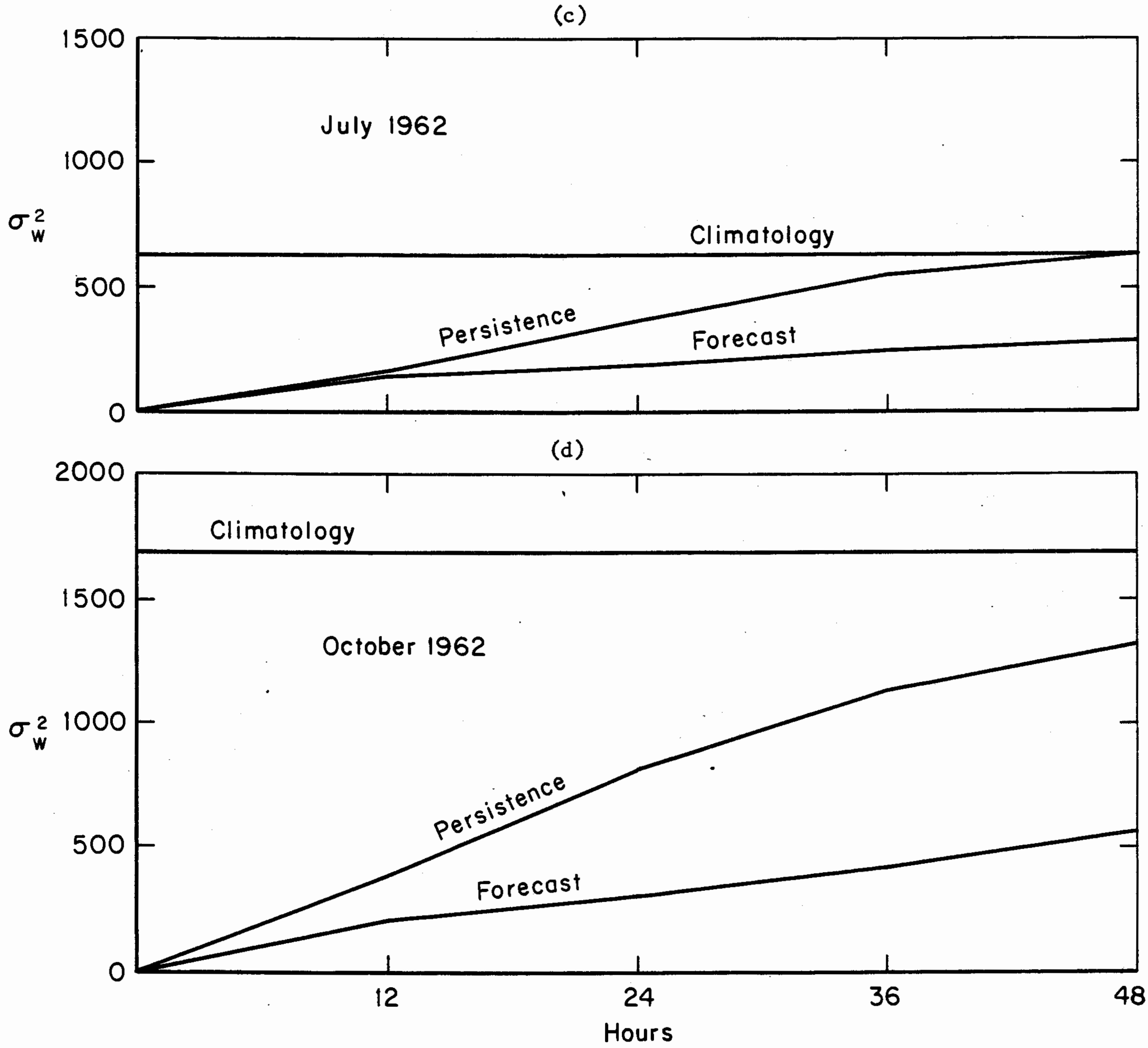

Fig. C-3(c,d) Forecast decay diagram representations of the NWP verification data

The scheduled transmissions on Facsimile Service C are given in Table C-1.

Table C-1

NORTH AMERICA, 300 mb WIND FORECAST.

FACSIMILE SERVICE C ANALYSIS

AND FORECAST TRANSMISSION SCHEDULE

(GREENWICH CIVIL TIME)

	Data Time	Transmission Time
Analysis	0000 1200	0525 1725
Forecast	0000 1200	0935 2135

Nonstop flights between New York and Los Angeles were considered. The no-wind time $\left(\frac{D_o}{V_a}\right)$ at cruising altitude was assumed to be 4.9 hours, and the cruising speed 465 knots. The operating cost per hour was assumed to be \$700.* Results are presented in Table C-2 as a function of $\overline{w} = (2\sigma)^{-1}|\overline{\tau}_2-\overline{\tau}_1|$. Some of these results have also been plotted in Figs. C-5(a,b) and C-6. Figures C-4(a) and C-4(b) show the variation of c_T with lag time for east- and westbound flights during January 1962.

No figures are available for direct comparison of the costs of using the numerical prognostic charts with the costs of using "conventional" prognostic charts. However, a few data on verification accuracy of "conventional" prognostic charts for other seasons and geographical

*Climatological data on mean winds were taken from Heastie, H., and P. M. Stephenson, "Upper Winds Over the World," Parts I and II, Geophysical Memoirs No. 103, M. O. 631C, Air Ministry, London, 1960; climatological vector standard deviations were taken from Tucker, G. B., "Upper Winds Over the World," Part III, Geophysical Memoirs No. 105, M. O. 631e, Air Ministry, London, 1960.

Table C-2

STANDARD DEVIATIONS OF JET EN ROUTE TIMES BETWEEN NEW YORK AND LOS ANGELES IN MINUTES, AND EXPECTED COSTS IN DOLLARS PER FLIGHT FOR CLIMATOLOGY, PERSISTENCE AND FORECASTS AS A FUNCTION OF $\bar{w}$

Month and Direction	Item	Minutes σ	$\bar{w}$ (Dollars Per Flight) 0	0.5	1.0	1.5	2.0
January 1962 Eastbound	Climatology	13.8	90.8	32.1	8.2	1.4	0.2
	Persistence	8.2	16.2	12.6	6.0	1.7	0.2
	Forecast	5.8	7.9	6.2	2.9	0.8	0.1
January 1962 Westbound	Climatology	24.6	161.9	57.3	14.7	2.5	0.3
	Persistence	14.6	28.6	22.3	10.5	3.0	0.4
	Forecast	10.3	14.0	10.9	5.2	1.5	0.2
April 1962 Eastbound	Climatology	13.4	88.5	31.3	8.0	1.4	0.2
	Persistence	7.9	15.0	11.7	5.5	1.6	0.2
	Forecast	5.3	6.7	5.2	2.5	0.7	0.1
April 1962 Westbound	Climatology	19.1	125.6	44.4	11.4	1.9	0.3
	Persistence	11.2	21.5	16.8	7.9	2.3	0.3
	Forecast	7.5	9.7	7.5	3.6	1.0	0.1
July 1962 Eastbound	Climatology	9.8	64.8	22.9	5.9	1.0	0.1
	Persistence	5.3	9.3	7.2	3.4	1.0	0.1
	Forecast	4.9	7.9	6.2	2.9	0.8	0.1
July 1962 Westbound	Climatology	11.8	77.8	27.5	7.1	1.2	0.2
	Persistence	6.4	11.3	8.8	4.1	1.2	0.2
	Forecast	5.9	9.7	7.5	3.6	1.0	0.1
October 1962 Eastbound	Climatology	14.5	95.2	33.7	8.7	1.5	0.2
	Persistence	7.2	11.9	9.2	4.4	1.2	0.2
	Forecast	5.3	6.3	4.9	2.3	0.7	0.1
October 1962 Westbound	Climatology	20.7	136.3	48.2	12.4	2.1	0.3
	Persistence	10.3	16.8	13.1	6.2	1.8	0.2
	Forecast	7.5	8.9	6.9	3.3	0.9	0.1
January 1963 Eastbound	Climatology	13.8	90.8	32.1	8.2	1.4	0.2
	Persistence	6.8	11.3	8.8	4.1	1.2	0.2
	Forecast	4.4	4.5	3.5	2.5	0.5	0.1
January 1963 Westbound	Climatology	24.6	161.9	57.3	14.7	2.5	0.3
	Persistence	12.3	20.1	15.7	7.4	2.1	0.3
	Forecast	7.9	8.3	6.5	3.1	0.9	0.1

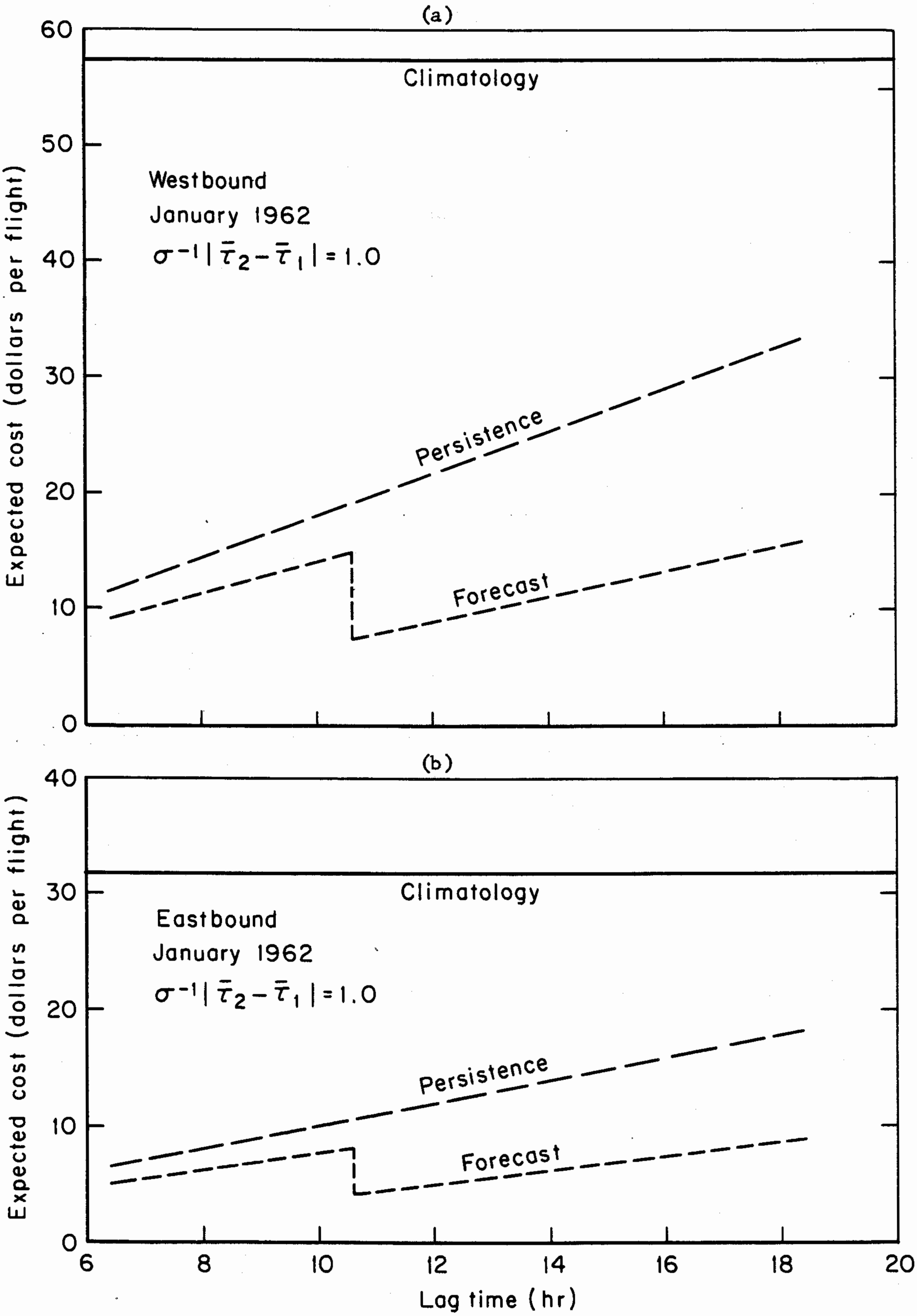

Fig. C-4(a,b) Expected costs for forecasts and persistence as a function of lag time for (a) westbound flights and (b) eastbound flights, January 1962

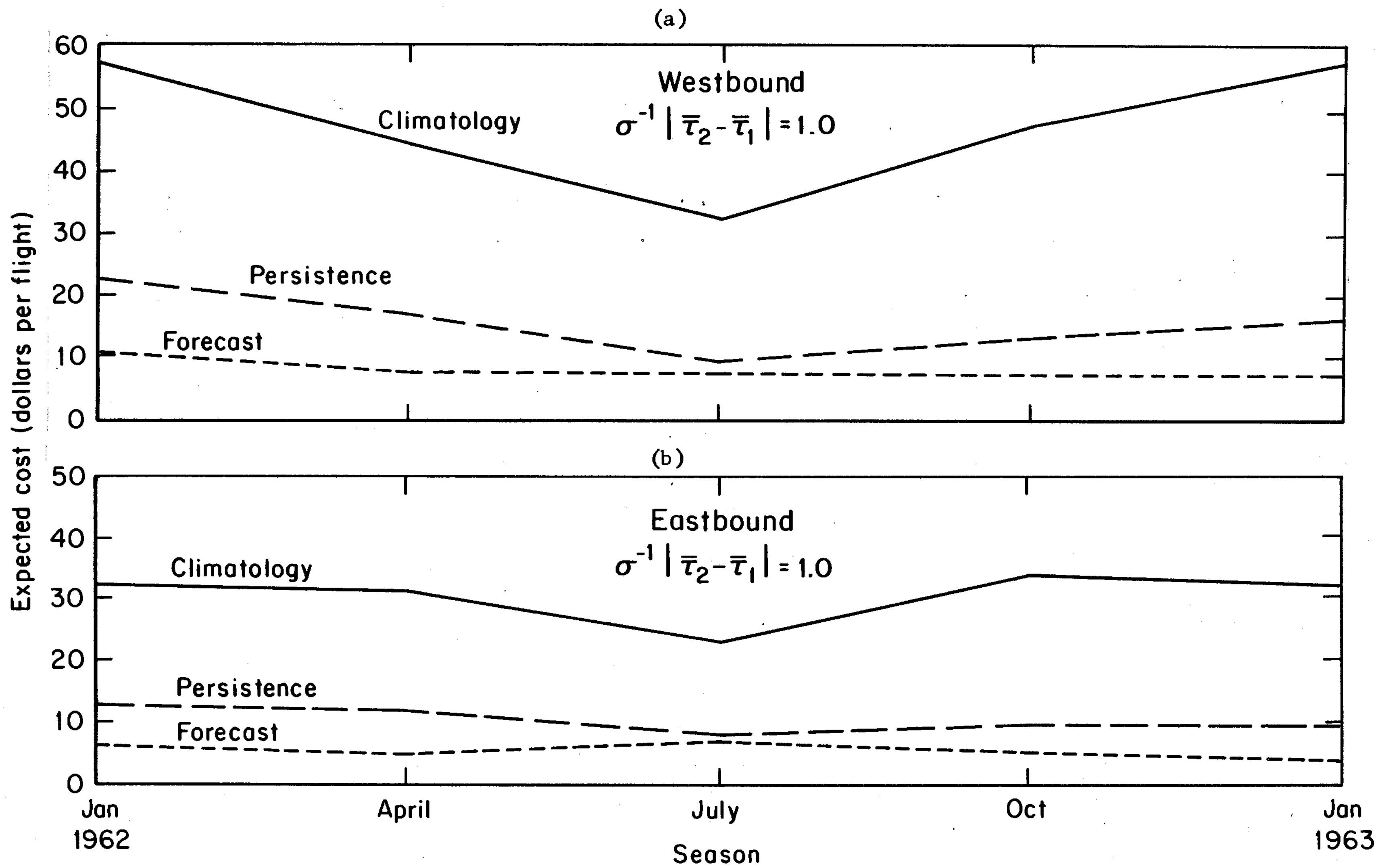

Fig. C-5(a,b) Variation with season of expected costs for climatology, persistence and forecast for (a) westbound flights and (b) eastbound flights during January 1962

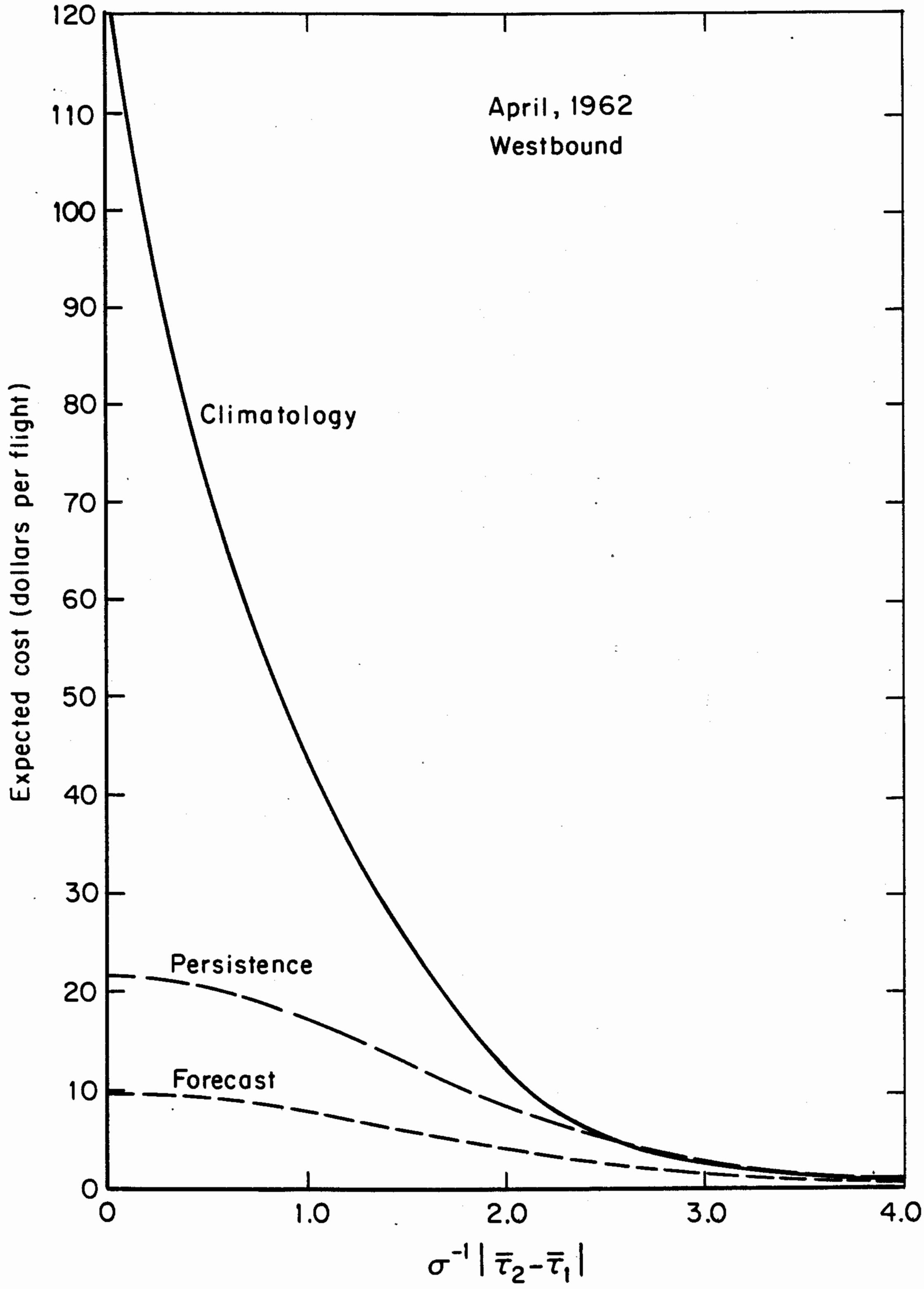

Fig. C-6 Relationship between expected costs of climatology, persistence and forecasting as a function of the separation of climatological mean times for the two routes; data is for westbound flights in April 1962

areas have been presented by Elasasser.* Since c_T is proportional to the parameter $S = \sigma_e^2 / \sigma^2 \simeq \sigma_{ew}^2 / \sigma_w^2$, this quantity has been tabulated in Table C-3 for 24-hour lag for both persistence and forecasts from the data used in this study and from Elsasser's data. It is noteworthy that in the conventional forecast verification studies, the persistence parameter, S_p, was considerably larger than for the present study. A better measure than S_f of the "goodness" of the forecast may therefore be the ratio S_f/S_p. This quantity also appears in Table C-3. Although the conventional and numerical forecasting data are not truly comparable because of the differences in location, period of study, and verification methods, the values of this ratio suggest that the numerical forecasts represent a significant improvement over the conventional forecasts. The last two columns of Table C-3 give values of the parameter S_o and the ratio S_o/S_p, where S_o results from errors in observations, analysis, and small-scale fluctuations only. These errors were estimated in one of the studies discussed by Elsasser. They represent a better estimate of the practical upper limit to forecasting accuracy than the hypothetical perfect forecasting scheme, I_o.

5. The n-Route Model

Assume that there are n possible actions, each of which is associated with a cost that in turn is a continuous or piecewise continuous function of a set of weather parameters. It is helpful to think of the cost for each action as comprising one coordinate of an n-dimensional "cost space." The space can be divided into n cells, in each of which one of the cost coordinates is less than any other cost coordinate. For a particular weather state there is a particular set of costs which can be thought of as a vector, $\underline{c}$, in cost space, and for any forecast weather state (or forecast cost vector, $\underline{y}$) there is a distribution of these actual cost vectors. Let this distribution be defined by means of the conditional probability density function

$$P_f(\underline{c}|\underline{y}).$$

*Elsasser, H. W., "An Investigation of the Errors in Upper-Level Wind Forecasts," Air Weather Service Technical Report TR-105-140/2, November, 1957.

Table C-3

24-HOUR LAG RATIOS $(\sigma_e/\sigma)^2 = S$

Subscript p for persistence, subscript f for forecast.
Subscript o is for perfect forecasts, i.e.,
error due to observations, analysis
and small-scale fluctuations only.

Month	Numerical Forecast			Conventional Forecast				
	S_p	S_f	S_f/S_p	S_p	S_f	S_f/S_p	S_o	S_o/S_p
Jan. 1962	.69	.27	.40	-	-	-	-	-
Apr.	.71	.23	.32	1.04	.85	.81	-	-
July	.58	.29	.50	-	-	-	-	-
Oct.	.49	.18	.37	.96	.88	.92	-	-
Jan. 1963	.46	.16	.35	-	-	-	-	-
All months	-	-	-	.90	.41	.45	.09	.10

When multiplied by the cost space volume element, $dc_1 \ldots dc_n$, $P_f(\underline{c}|\underline{y})$ gives the probability that $\underline{c}$ falls within the volume element, given $\underline{y}$. The subscript f indicates the dependence of this function on the particular forecasting system, I_f, which is being used.

The probability that $\underline{c}$ falls in the particular cell in which c_m is less than any other component of $\underline{c}$, given the forecast $\underline{y}$, is:

$$\int \cdots \int_{V_m} P_f(\underline{c}|\underline{y})\, dc_1 \ldots dc_n \quad ,$$

where V_m indicates that the integration is over the entire volume of the cell in which c_m is the smallest component of $\underline{c}$.

It will be assumed that the decision maker always selects that action with the smallest forecast cost (or, what is equivalent, the highest forecast utility). Although this is a reasonable procedure, it is not necessarily the best one. The decision maker would be better off choosing that action with the smallest expected cost corresponding to the forecast vector $\underline{y}$. This may be different from the smallest component of $\underline{y}$. This point will be discussed further under 6 below. The expected cost of using the forecast system I_f will be denoted by $c_T(I_f)$, and it will be defined as the increase in expected cost using I_f over the expected cost of using the hypothetical perfect forecasting system, I_o. The forecasting system for which $\underline{c} = \underline{y}$ is I_o, or

$$P_o\ (\underline{c}|\underline{y}) = \delta\ (\underline{c} - \underline{y}) \quad ,$$

where $\delta\ (\underline{c} - \underline{y})$ is the delta function.

For a single application of the system, the expected cost is the difference between the actual cost of the action with the forecast least cost, c_j, and the action with the actual least cost, c_m, multiplied by $P_f(\underline{c}|\underline{y})$, integrated over that cell in which c_m is the smallest component of $\underline{c}$, and summed over all $m \neq j$. In other words, if $c_1(I_f)$ is the expected cost of one selection of action based on I_f, then

$$c_1(I_f) = \sum_{\substack{m=1 \\ m\neq j}}^{n} \int \cdots \int_{V_m} (c_j - c_m)\, P_f\, (\underline{c}|\underline{\gamma})\, dc_1 \,..\, dc_n$$

$$= \sum_{m=1}^{n} \int \cdots \int_{V_m} (c_j - c_m)\, P_f\, (\underline{c}|\underline{\gamma})\, dc_1 \ldots dc_n \quad . \tag{25}$$

The expected cost averaged over many selections of action is obtained by multiplying $c_1(I_f)$ by the probability of obtaining $\underline{\gamma}$, integrating over the cell, V_j, in which γ_j is the forecast least component of $\underline{\gamma}$, and summing over all j, i.e.,:

$$c_T(I_f) = \sum_{j=1}^{n} \int \cdots \int_{V_j} \pi_f(\underline{\gamma}, \overline{\underline{\gamma}}) \sum_{m=1}^{n} \int \cdots \int_{V_m} (c_j - c_m) P_f(\underline{c}|\underline{\gamma}) dc_1 .. dc_n d\gamma_1 .. d\gamma_n \quad , \tag{26}$$

where $\pi_f(\underline{\gamma}, \overline{\underline{\gamma}})$ is the probability density function for obtaining $\underline{\gamma}$ using I_f. The dependence of this distribution on the mean value, $\overline{\underline{\gamma}}$, is specifically indicated.

This formulation is only useful when cost distributions can be derived from distributions of weather states, since normally it is the weather states rather than the costs themselves which are forecast. Furthermore, it is necessary to make the limits of the integrations over V_m and V_j specific. For this purpose it is helpful to note that cell boundaries are given by the equations $c_m - c_K - 0$, or $\gamma_j - \gamma_K = 0$. In addition, the interfaces between cells all intersect in the infinite line passing through (0, 0, 0 .. 0) and (1, 1, 1 ... 1). Let us introduce the set of transformations

$$x_i^m = T_{i\ell}^m \; c_\ell \quad , \qquad\qquad x_i^m = T_{i\ell}^m \; c_\ell \quad , \tag{27}$$

where the matrices $T_{i\ell}^m$ have all elements in the m^{th} row and all elements in the m^{th} column equal to +1, all elements in the principal diagonal equal to -1 (except for T_{mm}^m), and all other elements equal to 0. Notice that these transformations are not orthogonal (except when n = 2); the volume elements in x^m space and c space are related by:

$$dx_1^m \ldots dx_n^m = n \sin\left(\frac{\pi}{n}\right)^{2-n} dc_1 \ldots dc_n \quad .$$

From the two properties of the cell interfaces given above, it follows that the result of applying the transformation to the m[th] term of the inner summation in Eq. ~~(26)~~ gives

$$\int \cdots \int_{V_m} (c_j - c_m) P_f(\underline{c}|\underline{\gamma}) dc_1 .. dc_n = - \frac{\left[\sin(\pi/n)\right]^{n-2}}{n} \underbrace{\int_{-\infty}^{0} \cdots \int_{-\infty}^{0}}_{n-1}$$

$$\left[\int_{-\infty}^{\infty} x_j^m P'_f(\underline{x}^m | \underline{\chi}^m)\, dx_m^m \right] \underbrace{dx_1 \ldots dx_n^m}_{n-1} \quad , \qquad (28)$$

when $m \neq j$, or zero when $m = j$. The quantity $\underbrace{dx_1 \ldots dx_n}_{n-1}$ does not include the element dx_m^m.

Here $P'_f(\underline{x}|\underline{\chi})$ is the transformed conditional probability density. This form may considerably simplify the integrations, especially since the integration over x_m^m can sometimes be carried out immediately, reducing the problem effectively to a 2(n-1)-fold integration. The same procedure can also be used to simplify the integrations over γ.

6. The Optimal Choice of Route

As mentioned under 5 above, the choice of the forecast fastest route may not be the optimal choice. Consider the consequences in the two-route problem of selecting the route with the smallest expected time rather than the smallest forecast time. Under the assumptions of 2 and 3 above, the expected time on route 1 is $\rho\tau_1 + (1-\rho)\bar{\tau}_1$ and on route 2 it is $\rho\tau_2 + (1-\rho)\bar{\tau}_2$. Then route 1 would be picked when $\rho(\tau_2 - \tau_1) + (1-\rho)(\bar{\tau}_2 - \bar{\tau}_1) > 0$, and route 2 would be picked when $\rho(\tau_2 - \tau_1) + (1-\rho)(\bar{\tau}_2 - \bar{\tau}_1) < 0$.

In terms of u, $\bar{u}$, and x, total expected costs will be obtained by summing over all cases in the two categories:

$$(a)\quad \left\{ \begin{array}{l} \rho u + (1-\rho)\bar{u} > 0 \\ x < 0 \end{array} \right\}$$

and

$$(b)\quad \left\{ \begin{array}{l} \rho u + (1-\rho)\bar{u} < 0 \\ x > 0 \end{array} \right\} .$$

Now in Eq. (5), consider the quantity

$$I = \int_{-\infty}^{0} \exp\left[-\left(\frac{u-\bar{u}}{2\sigma}\right)^2\right] \int_{0}^{\infty} x \exp\left\{-[4\sigma^2(1-\rho^2)]^{-1} [x-\rho u-(1-\rho)\bar{u}]^2\right\} dxdu \quad ,$$

corresponding to category (b). Under the new selection rules, nothing in this integration changes, except the upper limit in the u integration. This changes to

$$u = -\left(\frac{1-\rho}{\rho}\right)\bar{u} \quad .$$

The lower limit of the u integration in the second term of Eq. (5) changes in a similar way. Now let

$$u' = \rho u + (1-\rho)\bar{u} \quad .$$

Substituting this into Eq. (5) we obtain

$$\begin{aligned} c_T = \frac{c_r}{4\pi\sigma^2\rho(1-\rho^2)^{1/2}} \Bigg(& \int_{-\infty}^{0} \exp\left[-\left(\frac{u'-\bar{u}}{2\rho\sigma}\right)^2\right] \int_{0}^{\infty} x \exp\left\{-[4\sigma^2(1-\rho^2)]^{-1} (x-u')^2\right\} dxdu \\ & - \int_{0}^{\infty} \exp\left[-\left(\frac{u'-\bar{u}}{2\rho\sigma}\right)^2\right] \int_{-\infty}^{0} x \exp\left\{-[4\sigma^2(1-\rho^2)]^{-1} (x-u')^2\right\} dxdu \Bigg) \\ = \frac{c_r}{4\pi\sigma^2\rho(1-\rho^2)} & \int_{0}^{\infty}\int_{0}^{\infty} \left\{ \exp\left[-\left(\frac{u'-\bar{u}}{2\rho\sigma}\right)^2\right] + \exp\left[-\left(\frac{u'+\bar{u}}{2\rho\sigma}\right)^2\right] \right\} . \\ & \left(x \exp\left\{-[4\sigma^2(1-\rho^2)]^{-1} (x-u')^2\right\} \right) dxdu. \end{aligned} \tag{29}$$

Letting

$$z = \frac{x}{2\rho\sigma}$$

$$w = \frac{u'}{2\rho\sigma}$$

$$\bar{w} = \frac{\bar{u}}{2\sigma}$$

$$r = \frac{(1-\rho^2)^{1/2}}{\rho} \quad ,$$

Eq. (29) can be written

$$c_T = \frac{2c_r\rho\sigma}{\pi r} \int_0^\infty \left\{ \exp\left[-\left(w - \frac{\bar{w}}{\rho} \right)^2 \right] \exp\left[-\left(w + \frac{\bar{w}}{\rho} \right)^2 \right] \right\} \cdot \left\{ \int_0^\infty z \exp\left[-\left(\frac{z - w}{r} \right) \right] dz \right\} dw \quad . \tag{30}$$

This integral can be evaluated, and the result is

$$c_T = \frac{c_r\sigma}{\sqrt{\pi}} \left\{ e^{-\bar{w}^2} - \rho e^{-(\bar{w}/\rho)^2} + \sqrt{\pi}\ \bar{w}\ [\mathrm{erf}(\bar{w}) - \mathrm{erf}(\bar{w}/\rho)] \right\} . \tag{31}$$

Figure 7 shows a comparison between the quantities

$$\left(\frac{\sqrt{\pi}\ c_T}{c_r\sigma} \right)$$

obtained when the forecast fastest route is selected, Eq. (7), and when the expected value of <u>en route</u> time is used to select the fastest route, Eq. (31). The value of ρ used here was 0.8. The use of the expected value of the route time gives some improvement only for rather large values of $\bar{w}$.

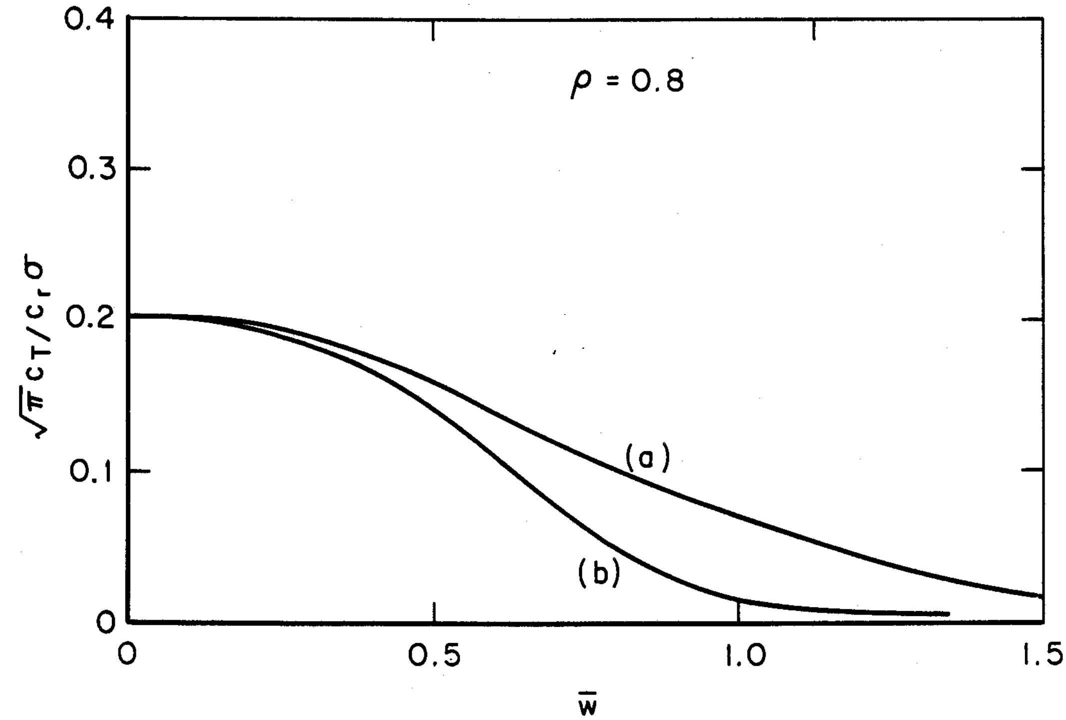

Fig. C-7 Comparison between $(c_T/c_r\sigma)$ for a decision scheme which selects the forecast fastest route (curve a), and one which selects the expected fastest route based on the forecast (curve b)

7. Conclusions

Because of the very great simplifications involved, the results of of this analysis must be interpreted cautiously in terms of actual airline operations. Nevertheless several conclusions seem justified.

1. Routes whose mean times are more than three or four standard deviations longer than the time on the normally fastest route should not be considered as possible alternatives unless a forecasting system substantially better than the one considered here is in use.

2. When properly utilized, the numerical prediction product can give a substantial improvement over persistence at the time ranges considered here. Proper utilization involves something akin to the linear interpolation used in the model.

3. For routes whose average times are close together (less than about two standard deviations apart), either persistence or forecasting gives a substantial improvement over always picking the climatologically best route. For routes that are three or more standard deviations apart in average time, persistence may be inferior to climatology.

4. Forecasts are at present quite good for the purpose of route selection. They are good in the sense that the margin for future improvement is small compared with the existing improvement over climatology (essentially no information). This is particularly true when one realizes that the existing observational network limits the hypothetical perfect forecast to an expected cost somewhat above the zero level.

5. Figures C-3(a) and C-3(b) suggest that one of the most promising and immediate ways of lowering expected cost would be to decrease the lag time of observations and forecasts. For example, from Fig. C-3, a decrease in lag time for observations of three hours and a decrease in lag time of forecasts of six hours might lower expected costs (in this simple model at least) by as much as 30%. This may be what the airlines actually do; by incorporating other data sources, including aircraft reports, they are actually lowering the effective lag times.

6. Seasonal variation in forecasting value is quite pronounced, and the differences between the two Januarys suggest that even year to year variations may be large.

7. A slight reduction in expected cost of using any forecasting system may be obtained by using the expected value of <u>en route</u> times based on the forecasts rather than the forecast <u>en route</u> times themselves. In general, the two times will not be the same. It is doubtful whether this reduction in expected cost would be operationally significant.

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