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The Potential Economic Benefits

of

Improvements in Weather Forecasting

FINAL REPORT

September 1972

J.C. Thompson
Project Director

Department of Meteorology
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PREFACE

This report describes an investigation of the future potential for economic gains associated with improvements in weather forecasting. The study was initiated as a consequence of the increased use of weather satellites, electronic computers and other technological developments which have become a virtual necessity for solving the complex problems of the earth's atmosphere. That the emphasis in this study is on their economic and hence, monetary, values stems from the not inconsiderable costs associated with such devices, a circumstance which suggests the desirability of an assessment in like dimensions.

It should be noted, however, that neither the economic emphasis, nor the monetary results of the study, are intended to imply their sole use as criteria for making decisions concerning the intrinsic value of technological improvements in meteorology. On the contrary, economic gains should be considered only in the context of the many benefits -- scientific, social and others -- which have always derived from the continuing search for fundamental knowledge of the atmospheric fluid in which man lives, and which constitutes a basic necessity for his very existence. It is within this framework that the study was undertaken.

The work was done at California State University, San Jose, with financial support furnished by the Office of Space Science and Applications, National Aeronautics and Space Administration. Valuable forecast data were made available by the National Weather Service, National Oceanographic and Atmospheric Administration, and extremely useful information on weather losses was provided by many industrial and agricultural organizations throughout the United States. Individual consultants, student research assistants and others directly, or indirectly, associated with the project also made invaluable contributions which are acknowledged elsewhere in the report.

The writer is greatly indebted, individually and collectively, to all of those who assisted in the study. That errors of fact, logic or inadvertance may have occurred during the investigation is, however, the sole responsibility of the writer.

The report itself is divided into three parts: Part 1, SUMMARY, is a condensed description of the purpose, methods and substantive results of the study. Part 2, REPORT IN DETAIL, is a comprehensive discussion of the fundamental concepts, meteorologic-economic models, computing procedures, and peripheral results. Part 3, APPENDICES, contains pertinent data tabulations.

J. C. Thompson
San Jose, California
September 1, 1972

PART 1. SUMMARY

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1.1 INTRODUCTION

Meteorology, as one of the environmental sciences, has been the beneficiary of many technological advances during recent years. These have included such sophisticated tools as meteorological satellites, electronic computers, and weather radar. However, not only has the development and use of these new devices required an expenditure of considerable time, effort and material resources, but there is no indication that such costs will decrease in the future. To a certain degree, these expenditures may be justified by the expanded scientific knowledge and other benefits that have been, and will be, accumulated. But, as costs rise, it seems inevitable that decisions regarding the approval of future programs will also require consideration of the potential monetary returns. It is therefore important that an attempt be made to examine the economic benefits which may be expected from continuing progress in meteorology.

While a number of studies have been made of the economic benefits associated with existing weather services, e.g., Bollay (1962), Lave (1963), Russo (1965), and a comprehensive survey of such studies has been compiled by Maunder (1970), few attempts have been made to assess the gains which may be expected from future improvements in such services. For the most part, efforts to examine this latter subject have involved surveys which, with questions of varying complexity, request the forecast user to estimate the economic benefits to his activity of improved weather predictions. Since the user would clearly like to have the weather forecast improved, but has little or no quantitative information upon which to base such an estimate, his reply tends to be an uncertain and subjective evaluation of the potential benefits.

In the present study, use has been made of (1) factual records compiled by the weather forecasting profession for the purpose of verifying its own technical competence, and (2) quantitative accounting information concerning the monetary value of weather-caused losses obtained from representative samples of agricultural, commercial and industrial organizations. Data from these two sources have been combined in a "meteorologic-economic model" which relates potential improvements in meteorological information to the associated economic gains, including the limits which are placed upon such gains by the nature of weather information itself. The model formulation, and the consequent mathematical and computational procedures, are discussed in Part 2. A descriptive summary is contained in the following pages.

1.2 METEOROLOGIC-ECONOMIC MODEL

Considering the general case of decisions involving whether or not to take protective measures against predicted adverse weather, it is postulated that economic gains resulting from improved weather forecasts may be achieved as a consequence of:

Operational Improvements. These may be accomplished by providing information concerning the uncertainty of the weather prediction so that the user, within a given state of the science, may make decisions which are of optimum utility for his purpose.

Scientific Advances. These may be attained by increasing scientific understanding of weather processes to such a degree that operationally errorless decisions (not necessarily scientifically without error) can be made by the forecast user.

Total Potential Gains. These represent the limit of economic gains due to both operational improvements and scientific advances.

Using the meteorologic-economic model, these statements can be translated into numerical form, and the future economic gains due to improved weather forecasts can then be evaluated quantitatively. In practice, it is found convenient to provide the results initially in a non-dimensional (percentage) form -- specifically as the potential economic gain, per unit forecast, per unit of economic loss due to adverse weather. This device provides an assessment which is independent of inflation or other secular economic factors which may seriously influence monetary evaluations. Moreover, if actual monetary or other dimensional quantities are desired, the potential gain can be obtained simply as the product of the appropriate percentage gain and the currently experienced, but protectable, weather-caused losses.

1.3 APPLICATION OF THE MODEL

The potential economic gains defined by the model have been computed from forecasts provided through the courtesy of the U.S. National Weather Service. These data include short range (3-, 5-, and 7-hour) forecasts of ceiling and visibility for major air terminals; medium range (12-, 24-, and 36-hour) predictions of precipitation for principal cities; and extended (5-day, 30-day and seasonal) forecasts of temperature and precipitation for the United States as a whole.

Within the broad outlines of the basic model, varying degrees of sophistication are possible. These arise from the different types of decision options and strategies which may accompany dissimilar operational practices of forecast users. Considerable variation in potential economic gains is obtained in individual situations when all of these differences are accounted for. However, for the economy as a whole, it is found that these variations are generally small, and that an adequate initial evaluation may be obtained by assuming simple dichotomous decisions (i.e., to protect, or not to protect against adverse weather), where the forecast user wishes, as a consequence of such decisions, to minimize his long-run weather expenses.

With respect to the user's operational risks, it is then proposed that limited capital resources will be an important consideration, so that he will desire to minimize the likelihood of encountering a sequence of weather-caused losses which would eliminate or severely deplete his capital. Such a decision tactic is exemplified by the so-called "mini-max" strategy, an operating procedure which is designed to minimize the maximum losses associated with adverse events, and which represents a variation in the strictly optimum use of decision making information.

Finally, to provide for the accomplishment of such decisions, weather predictions must include information concerning their uncertainty, a requirement which is gradually being met by the National Weather Service in the form of "probability forecasts".

With the preceding assumptions applied to available weather forecasting data, Figure 1.1 shows the potential

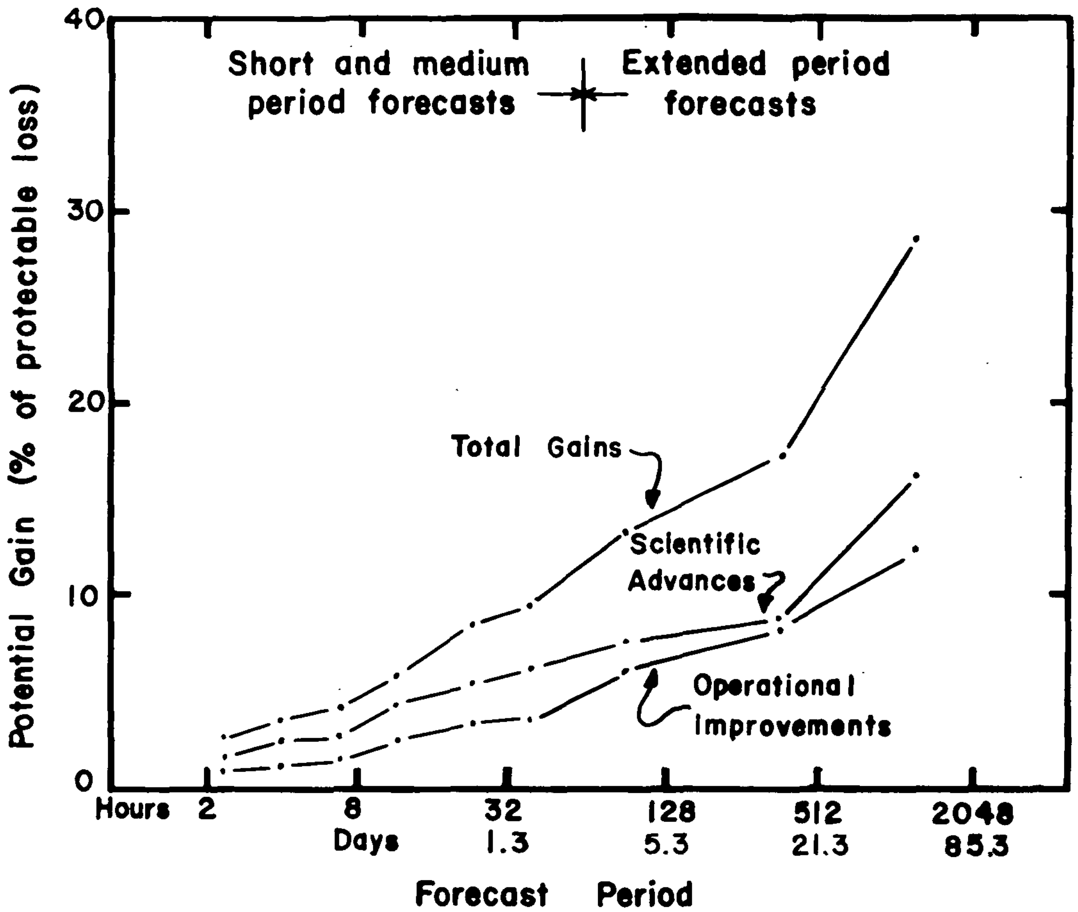

Figure 1.1 Variation in potential economic gains with length of the forecast period for dichotomous, mini-max decisions. (Extended period forecasts are mean predictions and are plotted at the middle of the appropriate range.)

economic gains due to "operational improvements", "scientific advances" and "total potential gains", as defined earlier, for various forecast periods.

An examination of Figure 1.1 shows that total potential gains range from about 3 percent of protectable losses for 3-hour predictions of ceiling and visibility, to nearly 30 percent for seasonal (90-day) predictions of temperature and precipitation. Qualitatively, this is in agreement with general experience, since the greater the length of the forecast period, the less accurate is the forecast and, in turn, the greater the potential for improvement.

Implicit in Figure 1.1 is the suggestion that the overall greatest economic potential, at least in terms of percentage of protectable losses, lies in the improvement of the longer-range predictions. However, because predictions for different periods vary in their operational importance to individual segments of the economy, it is of interest to interpret these results in more usual economic units, i.e., as the monetary value of potential gains.

1.4 POTENTIAL ECONOMIC BENEFITS

Using the framework of the meteorologic-economic model, the dimensional (e.g., monetary) economic gains associated with future improvements in weather forecasting may be evaluated by obtaining appropriate information from weather forecast users. Since results of the weather prediction analyses are expressed in terms of the percentage of protectable losses currently suffered due to the occurrence of unpredicted adverse weather, the dollar value of improvements in weather predictions may be determined as the product of such percentage figures and the appropriate weather losses expressed in monetary units.

For this study, the weather losses were obtained by conducting a survey of representative agricultural, industrial and other activities in the United States. Although much of the information obviously represented only estimates of such losses, a significant proportion was obtained from actual accounting records. Some survey respondents made special studies of their own operations in order to provide factual data. An illustration showing results of the survey is given in Figure 1.2.

The losses for all activities may be summarized as follows:

Based on a survey of agricultural, industrial and other activities, the current annual value of weather-caused losses in the United States is:

Losses which could be averted if adequate warnings were provided (protectable losses)	\$ 5,303 million
Total losses, irrespective of weather or not practical protective measures could be taken	\$12,685 million

Although these survey results are subject to the usual sampling uncertainties, they are generally in accord with such parallel information as is available.

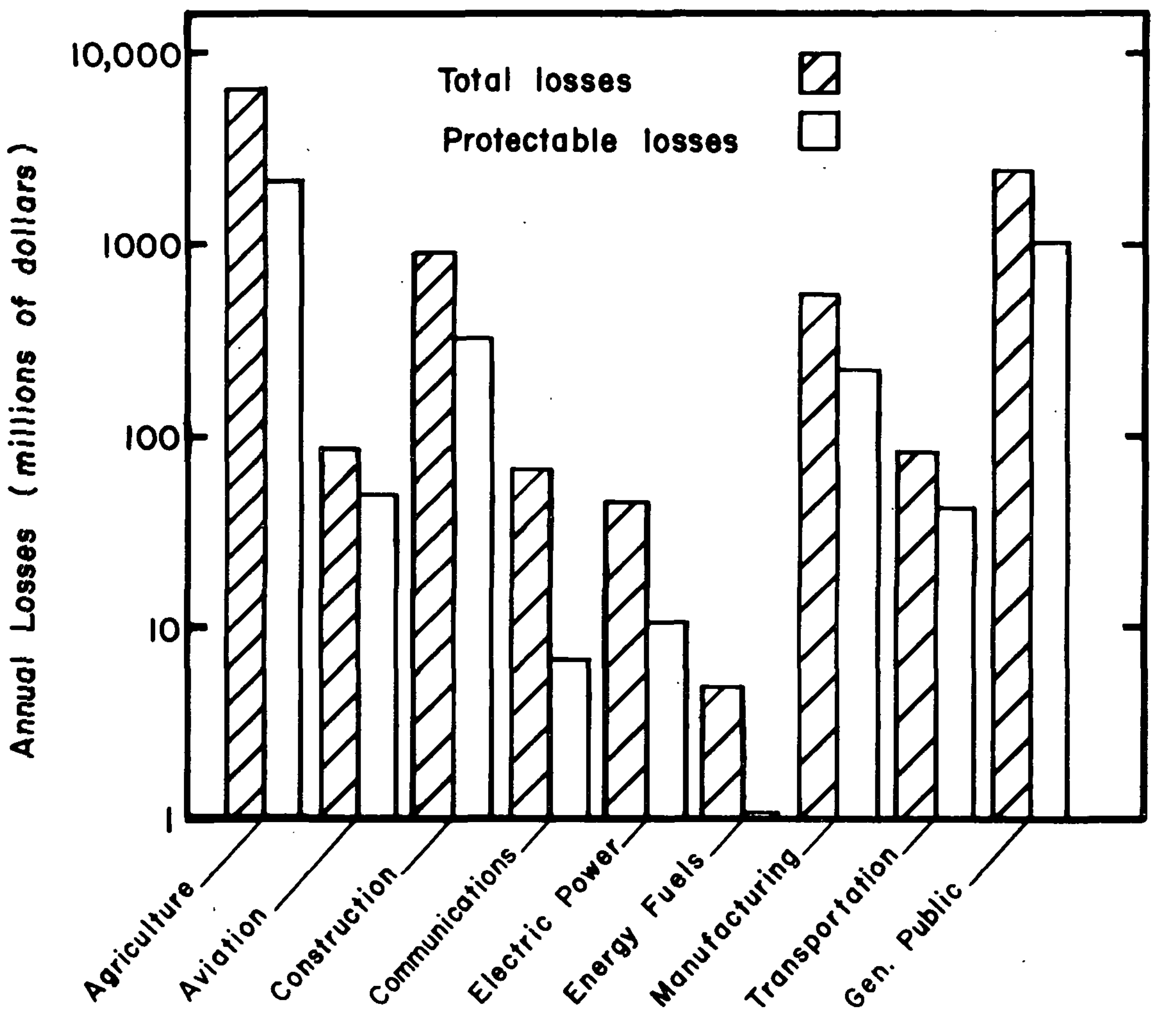

Figure 1.2 Annual monetary losses due to adverse weather in the United States. Shaded bar shows total losses, irrespective of whether or not protective measures could be taken; unshaded bar shows losses which could be protected against if adequate warnings for an appropriate period in advance could be provided. (See Table 2.9 for detailed numerical values.)

Evaluation of the potential savings associated with future improvements in weather forecasting may be accomplished by combining the meteorological and economic components of the model. These computations require consideration of a number of factors, including the nature of the adverse weather, the length of the forecast period, the economic risks inherent in individual activities, and the decision strategy employed by forecast users. Taking these factors into account, Figure 1.3 depicts the potential savings due to operational improvements, scientific advances, and total gains defined by the model.

The potential gains for all activities may be summarized as follows:

Based on this study, the total annual savings to the economy of the United States are potentially:

Due to better use of weather forecasts (operational improvements)	\$322 million
Due to more accurate weather forecasts (scientific advances)	\$417 million
Total potential gains	\$739 million

The total potential gains for the economy as a whole represent approximately 14% of current protectable losses. Clearly, even with "perfect forecasts" it is impossible to eliminate the entire expense of adverse weather since the cost of protection must still be accounted for. That only a modest percentage of the economic value of protectable weather losses can be saved by further forecast improvement

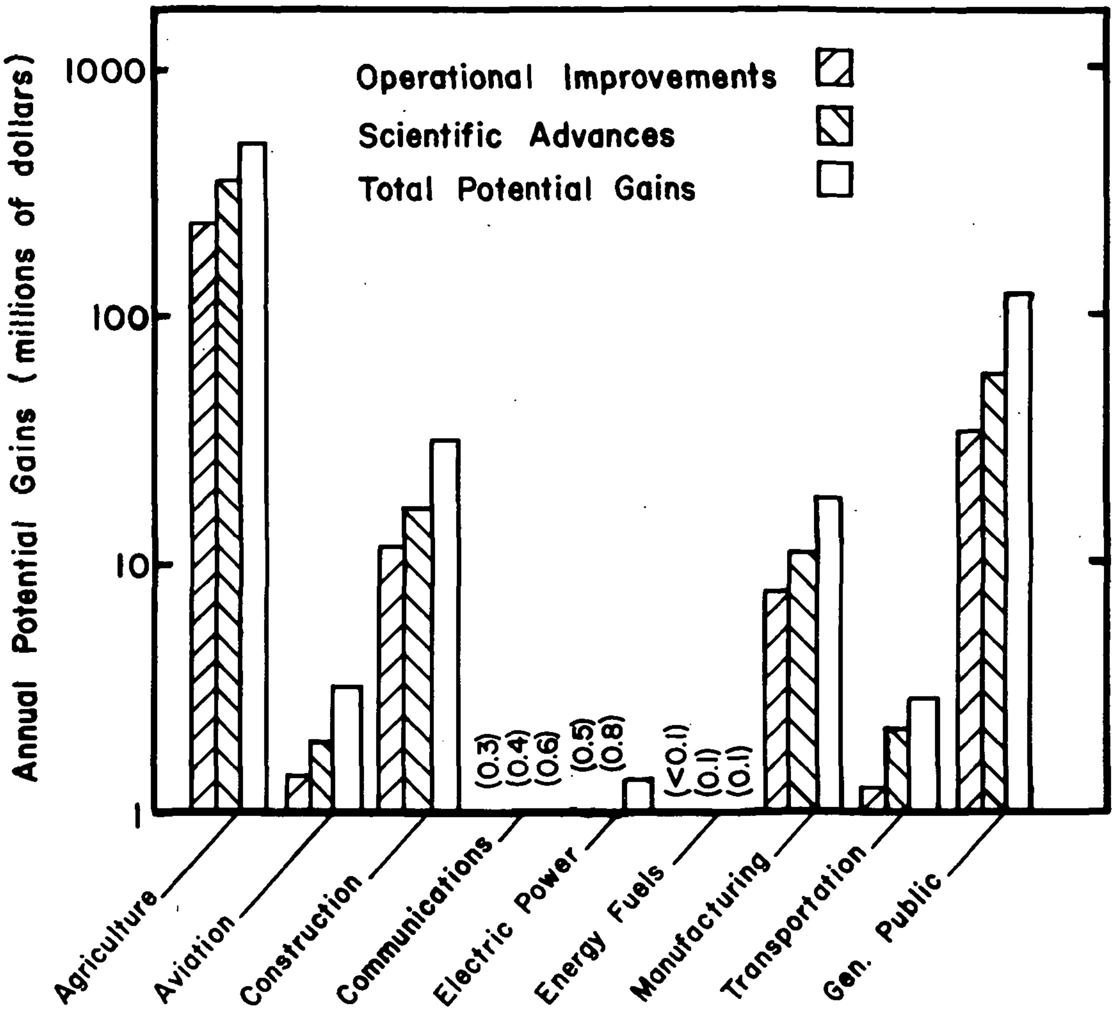

Figure 1.3 Potential annual savings for individual activities, due to operational improvements, scientific advances and total gains associated with future progress in weather forecasting in the United States. (See Table 2.11 for detailed numerical values.)

attests to the already relatively high utility of weather predictions. Only by modification of the weather itself -- a subject beyond the scope of this study -- could additional savings be achieved.

1.5 CONCLUSION

It is perhaps appropriate to conclude with an attempt to place the potential benefits in perspective. For the Fiscal Year 1973 (1 July 1972 to 30 June 1973), the total cost to the United States of its meteorological research program is planned to be slightly over $90 million, while the total <u>increase</u> for both weather services and supporting research is projected as slightly under $30 million (White, 1972). Both figures are pertinent to the improvement of weather forecasts, although it is difficult to determine either their relative importance in this effort, or the amount of improvement which may result. Indeed, any attempt to provide a meaningful benefit/cost estimate from these data would, at present, be decidely premature.

It seems evident, however, that the potential economic benefits alone would be sufficiently large to justify the costs of improving weather predictions. Furthermore, additional less tangible -- but none the less important -- gains (e.g., scientific knowledge, saving of human life), as well as international benefits from such technological developments as meteorological satellites, would be achieved. Considering the totality of all potential gains from weather forecast improvement, the current and proposed effort to attain such advances is unquestionably justified.

PART 2. REPORT IN DETAIL

PART 2. REPORT IN DETAIL

2.1 METEOROLOGICAL UNCERTAINTY AND DECISION MAKING

One important characteristic of weather information is its inherent uncertainty. This difficulty arises partly because the techniques used to observe the atmosphere provide only a crude measure of its initial state, and partly because determination of its future course is handicapped by a technological inability to obtain an exact formulation or solution of the prediction problem. There exists, in fact, a fundamental question concerning the ultimate predictability of the atmosphere. Depending somewhat upon the methods of prediction being used, Lorenz (1969) has shown that measurement errors for scales of motion small enough to be identified by the grid of points used for computing purposes appear to double in slightly less than three days. If the scale of motion is too small to be observed by the network of observing stations (currently, phenomena as small as a good sized thunderstorm), the errors may grow even more rapidly than this. As a consequence, Lorenz concludes that a maximum of a few weeks appears to be both a theoretical and practical limit for the predictability of a particular day's weather.

While the attainment of <u>perfect forecasting accuracy</u> would thus seem to be unlikely in the forseeable future, it is quite practicable, even at present, to achieve <u>optimum</u>

decisions on the part of the users of imperfect predictions. Where the decisions are dichotomous (i.e., to protect or not protect against adverse weather conditions), and it is desired to minimize the long-run total expense of weather protection, a criterion for making such decisions may be expressed:

$$P \gtreqless C/L \begin{cases} \text{Protect} \\ \text{Either course} \\ \text{Do not protect} \end{cases} \qquad (1)$$

where P = probability (i.e., relative frequency of occurrence) of adverse weather,

C = cost of protection against adverse weather,

L = loss if protection is not provided and adverse weather occurs.

A formal derivation of this criterion may be found in the literature (e.g., Thompson and Brier, 1955). However, the logic of the expression becomes evident if the criterion for the first alternative, i.e., protection against adverse weather, is written $P L > C$; the other alternatives may be clarified by a similar device. The value $P = C/L$ is therefore a critical ratio, above which protection should be provided, and below which it should not. Other, but generally more complex, expressions may be derived by defining the terms C and L in a different manner, e.g., Gringorton (1950).

2.2 METEOROLOGIC-ECONOMIC MODEL -- THEORY

If, now, a series of N probability weather predictions are made, the results may be presented as shown in Table 2.1. Here, W and No W are the occurrence and non-occurrence, respectively, of an operationally adverse weather event, and a, b, c, and d represent the frequencies in the indicated boxes in the table.

Table 2.1. Generalized contingency table showing the results of probability predictions.

		Forecast Probability		
		Do not Protect ($P<C/L$)	Protect ($P\geq C/L$)	Totals
Observed Weather	No W	a	b	a + b
	W	c	d	c + d
	Totals	a + c	b + d	N = a+b+c+d

Assuming that the criterion of equation (1) has been used, a series of optimum decisions will have been made. From the table, then, the total weather protection expense for the operation, E_f, will be due to the cost of protection whenever protective measures have been taken ($P\geq C/L$), plus the loss suffered whenever no protective measures have been provided ($P<C/L$) and adverse weather (W) occurs. Thus,

$$E_f = C(b + d) + Lc. \qquad (2)$$

On the other hand, if it were scientifically possible to improve weather forecasts so that errorless decisions were attainable, the total expense for the operation, E_p, would arise only from the necessity for protecting against adverse weather. Thus,

$$E_p = C(c + d). \tag{3}$$

It is now desired to obtain the economic gain which would be achieved if errorless decisions could be made, exceeding the value currently attainable within the current state of the science. It is convenient to present this information in a "non-dimensional" form, i.e., as the gain per unit forecast, per unit of loss. Thus, the potential gain for an operationally utopian improvement in scientific knowledge, G_s, would be,

$$G_s = \frac{E_f - E_p}{NL} = \frac{1}{N}\,[(b - c)C/L + c]. \tag{4}$$

However, since current weather forecasts do not usually contain quantitative information concerning their uncertainty the value of P is not normally available.* Instead, a working assumption, more or less equivalent to a constant (e.g.,

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*The U.S. National Weather Service has initiated a program to provide such information, but at present only the occurrence of precipitation at a limited number of locations is involved.

"average") value of the economic risks is used to produce a categorical prediction of the future weather. The results of a series of such forecasts may also be presented as in Table 2.1, but with the ratio C/L assumed invariant. The expense for these operating decisions, E_a, is given by

$$E_a = C(b_a + d_a) + Lc_a, \tag{5}$$

where the subscript "a" denotes frequencies associated with a categorical prediction made at a fixed decision level.

In this study, as in that by Carter (1972), it is assumed that the categorically predicted weather event is that which is most likely to occur (i.e., the modal value of the probability distribution). For a dichotomous problem, this is the weather event which is predicted with a probability exceeding 0.5; thus, by inference, the "average" operational risk ratio (C/L) is assumed to have been assigned this value by the forecaster.

The economic gain which could be realized from an optimum use of uncertainty information, exceeding the value of these "average" predictions, G_o, again presented in non-dimensional form, is

$$G_o = \frac{E_a - E_f}{NL} = \frac{1}{N}\left[(b_a + d_a - b - d)C/L + c_a - c\right]. \tag{6}$$

It should be noted that the economic gain expressed by the preceding equation is attainable at the present time, with no requirement for an improvement in "scientific" knowledge or understanding of the atmosphere.

Finally, the total potential economic gain may be obtained as the sum of equations (4) and (6). Denoting this total gain as G_t gives,

$$G_t = G_s + G_o = \frac{1}{N} [(b_a + d_a - c - d)C/L + c_a]. \tag{7}$$

2.2.1 Dichotomous Optimum Decisions

For weather predictions which have been issued in probability form, it is possible to apply equations (4), (6) and (7) to such data. Table 2.2 is an example of the results of such an application to forecasts of precipitation at Seattle, Washington.

Figure 2.1 is a graphical illustration of the potential economic gains for Seattle, as well as for several other locations, weather elements and forecast periods. In each example, the economic gain, G, is shown as a function of the operational risk ratio, C/L. The dot-dash curve indicates the economic gain due to scientific advances (G_s),

Table 2.2. Example of potential economic gains associated with improvements in precipitation forecasts issued for a period 36-hours in advance at Seattle, Washington. Dichotomous, optimum decisions.

Decision Level Fcst. Prbl'ty	Resulting Frequencies at Each Decision Level				Potential Economic Gains		
(P = C/L)	a	b	c	d	G_s	G_o	G_t
0	155	451	6	303	.007	.165	.172
.10	310	296	36	273	.068	.094	.162
.20	390	216	61	248	.100	.050	.150
.30	461	145	96	213	.121	.020	.141
.40	507	99	122	187	.123	.007	.130
.50	543	63	157	152	.120	.000	.120
.60	573	33	185	124	.103	.007	.110
.70	593	13	227	82	.084	.015	.099
.80	602	4	272	37	.063	.026	.089
.90	603	3	299	10	.036	.043	.079
1.00	606	0	309	0	.000	.069	.069
				Means	.075	.045	.120

the dashed curve shows the economic gain due to operational improvements (G_o), and the solid curve shows the total potential gain (G_t).

It will be observed that, in each case, for very small and very large values of the operational risk ratio, C/L, the economic gains due to improved operational decisions are greater than any possible gain which might be achieved by scientific advances. For values of C/L near the middle of the range, however, nearly optimum decisions are presumably already provided by "average" categorical forecasts. Accordingly, the operational gain is small, while the gain due to scientific advances is large.

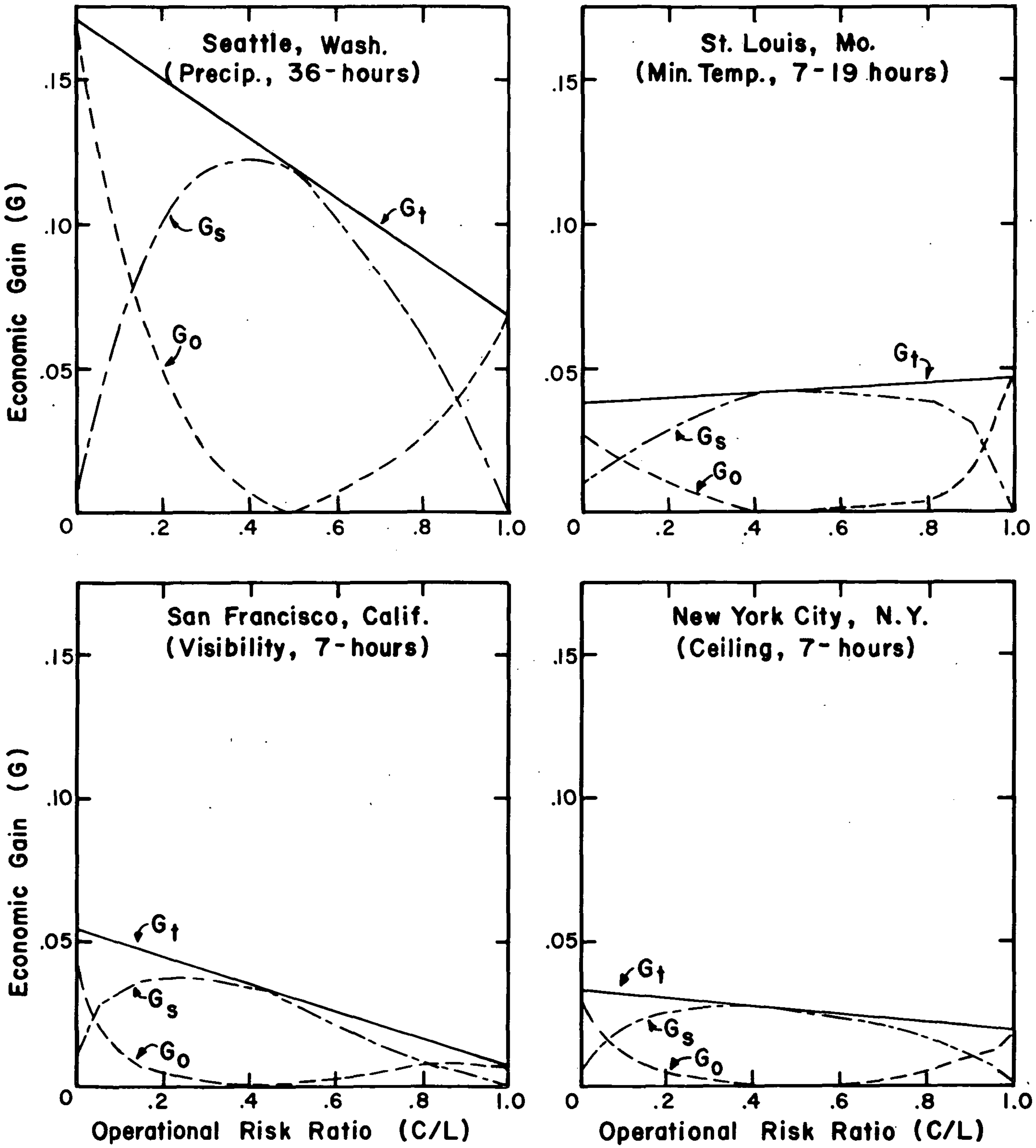

Figure 2.1 Examples of economic gains associated with potential improvements in weather forecasting. Gains may be interpreted as percentage of protectable loss, e.g., .05 = 5%, .10 = 10%, etc. G_s = scientific advances, G_o = operational improvements, G_t = total gains. Figures in headings, e.g., 36-hours, are forecast periods. Dichotomous, optimum decisions.

The solid curve representing the total potential gain is linear in G_t and C/L, since the frequencies with the subscript "a" are fixed decisions and the quantity (c+d) i.e., the "climatological" frequency, is also invariant for any one location. In the Seattle precipitation example, G_t decreases markedly with increasing C/L, a consequence of "underforecasting" adverse weather (c+d exceeds b_a+d_a) at the 0.50 probability level. Such a bias may seem undesirable to some forecasters, since a traditional rule that "adverse weather should be predicted with the same frequency as it is observed" is often quoted as a practical tactic for public categorical forecasts. However, it can be shown (Thompson, 1956) that this procedure is not necessarily equivalent to making the decision at the 0.50 probability level, although the difference is usually fairly small. Note in Table 2.2 that the rule quoted above would be realized if the categorical decision were made at about the 0.35 probability level where, by interpolation, b = c, approximately.

The selection of a single decision criterion for categorical public forecasts is, of course, purely arbitrary. However, a study was carried out to investigate the effect of (a) applying the 0.50 probability level, and (b) using a probability which would produce unbiased predictions. The results showed no statistically significant difference in the computed economic gains.

The examples of Figure 2.1 are quite typical of results obtained at other locations. In general, the shapes of the respective curves are similar, and potential gains are smallest for short-period forecasts and greatest for long-period predictions. Although data have been compiled on the basis of which curves similar to those of Figure 2.1 could be drawn for approximately 25 United States stations, four weather elements, and nine forecast periods, only summary data are included in this report.

It is now of interest to determine the overall potential gains indicated by application of the model to current weather forecast data. Preliminary considerations suggest that, for the economy as a whole, operational risks associated with weather-dependent activities probably include all values of C/L, ranging from near zero to near unity. If, therefore, it is assumed that all operations are equally likely and equally important, a first approximation to the overall gains may be obtained by computing the arithmetic means for each category of potential gain.

Using forecast verification data provided by the U.S. National Weather Service, computations of such mean values have been made for all weather elements and locations in the United States for which such data could be obtained. Because of the magnitude of the task (more than 50,000 individual forecasts were analyzed), the model equations

(4), (6) and (7) were programmed and computations were carried out by electronic computer methods. A summary of the results, showing the variation of potential gains as a function of the length of the forecast period, is provided in Figure 2.2. Detailed tables of individual station values are given in Appendix 3.1.

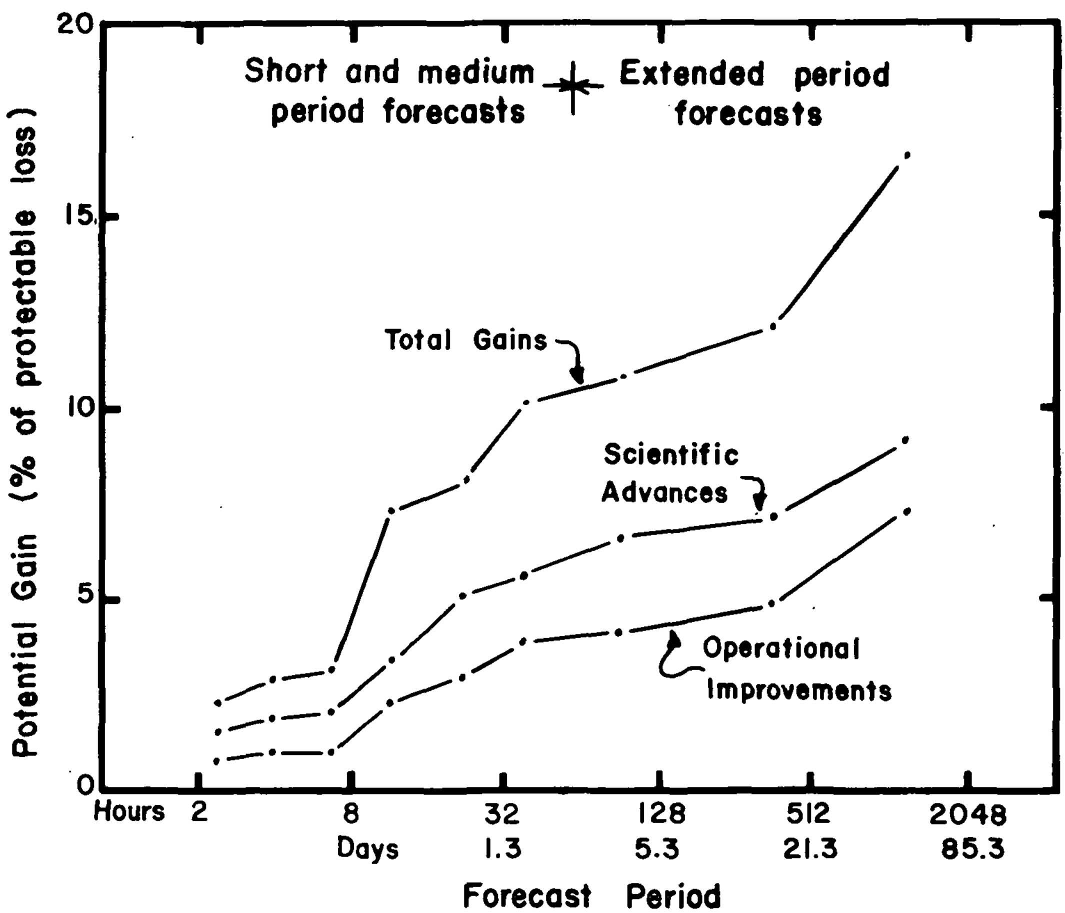

Figure 2.2 Variation in potential economic gains with length of the forecast period for dichotomous, optimum long-run decisions. (Extended period forecasts are mean predictions and are plotted at the center of the appropriate range.)

As in the case of Figure 1.1, where results for mini-max decisions are illustrated, the potential for improvement in the economic value of weather forecasts increases with the length of the forecast period. For the optimum decision tactic, however, the magnitudes of the potential gains are smaller than their mini-max counterparts. This arises primarily because the optimum decision strategy assumes that the forecast user has infinite capital resources, while the mini-max tactic accounts for the more realistic situation where limited capital must be considered.

For forecasts up to about two days in advance, about one third of the total potential for economic gains would be due to improved use of weather predictions, while two thirds would arise from advances in the science. It will be noted, however, that these fractions both tend to be somewhat closer to one-half for extended period forecasts -- a possible consequence of the availability of individual *a priori* probability estimates for short and medium period forecasts, while collective *a posteriori* probability information must be used for extended predictions. It is possible that the latter ratio might more nearly approach the former, thus providing an "operational improvement" in extended predictions, if *a priori* probability estimates could be provided for such predictions. This is a possibility which has briefly, but encouragingly, been explored by Stäel-von Holstein (1971).

2.2.2 Dichotomous Mini-max Decisions

While the preceding formulation provides a vehicle for assessing the economic gains for operations where the forecast user wishes to optimize his long-run weather protection decisions, other decision tactics may be required in practical operations. In particular, where limited capital resources are an important consideration, some form of mini-max* strategy is probably a more common procedure.

Under such circumstances, a weather forecast user may wish to decrease the likelihood of encountering an undesirable sequence of weather-caused losses by taking protective measures more frequently than would be required by an optimum long-run gain procedure. In terms of the initial dichotomous meteorologic-economic model used in this study, a mini-max tactic may be achieved by providing a second-order estimate of the meteorological uncertainty, i.e., by determining the lower confidence limit associated with each increment of probability provided in the weather forecast.

Such lower confidence limits for certain weather elements were established by computing the relative frequency of occurrence of the adverse weather (e.g., precipitation, low airport ceiling and visibility) for a sample series of

*The phrase "mini-max" is a term in decision theory meaning "to minimize the likelihood of incurring maximum losses", e.g., Bross (1953). Various procedures can be employed to achieve this end: one of those appropriate to the decision model used in this study is described here.

occurrences as a function of each class of predicted probability. Then, for each such class, the relative frequency which included 95% of the sample was determined, thus obtaining values which represented the 95% lower limit of "confidence" which could be attached to the probability estimates provided by the forecaster and/or forecasting system.* Further details concerning this procedure are described in the study by Carter (1972).

Table 2.3 shows examples of the confidence limits for certain weather elements and forecast periods. No systematic variation was apparent for different locations; the values shown are mean values applicable to the United States as a whole.

Assuming, now, that a forecast user desires to insure, with a confidence of 95%, that relative frequencies of adverse weather in excess of those predicted will not be observed during an operation of finite duration, he may protect against such weather by using the confidence limits, instead of the predicted probabilities, as a basis for his decision. Thus he will "over-protect" in the sense of a long-run optimum decision procedure, but will minimize (at the 95% level) the chances of incurring large losses due to a short-run sequence of adverse weather.

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*The selection of 95% for the confidence limit is arbitrary. Other values, depending upon the nature of the operating risks, could be chosen.

Table 2.3. Examples of 95% lower confidence limits for weather forecasts issued in terms of probability.

Forecast Probability	Lower 95% Confidence Limits for Indicated Weather Element and Forecast Period: Ceiling & Visibility 7 hours	Precipitation 12 hours	Precipitation 24 hours	Precipitation 36 hours
0	0	0	0	0
.10	.05	.06	.05	.04
.20	.10	.14	.13	.11
.30	.15	.22	.20	.18
.40	.20	.30	.27	.25
.50	.27	.38	.35	.32
.60	.34	.46	.42	.38
.70	.42	.54	.49	.45
.80	.52	.63	.57	.52
.90	.62	.73	.66	.60
1.00	.74	.88	.80	.71

In a manner similar to that described for the optimum decision tactic, computations of the potential economic gains for mini-max decisions were carried out. Table 2.4 is an example which shows the results of such mini-max computations for Seattle, Washington (compare with Table 2.2 which provides counterpart results for an optimum decision tactic).

Note an example of a slightly negative value of G_o for $C/L = 0.40$, a consequence of the mini-max strategy which requires the decision to protect to be made at $P = 0.25$ (instead of $P = 0.40$). Such small negative values were occasionally computed for optimum decisions as well, where they represented an operationally significant lack of equivalence between the predicted probabilities and the resulting relative frequencies. Such cases illustrate the

Table 2.4. Potential economic gains associated with improvements in precipitation forecasts issued for a period 36-hours in advance at Seattle, Washington. Dichotomous, mini-max decisions.

Fore-cast Prob. P=C/L	Mini-Max Dec'n Level	Resulting Mini-Max Frequencies Interpolated at Each Decision Level#				Potential Economic Gains		
		a	b	c	d	G_s*	G_o*	G_t*
0	0	155	451	6	303	.007	.104	.111
.10	.04	217	389	18	291	.060	.054	.114
.20	.11	318	288	39	270	.097	.022	.118
.30	.18	374	232	56	253	.119	.003	.122
.40	.25	425	181	79	230	.130	-.004	.126
.50	.32	468	138	101	208	.130	.000	.130
.60	.38	498	108	117	192	.122	.011	.133
.70	.45	525	81	140	169	.108	.029	.137
.80	.52	549	57	163	146	.085	.056	.141
.90	.60	573	33	185	124	.053	.092	.145
1.00	.71	606	0	309	0	.000	.148	.148
					Means	.083	.047	.131

Frequencies rounded off to whole numbers.
* Values may not verify exactly due to rounding off.

desirability, not only of "resolution" in probability estimates, but "reliability" as well -- a subject discussed in some detail by Murphy (1972).

Figure 2.3 illustrates, in graphical form, the potential economic gains shown in Table 2.4.

Comparing Figure 2.3 with the results for optimum decisions of Figure 2.1 (upper left hand corner), it will be noted that, although the general configuration of the curves are similar, the linear curve representing the total potential gain (G_t) now slopes in the opposite sense, i.e., G_t increases with increasing C/L. This arises because, as pointed out

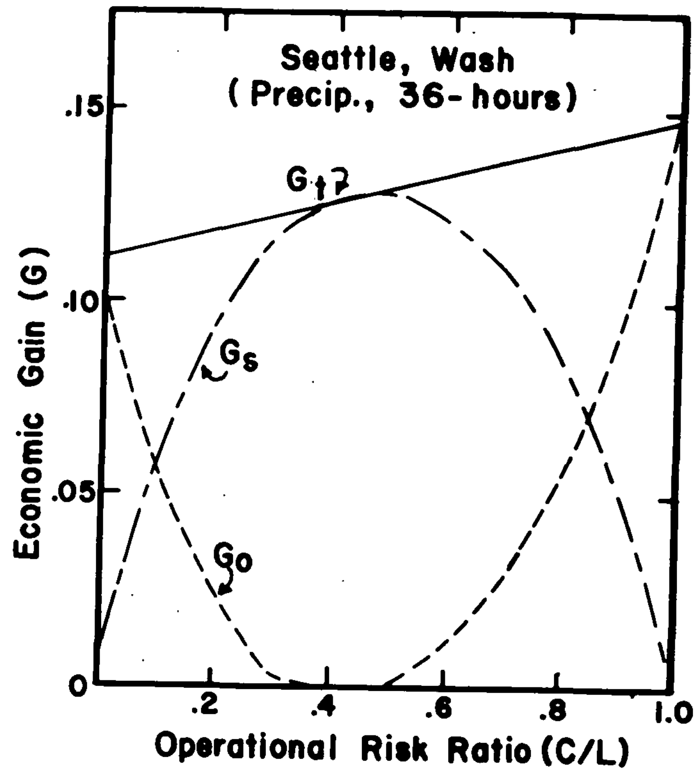

Figure 2.3 Example of economic gains associated with potential improvements in weather forecasting for Seattle, Washington. Dichotomous, mini-max decisions.

earlier, mini-max decisions are designed to "overforecast" adverse weather; thus, (b_a+d_a) exceeds (c+d) at the 0.50 forecast probability level.

A summary of the results of applying the mini-max decision model to weather forecast verification data for the United States as a whole is shown in Figure 1.1, page 6, while detailed tables of individual station values are given in Appendix 3.2.

Since, as noted in section 1.3, page 5, it is likely that practical users of weather forecasts will tend to use a form of mini-max decision tactic, the results from this analysis have been used in assessing the potential monetary gains for the economy as a whole (see sections 1.4 and 2.3).

2.2.3 Multiple Decision Options

While simple dichotomous decision problems clearly exist in the practical use of weather information, it is evident that certain operations are also faced with multiple decisions, e.g., whether or not to take greater protective measures as the severity of the predicted adverse weather increases. In order to obtain some information concerning possible deviations in the model results from those of the simpler dichotomous decision problems already described, experiments were carried out using the more complex multiple decision option.

The application of the basic model to the multiple decision problem requires that the user provide a "utility matrix", in which the economic risks, i.e., the costs, losses and/or profits associated with the decisions and the resulting weather events, are specified. Using a notation similar to that of Gleeson (1960) and Thompson (1966) such a utility matrix may be represented as in Table 2.5.

Table 2.5. Economic expenses (a_{ij}) associated with various weather events (X_j) and decisions (D_i) for a given operation. Also predicted probability (P) of occurrence of each X_j, and upper and lower confidence limits (P") and (P'), respectively, issued with each predicted probability.

			Weather Events				
			X_1	...	X_j	...	X_k
		D_1	a_{11}	...	a_{1j}	...	a_{1k}
		⋮					
Decisions		D_i	a_{i1}	...	a_{ij}	...	a_{ik}
		⋮					
		D_n	a_{n1}	...	a_{nj}	...	a_{nk}
Probability		P	p_1	...	p_j	...	p_k
Confidence Limits	Upper	P"	p_1''	...	p_j''	...	p_k''
	Lower	P'	p_1'	...	p_j'	...	p_k'

Referring to Table 2.5, for each alternative decision, D_i, the long-run economic expectation, E_i, is given by

$$E_i = \sum_{j=1}^{k} a_{ij} p_j, \tag{8}$$

and a decision which provides for a minimum E_i will, in the long-run, produce the optimum (lowest) weather expense for the operation. This will, in turn, provide a value of E_f for use in the meteorologic-economic model, i.e., equations (4), (6) and (7).

The corresponding value of E_p (the expense associated with errorless decisions) is also determined from equation (8), where the term p_j takes on a value of unity for observed weather events, and zero for all others.

The related value of E_a (the expense associated with categorical predictions) is then obtained from equation (8) by selecting the weather event associated with the modal value of p_j (see page 17).

Weather expenses resulting from a mini-max tactic in multiple decision problems may be evaluated by a procedure proposed by Gleeson (1960). Here, upper and lower confidence limits, p_j'' and p_j', associated with the probability for each weather event X_j, are determined subject to the restriction

$$1 \geqslant (p_j'' - p_j') \geqslant 0. \tag{9}$$

For each alternative decision, D_i, the expense, $E_i^{(max)}$, which results from associating the maximum expense with the upper confidence limit, and vice versa, is given by

$$E_i^{(max)} = \sum_{j=1}^{k} a_{ij} p_{ij}^{(max)}, \tag{10}$$

where $p_{ij}^{(max)}$ is a derived probability which is a maximum or minimum when a_{ij} is a maximum or minimum, respectively, such that

$$p_j'' \geqslant p_{ij}^{(max)} \geqslant p_j'. \qquad (11)$$

The mini-max decision is then the D_i for which $E_i^{(max)}$ is a minimum. This value of $E_i^{(max)}$ thus provides the mini-max expense to be substituted for the quantity E_f in the model equations (4), (6) and (7).

Finally, in order to provide a counterpart comparison of a categorical prediction for the mini-max strategy, it is assumed that a "play it safe" user would, with only a categorical prediction available, take protective measures as if adverse weather one category more severe than actually predicted would occur. Such an assumption is, of course, rather arbitrary, and actual practice may vary considerably in individual cases. However, it probably is close to an average procedure if a large number of forecast users are considered.

In order to examine the effect of multiple decision problems within this framework, two examples were selected. Both represent typical and significant activities within the United States economy.

2.2.31 An Aviation Operation

The initial case involves the use of weather forecasts for aviation flight operations. Table 2.6 is a utility matrix showing the economic risks which arise in scheduling the take-off and landing of aircraft at a major airport.

Table 2.6. Relative economic expense due to the prediction and/or occurrence of indicated categories of ceiling and visibility.*

Forecast Category	Observed Category 1	2	3	4	5
1	.70	.60	.65	.70	.75
2	.90	.40	.30	.25	.10
3	.95	.40	.30	.25	.05
4	.95	.45	.35	.20	.05
5	1.00	.50	.40	.30	0

Explanation of categories:

Category	Ceiling (feet)	Visibility (miles)
1	$\leq$ 100	$\leq$ 3/8
2	200-400	1/2-1 3/8
3	500-900	1 1/2-2 1/2
4	1000-2900	3-4
5	$\geq$ 3000	$\geq$ 5

*The matrix was developed by Professor Gerald Shreve of the Aeronautics Department, San Jose State University, in consultation with a number of private, business and commercial aircraft operators. The operational basis for relative economic expenses given in the matrix is provided in Appendix 3.3.

Based on a non-dimensional scale of zero to one, Table 2.6 indicates the relative economic expense (cost of protection plus losses if protective measures are not taken and adverse weather occurs) associated with the prediction and/or occurrence of certain categories of airport ceiling and/or visibility. *Categories had previously been selected* by the National Weather Service, which also furnished the forecast verification information used with the matrix data. The table represents an approximate "average" estimate based on a number of varied operations. Accordingly, some deviation from these values may be expected in individual circumstances.

Using the procedure described in Section 2.2.3, an application of the meteorologic-economic model to the utility matrix of Table 2.6 is shown in Figure 2.4.

Illustrated in Figure 2.4 are results for both optimum long-run and mini-max tactics. Potential gains are in all cases slightly smaller than for the dichotomous decisions (Figures 1.1 and 2.2), presumably because the utility matrix, having been designed specifically for aviation operations, prescribes a more efficient use of the weather predictions than is the case for the simpler dichotomy. Also, for this multiple decision matrix, no operational improvements were associated with the use of a mini-max strategy. This may be the result of a recognition by practicing forecasters of the

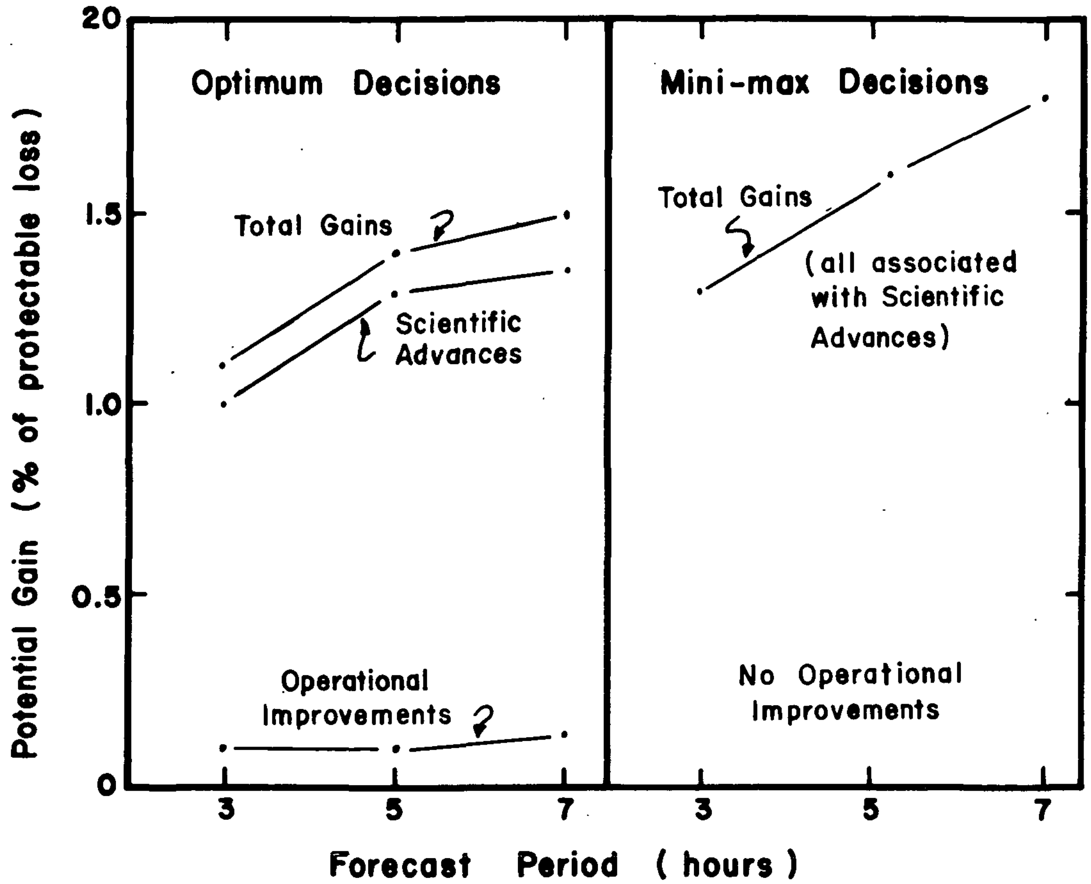

Figure 2.4 Variation in potential economic gains with length of the forecast period for multiple decisions associated with short period (3-, 5- and 7-hour) ceiling and visibility predictions.

critical risks to passengers and aircraft of unpredicted low ceilings and visibilities, a circumstance which would tend to produce an already-existing mini-max bias in the predictions. In general, however, these results confirm the earlier (dichotomous) conclusions that, for short period forecasts, differences in users' decision tactics produce only small variations in the potential gains determined by the meteorologic-economic model.

2.2.32 An Industrial Operation

Another illustration of the multiple decision problem involves a utility matrix developed for an industrial (construction) operation which requires that protective measures be taken against the occurrence of precipitation. The matrix is shown in Table 2.7.

Table 2.7. Relative economic expense due to the prediction and/or occurrence of indicated categories of precipitation.*

Forecast Category	Observed Category 1	2	3	4	5
1	0	.024	.119	.476	1.000
2	.008	.008	.103	.460	.974
3	.040	.040	.040	.396	.920
4	.159	.159	.159	.159	.682
5	.333	.333	.333	.333	.333

Explanation of categories:

Category	Precipitation (inches)
1	< .01
2	.01-.15
3	.16-.49
4	.50-1.50
5	> 1.50

*The matrix was developed by Dr. R. Robert Rapp, Certified Consulting Meteorologist, Santa Monica, California, for a specific construction operation in the Los Angeles area.

Application of this matrix to a precipitation prediction system developed previously for the Los Angeles area (Thompson, 1950) is shown in Table 2.8.

Table 2.8. Potential economic gains, in percent of protectable loss, for 24-hour precipitation forecasts associated with multiple decisions made for a construction operation in Los Angeles.

Decision Tactic	Operational Improvements	Scientific Advances	Total Gains
Optimum long-run	0.3	1.7	2.0
Mini-max	0.3	1.7	2.0

Again, presumably due to the more efficient use of the forecasts for this operation, the potential gains are smaller than those of the dichotomous decision computations for a comparable forecast period at Los Angeles (see Appendix 3.2). Also no difference in potential gains between optimum long-run and mini-max tactics are indicated in the above Table, a result which closely parallels the small differences observed for dichotomous decisions.

These two examples of multiple decision options are illustrative of a more sophisticated decision model which might be proposed to study the economic benefits of advances in meteorology. Clearly, however, the task would require establishment of many "utility matrices" covering at least the more typical activities of the economy. Whether the effort and financial support required to carry out such an investigation would be worth a possible improvement in the result is, at this stage, questionable. From these examples, there is a suggestion that the differences would be small.

2.2.4 Other Decision Tactics

A number of other decision strategies can be considered within the framework of the basic meteorologic-economic model. An example is the so-called "maxi-max" strategy which, in principle, is applicable to an operation for which the decision maker wishes to maximize his maximum gains. While this is a hazardous undertaking, it may -- at least in modified form -- be used in some operations. Accordingly, computations involving the use of a maxi-max decision strategy were carried out for short and medium period forecasts.

The resulting potential gains were similar to those for the counterpart tactic, i.e., the mini-max strategy. Qualitatively, this is what might be expected since both decision strategies are not, in the long-run, optimum. That the magnitudes of the potential gains would be similar could not have been anticipated, but the results are not unreasonable. Because of this similarity, the results for the maxi-max experiments are not included here.

No additional decision tactics were studied, partly due to the need to tackle other problems, but also because there would seem to be little to be gained in pursuing these variations in any greater detail.

2.2.5 Geographic and Seasonal Variability

In order to obtain some idea of the potential economic gains associated with geographical and seasonal variations in the weather, an analysis was made of precipitation forecast data used for the dichotomous, optimum decision computations discussed in section 2.2.1. Examples of such analyses are shown in Figures 2.5 through 2.8.

Figures 2.5 and 2.6 illustrate the geographical distribution of total potential economic gains for "summer" and "winter" seasons in the United States. Comparing the patterns of economic gains with those of precipitation frequency shown in Figures 2.7 and 2.8, it is evident that a direct relationship exists between the magnitude of the future potential gains and the seasonal precipitation frequency. For the stations indicated on these figures, the linear correlation coefficients between economic gains and precipitation frequencies are for "summer", 0.86; for "winter", 0.92. These figures suggest that the greater the frequency of adverse weather (in this case, precipitation), not only does the total expense involved in protecting

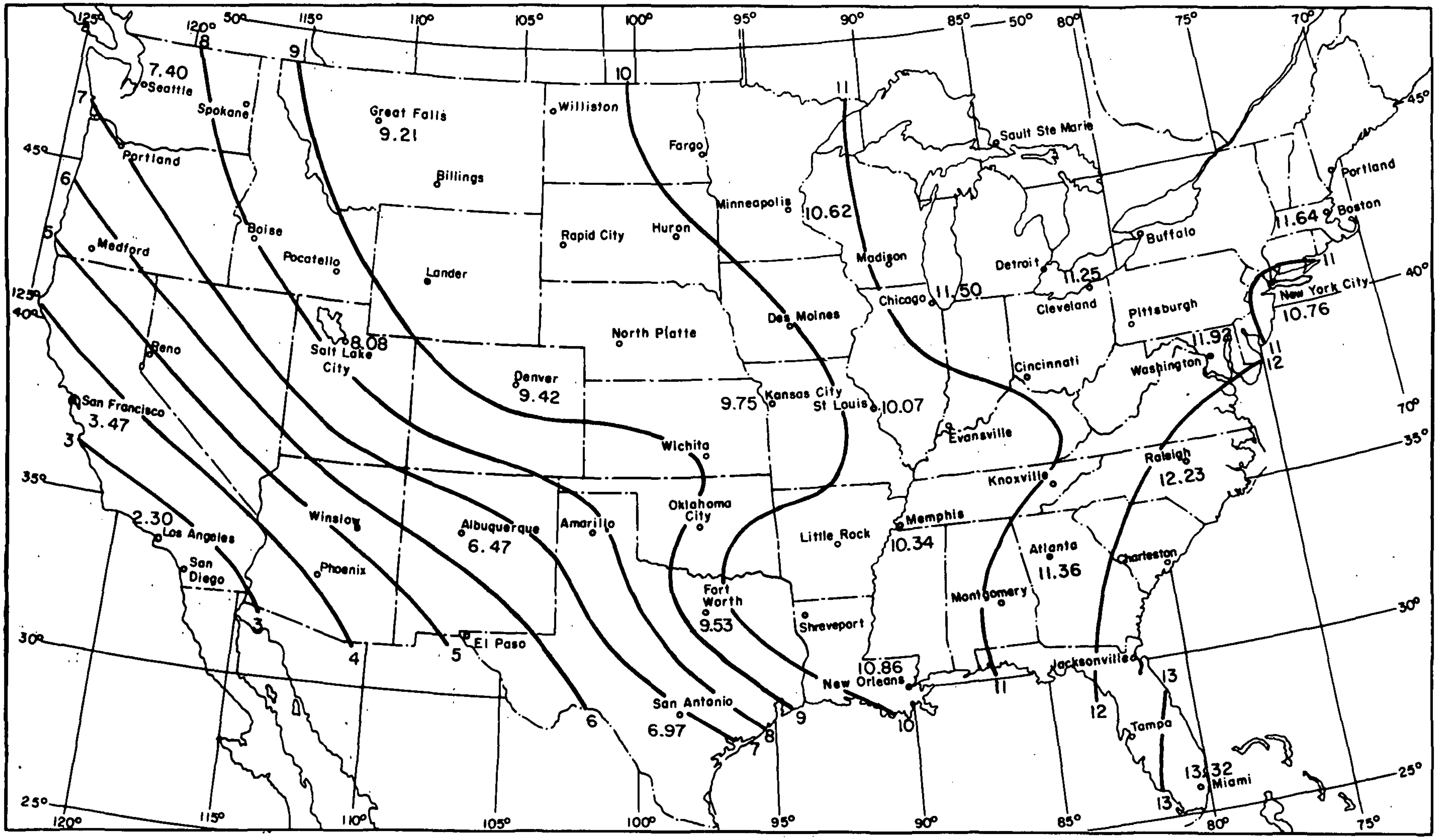

Figure 2.5 Total potential economic gains for "summer" season (April-September, inclusive), for 24-hour precipitation forecasts. Units are percent of mean protectable loss.

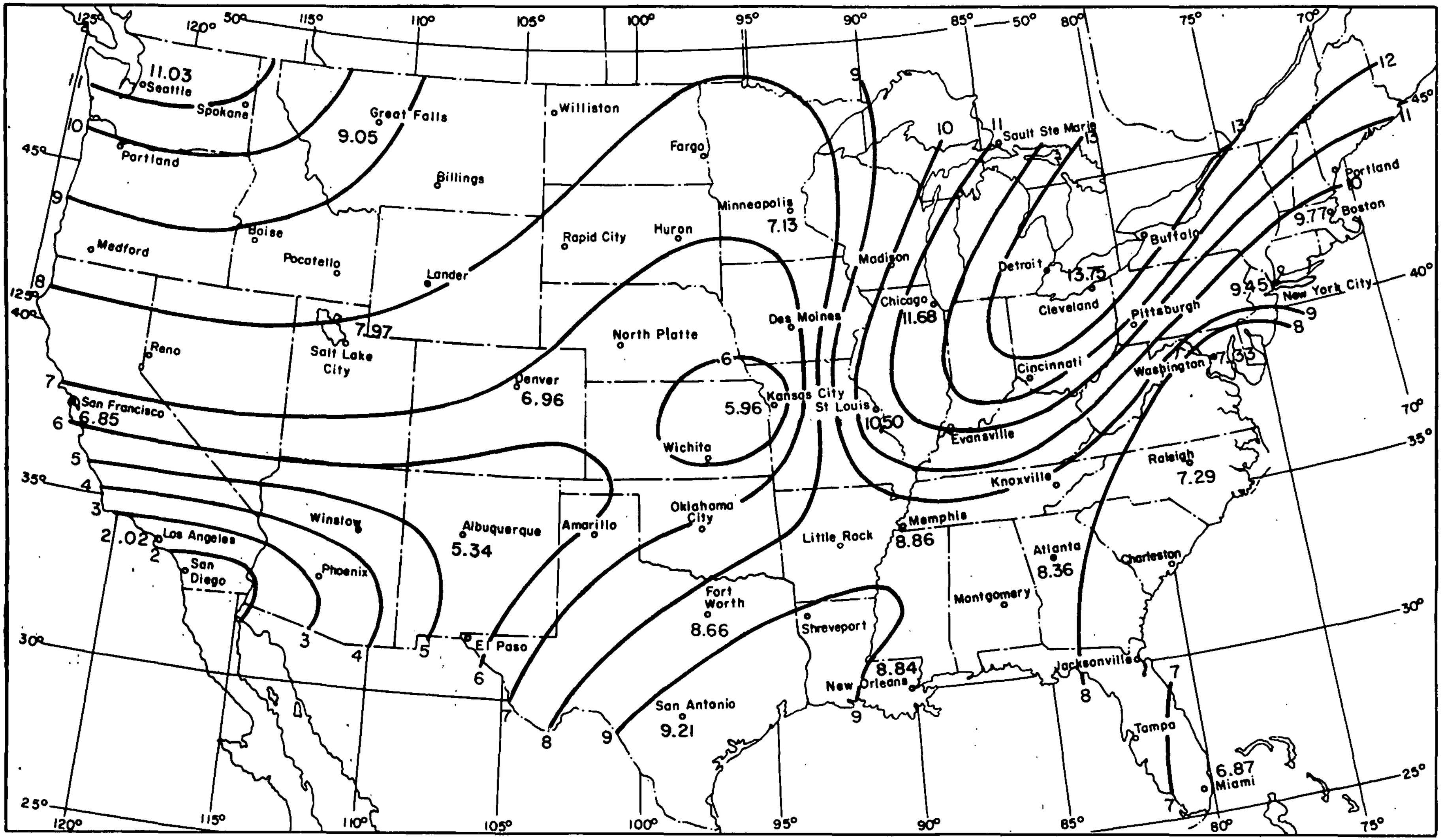

Figure 2.6 Total potential economic gains for "winter" season (October-March, inclusive), for 24-hour precipitation forecasts. Units are percent of mean protectable loss.

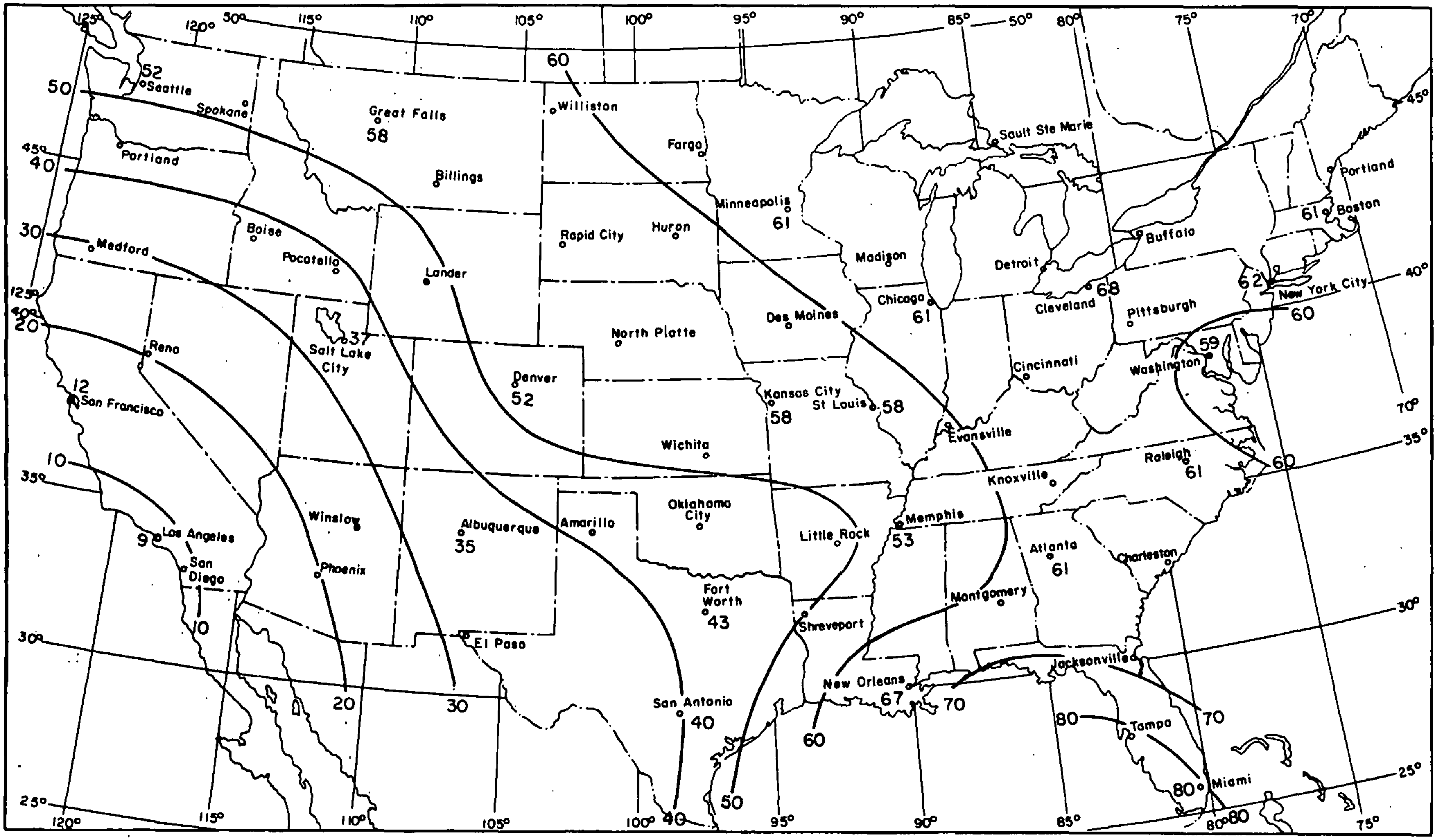

Figure 2.7 Mean number of days with measurable precipitation (≥0.01 inch) for "summer" season (April-September, inclusive).

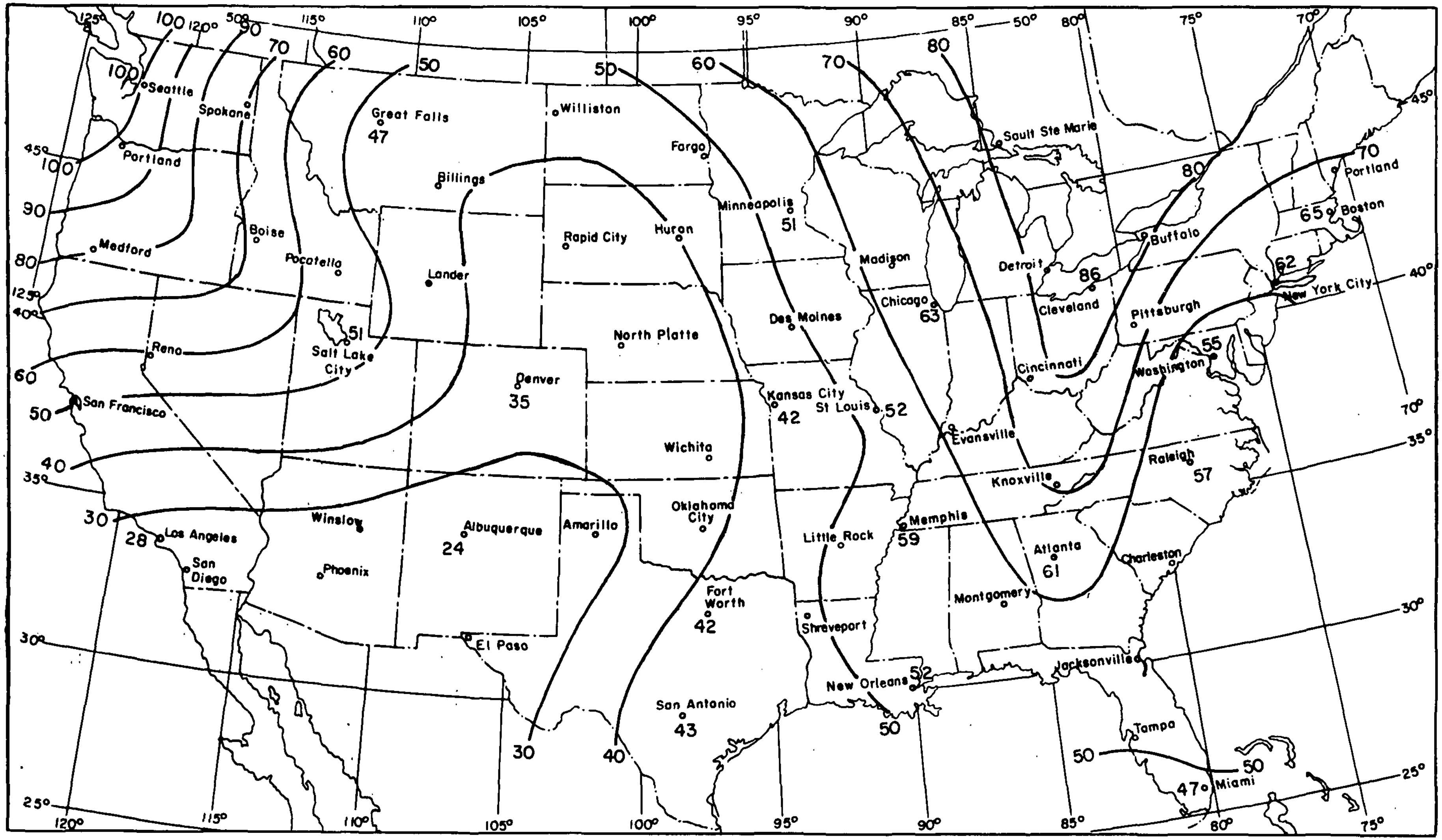

Figure 2.8 Mean number of days with measurable precipitation ($\geq$0.01 inch) for "winter" season (October-March, inclusive).

against such weather increase, but also the future potential for alleviating that expense.

It will also be observed that "summer" precipitation in the southeastern United States is associated with large potential economic gains. Here, not only is the precipitation a frequent phenomenon, but it occurs primarily in the form of random showers and thunderstorms. Such precipitation is difficult to predict 24 hours in advance and, accordingly, there exists a considerable potential for economic improvement. In the arid Southwest, on the other hand, precipitation is infrequent and the potential for economic gains due to improved forecasts is relatively small for both seasons.

Additional information concerning the geographic variability of potential gains associated with dichotomous, mini-max decisions can be derived from Appendix 3.2. See also Carter (1972) for similar analyses related to weather protection expenses.

2.3 ECONOMIC SURVEY

While the preceding analyses provide basic quantitative data concerning the magnitude of potential advances in meteorology, the results are presented in dimensionless form, i.e., as the percentage of protectable weather-caused losses. In order to obtain dimensional, e.g., monetary, results, it is necessary to secure information concerning such losses in the required form. For this purpose, a survey of major agricultural, industrial and commercial organizations in the United States was conducted. The survey took the form of a questionnaire (see Appendix 3.4). About 250 replies were received, representing an approximate 22% response on the part of those queried.

Since it was realized that no survey could, inherently, secure data on the total weather-caused losses in the United States, information on the percentage of his gross revenue represented by such losses was requested of each respondent. Assuming, then, that the mean percentage thus obtained from the survey sample was representative of the major activity of which it was a part, estimates of total losses for the United States were computed from total gross revenues for each activity compiled by the U.S. Bureau of the Census (1971). The results of such computations are shown in Table 2.9.

For the economy as a whole, the total annual losses computed from the survey (close to $13 billion), and the protectable weather losses (over $5 billion) are, considering the sampling difficulties involved, very close to the values quoted in a recently published plan for meteorological services and research for the United States government (White, 1972), i.e., total losses of $15 billion and protectable losses of $7 to $10 billion. Both appraisals

Table 2.9. Summary of annual dollar and percentage losses due to adverse weather in the United States. Figures are overall losses for each activity, and (in parentheses) percent of annual gross revenue.

Activity	Total losses, irrespective of whether or not protective measures could be taken against adverse weather.		Losses due to adverse weather which could be protected against if adequate warnings for appropriate period in advance could be provided.	
	($\$ \times 10^6$)	(%)	($\$ \times 10^6$)	(%)
Agriculture	8,240.4	(15.5)	3,554.2	(6.7)
Aviation (commercial)	92.4	(1.1)	56.9	(0.7)
Construction	998.0	(1.0)	328.6	(0.3)
Communications	77.4	(0.3)	6.4	(0.1)
Electric Power	45.7	(0.2)	13.9	(0.1)
Energy (e.g., fossil) Fuels	5.1	(0.1)	1.0	(0.1)
Manufacturing	597.7	(0.2)	238.0	(0.1)
Transportation (rail highway & water)	96.3	(0.3)	45.8	(0.2)
Other (gen. public, government, etc.)	2,531.8	(2.0)	1,057.8	(0.9)
Totals	12,684.8		5,302.6	

also seem compatible with an earlier unpublished study by Senko (1964), who estimated the total weather-caused losses in the United States in 1963 to be about $10 billion.

The total losses for the construction industry (about $1 billion) are lower than previous estimates of $3 billion to $10 billion made in a comprehensive study of the construction industry (Russo, 1965). However, the larger of the two latter values seems rather high when related to the total for all activities of $13 billion and $15 billion determined by the present study and by White (loc. cit.). Furthermore, a review of other literature concerning the construction industry suggests that at least some of the discrepancy may lie in the interpretation of "weather caused losses". For example, a study of home building problems (Urban Housing Committee, 1969) states that loss of income due to lack of wintertime building in the United States stems largely from consumer preferences, psychological attitudes and union work rules, rather than from winter weather itself.

In the field of aviation, a study of commercial airline weather problems (United Research, Inc., 1961) concluded that weather losses due to cancellations, delays and diversion of airline flights in the United States during the early 1960's would approximate $55 million, while Bollay (1962) predicted that airline losses due to weather would reach $148 million in 1970. The figure of $92 million obtained in the present study would suggest that his prediction may have been too high, perhaps because of greater than anticipated improvements in aircraft and navigational take-off and landing techniques.

As far as is known, no other estimates of current weather-caused losses for the United States as a whole have been published. The correspondence between the examples just described and those of this study would suggest, however, that the values shown in Table 2.9 are, at least within an order of magnitude, a reasonable estimate of such losses.

Another analysis of the survey data was concerned with respondents' replies to a question concerning the minimum amount of advance warning needed to implement protective measures against adverse weather. A summary of these data is given in Table 2.10.

An inspection of Table 2.10 shows considerable variation in the length of the useful forecast period. Whereas agricultural activities are most concerned about predictions for several days up to a season in advance, the modal period for other activities is generally in the 12 to 36 hour range, and aviation is most interested in predictions of less than 12 hours. In general, the emphasis indicated by these data seems reasonable -- it is obvious, for example, that a large proportion of agricultural operations (e.g., planting, irrigating, harvesting) should be planned days or weeks in advance, while aircraft flying operations, from flight plan to terminal landing, are usually executed in less than 8 hours or so.

Table 2.10. Percent of respondents in each activity group who designated the indicated forecast period as the minimum required for an adequate warning against adverse weather.

	Forecast Period					
Activity	1-5 hours	6-11 hours	12-36 hours	2-5 days	30 days	90 days
Agriculture	2.2	5.0	20.9	26.9	24.0	21.0
Aviation (commercial)	25.0	42.1	18.2	11.4	3.3	
Construction	7.1	18.3	46.0	19.0	6.1	3.5
Communications	5.2	10.3	50.4	28.5	5.6	
Electric Power	28.5	20.0	25.7	10.1	5.0	10.7
Energy (e.g., fossil) Fuels	4.5	14.2	48.0	18.4	14.9	
Manufacturing	25.0	18.0	37.2	10.8	3.2	5.8
Transportation (rail, highway & water)	28.0	19.7	40.8	9.3	1.4	0.8
Other (gen. public, government, etc.)	14.7	17.8	30.4	18.7	9.8	8.6

Although the survey responses contain information concerning the nature of the weather elements which most adversely affect individual activities, consideration of this factor in the meteorologic-economic model is restricted by available forecast verification data. Adequate probability predictions have, as far as is known, been made only for ceiling, visibility, temperature and precipitation.

Between these elements, however, a study showed that only small differences in potential gains were observed -- the primary variations in the computed results were due to differences in the length of the forecast period. Accordingly, while some information concerning the nature of the adverse weather is contained implicitly in the forecast period data (i.e., short period verifications are for ceiling and visibility; medium and extended verifications are for temperature and precipitation), the weather element factor cannot be considered explicitly at this stage.

Only fragmentary additional "comments" are contained in the survey responses, and no summary of these data is included. The questionnaire was designed to be brief in order to elicit the maximum response from busy organizations.

2.4 ECONOMIC BENEFITS -- COMPUTATION

A monetary evaluation of the potential economic benefits due to improvements in weather forecasting may be determined, in principle, simply as the product of the meteorological (non-dimensional) appraisal of potential gains and the economic (dimensional) estimates of currently observed, but protectable, weather-caused losses. However, an improvement in this simple computation of the potential gains may be achieved by weighting the results by the length of the forecast period designated by survey respondents as the minimum necessary to provide adequate warning of adverse weather (Table 2.10). The potential gains due to "operational improvements" and/or "scientific advances" (denoted here by the general symbol, G') thus may be computed from the following expressions:

$$G'_a = \Sigma_f \; G_f \; L_a \; W_{af} \tag{12}$$

$$G'_f = \Sigma_a \; G_f \; L_a \; W_{af} \tag{13}$$

where G'_a = potential gains, in dollars, associated with activity group a, e.g., agriculture, aviation, etc.

G'_f = potential gains, in dollars, associated with forecast period f, e.g., 3-5 hours, 7-hours, etc.

Σ_f = summation over forecast periods, f.

Σ_a = summation over activity groups, a.

G_f = percent of protectable loss for forecast period f representing the non-dimensional gain in weather forecast usage (from Appendix 3.2).

L_a = protectable loss, in dollars, associated with adverse weather events which affect activity group a (from Table 2.9).

W_{af} = weighting factor -- percent of respondents in activity group a who designated forecast period f as the minimum required for an adequate warning of adverse weather (from Table 2.10).

A computation matrix showing the solution of equations (12) and (13) is given in Appendix 3.5. The results of these solutions are contained in Table 2.11 for equation (12) and in Table 2.12 for equation (13).

Table 2.11. Summary, as a function of economic activity, of potential annual savings due to operational improvements, scientific advances and total gains due to improvements in weather forecasting in the United States. Figures are in millions of dollars. (See also Figure 1.3.)

Activity	Operational Improvements	Scientific Advances	Total Gains*
Agriculture	250.3	316.7	567.0
Aviation (commercial)	1.4	2.2	3.6
Construction	13.1	18.4	31.5
Communications	0.3	0.4	0.6
Electric Power	0.5	0.8	1.3
Energy (e.g., fossil) Fuels	#	0.1	0.1
Manufacturing	8.1	11.9	20.0
Transportation (rail, highway & water)	1.3	1.9	3.2
Other (gen. public, government, etc.)	47.3	64.5	111.8
Totals*	322.2	416.9	739.1

*All sums may not balance due to rounding off.
#Less than 0.05.

A striking result of these computations is the decidedly larger potential saving indicated for agriculture than for any other activity. However, this quantitative assessment clearly confirms an earlier qualitative description of the economic consequences of research efforts aimed at improving weather prediction by the U.S. Weather Bureau (1964), which ranked agriculture first among all activities in "economic benefit potential".

Further, a survey of agricultural interests by Stanford University (1966) indicated that annual savings of $313 million could be achieved with a proposed meteorological satellite system which would provide improved weather forecasts. Considering the probable inflationary influence of the six-year difference between surveys and the fact that errorless operational decisions were not postulated by the Stanford study, the value of $567 million for total potential agricultural benefits in Table 2.11 of this report seems quite compatible with the Stanford assessment.

Table 2.12 is a similar analysis related to the length of the forecast period.

The data in Table 2.12 were derived by considering, for each forecast period, the potential improvement indicated by the study model, the value of protectable losses and the relative importance attributed by survey respondents to the predictions (see Appendix 3.5). The maximum saving at the 90-day (seasonal) prediction period arises primarily as a consequence of the relatively high potential for improving such forecasts, combined with the importance attached to

Table 2.12. Summary, as a function of forecast period, of potential annual savings due to operational improvements, scientific advances and total gains due to improvements in weather forecasting in the United States. Figures are in millions of dollars.

Forecast Period	Operational Improvements	Scientific Advances	Total Gains*
1-5 hours	3.8	7.6	11.5
6-11 hours	8.1	14.1	22.2
12-36 hours	42.9	69.7	112.6
2-5 days	79.1	94.2	173.3
30 days	82.0	86.9	168.9
90 days	106.3	144.4	250.7
Totals*	322.2	416.9	739.1

*All sums may not balance due to rounding off.

that time period by agricultural users. Consequently, while implicit in these data is the suggestion that the overall greatest economic potential lies in the improvement of 90-day forecasts, it should be noted that some activities would obtain little or no benefit from a unique improvement in 90-day forecasts. For example, Table 2.10 shows that aviation respondents attached primary importance to very short range predictions, i.e., 3-12 hours, and very little to forecasts beyond 5 days.

2.5 RECOMMENDATIONS FOR FURTHER WORK

The purpose of this study was to obtain an overall estimate of the potential for economic gains associated with future improvements in weather forecasting based, insofar as possible, on factual information. The approach involved the development of a "meteorologic-economic" model which, recognizing a basic goal of meteorology to provide weather information of maximum practical value, made use of the consequent interconnection between the two disciplines. It is, however, appropriate to conclude with a "caveat" with respect to the assumptions involved in the use of the model and to the nature of the data to which it was applied, thereby delineating certain features of the work which may bear further investigation.

With regard to the basic model used in the study, a major consideration was the nature of the decision options and tactics carried out by forecast users. While a number of alternative decision configurations were explored, and the consequent differences in the model results appeared to be small, further studies of individual operations would be useful. In particular, attempts to develop multiple-category decision matrices, similar to those suggested for aviation and construction operations (Tables 2.6 and 2.7) but for other activities, would be desirable.

In this connection also, the nature of decision tactics used by individual organizations should be explored. Although a form of "mini-max" strategy was assumed as a practical consequence of limited capital and other operating constraints, a study of this assumption has not, as far as is known, been carried out for an actual weather-dependent operation. Here, the difficulty of the problem should not be minimized; only very few, if any, operations are likely to have developed conscious and explicit decision strategies for their weather problems.

Sources of information concerning <u>protectable</u> weather losses are required. While there are many agencies (e.g., U.S. National Weather Service, Civil Defense, Red Cross, Insurance Companies) which make direct assessments of <u>total</u> weather losses, or assemble estimates made by others, there are little or no published data concerning losses which improved weather forecasts would be most useful in alleviating. In many cases, the protectable losses are only a small fraction of the total damage. For example, severe hurricanes which affect the Atlantic and Gulf Coasts are generally predicted with dependable accuracy nowadays, but damage to buildings, bridges and other unprotectable structures still runs into hundreds of millions of dollars each year (White, 1972). However, the hurricane-caused loss of life, and damage to automobiles, aircraft and other movable (and hence protectable) property is very small.

In this study, an attempt was made to obtain data on such protectable losses (see Appendix 3.4). How well this was accomplished is not known with any degree of certainty. Although some organizations had available data on such losses, and a few made special accounting studies for this purpose, it is recognized that others provided only subjective estimates.

In order to determine the "overall" economic gains, it was assumed that the operational risks for all activities would be equally likely and equally important so that a simple arithmetic mean of individual operations would provide an adequate overall assessment. However, further considerations suggest that mans' activities, especially in agriculture, tend to become adjusted to the normal weather in such a fashion that the distribution of operational risks for a regional economy may be peaked near a value where the climatic expectancy of adverse weather is numerically equal to those risks (i.e., in Table 2.1 (c+d)/N equals the ratio C/L). Accordingly, it is possible that an improvement in the overall economic assessment may be obtained by weighting the risks to account for such distributions. At present, however, no quantitative information concerning this point exists.

Because the optimum utility of uncertain information such as weather forecasts can only be realized when the nature of the uncertainty is considered in making operational decisions, it is clearly desirable that such information be provided to the forecast user. At present, partly because the meteorologist has not perfected a general methodology for providing "probability forecasts", and partly because the user lacks experience in their application, such data are not yet available for all weather elements. For studies like the present one, even experimental probability predictions of strong winds, heavy snows and other critical weather events would be useful.

Clearly, the problem of assessing the economic value of improvements in weather forecasts is complex, and it is likely that other suggestions for additional work will occur to readers of this report. Such studies would not only provide useful information for further refinement of the present results, but could also make available useful basic data for attacks on the important parallel problem of improving the operational utility of the weather forecasts themselves.

2.6 REPORTS, PAPERS AND SEMINARS OF THE PROJECT

Thompson, J. C. (1968): Economic Aspects of Improved Weather Forecasting. AIAA Paper No. 68-1097. Presented at the 5th Annual Meeting of the American Institute of Aeronautics and Astronautics, Philadelphia, Penn., October 21-24, 1968.

Thompson, J. C. (1969): The Value of Weather Forecasts. Science Journal, Vol. 5A, No. 6, pp. 62-67.

Thompson, J. C. (1970): The Potential Economic Value of Improved Weather Forecasts. Seminar presented at the Pacific Southwest Council Meeting, American Society of Civil Engineers, Sacramento, California, March 23-24, 1971.

Thompson, J. C. (1971): Effects of Alternative Decisions on the Value of Weather Forecasts. Paper presented at the 51st Annual Meeting of the American Meteorological Society, San Francisco, California, January 11-14, 1971.

Smith, Clark L. (1971): An Extension of Decision Theory Applied to the Optimum Use of Weather Forecasts. Department of Meteorology, San Jose State College, April 1971. (Master's Thesis)

Thompson, J. C. (1971): Probability, Decision Models and the Value of Improved Weather Forecasts. Paper presented at the International Symposium on Probability and Statistics in the Atmospheric Sciences, Honolulu, Hawaii, June 1-4, 1971.

Thompson, J. C. (1971): The Potential Value of Future Improvements in Weather Forecasting. Seminar presented at the Department of Meteorology, San Jose State College, October 5, 1971.

Thompson, J. C. (1972): Meteorological Satellites: Potential Economic Benefits from Improved Weather Forecasts. Paper presented at the 5th U.S. - European Conference of EUROSPACE, San Francisco, California, May 22-25, 1972.

Carter, Gary M. (1972): Weather Forecasts, Users' Economic Expenses and Decision Strategies. Department of Meteorology, San Jose State College, June 1972. (Master's Thesis)

Thompson, J. C. (1972): The Potential Benefits of Advances in Meteorology -- Final Report. Department of Meteorology, California State University, San Jose. September 1972.

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2.8 REFERENCES

Bollay Associates. (1962): Economic Impact of Weather Information on Aviation Operations. Final Report, Contract FAA/BRD-410, Project No. 151-15. Federal Aviation Agency, Washington, D.C.

Bross, Irwin J. (1953): Design for Decision. McMillan and Company, New York. 276 pp.

Carter, Gary M. (1972): Weather Forecasts, Users' Economic Expenses and Decision Strategies. Department of Meteorology, San Jose State College, San Jose, Calif. 64 pp.

Gleeson, Thomas A. (1960): A Prediction and Decision Method for Applied Meteorology, Based Partly on the Theory of Games. Journal of Meteorology, Vol. 17, No. 2, pp 116-121.

Gringorton, I. I. (1950): Forecasting by Statistical Inferences. Journal of Meteorology, Vol. 7, No. 6, pp 388-394.

Lave, L. B. (1963): The Value of Better Weather Information for the Raisin Industry. Econometrica, Vol. 31, No. 1-2, pp 151-164.

Lorenz, Edward N. (1969): Three Approaches to Atmospheric Predictability. Bulletin of the American Meteorological Society, Vol. 50, No. 5, pp 345-349.

Maunder, W. J. (1970): The Value of Weather. Methuen and Co., London. 388 pp.

Murphy, Allan H. (1972): Scalar and Vector Partitions of the Probability Score: Two-state Situation. Journal of Applied Meteorology, Vol. 11, No. 2, pp 273-282.

Russo, J. A., et. al. (1965): The Operational and Economic Impact of Weather on the Construction Industry in the United States. Travelers Research Center, Hartford, Conn.

Stäel von Holstein, C.-A. S. (1971): An Experiment in Probabilistic Weather Forecasting. Journal of Applied Meteorology, Vol. 10, No. 4, pp 635-645.

Senko, M. E. (1964): Weather Satellite Study -- A Special Report. U. S. Department of Commerce, Washington, D.C. 28 pp. (Unpublished)

Stanford University (1966): Stanford Proposal for an International Network for Meteorological Analysis and Prediction. School of Engineering, Stanford University, Stanford, Calif. 370 pp.

Thompson, J. C. (1950): A Numerical Method for Forecasting Rainfall in the Los Angeles Area. Monthly Weather Review, Vol. 78, No. 7, pp 113-124.

Thompson, J. C. and Brier, G. W. (1955): The Economic Utility of Weather Forecasts. Monthly Weather Review, Vol. 83, No. 11, pp 249-254.

Thompson, J. C. (1956): Forecasting Decisions and Forecast Verification. Presented at the 155th National Meeting of the American Meteorological Society, Washington, D.C. (Unpublished)

Thompson, J. C. (1966): A Note on Meteorological Decision Making. Journal of Applied Meteorology, Vol. 5, No. 4, pp 532-533.

Thompson, J. C. (1966): The Potential Economic and Associated Values of the World Weather Watch. Planning Report No. 4. World Meteorological Organization, Geneva. 35 pp.

United Research Inc. (1961): Forecast of Losses Incurred by U. S. Commercial Air Carriers Due to Inability to Deliver Passengers to Destination Airports in All-Weather Conditions. Contract No. FAA/BRD-309, Federal Aviation Agency, Washington, D.C.

Urban Housing Committee of the President (1969): A Decent Home. U. S. Government Printing Office, Washington, D.C.

U. S. Bureau of the Census (1971): Statistical Abstract of the United States, 92nd Edition. Washington, D.C. 1008 pp.

U. S. Weather Bureau (1964): The National Research Effort on Improved Description and Prediction for Social and Economic Purposes. U. S. Department of Commerce, ESSA, Washington, D.C.

White, Robert M. (1972): The Federal Plan for Meteorological Services and Supporting Research. U. S. Department of Commerce, NOAA, Washington, D. C. 70 pp.

PART 3. APPENDICES

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Appendix 3.1 Values of mean potential scientific advances (G_s), operational improvements (G_o) and total gains (G_t) for various forecast periods, weather elements and locations in the United States. Figures are mean percentage of protectable loss for dichotomous, optimum decisions.

Location	Ceiling (< 1000 ft.)			Visibility (< 2 1/2 mi.)		
	G_s	G_o	G_t*	G_s	G_o	G_t*
	Forecast Period: 3-hours					
Albany, N.Y.	1.4	0.6	2.0	2.0	1.2	3.3
Baltimore, Md.	1.1	0.3	1.5	1.8	0.8	2.6
Chicago, Ill.	1.2	0.5	1.7	1.5	1.2	2.6
Los Angeles, Calif.	1.6	0.7	2.3	2.1	1.1	3.1
New York City, N.Y.	1.3	1.0	2.3	1.8	1.1	2.9
San Francisco, Calif.	1.4	0.4	1.8	1.3	0.6	1.8
Seattle, Wash.	2.2	1.0	3.2	2.4	1.4	3.9
Washington, D.C.	1.0	0.6	1.6	1.4	1.0	2.4
Means	1.4	0.6	2.0	1.8	1.1	2.8
	Forecast Period: 5-hours					
Albany, N.Y.	1.7	0.9	2.6	2.9	1.3	4.1
Baltimore, Md.	1.2	1.0	2.3	2.4	1.4	3.8
Chicago, Ill.	1.6	1.1	2.6	2.1	1.4	3.5
Los Angeles, Calif.	1.6	0.7	2.4	2.7	1.6	4.3
New York City, N.Y.	1.2	0.6	1.8	2.1	1.1	3.2
San Francisco, Calif.	1.7	0.8	2.5	1.6	0.6	2.2
Seattle, Wash.	3.2	1.5	4.7	2.7	1.1	3.8
Washington, D.C.	1.3	0.8	2.0	1.4	0.6	2.0
Means	1.7	0.9	2.6	2.2	1.1	3.4
	Forecast Period: 7-hours					
Albany, N.Y.	1.9	0.7	2.6	3.0	0.9	4.0
Baltimore, Md.	1.3	0.9	2.2	2.8	1.4	4.2
Chicago, Ill.	1.3	0.8	2.0	1.9	0.7	2.5
Los Angeles, Calif.	2.2	1.3	3.5	3.0	1.2	4.2
New York City, N.Y.	1.8	0.8	2.6	1.9	0.8	2.8

Location	Ceiling G_s	Ceiling G_o	Ceiling G_t*	Visibility G_s	Visibility G_o	Visibility G_t*
	Forecast Period: 7-hours					
San Francisco, Calif.	2.0	0.6	2.6	1.9	0.9	2.8
Seattle, Wash.	3.3	1.3	4.6	2.9	1.3	4.2
Washington, D.C.	1.3	0.8	2.1	1.4	0.9	2.3
Means	1.9	0.9	2.8	2.4	1.0	3.4
	Precipitation (> .01 inch)			Temperature (< normal)		
	Forecast Period: 12-hours					
Albuquerque, N.M.	3.3	2.6	5.9			
Atlanta, Ga.	4.9	4.6	9.5			
Boston, Mass.	4.6	3.5	8.1			
Chicago, Ill.	4.9	4.6	9.5			
Cleveland, Ohio	4.9	4.3	9.2			
Denver, Colo.	3.3	2.8	6.1			
Fort Worth, Tex.	4.3	3.1	7.4			
Great Falls, Mont.	4.1	3.1	7.2			
Kansas City, Mo.	3.9	2.8	6.7			
Los Angeles, Calif.	1.4	0.8	2.2			
Memphis, Tenn.	4.0	3.5	7.5			
Miami, Fla.	5.8	5.3	11.0			
Minneapolis, Min.	3.9	3.2	7.1			
New Orleans, La.	4.8	4.7	9.5			
New York City, N.Y.	4.4	3.9	8.3			
Raleigh, N.C.	4.5	3.9	8.4			
St. Louis, Mo.	4.5	4.3	8.8	2.9	1.4	4.3
Salt Lake City, Utah	3.8	3.1	6.9			
San Antonio, Tex.	4.0	3.4	7.4			
San Francisco, Calif.	1.8	1.1	3.0			
Seattle, Wash.	3.2	2.6	5.9			
Washington, D.C.	3.9	3.4	7.3			
Means	4.0	3.4	7.4			
	(Note: Except for an experimental series at St. Louis, Mo., shown below, probability forecasts of temperature for medium-period forecasts have not been made.)					
	Forecast Period: 24-hours					
Albuquerque, N.M.	3.4	2.3	5.6			
Atlanta, Ga.	5.5	3.8	9.3			
Boston, Mass.	5.6	4.8	10.3			
Chicago, Ill.	6.1	5.8	12.0			
Cleveland, Ohio	6.2	5.9	12.1			
Denver, Colo.	5.0	4.2	9.2			

Location	Precipitation G_s	Precipitation G_o	Precipitation G_t*	Temperature G_s	Temperature G_o	Temperature G_t*
	Forecast Period: 24-hours					
Fort Worth, Tex.	5.4	3.7	9.1			
Great Falls, Mont.	5.3	3.8	9.1			
Kansas City, Mo.	4.9	4.1	9.0			
Los Angeles, Calif.	1.9	0.9	2.8			
Memphis, Tenn.	5.4	4.3	9.7			
Miami, Fla.	5.4	4.1	9.5			
Minneapolis, Min.	5.3	4.2	9.6			
New Orleans, La.	4.9	3.2	8.0			
New York City, N.Y.	5.1	4.9	10.0			
Raleigh, N.C.]	5.2	4.0	9.2			
St. Louis, Mo.	5.1	4.6	9.6			
Salt Lake City, Utah	4.5	3.5	8.0			
San Antonio, Tex.	4.6	2.8	7.4			
San Francisco, Calif.	2.8	2.1	4.9			
Seattle, Wash.	4.7	3.9	8.6			
Washington, D.C.	4.8	4.1	9.0			
Means	4.9	3.9	8.7			
	Forecast Period: 36-hours					
Albuquerque, N.M.	4.2	2.7	6.9			
Atlanta, Ga.	6.9	5.5	12.4			
Boston, Mass.	6.6	6.1	12.7			
Chicago, Ill.	6.6	6.2	12.8			
Cleveland, Ohio	6.7	6.7	13.4			
Denver, Colo.	5.0	3.8	8.7			
Fort Worth, Tex.	6.3	3.1	9.4			
Great Falls, Mont.	5.7	4.2	9.9			
Kansas City, Mo.	5.0	3.5	8.6			
Los Angeles, Calif.	2.2	1.0	3.2			
Memphis, Tenn.	6.4	5.2	11.6			
Miami, Fla.	7.0	6.8	13.8			
Minneapolis, Min.	5.5	4.2	9.7			
New Orleans, La.	6.4	5.3	11.7			
New York City, N.Y.	6.0	5.3	11.4			
Raleigh, N.C.	6.1	5.5	11.6			
St. Louis, Mo.	6.1	5.8	11.9			
Salt Lake City, Utah	5.4	3.7	9.2			
San Antonio, Tex.	5.3	3.1	8.5			
San Francisco, Calif.	2.9	1.6	4.5			
Seattle, Wash.	7.5	4.5	12.0			
Washington, D.C.	6.0	5.7	11.7			
Means	5.7	4.5	10.3			

Location	Precipitation G_s	Precipitation G_o	Precipitation G_t*	Temperature G_s	Temperature G_o	Temperature G_t*
		Forecast Period: 5-days				
Entire U.S.#	8.9	6.0	14.8	6.1	3.8	9.9
		Forecast Period: 30-days				
Entire U.S.#	8.6	5.0	13.7	7.0	4.8	11.7
		Forecast Period: 90-days				
Entire U.S.#	9.2	6.0	15.2	9.2	8.1	17.3

#Forecast verification for extended period forecasts (5-days and over) not summarized for individual locations.
*Sums may not balance due to rounding off.

Appendix 3.2 Values of mean potential scientific advances (G_s) operational improvements (G_o) and total gains (G_t) for various forecast periods, weather elements and locations in the United States. Figures are mean percentage of protectable loss for dichotomous, mini-max decisions.

	Ceiling (< 1000 ft.)			Visibility (< 2 1/2 mi.)		
Location	G_s	G_o	G_t*	G_s	G_o	G_t*
			Forecast Period: 3-hours			
Albany, N.Y.	1.7	0.8	2.5	2.5	1.0	3.5
Baltimore, Md.	1.2	1.0	2.2	2.1	1.4	3.4
Chicago, Ill.	1.5	0.8	2.3	2.0	0.8	2.8
Los Angeles, Calif.	2.0	1.3	3.3	2.4	1.1	3.4
New York City, N.Y.	1.7	1.1	2.8	2.2	1.1	3.4
San Francisco, Calif.	1.6	0.7	2.3	1.3	0.8	2.0
Seattle, Wash.	2.7	1.4	4.0	2.8	1.1	3.9
Washington, D.C.	1.3	0.8	2.1	1.7	0.9	2.5
Means	1.7	1.0	2.7	2.1	1.0	3.1
			Forecast Period: 5-hours			
Albany, N.Y.	2.4	1.3	3.7	3.3	1.6	4.9
Baltimore, Md.	1.4	0.7	2.1	2.6	1.3	4.0
Chicago, Ill.	2.2	0.9	3.1	2.8	1.0	3.7
Los Angeles, Calif.	2.3	1.3	3.5	3.4	1.4	4.8
New York City, N.Y.	1.5	0.6	2.1	2.4	1.1	3.5
San Francisco, Calif.	2.3	0.6	2.8	1.8	0.7	2.5
Seattle, Wash.	4.2	1.9	6.1	3.5	1.4	4.9
Washington, D.C.	1.5	1.0	2.5	1.8	1.4	3.3
Means	2.2	1.0	3.2	2.7	1.2	4.0
			Forecast Period: 7-hours			
Albany, N.Y.	2.6	1.7	4.3	3.8	1.6	5.4
Baltimore, Md.	1.5	1.0	2.5	3.2	2.1	5.2
Chicago, Ill.	1.9	0.8	2.7	2.7	1.5	4.2
Los Angeles, Calif.	3.1	1.9	5.0	4.1	2.4	6.5
New York City, N.Y.	2.1	1.2	3.3	2.5	1.1	3.6

Location	Ceiling Gs	Ceiling Go	Ceiling Gt*	Visibility Gs	Visibility Go	Visibility Gt*
	Forecast Period: 7-hours					
San Francisco, Calif.	2.4	0.7	3.1	2.3	1.2	3.4
Seattle, Wash.	4.9	2.4	7.3	3.8	2.1	6.0
Washington, D.C.	1.6	1.2	2.8	2.1	1.4	3.5
Means	2.5	1.4	3.9	3.1	1.7	4.7

Location	Precipitation (> .01 inch)			Temperature (< normal)		
	Forecast Period: 12-hours					
Albuquerque, N.M.	3.3	1.6	4.9			
Atlanta, Ga.	5.0	3.4	8.3			
Boston, Mass.	5.2	3.4	8.6	(Note: Except for an experimental series at St. Louis, Mo., shown below, probability forecasts of temperature for medium-period forecasts have not been made.)		
Chicago, Ill.	5.3	3.7	8.9			
Cleveland, Ohio	5.3	3.3	8.6			
Denver, Colo.	3.5	2.1	5.7			
Fort Worth, Tex.	4.4	2.7	7.0			
Great Falls, Mont.	4.7	2.7	7.4			
Kansas City, Mo.	4.0	2.0	6.0			
Los Angeles, Calif.	1.2	0.5	1.7			
Memphis, Tenn.	4.2	2.9	7.1			
Miami, Fla.	6.3	5.0	11.3			
Minneapolis, Min.	4.1	2.2	6.3			
New Orleans, La.	5.1	3.4	8.5			
New York City, N.Y.	4.9	3.3	8.1			
Raleigh, N.C.	4.9	3.2	8.1			
St. Louis, Mo.	4.6	2.9	7.5	3.4	2.0	5.5
Salt Lake City, Utah	4.2	2.5	6.7			
San Antonio, Tex.	4.1	2.6	6.7			
San Francisco, Calif.	1.8	1.1	2.9			
Seattle, Wash.	3.5	2.4	5.9			
Washington, D.C.	4.3	3.1	7.4			
Means	4.3	2.7	7.0			
	Forecast Period: 24-hours					
Albuquerque, N.M.	3.4	1.6	5.0			
Atlanta, Ga.	5.4	3.1	8.5			
Boston, Mass.	6.3	4.3	10.6			
Chicago, Ill.	6.8	4.9	11.7			
Cleveland, Ohio	6.8	4.3	11.1			
Denver, Colo.	5.1	3.0	8.1			

Location	Precipitation G_s	Precipitation G_o	Precipitation G_t*	Temperature G_s	Temperature G_o	Temperature G_t*
	Forecast Period: 24-hours					
Fort Worth, Tex.	5.7	3.4	9.1			
Great Falls, Mont.	6.0	3.8	9.7			
Kansas City, Mo.	5.0	3.1	8.1			
Los Angeles, Calif.	1.9	0.8	2.7			
Memphis, Tenn.	5.5	3.4	8.9			
Miami, Fla.	6.3	4.2	10.5			
Minneapolis, Min.	5.6	3.3	8.8			
New Orleans, La.	5.1	2.9	8.0			
New York City, N.Y.	5.6	3.8	9.4			
Raleigh, N.C.	5.6	3.5	9.1			
St. Louis, Mo.	5.4	3.6	8.9			
Salt Lake City, Utah	4.8	2.9	7.7			
San Antonio, Tex.	4.7	2.3	7.0			
San Francisco, Calif.	2.8	1.6	4.4			
Seattle, Wash.	5.2	3.0	8.2			
Washington, D.C.	5.4	3.8	9.2			
Means	5.2	3.2	8.4			
	Forecast Period: 36-hours					
Albuquerque, N.M.	4.1	1.7	5.8			
Atlanta, Ga.	6.8	3.9	10.6			
Boston, Mass.	7.8	5.5	13.3			
Chicago, Ill.	7.2	5.2	12.4			
Cleveland, Ohio	7.4	4.9	12.3			
Denver, Colo.	5.1	2.6	7.7			
Fort Worth, Tex.	6.1	2.7	8.8			
Great Falls, Mont.	6.8	4.7	11.4			
Kansas City, Mo.	5.2	2.6	7.8			
Los Angeles, Calif.	2.4	1.1	3.5			
Memphis, Tenn.	6.6	4.2	10.7			
Miami, Fla.	8.4	6.0	14.4			
Minneapolis, Min.	5.8	3.1	8.9			
New Orleans, La.	6.9	5.2	12.1			
New York City, N.Y.	6.7	4.4	11.0			
Raleigh, N.C.	6.8	5.1	11.9			
St. Louis, Mo.	6.4	4.3	10.6			
Salt Lake City, Utah	5.5	3.2	8.7			
San Antonio, Tex.	5.4	2.4	7.8			
San Francisco, Calif.	3.0	1.6	4.6			
Seattle, Wash.	8.3	4.7	13.0			
Washington, D.C.	6.6	4.9	11.5			
Means	6.2	3.8	10.0			

Location	Precipitation G_s	Precipitation G_o	Precipitation G_t*	Temperature G_s	Temperature G_o	Temperature G_t*
	Forecast Period: 5-days					
Entire U.S.#	7.9	7.1	14.9	7.0	5.5	12.5
	Forecast Period: 30-days					
Entire U.S.#	8.9	8.5	17.4	8.6	8.0	16.6
	Forecast Period: 90-days					
Entire U.S.#	18.1	12.3	30.4	15.3	12.2	27.5

#Forecast verification for extended period forecasts (5-days and over) not summarized for individual locations.

*Sums may not balance due to rounding off.

Appendix 3.3 Summary of basis for relative values of economic expense given in Table 2.6.

Forecast Category	Observed Category	Economic Expense	Comment
1	1	.70	Probable trip cancellation; if attempted, would require diversion.
1	2	.60	Probable trip cancellation; if attempted, subject to ILS approach delays.
1	3	.65	If trip cancelled, loss of revenue and intangible dissatisfaction since flight could be completed; if attempted, subject to some delays.
1	4	.70	Same as previous comment, except if attempted, little or no delay.
1	5	.75	Same as previous comment, except if attempted, no delay.
2	1	.90	Diversion or holding probably anticipated; alternate planned and holding fuel carried, but serious delay encountered.
2	2	.40	Same as previous comment, except no diversion necessary; delay due to ILS approaches.
2	3	.30	Some traffic delay, but weather better than forecast; holding fuel carried.
2	4	.25	Same as previous comment, except less traffic delay.
2	5	.10	Traffic flow optimum, but holding fuel carried.

Forecast Category	Observed Category	Economic Expense	Comment
3	1	.95	Alternate probably not named; insufficient fuel for holding; must divert or land short of destination, but pilot might expect need for holding.
3	2	.40	Traffic flow reduced with ILS approaches; pilot may anticipate need for holding.
3	3	.30	Weather observed as predicted, but considerable delay likely.
3	4	.25	Slight traffic delay, but holding fuel carried due to adverse weather forecast.
3	5	.05	Traffic movement optimum, but holding fuel carried.
4	1	.95	Alternate probably not named; insufficient fuel for holding; must divert or land short of destination, but pilot might expect need for holding.
4	2	.45	Traffic flow delay with unexpected ILS approaches; holding fuel necessary, but probably no diversion.
4	3	.35	Same as previous comment, but probably less traffic delay.
4	4	.20	Weather observed as predicted, but some traffic delay.
4	5	.05	Traffic movement optimum, but extra fuel carried due to slightly adverse forecast.
5	1	1.00	Alternate probably not named; insufficient fuel for holding; must divert or land short of destination.

Forecast Category	Observed Category	Economic Expense	Comment
5	2	.50	Same as previous comment, except may be able to make destination after ILS delays.
5	3	.40	Same as previous comment, but may land with only general approach delays.
5	4	.30	Same as previous comment, but traffic moving well with visual approach used.
5	5	0	Traffic movement optimum.

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Department of Meteorology

Appendix 3.4 Questionnaire on weather losses.

The Department of Meteorology of San Jose State College, under a research grant provided by the National Aeronautics and Space Administration, is conducting a study of the potential advantages of improvements in weather forecasts. Such information will be of considerable value for making decisions concerning the amount and nature of future meteorological services and research which may be justified on the basis of their increased economic benefits.

In order to obtain some basic data for this study, we would greatly appreciate your assistance in completing the enclosed questionnaire. It is realized that information regarding monetary losses due to adverse weather may not be immediately available. However, even a rough estimate based on your experience would be extremely helpful.

The information will be published only in summary form -- no respondent will be identified. If you wish, we shall be glad to provide you with a copy of the results of the survey.

Thank you for your help.

Sincerely yours,

J. C. Thompson
Project Director.

Enclosure

S A N J O S E S T A T E C O L L E G E
Department of Meteorology
San Jose, Calif. 95114

THE VALUE OF WEATHER FORECASTS
(Questionnaire)

(1) Indicate your general category of business or service (check one):

Agriculture	___	Rail Transportation	___	Energy (e.g., fossil) Fuels	___
Construction	___	Water Transportation	___	Merchandising	___
Aviation	___	Public Safety	___	Other (specify)	
Highway Transportation	___	Electric Power	___	____________	___

(2) Estimate the total annual losses due to all weather conditions which adversely affect your business or service. Include all losses, even if it is too expensive, or otherwise impractical to take protective measures against certain weather elements (for example, it may be too expensive to build a warehouse which would withstand the wind forces of a mature tornado, or it may be impractical to provide irrigation in certain areas even during severe drought conditions).

$ ______________ per year

(3) Estimate the percentage of your total annual (gross) revenue which is represented by the weather-caused losses indicated in the answer to question number (2):

______________ percent

(4) Indicate the weather element(s) which most adversely affect your business or service and, if protective measures are, or could be taken, check the minimum amount of advance warning which would be needed to implement such protective measures:

WEATHER ELEMENTS (Indicate rain, snow, low visibility, high temperature, or other elements)	MINIMUM PERIOD OF USEFUL ADVANCE WARNING (check one for each weather element listed)					
	1-5 hrs.	6-11 hrs.	12-36 hrs.	2-5 days	30 days	90 days

(5) Estimate the average annual value of losses which are currently associated with the adverse weather element(s) listed in (4) above. Include only losses against which it would be practical to take protective measures if adequate weather information were provided.

$ ______________ per year

(6) Additional comments: ______________________________

Signature & Organization (optional) ______________________________

Appendix 3.5 Computation table for determining monetary value of potential savings due to future improvements in weather forecasting. (See text, Section 2.4 for explanation of notation.)

Forecast Period	G_{of} (a)	G_{sf} (b)	L_a (c) ($\$x10^6$)	W_{af} (d)	G'_{of} (axbxd) ($\$x10^6$)	G'_{sf} (bxcxd) ($\$x10^6$)	G'_{tf}* $G'_{of}+G'_{sf}$ ($\$x10^6$)
				Agriculture			
1-5 hr	.011	.022	3554.2	.022	0.9	1.7	2.6
6-11 hr	.016	.028	"	.050	2.8	5.0	7.8
12-36 hr	.032	.052	"	.209	23.8	38.6	62.4
2-5 days	.063	.075	"	.269	60.2	71.7	131.9
30 days	.083	.088	"	.240	70.8	75.1	145.9
90 days	.123	.167	"	.210	91.8	124.7	216.5
Totals (G'_{oa}, G'_{sa}, G'_{ta})*					250.3	316.7	567.0
				Aviation			
1-5 hr	.011	.022	56.9	.250	0.2	0.3	0.5
6-11 hr	.016	.028	"	.421	0.4	0.7	1.1
12-36	.032	.052	"	.182	0.3	0.5	0.9
2-5 days	.063	.075	"	.114	0.4	0.5	0.9
30 days	.083	.088	"	.033	0.2	0.2	0.3
90 days	.123	.167	"	0	0	0	0
Totals (G'_{oa}, G'_{sa}, G'_{ta})*					1.4	2.2	3.6
				Construction			
1-5 hr	.011	.022	328.6	.071	0.3	0.5	0.8
6-11 hr	.016	.028	"	.183	1.0	1.7	2.6
12-36 hr	.032	.052	"	.460	4.8	7.9	12.7
2-5 days	.063	.075	"	.190	3.9	4.7	8.6
30 days	.083	.088	"	.061	1.7	1.8	3.4
90 days	.123	.167	"	.035	1.4	1.9	3.3
Totals (G'_{oa}, G'_{sa}, G'_{ta})*					13.1	18.4	31.5
				Communications			
1-5 hr	.011	.022	6.4	.052	#	#	#
6-11 hr	.016	.028	"	.103	#	#	#
12-36 hr	.032	.052	"	.504	.1	.2	.3
2-5 days	.063	.075	"	.285	.1	.1	.3
30 days	.083	.088	"	.056	#	#	.1
90 days	.123	.167	"	0	0	0	0
Totals (G'_{oa}, G'_{sa}, G'_{ta})*					0.3	0.4	0.6

Forecast Period	G_{of} (a)	G_{sf} (b)	L_a (c) ($\$x10^6$)	W_{af} (d)	G'_{of} (axbxd) ($\$x10^6$)	G'_{sf} (bxcxd) ($\$x10^6$)	G'_{tf}* $G'_{of}+G'_{sf}$ ($\$x10^6$)
Electric Power							
1-5 hr	.011	.022	13.9	.285	#	.1	.1
6-11 hr	.016	.028	"	.200	#	.1	.1
12-36 hr	.032	.052	"	.257	.1	.2	.3
2-5 days	.063	.075	"	.101	.1	.1	.2
30-days	.083	.088	"	.050	.1	.1	.1
90 days	.123	.167	"	.107	.2	.3	.4
Totals	(G'_{oa}, G'_{sa}, G'_{ta})*				0.5	0.8	1.3
Energy Fuels							
1-5 hr	.011	.022	1.0	.045	#	#	#
6-11 hr	.016	.028	"	.142	#	#	#
12-36 hr	.032	.052	"	.480	#	#	#
2-5 days	.063	.075	"	.184	#	#	#
30 days	.083	.088	"	.149	#	#	#
90 days	.123	.167	"	0	0	0	0
Totals	(G'_{oa}, G'_{sa}, G'_{ta})*				#	#	0.1
Manufacturing							
1-5 hr	.011	.022	238.0	.250	0.7	1.3	2.0
6-11 hr	.016	.028	"	.180	0.7	1.2	1.9
12-36 hr	.032	.052	"	.372	2.8	4.6	7.4
2-5 days	.063	.075	"	.108	1.6	1.9	3.5
30 days	.083	.088	"	.032	0.6	0.7	1.3
90 days	.123	.167	"	.058	1.7	2.3	4.0
Totals	(G'_{oa}, G'_{sa}, G'_{ta})*				8.1	11.9	20.0
Transportation							
1-5 hr	.011	.022	45.8	.280	0.1	0.3	0.4
6-11 hr	.016	.028	"	.197	0.1	0.3	0.4
12-36 hr	.032	.052	"	.408	0.6	1.0	1.6
2-5 days	.063	.075	"	.093	0.3	0.3	0.6
30 days	.083	.088	"	.014	0.1	0.1	0.1
90 days	.123	.167	"	.008	0.1	0.1	0.1
Totals	(G'_{oa}, G'_{sa}, G'_{ta})*				1.3	1.9	3.2

Forecast Period	G_{of} (a)	G_{sf} (b)	L_a (c)	W_{af} (d)	G'_{of} (axbxd) ($\$x10^6$)	G'_{sf} (bxcxd) ($\$x10^6$)	G'_{tf}* $G'_{of}+G'_{sf}$ ($\$x10^6$)
				Other			
1-5 hr	.011	.022	1057.8	.147	1.7	3.4	5.1
6-11 hr	.016	.028	"	.178	3.0	5.3	8.3
12-36 hr	.032	.052	"	.304	10.3	16.7	27.0
2-5 days	.063	.075	"	.187	12.5	14.8	27.3
30 days	.083	.088	"	.098	8.6	9.1	17.7
90 days	.123	.167	"	.086	11.2	15.2	26.4
Totals (G'_{oa}, G'_{sa}, G'_{ta})*					47.3	64.6	111.8
GRAND TOTALS*			5302.6		322.2	416.9	739.1

*Totals may not balance exactly due to rounding off.
#Less than 0.05.