SCIENCE

The Decision to Seed Hurricanes

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On the basis of present information, the probability of
severe damage is less if a hurricane is seeded.

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The possibility of mitigating the destructive force of hurricanes by seeding them with silver iodide was suggested by R.H.. Simpson in 1961. Early experiments on hurricanes Esther (1961) and Beulah (1963) were encouraging (1), but strong evidence for the effectiveness of seeding was not obtained until the 1969 experiments on Hurricane Debbie (2). Debbie was seeded with massive amounts of silver iodide on 18 and 20 August 1969. Reductions of 31 and 15 percent in peak wind speed were observed after the seedings.

Over the last 10 years property damage caused by hurricanes has averaged $440 million annually. Hurricane Betsy (1965) and Hurricane Camille (1969) each caused property damage of approximately $1.5 billion. Any means of reducing the destructive force of hurricanes would therefore have great economic implications.

Decision to Permit Operational Seeding

In the spring of 1970 Stanford Research Institute began a small study for the Environmental Science Service Administration (ESSA) (3) to explore areas in which decision analysis (4, 5) might make significant contributions to

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ESSA, both in its technical operations and in its management and planning function. At the suggestion of Myron Tribus, Assistant Secretary of Commerce for Science and Technology, we decided to focus the study on the decision problems inherent in hurricane modification (6).

The objective of the present U.S. government program in hurricane modification, Project Stormfury, is strictly scientific : to add to man's knowledge about hurricanes. Any seeding of hurricanes that threaten inhabited coastal areas is prohibited. According to the policy currently in force, seeding will be carried out only if there is less than a 10 percent chance of the hurricane center coming within 50 miles of a populated land area within 18 hours after seeding.

If the seeding of hurricanes threatening inhabited coastal areas is to be undertaken, it will be necessary to modify the existing policies. The purpose of our analysis is to examine the circumstances that bear on the decision to change or not to change these existing policies.

The decision to seed a hurricane threatening a coastal area should therefore be viewed as a two-stage process: (i) a decision is taken to lift the present prohibition against seeding threatening hurricanes and (ii) a decision is taken to seed a particular hurricane a few hours before that hurricane is expected to strike the coast. Our study is concentrated on the policy decision rather than on the tactical decision to seed a particular hurricane at a particular

time. It is also addressed to the experimental question: What would be the value of expanding research in hurricane modification, and, specifically, what would be the value of conducting additional field experiments such as the seedings of Hurricane Debbie in 1969?

Our approach was to consider a representative severe hurricane bearing down on a coastal area and to analyze the decision to seed or not to seed this " nominal" hurricane. The level of the analysis was relatively coarse, because for the policy decision we did not have to consider many geographical and meteorological details that might influence the tactical decision to seed. We described the hurricane by a single measure of intensity, its maximum sustained surface wind speed, since it is this characteristic that seeding is expected to influence (7). The surface winds, directly and indirectly (through the storm tide), are the primary cause of the destruction wrought by most hurricanes (8). The direct consequence of a decision for or against seeding a hurricane is considered to be the property damage caused by that hurricane. (Injuries and loss of life are often dependent on the issuance and effectiveness of storm warnings; they were not explicitly included in our analysis.)

However, property damage alone is not sufficient to describe the consequence of the decision. There are indirect legal and social effects that arise from the fact that the hurricane is known to have been seeded. For example, the government might have some legal responsibility for the damage caused by a seeded hurricane (9). Even if legal action against the government were not possible, a strong public outcry might result if a seeded hurricane caused an unusual amount of damage. Nearly all the government hurricane meteorologists that we questioned said they would seed a hurricane threatening their homes and families-if they could be freed from professional liability.

The importance of the indirect effects stems in large part from uncertainty about the consequences of taking either decision. A hurricane is complex and highly variable, and at present meteor-

Fig. 1. Maximum sustained winds over time.

ologists cannot predict accurately how the behavior of a hurricane will evolve over time. The effect of seeding is uncertain also; consequently, the behavior of a hurricane that is seeded will be a combination of two uncertain effects: natural changes and the changes induced by seeding.

The seeding decision would remain difficult even if the uncertainty were removed. Suppose that, if the hurricane is not seeded, the surface wind intensifies as shown by the curve $w(t)$ in Fig. 1 and that, if the hurricane is seeded, the behavior of the wind is that shown by the curve $w'(t)$. The effect of the seeding has been to diminish the wind, thus reducing property damage, yet the wind speed $w'(t_1)$ when the hurricane strikes land at time t_1 is higher than the wind speed when the seeding was initiated at time t_0. Even if the decision maker were certain of $w(t_1)$ and $w'(t_1)$, he would still have a difficult choice. If he chooses not to seed, the citizens may have more property damage. On the other hand, if he chooses to seed, the citizens may not perceive themselves as better off because of his decision. Instead, they may perceive only that the storm became worse after the seeding and they may blame the decision-maker for his choice. The trade off between accepting the responsibility for seeding and accepting higher probabilities of severe property damage is the crucial issue in the decision to seed hurricanes.

Decision under Uncertainty

The decision to seed a threatening hurricane would be taken about 12 hours before the hurricane is predicted to strike the coast. At this time the con-

sequences are uncertain for both alternatives; the decision-maker does not know what amount of property damage will be sustained if the hurricane is seeded or is not seeded. We may illustrate the situation facing him in the form of a decision tree, as shown in Fig. 2. The decision-maker must select one of the two alternatives, seeding or not seeding. The decision cannot be avoided for inaction is equivalent to selecting the alternative of not seeding. Each alternative leads to a set of possible consequences: property damage caused by the hurricane and the responsibility incurred by the government. These consequences are, in turn, related to the intensity of the hurricane and whether or not it was seeded. The consequences for each alternative are uncertain at the time the decision is made; the uncertainty will be resolved after the decision-maker selects his choice. This decision under uncertainty may be examined according to the usual procedures of a decision analysis. We use the information that is currently available to develop a probability distribution over changes in the intensity of the hurricane as measured by its maximum sustained surface wind speed for each of the two decision alternatives. Then we use data from past hurricanes to infer a relation between wind speed and property damage. By assessing the consequences in property damage and government responsibility and the probability that these consequences will be achieved, we are able to determine which of the decision alternatives is the preferred choice.

Uncertainty in Hurricane Wind Changes

We began our analysis by considering the change in maximum sustained surface winds over a 12-hour period for a hurricane that is not seeded. If enough data had been available on the changes

in hurricane wind speeds with time, a probability distribution for wind changes could have been based largely on these past data. Wind-change data were not available, but data were available for changes over time in the central pressure of hurricanes. The central pressure and the maximum wind speed of a hurricane are closely related; Holliday has shown that the available data can be summarized fairly well by a linear relation (10). We combined this relation with observations of the change in central pressure over a 12-hour period, using the assumption that the discrepancies from the Holliday relation are independent over a 12-hour period and independent of the change in central pressure. These assumptions imply a probability distribution on wind changes over a 12-hour period that is normal with a mean of zero and a standard deviation of 15.6 percent (11).

Therefore, present information is consistent with rather large natural changes in hurricane intensity over a 12-hour period. There is about one chance in six that a hurricane whose maximum sustained wind speed is 100 miles per hour will intensify over a 12hour period to a maximum wind speed of over 115 miles per hour; there is also about one chance in six that the winds would naturally diminish to less than 85 miles per hour. In assessing these probabilities only general historical and meteorological information has been used. In a specific hurricane situation additional meteorological information might indicate that the hurricane would be more likely to intensify or more likely to diminish.

Effect of Seeding

The next step is to develop a probability distribution for the wind speed if the hurricane is seeded. The change in wind speed over 12 hours would then be a combination of the natural change occurring in the hurricane and the change caused by seeding. With the limited data available it is reasonable to assume that the two effects would be independent of each other and act in an additive fashion; for example, if the natural change is an intensification such that the maximum sustained wind speed is increased from 100 to (100 + x) percent, and if the effect of seeding is to diminish the maximum sustained wind speed from 100 to (100 - y) percent, the net observed change over 12

hours is from 100 to $(100 + x - y)$ per cent. A probability distribution has already been assigned for natural changes; we need to assign a probability distribution for the change caused by seeding. In developing this probability distribution it is necessary to distinguish between the effect of seeding on one hurricane and the average effect of seeding on many hurricanes. The effect of seeding on a particular hurricane might be quite different from its average effect.

After discussion with meteorologists associated with Project Stormfury, we concluded that the major uncertainty about the effect of seeding would be resolved if we knew which of the following mutually exclusive and collectively exhaustive hypotheses described the effect of seeding:

1) H_1, the "beneficial" hypothesis. The average effect of seeding is to reduce the maximum sustained wind speed.

2) H_2, the "null" hypothesis. Seeding has no effect on hurricanes. No change is induced in maximum sustained wind speed.

3) H_3, the "detrimental" hypothesis. The average effect of seeding is to increase the maximum sustained wind speed.

The scientific basis for the "beneficial" hypothesis, H_1, had its origins in the original Simpson theory (1). It has been modified and strengthened by Project Stormfury studies involving a computer model of hurricane dynamics (1,12). This hypothesis, in fact, motivated the formation of the Project Stormfury research program. A possible basis for the "null" hypothesis, H_2, is that seeding does not release enough latent heat to affect the dynamics of the hurricane. The "detrimental" hypothesis, H_3, has been added to complete the set. Meteorologists do not have a basis in physical theory for H_3 that is comparable to that for H_1 or H_2.

Even if we know which of the hypotheses is true, there remain uncertainties about the effects of seeding. We now describe the approach we followed in creating a model to formalize existing knowledge about these uncertainties. Then we shall return to the hypotheses.

Let us suppose we have access to a clairvoyant who can tell us which hypothesis, H_1, H_2, or H_3, represents the actual effect of seeding on hurricanes. What probability would we assign to the 12-hour change in the maximum sus-

tained winds of a seeded hurricane for each of his three possible answers? If the clairvoyant says H_2 is true, the assignment process is simple. Seeding has no effect, and the same probabilities are assigned to the wind speed w' if the hurricane is seeded as to the wind speed w if the hurricane is not seeded (13).

$$P(w' \mid H_2) = P(w) = f_N(100\%, 15.6\%) \quad (1)$$

If H_1 is the clairvoyant's answer, the process is more difficult. The average effect is known to be a reduction in storm intensity, but the amount of this average reduction is uncertain. The Simpson theory and the computer studies indicate that a reduction of 10 to 20 percent in wind speed should be expected, with 15 percent as the most likely value. This information was summarized by assigning to the change in wind speed a normal probability distribution with a mean of -15 percent and a standard deviation of 7 percent. An average reduction greater than 15 percent is considered as likely as an average reduction less than 15 percent, and the odds are about 2 to 1 that the average reduction will lie between 22 and 8 percent rather than outside this interval.

The effect of seeding on an individual hurricane would be uncertain even if the average effect of seeding were known. Odds of about 2 to 1 were considered appropriate that the effect of

seeding would not differ from the average effect by more than about 7 percent; thus, a normal distribution centered at the average value with a standard deviation of 7 percent was judged an adequate summary of the information available on fluctuations in seeding effects. Combining the uncertainty about fluctuations with the uncertainty about the average effect leads to a probability distribution for the effect of seeding a specific hurricane that is normal with a mean equal to -15 percent and a standard deviation of 10 percent (14).

Adding the natural change in the hurricane over a 12-hour period to the change resulting from seeding gives the total 12-hour change occurring in a seeded hurricane if hypothesis H_1 is true. The probability distribution assigned to w' is then normal with a mean of 85 percent and a standard deviation of 18.6 percent (1-5):

$$P(w' \mid H_1) = f_N(85\%, 18.6\%) \quad (2)$$

The development of a probability distribution for w', if it is considered that H_3 is true, proceeds in a similar way. The average change effected by seeding is described by a normal probability distribution with a mean of +10 percent and a standard deviation of 7 percent. The fluctuations expected when an individual hurricane is seeded are normally distributed around the average with a standard deviation of 7 percent. Combining these uncertainties
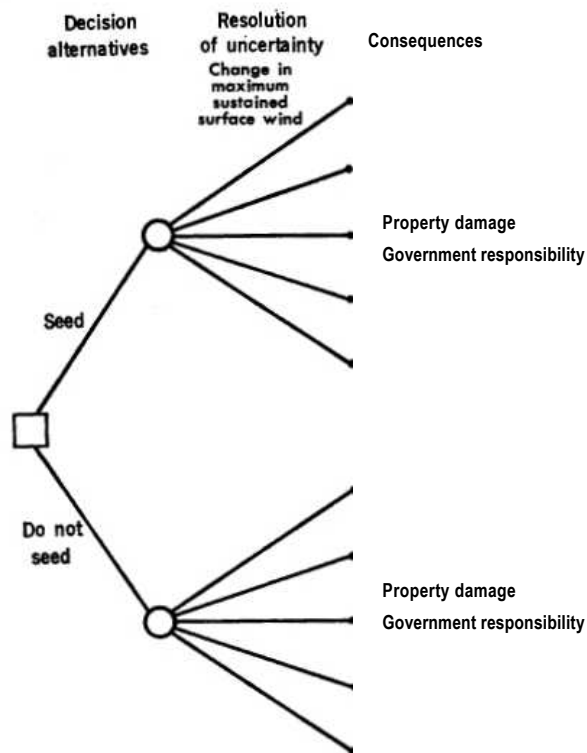

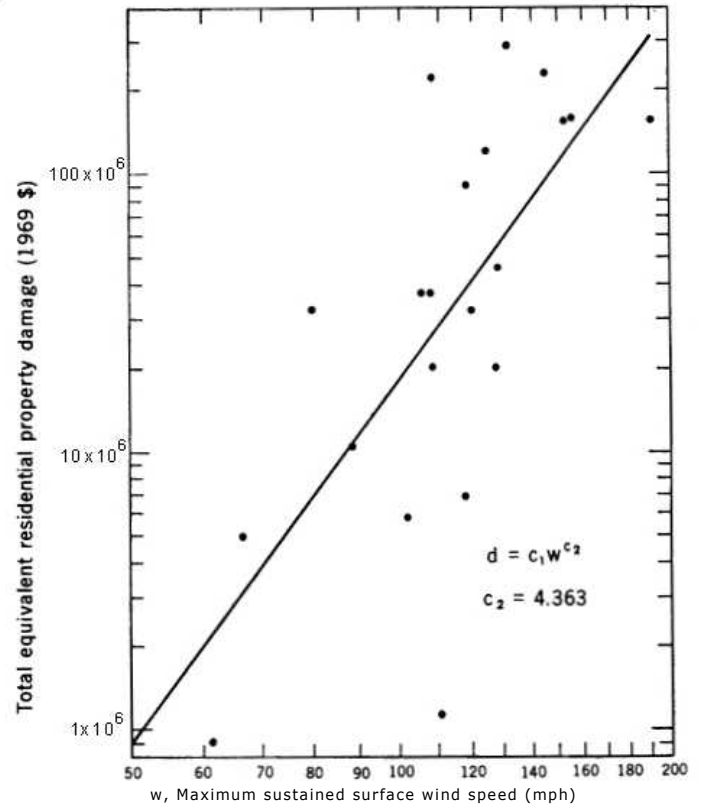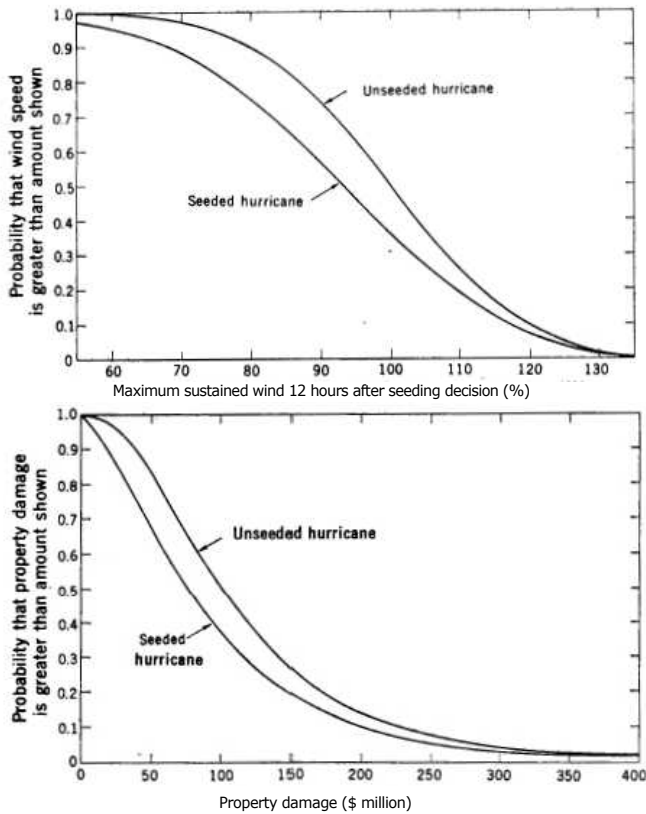*Fig. 2. The seeding decision: decision tree.*

Fig. 3 (upper left). Probability distributions on 12-hour wind changes for the seeded and unseeded hurricane.
Fig. 4 (right). Property damage plotted against maximum sustained wind speed.
Fig. 5 (lower left). Probability distributions on property damage for the seeded and unseeded hurricane.

with the uncertainty about the natural change in the hurricane over a 12-hour period, we obtain a probability distribution for w' that is normal with a mean of 110 percent and a standard deviation of 18.6 percent

$$P(w'|H_3) = f_N(110\%, 18.6\%) \quad (3)$$

We have now developed probability distributions for the wind speed w' over a 12-hour period following the initiation of seeding for each of the three hypotheses. To obtain the probability distribution for w' that represents present information about the change in a seeded hurricane, we multiply each of the above distributions by the probability that is presently assigned to each of the hypotheses being true and sum over the three hypotheses:

$$P(w') = \sum_{i=1}^{3} P(w'|H_i)P(H_i) \quad (4)$$

Assigning Probabilities to the Hypotheses

The last element in developing a probability distribution for w' is to assign the probabilities $P(H_1)$, $P(H_2)$, and $P(H_3)$. These probabilities should

take into account both present meteorological information and meteorological information before the results of the 1969 Debbie experiments. The models we have just constructed allow us to examine the effect of experimental observations, such as the Debbie results, in revising the probabilities assigned to the three hypotheses. If a wind speed w' = u has been observed after a seeding experiment, the posterior probabilities $P(H_i|u)$ are related to the probabilities $P(H_i)$ assigned before the experiment by Bayes' equation (5, 16, 17):

$$P(H_i|u) = \frac{P(u|H_i)P(H_i)}{P(u)} \quad (5)$$

where the denominator is

$$P(u) = P(w' = u) =$$
$$\sum_{i=1}^{3} P(w' = u|H_i)P(H_i) \quad (6)$$

The extension to several independent experiments is straightforward. The Debbie results are considered as two independent experiments in which reductions of 31 and 15 percent in wind speed were observed over a 12-hour period. The posterior probabilities assigned to the hypotheses are computed by multiplying together the appropriate

values of two normal probability density functions. The probability density function for the Debbie results if hypothesis H_i is true, $P(u_1 = 69$ percent, $u_2 = 85$ percent $| H_i)$, is

$$P(69\%, 85\% | H_1) = 1.50 \times 2.14 = 3.21$$
$$P(69\%, 85\% | H_2) = 0.372 \times 1.64 = 0.61$$
$$P(69\%, 85\% | H_3) = 0.195 \times 0.886 = 0.173$$

$$(7)$$

These numbers can be used to compute the posterior probabilities appropriate after the Debbie results from any set of probabilities assigned to the hypotheses before the Debbie results were known. For example, suppose that before the Debbie experiments the three hypotheses H_1, H_2, and H_3 were considered to be equally likely, that is, each had a probability of 1/3. Then, after the Debbie results are incorporated through Bayes' equation, the corresponding posterior probabilities assigned to the hypotheses are

$$P(H_1 | \text{Debbie}) =$$

$$\frac{3.21 \times 1/3}{3.21 \times 1/3 + 0.61 \times 1/3 + 0.173 \times 1/3}$$
$$= .81$$

$$P(H_2 | \text{Debbie}) = .15$$
$$P(H_3 | \text{Debbie}) = .04 \quad (8)$$

However, meteorologists did not believe that H_1, H_2, and H_3 were equally likely before the Debbie experiments. They thought that seeding was unlikely to have any effect but that, if seeding did have an effect, it was more likely to be a reduction in wind speed than an increase, because a reduction was expected from both the Simpson theory and the computer model studies. Further, the four field experiments that were conducted before Debbie all led to no change or to reductions in the maximum wind speeds (1).

We determined probability assignments for the three hypotheses to reflect present information by two conditions: (i) Before Debbie, meteorologists believed that H_1 was more likely than H_3 if seeding had any effect on a hurricane. (ii) Since Debbie, meteorologists believe that H_1 and H_2 are equally likely.

These conditions led us to use the probabilities

$$P(H_1) = .49$$
$$P(H_2) = .49 \qquad (9)$$
$$P(H_3) = .02$$

in our analysis. These posterior probabilities correspond to the pre-Debbie probabilities

$$P(H_1) = .15$$
$$P(H_2) = .75 \qquad (10)$$
$$P(H_3) = .10$$

This set of probability assignments implies that prior to Debbie the odds were 3 to 1 that seeding would have no effect but that, if seeding did have an effect, the odds were 3 to 2 for wind reduction rather than wind intensification. Since the Debbie results, the chance of seeding causing an average intensification of hurricanes is assessed at 1 in 50, and the "null" hypothesis, H_2, of no effect and the "beneficial" hypothesis, H_1, of an average reduction are judged equally likely.

The probability assignments (Eq. 9) representing present information were reviewed with Project Stormfury officials before being used in the analysis. However, the results of the analysis are not particularly sensitive to the specific numbers, as we discuss below.

Probability Distributions on

Wind Speed

We now can compute the probability distributions on wind speed for the seeding and not-seeding alternatives (from Eqs. 1-4 and Eq. 9). These dis-

tributions are plotted in Fig. 3 as complementary cumulative distribution functions. By reading the ordinate values corresponding to an initial wind intensity of 100 percent, we find that the probability assigned to intensification if a hurricane is seeded is .36; if the hurricane is not seeded, the probability is .50. The probability of intensification by 10 percent or more is .18 if a hurricane is seeded and .26 if it is unseeded. For any particular wind speed, the probability that this speed will be exceeded is always greater if the hurricane is unseeded than if it is seeded because the complementary cumulative distribution function for the not-seeding alternative is always above the curve for the seeding alternative. This result is called stochastic dominance of the seeding alternative.

We have now specified the uncertainties about the outcome of the decision to seed. The same methods could be applied if the outcome were specified by several variables rather than simply by the relative change in maximum sustained wind speed. Much of the uncertainty in the outcome is the result of uncertainty about the natural change in hurricane behavior, not about the effect of seeding. This characteristic holds even more strongly if other aspects of hurricane behavior are examined, such as the trajectory of a hurricane or the precipitation it generates. Although it is considered unlikely that seeding would have a significant effect on these features of hurricanes, substantial variations may occur from natural causes.

The uncertainty about the natural behavior of a hurricane makes the issue of government responsibility of paramount importance. The intensification after seeding illustrated in Fig. 1 is a distinct possibility. Even if further experiments confirm that the "beneficial" hypothesis H_1, is true, there would still be about one chance in ten that a seeded hurricane will intensify by 10 percent or more. Meteorological advances and improved computer models may eventually allow many of the natural changes in a hurricane to be predicted accurately, but this capability may require many years to achieve.

Wind Changes and Property Damage

The winds of a hurricane cause property damage directly and indirectly, the latter by creating a high storm tide that can flood low-lying coastal areas.

The data available for past hurricanes do not distinguish wind and storm-tide damage; consequently, a detailed basis is lacking for a causal model relating wind and property damage. In our analysis, we assumed a general power law of the form

$$d = c_1 w^{c_2} \qquad (11)$$

where d is property damage in millions of dollars, w is the maximum sustained wind speed in miles per hour, and c_1 and c_2 are empirical constants to be determined from historical data on hurricanes. We estimated c_2 from data obtained from the American Red Cross on residential damage from 21 hurricanes. Since the Red Cross data were available for counties, we could isolate the damage caused by precipitation-induced flooding rather than by the wind or the storm tide by assuming that such damage occurred well inland. (The Red Cross data are the only statistics available that permit even this crude distinction between causes of damage.) Corrections for construction cost inflation and population growth were included, and c_2 was determined as 4.36 by a linear least-squares fit of the logarithms (Fig. 4). Thus, a change in the wind speed by a factor x implies a change in property damage by the factor x to the power 4.36. If x is 0.85, corresponding to a 15 percent reduction in maximum wind speed, the corresponding reduction in property damage is 51 percent (18).

The approximations of this method and the limited data indicate that broad limits are appropriate in a sensitivity analysis. If c_2 is 3, the reduction in damage corresponding to a 15 percent reduction in wind speed is 39 percent; if c_2 is 6, the corresponding damage reduction is 62 percent.

Since the probability assignments to wind changes were made on relative rather than absolute changes in maximum sustained wind speeds, the scaling factor c_1 can be assigned as the last step in the analysis. We assume a nominal hurricane whose maximum wind speed at the time of the seeding decision is such that, if no change occurs in the 12 hours before landfall, the property damage will be $100 million. The analysis for a more or a less severe hurricane can be obtained by a suitable change in scale factor (19).

Using this relationship between property damage and maximum wind speed, we can develop the probability distributions for property damage for the nominal hurricane, whether seeded or unseeded. Figure 5 shows that the seed-

ing alternative stochastically dominates the not-seeding alternative : the probability of exceeding a particular amount of property damage is always greater if the hurricane is not seeded than if it is seeded. Hence, if property damage is the criterion, the better alternative is to seed.

Further Analysis of the

Decision to Seed

The decision to seed is shown in the form of a decision tree in Fig. 6. The decision to seed or not to seed is shown at the decision node denoted by the small square box; the consequent reso-

lution of the uncertainty about wind change is indicated at the chance nodes denoted by open circles. For expository clarity and convenience, especially in the later stages of the analysis, it is convenient to use discrete approximations to the probability distributions for wind change (20) (Table 1).

As a measure of the worth of each alternative we can compute the expected loss for each alternative by multiplying the property damage for each of the five possible outcomes by the probability that the outcome will be achieved and summing over the possible consequences. The expected loss for the seeding alternative is $94.33 million (including a cost of $0.25 million to

carry out the seeding) ; the expected loss for the not-seeding alternative is $116 million; the difference is $21.67 million or 18.7 percent.

These results should be examined to see how much they depend on the specific assumptions in the model. Stochastic dominance is a general result that does not depend on the specific form of the relationship between property damage and maximum wind speed (see Eq. 11) ; rather, it depends on the probabilities assigned to hypotheses H_1, H_2, and H_3. The probability of H_3 must be raised to .07 before stochastic dominance no longer holds. Even if the probability of H_3 is raised much higher, seeding still results in the least expected property damage. If $P(H_1)$ is .40, $P(H_2)$ is .40, and $P(H_3)$ is .20, the expected loss for the seeding alternative is $107.8 million - 7 percent less than for the not-seeding alternative. Variation of the exponent c_2 from 3 to 6 does not change the decision: if c_2 is 3, the expected property damage with seeding is 14 percent less; if c_2 is 6, the expected reduction in damage is 22 percent. If the criterion of expected cost is replaced by a nonlinear utility function reflecting aversion to risk, the relative advantage of the seeding alternative is even greater (21). The results of extensive sensitivity analysis may be summarized as follows : The expected loss in terms of property damage appears to be about 20 percent less if the hurricane is seeded. Varying the assumptions of the analysis causes this reduction to vary between 10 and 30 percent but does not change the preferred alternative.

Government Responsibility

The analysis in the section above indicates that, if minimizing the ex pected loss in terms of property damage (and the cost of seeding) is the only criterion, then seeding is preferred. However, an important aspect of the decision-the matter of government responsibility-has not yet been included in the analysis. We have calculated a probability of .36 that a seeded hurricane will intensify between seeding and landfall and a probability of .18 that this intensification will be at least 10 percent. This high probability is largely the result of the great natural variability in hurricane intensity. It is advisable to consider both the legal and the social consequences that might
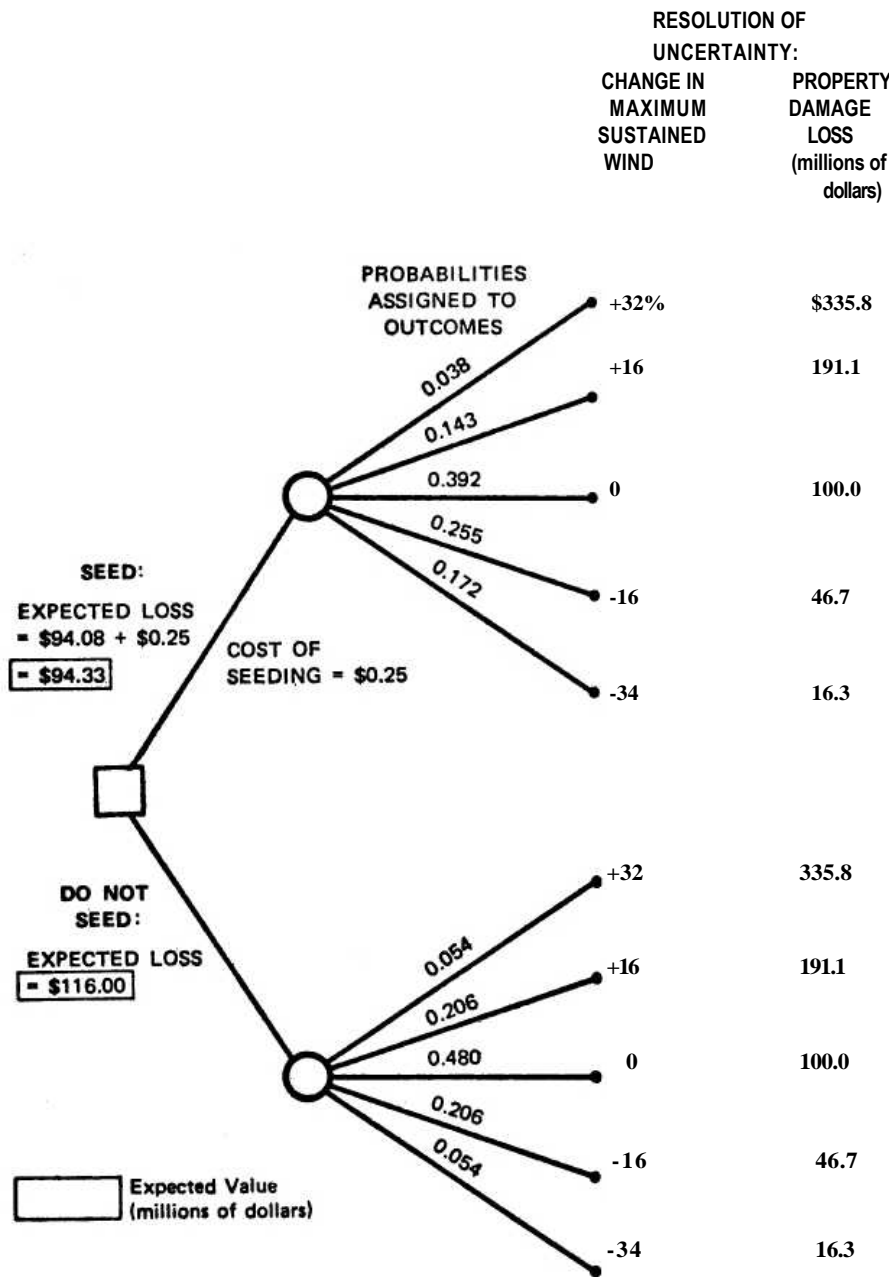

Fig. 6. The seeding decision for the nominal hurricane.

occur if a seeded hurricane intensified.

The crucial issue in the decision to seed a hurricane threatening a coastal area is the relative desirability of reducing the expected property damage and assuming the responsibility for a dangerous and erratic natural phenomenon. This is difficult to assess, and to have a simple way of regarding it we use the concept of a government responsibility cost, defined as follows. The government is faced with a choice between assuming the responsibility for a hurricane and accepting higher probabilities of property damage. This situation is comparable to one of haggling over price : What increment of property-damage reduction justifies the assumption of responsibility entailed by seeding a hurricane? This increment of property damage is defined as the government responsibility cost. The government responsibility cost is a means of quantifying the indirect social, legal, and political factors related to seeding a hurricane. It is distinguished from the direct measure-property damage-that is assumed to be the same for both modified and natural hurricanes with the same maximum sustained wind speed.

We define the government responsibility cost so that it is incurred only if the hurricane is seeded. It is conceivable that the public may hold the government responsible for not seeding a severe hurricane, which implies that a responsibility cost should also be attached to the alternative of not seeding. Such a cost would strengthen the implication of the analysis in favor of permitting seeding.

The assessment of government responsibility cost is made by considering the seeding decision in a hypothetical situation in which no uncertainty is present. Suppose the government must choose between two outcomes

1) A seeded hurricane that intensifies 16 percent between the time of seeding and landfall.

2) An unseeded hurricane that intensifies more than 16 percent between the time of seeding and landfall. The property damage from outcome 2 is x percent more than the property damage from outcome 1.

If x is near zero, the government will choose outcome 2. If x is large, the government will prefer outcome 1. We then adjust x until the choice becomes very difficult; that is, the government is indifferent to which outcome it receives. For example, the indifference

point might occur when x is 30 percent. An increase of 16 percent in the intensity of the nominal hurricane corresponds to property damage of $191 million, so that the corresponding responsibility cost defined by the indifference point at 30 percent is (.30) ($191 million), or $57.3 million. The responsibility cost is then assessed for other possible changes in hurricane intensity.

The assessment of government responsibility costs entails considerable introspective effort on the part of the decision-maker who represents the government. The difficulty of determining the numbers does not provide an excuse to avoid the issue. Any decision or pol-

icy prohibiting seeding implicitly determines a set of government responsibility costs. As shown in the last section, seeding is the preferred decision unless the government responsibility costs are high.

Let us consider an illustrative set of responsibility costs. The government is indifferent, if the choice is between:

1) A seeded hurricane that intensifies 32 percent and an unseeded hurricane that intensifies even more, causing 50 percent more property damage.

2) A seeded hurricane that intensifies 16 percent and an unseeded hurricane that causes 30 percent more property damage.

Table 1. Probabilities assigned to wind changes occurring in the 12 hours before hurricane landfall. Discrete approximation for five outcomes.

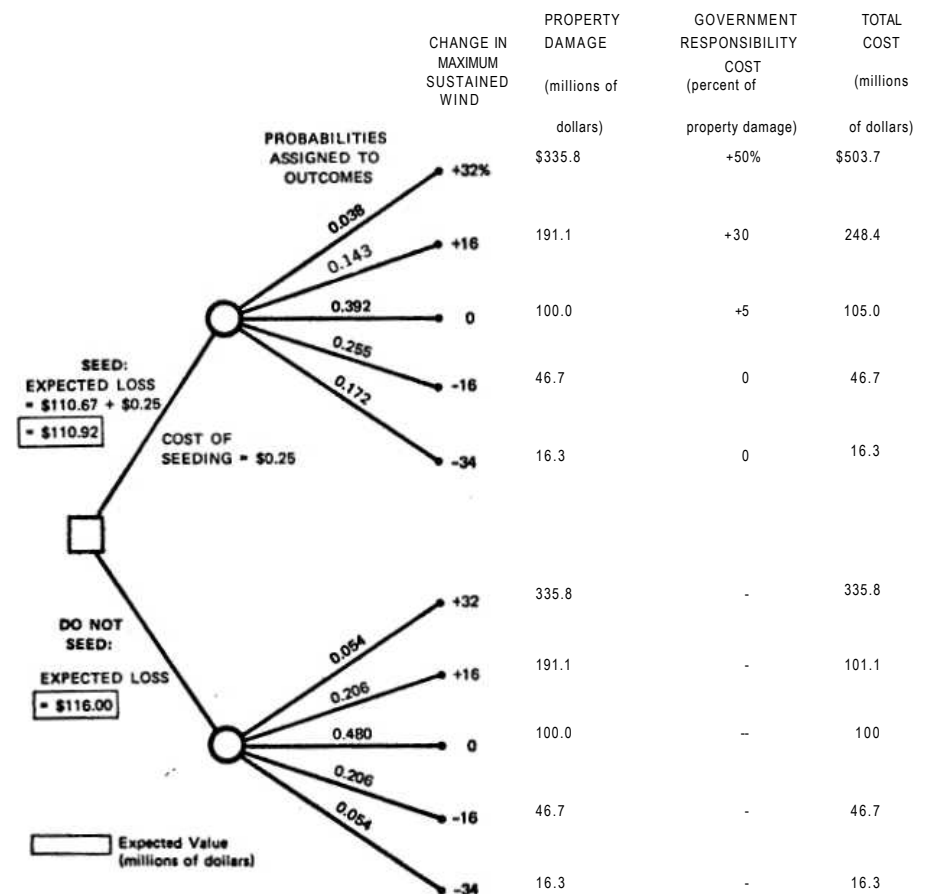| Interval of changes in maximum sustained wind	Representative value in discrete approximation	Probability that wind change will be within interval	
	(%)	If seeded	If not seeded
Increase of 25% or more	+32	.038	.054
Increase of 10 to 25%	+16	.143	.206
Little change, +10 to -10%	0	.392	.480
Reduction of 10 to 25%	-16	.255	.206
Reduction of 25% or more	-34	.172	.054

Fig. 7. The seeding decision for the nominal hurricane (government responsibility cost included).

3) A seeded hurricane that neither intensifies nor diminishes (0 percent change in the maximum sustained wind speed after the seeding) and an unseeded hurricane that intensifies slightly, causing 5 percent more property damage.

4) A seeded hurricane that diminishes by more than 10 percent and an unseeded hurricane that diminishes by the same amount. (If the hurricane diminishes after seeding, everyone agrees that the government acted wisely; thus, responsibility costs are set at zero.)

The analysis of the seeding decision with these government responsibility costs included is diagramed in Fig. 7. Even with these large responsibility costs, the preferred decision is still to seed.

The responsibility costs needed to change the decision are a substantial fraction of the property damage caused by the hurricane. For the $100-million hurricane chosen as the example for this section, the average responsibility cost must be about $22 million to change the decision. If the hurricane were in the $1-billion class, as Camille

(1969) and Betsy (1965) were, an average responsibility cost of $200 million would be needed. In other words, an expected reduction of $200 million in property damage would be foregone if the government decided not to accept the responsibility of seeding the hurricane.

The importance of the responsibility issue led us to investigate the legal basis for hurricane seeding in some detail. These investigations were carried out by Gary Widman, Hastings College of the Law, University of California. A firm legal basis for operational seeding apparently does not now exist. The doctrine of sovereign immunity provides the government only partial and unpredictable protection against lawsuits, and substantial grounds for bringing such lawsuits might exist (22). A better legal basis for government seeding activities is needed before hurricane seeding could be considered other than as an extraordinary emergency action. Specific congressional legislation may be the best means of investing a government agency with the authority to seed hurricanes threatening the coast of the United States.

Value of Information

One of the most important concepts in decision analysis is the value of information: How much it would be worth to make the decision after rather than before uncertainty is resolved? In the case of hurricane modification, how much should be the government pay to learn which of the three hypotheses, H_1, H_2, or H_3, is actually true (23) ? We imagine that the government has access to a clairvoyant who has this information and is willing to sell it to the government, if he is paid before he makes the information available. It is easiest to understand the calculation in terms of the decision to seed one hurricane threatening a coastal area.

Let us consider the choice between the two decision situations shown in Fig. 8. The government can choose to buy the information and make the decision after it has learned which hypothesis is true, or it can choose not to buy the information and can make the seeding decision on the basis of the present uncertainty.

Let us, for the moment, consider only property damage and the cost of seeding and disregard government responsibility costs. If H_1 is true, the preferred decision is to seed because the expected
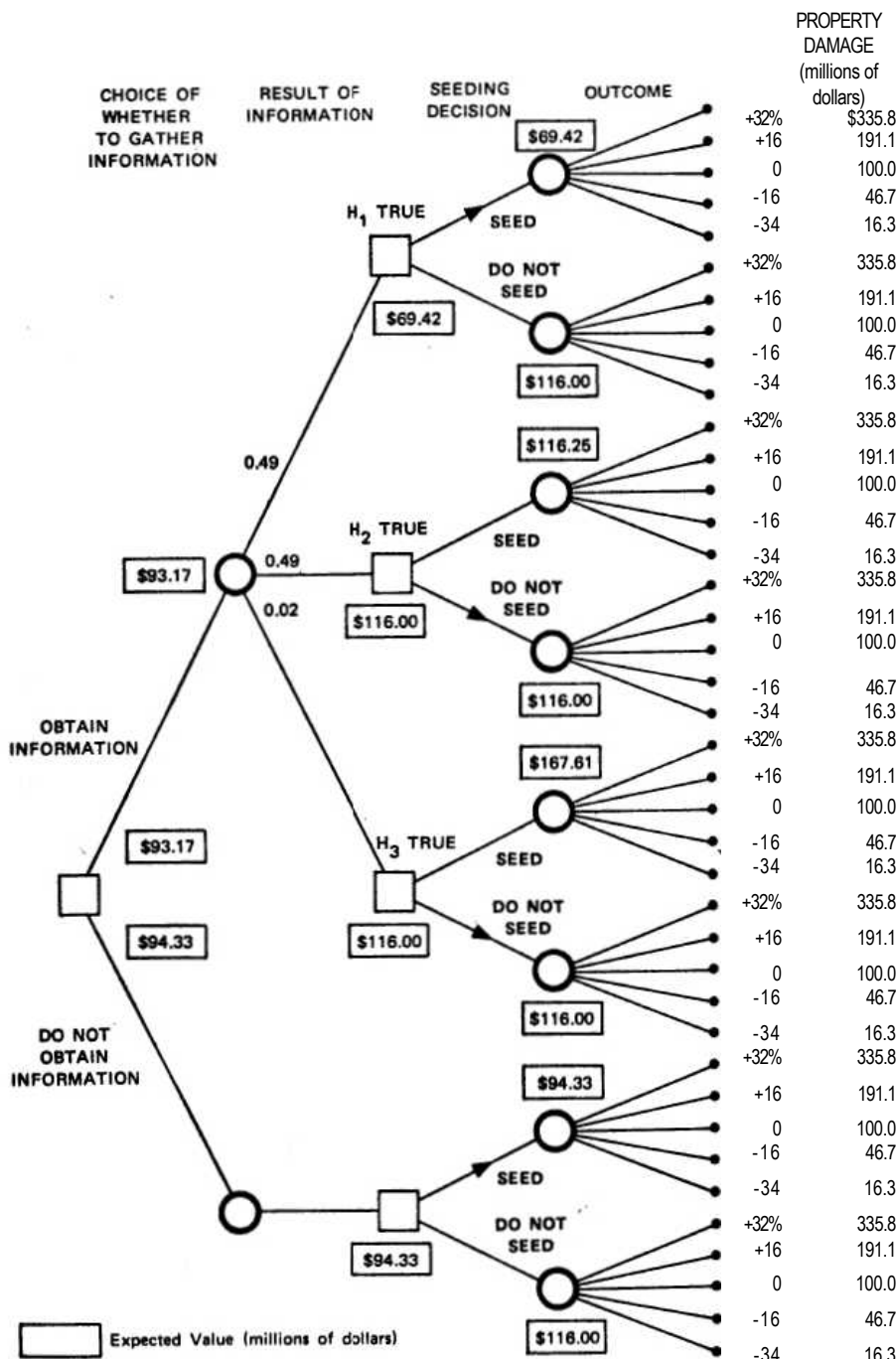

Fig. 8. Expected value of the clairvoyant's information-which hypothesis describes the effect of seeding? (There is no government responsibility cost.)

loss is $69.42 million compared with a loss of $116.00 million for the alternative of not seeding. If H_2 is true, then by choosing not to seed, the government saves the $0.25-million cost of seeding; the loss expected from property damage is the same for both alternatives $116.00 million. If H_3 is true, seeding is a poor choice; the expected loss from property damage is $167.61 million, $51.61 million more than for the alternative of not seeding. At the present time, the government does not know what the clairvoyant will say, but probabilities have been assigned to his answers

$$P(H_1) = .49$$
$$P(H_2) = .49 \qquad (12)$$
$$P(H_3) = .02$$

The expected loss corresponding to the decision situation in Fig. 8 is then computed by multiplying the probability of each of the clairvoyant's answers by the expected loss associated with that answer and summing over the three possible answers

$$(.49) (\$69.42) + (.49) (\$116.00) +$$
$$(.02) (\$116.00) = \$93.17 \text{ million}$$
$$(13)$$

Comparing this with the expected loss for the best alternative (seed) without the clairvoyant's information, which was $94.33 million, we see that it is $1.16 million less. This difference represents the expected value of the clairvoyant's information in allowing the government to make a better decision. It is a relatively small number compared with the expected losses because the information is not expected to be of much value---the probability assignments indicate that seeding is already a good idea. Without the clairvoyant's information the government should seed; with the clairvoyant's information, with probability .49, the government will save the cost of seeding ($0.25 million), and with the low probability .02 it will avert the potentially disastrous intensification expected from H_3, saving $167.61 million - $116 million = $51.61 million. By this reasoning we got the same answer as before for the value of information

$$(.49) (\$0.25) + (.02) (\$51.61) =$$
$$\$1.16 \text{ million} \qquad (14)$$
and we can see that the value is very sensitive to the small probability assigned to H_3.

Now suppose that the government responsibility costs assumed previously are included. The expected value of perfect information is then much higher

because, if H_2 is true, the government responsibility costs can be saved by not seeding. If the decision without perfect information is to seed, the expected saving from engaging the clairvoyant is

$$(.49) (\$0.25 + 23.28) +$$
$$(.02) (\$51.61 + \$53.57) =$$
$$\$13.63 \text{ million} \qquad (15)$$
This figure represents 11.75 percent of the expected property damage if the alternative of not seeding is taken for the nominal 'hurricane.

The value of information largely derives from the fact that it allows the government to avoid the responsibility for seeding if seeding turns out to have no effect. The large increase over the value computed in Eq. 13 is due to the contribution of the government responsibility costs. Most of the increase of $12.47 million, namely $11.41 million, comes from the first or H_2 term.

The value of information depends on the extent to which the government is willing to assume responsibility for seeding a hurricane. If responsibility were not an issue, the government would seed operationally now, and information would have a comparatively low value in the context of this decision. The value of information is great-

est when the government responsibility costs are large enough to make the decision essentially even between seeding and not seeding. Still higher responsibility costs cause the value of information to decrease (24).

Value of Further Seeding Experiments

The analysis of the value of a seeding experiment is similar to the determination of the value of the clairvoyant's information. The difference is that the resolution of uncertainty is only partial. The information obtained in the experiment is used in Bayes' equation (Eq. 5) to revise the prior probability assignments to the hypotheses. The original decision is then reevaluated with the posterior probabilities (Fig. 9). The result of the experiment is uncertain when the decision to experiment is made; consequently, the value of experimentation must be computed as an expectation over the possible posterior decision situations. The situation can be diagramed in tree form as shown in Fig. 9.

The analysis for two experimental seedings is given in Table 2 (25). The values assumed above for the govern-
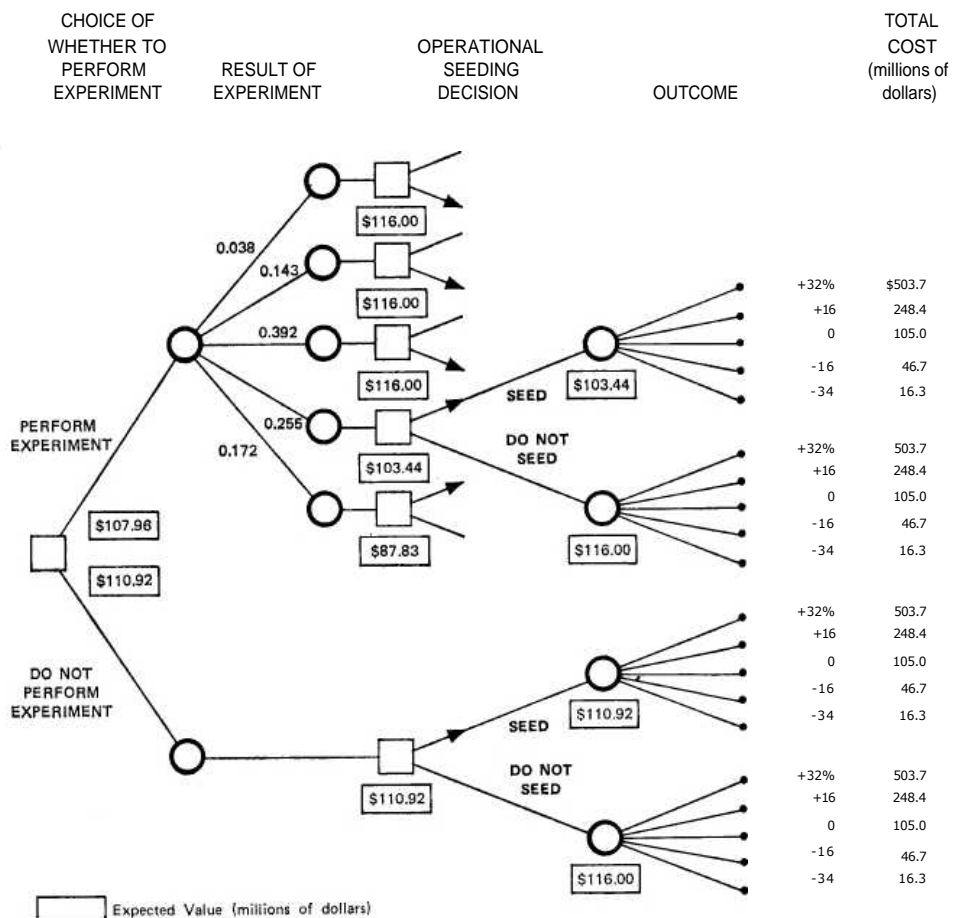

Fig. 9. Value of a seeding experiment (government responsibility cost included).

ment responsibility costs have been used. The expected value of the experiment in improving one operational seeding decision is $5.39 million, slightly less than twice the value of a single experimental seeding and more than ten times the assumed experimental cost, $0.50 million. This value represents 4.7 percent of the expected property damage if the alternative of not seeding is taken. In the discrete version used in the analysis, one of five possible value (see Table 1) is taken as representative of the observed change in hurricane intensity over a 12-hour period following seeding: - 34, - 16, 0, + 16, and + 32 percent. The order in which the results are obtained is not significant, and a total of 15 pairs of results could be obtained with two experiments (Table 2). These pairs might be placed in three groups: favorable, unfavorable, and mixed results. The probability of obtaining a pair of favorable results (- 34, - 34; - 34, - 16; - 34, 0; and - 16, - 16 percent) (26) in the two experimental seedings is .327; a pair of results in this group would provide substantial confirmation of hypothesis H_1.

For example, a repetition of the pair of results obtained with Debbie in 1969 (- 34, - 16 percent in the discrete approximation) would lead to posterior probabilities of .89 for H_1, .11 for H_2, and less than .005 for H_3. A probability of .075 is computed for a pair of strongly unfavorable results (0, +32; +16, +16; +16, +32; +32, +32 percent); in this case the probability assigned to H_1 would be revised strongly downward. The remaining mixed pairs of results do not significantly confirm or deny H_1, and these results have a total probability of .595. Within this group a small probability (.055) is accorded to conflicting results in the two experiments (- 34, + 16; - 34, + 32; -16, + 16; - 16, + 32 percent).

Another Approach to Determining the Value of Seeding Experiments

The preceding discussion indicates that the value of experiments is sensitive to the government responsibility costs that are assumed in the analysis. We may wish to determine the value of experiments in a different manner in which the issue of government responsibility is treated implicitly.

Suppose that operational seeding will be permitted only after another successful result is obtained in a pair of experiments of the Debbie type. This approximation gives a lower bound to the value of experiments because only a successful experimental result is regarded as valuable. Even if wind reductions are not observed, knowledge gained about the effects of seeding may have implications for future successful operational seeding.

The probability of a favorable pair of results in two experimental seedings of a hurricane was computed as .327. If favorable experimental results are obtained and a subsequent hurricane is seeded operationally, the expected reduction in property-damage losses is $37.88 million. Even if government responsibility costs are included, the reduction in expected losses is $26.80 million. Since these reductions occur with a probability of .327, the expected value of the experiment in improving one operational decision is $12.40 million if only the property damage is considered and $8.77 million if the decrease in property damage is partially offset by the government responsibility costs. The figures $8.77 million and $12.40 million represent 7.6 and 10.7 percent, respectively, of the $116-million property damage expected from the not-seeding alternative in the seeding decision for the nominal hurricane.

We see that the value of experiments is considerably higher than the values computed earlier. This difference results from the high responsibility costs implicit in the decision not to seed on the basis of present information. It may be a reasonable assumption that a bad outcome for the first seeding of a hurricane threatening a coastal area would have much less severe legal and social consequences if it were preceded by another successful experiment. Therefore, lowering the government responsibility costs may be appropriate after another successful field experiment.

Generalizing the Value of Additional Information

The preceding discussions are directed specifically toward updating our information about which hypothesis, H_1, H_2, or H_3, describes the effect of seeding on the maximum sustained wind speed of a hurricane. The analysis has been done for a single seeding decision for a moderately intense hurricane threatening a coastal area. Per-

Table 2. Evaluation of a future experiment with two (independent) experimental seedings. Government responsibility cost is included.

Observed change in wind speed		Prior prob-ability of obser-vation	Posterior probability of hypotheses			Subsequent operational seeding decision expected values (million dollars)		
U_1	U_2		H_1	H_2	H_3	Loss with seeding alter-native	Loss with the better alter-native	Posterior value of perfect informa-tion
- 34	- 34	.0441	.97	.03	<.005	79.87	79.87	0.80
- 34	- 16	.1009	.89	.11	<.005	84.67	84.67	2.68
- 34	0	.1140	.77	.22	<.005	92.11	92.11	5.64
- 16	- 16	.0684	.69	.30	<.005	97.08	97.08	7.53
		.3274						
- 34	+16	.0324	.65	.34	.01	100.16	100.16	9.06
- 34	+32	.0078	.60	.37	.03	105.27	105.27	12.10
- 16	0	.1915	.49	.51	.01	110.25	110.25	12.78
- 16	+16	.0651	.34	.64	.02	120.07	116.00	13.05
0	0	.1610	.28	.70	.02	123.37	116.00	10.81
- 16	+32	.0167	.29	.65	.06	126.05	116.00	11.15
0	+16	.1229	.18	.79	.03	131.35	116.00	6.78
		.5974						
0	+32	.0332	.14	.77	.09	138.02	116.00	5.51
+16	+16	.0251⁻	.10	.83	.07	138.62	116.00	3.98
+16	+32	.0145	.08	.75	.17	148.37	116.00	3.02
+32	+32	.0024	.05	.59	.36	165.72	116.00	1.98
		.0752						

Value of seeding decision with prior information	110.92
Expected value of seeding decision with seeding experiments	105.53
Value of experiment	5.39
Cost of experiment	0.50
Net expected value of experiment	4.89

feet information applies not only to a single hurricane but to all hurricanes that might be seeded operationally. The numerical results for the single nominal hurricane are summarized in the extreme left column of Table 3 and are extended to multiple hurricanes in the remaining columns.

Even if only half the hurricanes could be seeded because of tactical considerations having to do with precipitation, hurricane trajectory, and so on, the expected annual benefit from perfect information is $26 million. If we assume that only half the hurricanes could be seeded, and discount the expected benefits of perfect information for all future hurricane seasons at a discount rate of 7 percent, we arrive at $370 million. This figure represents the value of a "perfect" experiment that would determine whether H_l is true.

A single repetition of the 1969 Hurricane Debbie experiment has an expected value of $5.39 million in the context of the nominal hurricane, or about 4.7 percent of expected property damage. For the decision to seed a single hurricane in the billion-dollar range, the expected value of the experiment is ten times as high, about $50 million. For one hurricane season the value is 4.7 percent of $220 million, or $10.2 million (it is assumed again that various tactical considerations might preclude seeding in half of the cases). For all future hurricane seasons, with a discount rate of 7 percent, the value is $146 million compared with an experimental cost of about $500,000. The benefit to cost ratio is therefore about 300 . Even if only a single hurricane season is considered, the expected benefits are 20 times greater than the cost of the experiment and ten times the present annual budget for Project Stormfury.

Experimental Capability Decision

The occurrence of hurricanes is a random phenomenon. Therefore, it is uncertain whether there will be an opportunity for an experimental seeding before the arrival of a threatening storm that might be operationally seeded. Opportunities for experimental seeding have been scarce. In the last few years there have been only six experimental seedings, and these have been conducted on three hurricanes, Esther (1961), Beulah (1963), and Debbie (1969) (7). Experimental seedings have been limited to a small region

Table 3. Summary of the value of additional information on the effect of seeding. Only the 50 percent of hurricanes that are assumed to be possible candidates for seeding on the basis of tactical considerations are considered. If all hurricanes are assumed to be candidates for operational seeding, the figures of the last two columns should be doubled.

Item	Nominal hurricane used in analysis		Single hurricane season (million dollars)	All future hurricane seasons, discounted at 7% (million dollars)
	Million dollars	Per-cent-age		
Expected property damage without seeding	116.0	100.0	220.0	3142
Expected value of perfect information	13.6	11.8	26.0	370
Expected value of a field experiment consisting of two experimental seedings	5.4	4.7	10.2	146
Expected value of field experiments:				
With government responsibility costs	8.8	7.6	16.6	238
Government responsibility costs = 0	12.4	10.7	23.5	335

* If it is assumed that prior operational seeding is not permitted.

of the Atlantic Ocean accessible to aircraft based in Puerto Rico, and few hurricanes have passed through this region.

There are many other regions of the ocean where hurricanes might be found that satisfy the present criterion for experimental seeding - that is, the hurricane will be seeded only if the probability is less than .10 that it will come within 50 miles of a populated land area within 18 hours after seeding. However, a decision to expand the present experimental capability of Project Stormfury would need to be made well before the experiment itself. Whereas the seeding itself requires only that an aircraft be fitted with silver iodide pyrotechnic generators, the monitoring of the subsequent development of the hurricane requires other aircraft fitted with the appropriate instrumentation. The requirements in equipment, crew training, and communications and support facilities are substantial. In addition, permission may be needed from nations whose shores might be threatened by the seeded hurricane. The experimental decision, then, involves an investment in the capability to perform an experimental seeding. Whether an experiment is performed depends on the uncertain occurrences of hurricanes in the experimental areas.

The expected time before another experimental opportunity for Project Stormfury's present capability is about one full hurricane season. There was no opportunity during 1970. Preliminary estimates of the cost of a capability to seed hurricanes in the Pacific are about $ 1 million (27). The incidence of experimentally seedable hurricanes in the Pacific appears to be more than twice that in the Atlantic (28). Therefore, it appears advisable to develop a

capability to conduct experimental hurricane seeding in the Pacific Ocean since the benefits expected from this capability outweigh the costs by a factor of at least 5 (29).

Conclusions from the Analysis

The decision to seed a hurricane imposes a great responsibility on public officials. This decision cannot be avoided because inaction is equivalent to a decision not to permit seeding. Either the government must accept the responsibility of a seeding that may be perceived by the public as deleterious, or it must accept the responsibility for not seeding and thereby exposing the public to higher probabilities of severe storm damage.

Our report to the National Oceanic and Atmospheric Administration recommended that seeding be permitted on an emergency basis. We hope that further experimental results and a formal analysis of the tactical decision to seed a particular hurricane will precede the emergency. However, a decision may be required before additional experimental or analytical results are available. A hurricane with the intensity of Camille threatening a populous coastal area of the United States would confront public officials with an agonizing but unavoidable choice.

The decision to seed hurricanes can not be resolved on strictly scientific grounds. It is a complex decision whose uncertain consequences affect many people. Appropriate legal and political institutions should be designated for making the hurricane-seeding decision, and further analysis should be conducted to support these institutions in carrying out their work.

Role of Decision Analysis

The results of a decision analysis depend on the information available at the time it is performed. Decision analysis should not be used to arrive at a static recommendation to be verified by further research, rather it should be used as a dynamic tool for making necessary decisions at any time. Various sensitivity analyses included here indicate how new information might be expected to influence policy recommendations. However, the advent of a severe hurricane will necessitate a decision on the basis of the information then available.

The analysis of hurricane modification points up a difficulty that is common in public decision-making on complex technological issues. When the consequences of deploying new technology are uncertain, who will make the choice? While many individuals or groups may share responsibility, decision analysis conceptually separates the roles of the executive decision-maker, the expert, and the analyst. The analyst's role is to structure a complex problem in a tractable manner so that the uncertain consequences of the alternative actions may be assessed. Various experts provide the technical information from which the analysis is fashioned. The decision-maker acts for society in providing the basis for choosing among the alternatives. The analysis provides a mechanism for integration and communication so that the technical judgments of the experts and the value judgments of the decision maker may be seen in relation to each other, examined, and debated. Decision analysis makes not only the decision but the decision process a matter of formal record. For any complex decision that may affect the lives of millions, a decision analysis showing explicitly the uncertainties and decision criteria can and. should be carried out.

References and Notes

1. R. H. Simpson and J. S. Malkus, *Sci. Amer.* **211**, 27 (Dec. 1964).
2. R. C. Gentry, *Science* 168, 473 (1970).
3. Now incorporated in the National Oceanic and Atmospheric Administration.
4. R. A. Howard, *Proceedings of the Fourth International Conference on Operational Research* (Wiley, New York, 1966).
5. -----, *IEEE Trans. Syst. Sci. Cybern. 4* (1968), p. 211.
6. A detailed discussion of the research is to be found in the project's final report [D. W. Boyd, R. A. Howard, J. E. Matheson, D. W. North, *Decision Analysis of Hurricane Modification* (Project 8503, Stanford Research Institute, Menlo Park, Calif., 1971)]. This report is available through the National Technical Information Service, U.S. Department of Commerce, Washington, D.C., accession number COM-71-00784.
7. The meteorological information leading to this approximation is discussed in detail in the SRI project final report (6), especially appendix B. Meteorologists connected with Project Stormfury believe it highly improbable that seeding will cause any substantial change in the course of the hurricane, and other important consequences of seeding are not foreseen at this time. We wish to stress that our role in the decision analysis of hurricane modification has been to provide the methodology for analyzing a complex decision with uncertain consequences. The specific assumptions have been provided by the hurricane meteorologists associated with Project Stormfury and by other experts in relevant fields. Because of space limitations these assumptions cannot be discussed in detail in this article; the interested reader is advised to consult the project's final report or communicate directly with the authors. The type of seeding is assumed to be the same as that used in the Hurricane Debbie experiments: massive multiple seeding of the clouds in the outer eyewall-region with silver iodide. During September 1971, Project Stormfury conducted seeding experiments of a different type on Hurricane Ginger (R. C. Gentry, internal communication, National Oceanic and Atmospheric Administration, October 1971). The Ginger experiment involved the seeding of clouds in the rain bands well outside the eyewall region. This "rain-sector" experiment was selected because Ginger had a large and poorly formed eyewall and was judged not to be a good subject for eyewall-region seeding. Although some changes in cloud structure and wind field occurred at a time when they might have been caused by seeding, these changes were minor compared with the dramatic changes that occurred in Hurricane Debbie after seeding. Because of the difference in type of seeding, the Ginger results do not imply a need for revision of the analysis or data presented in this article.
8. In some hurricanes, such as Diane (1955) and Camille (1969), precipitation-induced inland flooding has also been an important cause of property damage. Seeding might cause some increase in precipitation. In considering the policy decision to permit seeding we ignored these precipitation effects, but they might sometimes be important in the decision to seed a specific hurricane.
9. Throughout the analysis it is assumed that seeding would be authorized and carried out by some agency of the federal government.
10. C. Holliday, *Technical Memorandum WBTM* SR-45 (Environmental Science Service Administration, Washington, D.C., 1969).
11. The details of the derivation of this probability distribution are given in appendix B of (6). The indirect approach of using the Holliday relation combined with pressure change observations was first suggested by R. C. Sheets of the National Hurricane Research Laboratory.
12. S. L. Rosenthal, *Technical Memorandum ERLTM-NHRL 88* (Environmental Science Service Administration, Washington, D.C., 1970). See also *Project Stormfury Annual Report 1970* (National Hurricane Research Laboratory, Miami, 1971).
13. A probability distribution on an uncertain quantity x will be denoted P(x) whether x takes on discrete or continuous values. If x is discrete, P(x) will be the probability mass function; if x is continuous, P(x) will be the probability density function. A probability distribution of the normal or Gaussian family specified by its mean m and standard deviation σ will be denoted $f_x(m, \sigma)$.
14. The average effect of seeding and the fluctuation from the average may be regarded as (independent) normal random variables whose sum represents the effect of seeding on a specific hurricane. According to well-known results in probability theory, this sum will be normally distributed with a mean equal to the sum of the two means and a standard deviation equal to the square root of the sum of the squares of the two standard deviations.
15. The effect of seeding and the natural change in the storm are described as independent normal random variables and the total change is their sum. The independence assumption is judged an appropriate summary of present knowledge; sensitivity to this assumption is examined in (6). Important assumptions such as this one were reviewed with Project Stormfury meteorologists. A letter to us from R. C. Gentry (October 1970) stated, "while seeding may "affect different hurricanes by differ-ent amounts, we are not yet prepared to predict these differences." The assumption of independence does not deny that there may be a relationship between the natural change occurring in a hurricane and the effect of modification. When information about this relationship becomes available, it should be incorporated into the analysis and the independence assumption should be withdrawn.
16. H. Raiffa, *Decision Analysis: Introductory Lectures on Choices Under Uncertainty* (Addiscn-Wesley, Reading, Mass., 1968); M. Tribus, *Rational Descriptions, Decisions, and Designs* (Pergamon, New York, 1969).
17. D. W. North, *IEEE Trans. Syst. Sci. Cybern.* 4 (1968), p. 200.
18. The details of the calculation of c_2 are given in (6). Similar relationships between maximum sustained wind speed and property damage have been stated by other investigators [R. L. Hendrick and D. G. Friedman, in *Human Dimensions in Weather Modification, W. R. Derrick Sewell, Ed. (Univ. of Chicago Press, Chicago, 1966), pp. 227246]. In November 1971, D. G. Friedman communicated to us some results from analyzing insurance claim data. He finds an exponent of 6.7; this value would lead to much larger reductions in property damage than were assumed in our analysis. Other investigators have suggested an equation of the form $d = c_1 (w - w_0)^2$, where c, and w_0 are empirical constants (R. C. Gentry, private communication).
19. This procedure is an approximation, which depends on the fact that seeding costs are small compared with costs of property damage.
20. It is shown in (6) that the results are not sensitive to the discrete approximation.
21. For example, if an exponential utility function with a risk aversion coefficient of y = 0.001 is used, the difference between the certain equivalents for the two alternatives increases from $21.67 million to $24.2 million. Because of stochastic dominance, any risk attitude will always leave seeding as the preferred alternative. Further discussion on risk preference may be found in (5) and (17).
22. These issues are discussed in detail in appendixes E and F of (6).
23. In answering this question we assume that the government is willing to pay up to $1 to avoid $1 of property damage.
24. It is possible for the responsibility costs to be so high that a hurricane would not be seeded even if it were certain that H_1 is true. This amount of responsibility cost implies that the government would prefer an unseeded hurricane to a seeded hurricane that caused only half as much property damage.
25. For these calculations a system of computer programs for evaluating large decision trees, developed by W. Rousseau of Stanford Research Institute, was used.
26. These discrete outcomes correspond to a reduction of 10 percent or more. The discrete approximation simplifies the analysis by restricting the number of possible experimental results. Earlier we considered the revision of probabilities based on the results of the 1969 Hurricane Debbie experiments. There the discrete approximation was not used, but it would have given equivalent results.
27. R. C. Gentry, personal communication. In arriving at this figure it was assumed that military aircraft based in the Pacific could be used in the seeding.
28. Project Stormfury Annual Report 1968 (National Hurricane Research Laboratory, Miami, 1969).
29. The details of this calculation are given in (6).
30. This article summarizes research performed for the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, contract 0-35172; the project leader is D. W. North. The authors acknowledge the substantial contribution of Dr. Dean W. Boyd. The authors also wish to acknowledge Professor Gary Widman of Hastings College of the Law, University of California, San Francisco, for legal research supporting the project and Dr. Cecil Gentry, Dr. Robert Simpson, Dr. Joanne Simpson, and many others who have been associated with Project Stormfury for their assistance and cooperation. The findings and conclusions presented are the sole responsibility of the authors and do not necessarily reflect the views of the U.S. government or any of the individuals mentioned above.