3

The value of weather information

STANLEY R. JOHNSON
and
MATTHEW T. HOLT

1. Introduction

The existing system for sensing, recording, and reporting weather conditions and producing forecasts has been developed mainly in response to demands of specific clients. Weather conditions and forecasts provided for airline navigation and agricultural production management are but two examples. The result is that the system for producing, storing, and disseminating weather data and forecasts has strong historical linkages to the demands of major clients and the sensing and recording technologies available at the time of implementation. Location of first-order stations at airports, the cooperative observer system, frequency of reporting, and the levels in the atmosphere at which data are observed all can be viewed as having a user-based history.

With the advent of new sensing, recording, and reporting technologies, and changing needs of existing clients and the entry of new clients, there has been a growing effort to justify economically the system supplying these services. Weather data and forecasts are produced to a large extent by the public sector and made available at a highly subsidized user cost; that is, the data are public goods. To provide an economic rationalization for the production and dissemination system, it must be shown that the rate of return, or benefit relative to cost, is consistent with that available from alternative employment of societal resources. For this calculation, the relevant cost and benefit concepts are, of course, social, as opposed to private or individual.

The effort to justify economically the weather information system has resulted in a number of research activities and suggested organizational changes. One way to value the weather information system would be to make it private in some way and then estimate its value from sales of privatized information. Proponents agree that this alternative would produce the service in such a manner that the market would automatically value it. This approach to valuation and resource allocation has recently received increased attention as indicated by the initiation of user charges for certain types of weather information and related services. Although still at an early stage, this method of organizing the production and delivery system for weather information can be viewed as "testing" the market for these services. In fact, extensive privatization of weather information services has already been implemented in countries such as New Zealand and Sweden.

It is, however, important to recognize that a market-based approach may not be efficient for valuing weather information or allocating resources. Weather information is a nonrival and, to a large extent, nonexcludable commodity. That is, two or more consumers can simultaneously use the same unit of weather information (nonrival) and it is not, in general, possible to prevent certain groups or individuals from using available weather information (nonexcludable). The implication is that market equilibrium is not optimal, since the economic externalities of weather information are not incorporated into individual decision making. Theoretically, either an artificial market must be established (i.e., a system that artificially assigns property rights for weather information) or a socially optimal tax-subsidy scheme must be implemented, if an efficient resource allocation to the weather information system is to be attained (Malinvaud, 1971). Hence information obtained from testing the market must be viewed cautiously as an input to the design of a socially optimal weather information service.

To complement the market experiments, research has been undertaken to develop more formal valuations of weather information systems in specific contexts. This research has involved one or two primary emphases. The first emphasis is related to determining the value of weather services, or specific components of those services, for both individual decision-making units and society as a whole. This applied research is carried out with the goal of actually assigning monetary values to the components of the weather information studied. Applied studies of information value at the individual decision level are the most numerous and the most cogent. The second research emphasis is on developing appropriate methods for measuring and estimating individual and societal values of weather information services.

The present chapter has the objective of reviewing the progress that has been made in valuing the weather information system. First, selected concepts from the economics of information are reviewed. The intent is to provide a general framework for analyzing valuation methods currently employed. Then, selected studies that have estimated the economic value of particular components of the weather information system are discussed. This exercise — comparing valuation theory with applications for the weather information system — raises a number of questions. Important issues posed by the questions pertaining to design of valuation studies, privatization, and resource allocation are then examined. Finally, a few observations are provided on the progress in valuation methods and the potential for new analyses to improve the basis for designing and organizing the weather information system.

A final caveat is in order. In this chapter we do not discuss what we refer to as "impact assessment" studies, which seek to determine the impact of a weather-related event on a particular segment of the economy or society. An excellent example of these types of studies is provided by Roll (1984), who examined the causal relationships between temperature and rainfall near Orlando, Florida, and the price of frozen concentrated orange juice contracts. While impact assessment studies provide valuable information for policy makers and for decision makers about the isolated effects of weather-related events on specific markets or market participants, these studies do not in any way represent true value-of-information assessments in the context of the system for producing and disseminating weather data and forecasts.

2. Economics and the value of information

The economic theory of information value has progressed significantly in recent years. With the development of the von Neumann–Morgenstern utility hypothesis, and the refinement of decision theory under uncertainty (Arrow, 1965; Pratt, 1964), the integration of value-of-information theory into mainstream economic thinking has occurred rapidly. In short, the development of risk or uncertainty theory has provided a basis for reconciling a number of important issues related to the value of information in society, investment in the production of information, impacts on price determination, relationships between information and prices, etc. (Fama, 1970; Grossman and Stiglitz, 1976; Gould, 1974; Hayek, 1945; Hess, 1982; Hirshleifer, 1971, 1989; Kunkel, 1982; Marschak, 1971; McCall, 1965; Riley, 1979). Surveys of value-of-information theory that provide an integration and synthesis of available results can be found in Hirshleifer and Riley (1979, 1992) and Stigler (1961). In addition, there have been a number of studies in the management science/statistics literature that have advanced basic concepts and methods for information valuation (e.g., Blackwell, 1953; Blackwell and Girshick, 1954; DeGroot, 1970; Hilton, 1981; Raiffa, 1968; Winkler, 1972). The present discussion reviews key theoretical concepts that are helpful in interpreting available empirical results on the valuation of weather information. We also suggest a possible framework for improving the generality and scope of future investigations.

2.1. Information and individual valuation

The approach in modern economic theory is simply to view information as a factor in the decision process that can be used by economic agents (or decision makers) to reduce uncertainty (i.e., so-called Bayesian decision theory). A stylized individual decision model illustrating the central concepts of the theory can be developed as follows. Subjective probabilities, along with the assumption that agents can assign a unique utility ranking to all possible outcomes, are keys to the theory (von Neumann and Morgenstern, 1944; Winkler, 1972).

Consider a set of actions or "terminal" moves, $a = 1, \ldots, N$, that an economic agent (i.e., a user of weather information) can choose among, and a set of possible states of the world (i.e., weather events in this case), $s = 1, \ldots, M$, over which the agent is assumed to have no direct control. A finite number of actions a, as well as a finite number of states s, are assumed for convenience; it is, however, a straightforward matter to extend the model to accommodate an infinite number of actions and states. The consequences resulting from each possible action and each possible state of the world $c(a, s)$ are, in all instances, presumed known to the agent. Furthermore, the agent is assumed to have the ability to rank the possible consequences of each action according to relative desirability. That is, the individual is assumed to possess a utility function u whose composition with c determines a preference relation $u[c(a, s)]$, which is defined over the set of all possible actions and consequences. In the present framework, uncertainty arises because the agent must choose an action prior to observing the realized state. This uncertainty is characterized formally by a set of subjective probabilities associated with realizing each of the various states.

The agent is assumed to have a prior probability distribution on the possible (finite) states of the world, with the subjective probabilities for the agent being denoted by p_s. In practice, these subjective probabilities may be based on historical weather data and are termed "climatological information" elsewhere in this volume. The individual decision problem is then to select the action a_o that satisfies

$$E\{u[c(a_o, \cdot)]\} = \max_a E\Big\{u[c(a, \cdot)]\Big\} = \max_a \Big\{\sum_s p_s u[c(a, s)]\Big\}, \quad (3.1)$$

where $E\{u[c(a, \cdot)]\}$ (the dot indicates expectation with respect to the distribution p_s for the state s) is the expected utility to the individual decision maker if action a is taken. Note that if the decision maker is risk neutral, the utility maximization problem is equivalent to choosing the action that maximizes the expected profit. This follows from the fact that marginal utility is constant in the risk neutral case, irrespective of the level of income.

The agent's subjective probability distribution on states of the world can be modified by acquiring information. In the present context, information can be viewed as a set of possible messages. These messages, denoted $i = 1, \ldots, I$, provide the basis for revising the probabilities associated with each state of the world. This revision process may, in turn, lead to a different choice of "terminal" action. The decision maker, however, does not know in advance which among the possible set of messages will be received. This result implies that *ex ante*, or before the message is received, the decision maker must determine a subjective probability q_i of receiving message i. The probability q_i is in turn related to the conditional probabilities or likelihoods $q_{i,s}$ of receiving message i given state s, and is determined by

$$q_i = \sum_s q_{i,s} p_s, \quad (3.2)$$

where p_s represents the previously defined subjective (or prior) probability associated with state s.

Bayes' theorem, in combination with the message probabilities defined in equation (3.2), provides a basis for revising or updating the probabilities attached to each state of the world. More specifically, after receiving message i, the decision maker can determine the posterior probability of state s given message i by

$$p^*_{s,i} = \frac{q_{i,s} p_s}{q_i}, \tag{3.3}$$

where $p^*_{s,i}$ denotes the posterior probability. We note that, in practice, the weather forecasting system can be viewed as directly producing these posterior probabilities (instead of the likelihoods).

Figure 3.1 provides an illustrative example of a Bayesian revision for the case of continuous s. (Here a continuous state space is assumed simply to facilitate graphical representation.) The likelihood function shows the probability of receiving message i given state s (i.e., $q_{i,s}$). The prior probability distribution defines unconditional probabilities p_s associated with state s before message i has been received. Initially the individual believes relatively higher values of s are more likely, as indicated by the location of the prior distribution. The likelihood function, however, shows that the probability of receiving message i is higher for relatively low values of s. The revised or posterior probability distribution then represents a composite of the prior distribution and the likelihood function, as determined by Bayes' theorem in equation (3.3). As is clear from equation (3.3), the more certain are the prior beliefs p_s, the more closely the posterior distribution will resemble the prior distribution irrespective of the values of q_i and $q_{i,s}$. This phenomenon is referred to in value-of-information theory literature as the distinction between "hard" versus "soft" prior beliefs about possible states of the world (Hirshleifer and Riley, 1992). Moreover, the foregoing observation suggests that the greater the level of initial confidence pertaining to a particular state s, the lower the value the individual will attach to receiving message i (but this is not necessarily the case in general). In weather applications, prior information is typically very diffuse.

Values of additional or new information (i.e., the message) are based on the expected utility from the more informed decision as

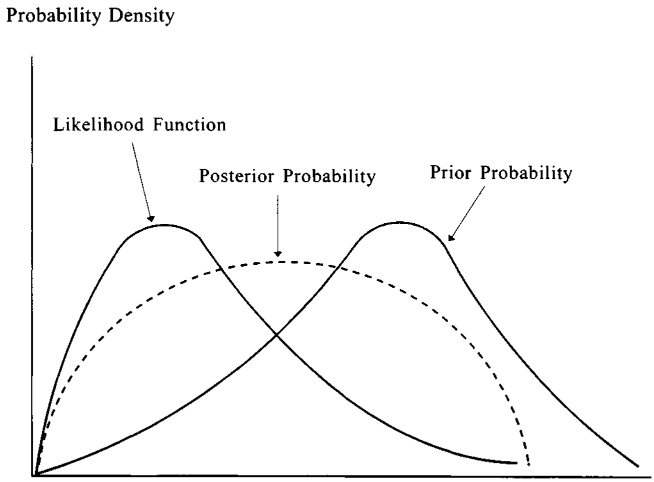

Figure 3.1. Bayesian probability revision.

compared to the expected utility without the information. Several measures of the economic value of imperfect information exist (Hilton, 1981). One measure of the value of information is the difference in expected utility,

$$V_i = E_i\{u[c(a_i, \cdot)]\} - E\{u[c(a_o, \cdot)]\}, \tag{3.4}$$

where E_i denotes expectation with respect to the posterior probabilities. The information decision problem for the individual decision maker is then one of comparing the two optimal choices, a_o and a_i. Under the first optimal choice, a_o, which is the optimal action given only prior information, the information or message i has yet to be received. Under the second optimal choice, a_i, where a_i denotes the optimal action given message i, the information has been received and processed in accordance with equation (3.3) to form $p^*_{s,i}$, the posterior probability associated with state s. Alternatively, another valuation measure is the "demand value," that is, the maximum amount that the decision maker would be willing to exchange for the system (Hilton, 1981).

The above illustrative valuation problem is *ex post* in nature in the sense that information is valued *after* the message has been received, but before the actual state of the world is known. While this simplified version of the information decision problem is useful and, in fact, characterizes much empirical work on information valuation, at the individual level, it must be stressed that the problem is not yet formulated as typically perceived by the decision maker. The information decision as typically encountered is an *ex ante* problem, in that the decision maker does not know *a priori* which message will ultimately be received.

To formulate the *ex ante* information valuation problem, consider the agent's decision about additional or new information. The individual in this circumstance does not know in advance which message will be received. To simplify, assume the agent purchases information from a vendor. Alternatively, this information could be provided by a public agency (e.g., a national weather service). If the information has no cost, then the *ex ante* value of information to the individual decision maker is characterized by

$$V^* = \sum_i q_i E_i\{u[c(a_i, \cdot)]\} - E\{u[c(a_o, \cdot)]\}, \qquad (3.5)$$

where the probability distribution q_i reflects the agent's uncertainty about receiving message i. The decision problem in this extended context is thus one of summing or integrating over all possible messages and associated probabilities. The *ex ante* valuation implied by equation (3.5) represents the expected utility gain associated with receiving information. As such, equation (3.5) is not a monetary measure of information value, but rather a utility-based measure. As already mentioned in conjunction with equation (3.4), an alternative to equation (3.5) is the demand value of this information. This measure is equivalent to equation (3.5) if the utility function is linear or negative exponential.

2.2. Information and market valuation

In principle the value-of-information problem for the individual agent can be developed in a straightforward manner; the market determination of information value, however, is more difficult. Two issues complicate the market valuation problem: (i) the equilibrium condition for the market and how this equilibrium condition is modified by the introduction of additional information; and (ii) the aggregation of individual responses to produce market level supply and/or demand functions used in establishing economic value. Of course, the *ex ante–ex post* decision problem remains (Choi and Johnson, 1987).

Recent developments in rational expectations theory provide a tractable way of formulating economic models when agents must make decisions on the basis of imperfect information. The rational expectations hypothesis essentially implies that individuals understand the underlying structure or fundamentals of the market in which they participate and act on that information (Muth, 1961). Although there are other expectations theories, and while the informational assumptions of the rational expectations hypothesis are rather rigid, the rational expectations approach is nevertheless useful as a benchmark against which to compare results of other expectations hypotheses. Moreover, the rational expectations approach is attractive for its consistency with other behavioral assumptions included in the economic model specification (i.e., expected utility maximization, etc.).

Results that are based on formulating economic models with rational expectations and developing appropriate microeconomic foundations for market equilibria when market participants face uncertainty have been obtained only recently (Newberry and Stiglitz, 1981; Wright, 1979; Innes, 1990). Many studies that have applied the rational expectations framework have evaluated price or revenue stabilization policies in competitive markets. They show that the benefits of intervention in competitive markets result from the more stable environment provided for producers and/or consumers. A modest extension of these results is to consider market intervention through added information about uncertain events, even if at a cost to participants (Babcock, 1990).

As a simple illustration of the above concepts, consider a case in which N identical producers of a homogeneous good face a demand schedule with a stochastic component. Producers are presumed to make production decisions *ex ante*, before the output demand is realized. The number of market participants, N, is also assumed large enough that the industry can be considered competitive. If q represents output of a single representative producer, then $Q = Nq$ is industry output. A general representation of the stochastic market demand function is given by

$$P = P(Q, \mu), \ \partial P/\partial Q < 0, \tag{3.6}$$

where μ is a random variable with distribution function $G(\mu)$. For a given level of market output Q, the distribution function

$G(\mu)$ determines completely a price distribution $F(P|Q)$, and an expected inverse demand function

$$\overline{P}(Q) = \int_{0}^{\infty} P dF(P|Q) = \int_{-\infty}^{\infty} P(Q, \mu) dG(\mu). \tag{3.7}$$

In previous studies the risk averse producer has been assumed to have a subjective distribution $F^e(P)$ of possible price outcomes (Baron, 1970; Sandmo, 1971; Leland, 1972). By invoking the rational expectations hypothesis in the present model, it is assumed that the true distribution $G(\mu)$ ultimately coincides with producers' subjective beliefs. That is, once producers make a subjective estimate Q^e of industry output Q, the subjective distribution $F^e(P) = F(P|Q^e)$ is completely determined.

Given the subjective price distribution $F^e(P)$, a producer will maximize expected utility of profit

$$E[U(\pi)] = \int_{0}^{\infty} U[Pq - c(q)] dF^e(P), \tag{3.8}$$

where $U(\cdot)$ is a von Neumann–Morgenstern utility function and $c(q)$ is an appropriate cost function. Since the representative producer's optimal output q^* depends on the subjective estimate Q^e, we can write optimal output as $q^* = q^*(Q^e)$. Thus, industry output is expressed as

$$Q^* = Nq^*(Q^e) = H(Q^e), \tag{3.9}$$

where $H(\cdot)$ denotes the mapping between expected output, Q^e, and optimal industry production, Q^*. The rational expectations hypothesis, as used in this simplified context, implies that firms' subjective price distribution $F^e(P)$ will equal the actual price distribution $F(P)$ (Choi and Johnson, 1991). Of course, at the end of the period when market demand is realized, producers only observe the actual market price and not a distribution. An important feature of the present model is that firms can verify *ex post* the rationality of their production decisions by comparing Q^e with Q. Because $F(P|Q^e) = F(P|Q)$ if and only if $Q = Q^e$, the rational expectations hypothesis implies that market equilibrium occurs in the present context only when actual and anticipated output are equal.

The above framework can be used to investigate the market valuation of information. As Chavas and Johnson (1983), Pesaran (1987), and others point out, a number of interesting parallels exist between value-of-information theory and the formation of rational expectations. The exact nature of the linkage depends on the amount of information available and its cost at the time the firm makes production decisions. With additional information, producers could revise their subjective estimates of the price distribution $F^e(P)$, as well as their subjective estimates of all relevant distribution parameters. Additional information should, in general, improve resource allocation and enhance market efficiency. Even if additional information did nothing more than bring about a change in dispersion without changing the distribution's mean (Rothschild and Stiglitz, 1970), however, we would still expect different outcomes or market results. The reason for this is that any change in the dispersion parameter of $F^e(P)$, even if the centrality parameter remains unchanged, will affect optimal output decisions for risk averse producers that maximize expected utility.

A number of refinements and extensions can be made to the above model. The simplified model is included only to suggest the complexity of the market valuation problem. For instance, the model could be extended to include a stochastic production process. In this case, q becomes a random variable with a distribution conditioned on the level of inputs. Producers would then determine subjective estimates of the joint distribution of P and Q in a manner consistent with the rational expectations approach. Not only does the rational expectations framework have important implications for estimating the market value of information, but it also raises a number of questions about the "appropriateness" of conventional valuation theory under a scenario of uncertainty, as well as questions about the empirical methods presently employed in estimating market relationships from *ex post* or observed market outcomes for use in valuation exercises.

It is now recognized that standard producer surplus is an inappropriate measure of welfare under conditions of uncertainty (see, e.g., Pope, Chavas, and Just, 1983). By employing the rational expectations market equilibrium framework, the information valuation problem can be addressed more systematically. The *ex post–ex ante* problem remains, however. Most surplus measures used in the economic theory of value are *ex post*, and based on the assumption that all relevant economic variables are known with certainty (i.e., are nonstochastic). Recently it has been shown that these concepts must be modified if the information valuation problem is viewed in an *ex ante* context (Choi and Johnson, 1987).

More specifically, three commonly applied welfare measures are Marshallian consumers' surplus, compensating variation, and equivalent variation. Marshallian consumers' surplus is simply the area under the demand curve and will be explained more fully in Section 3.2. Compensating variation is defined as the additional income necessary, after a price change, to restore an individual to the original level of well-being that was enjoyed before the price change occurred, assuming the new price level holds. Equivalent variation is the amount of income necessary, after a price change, to restore the individual to the original level of utility, assuming that the initial price still holds. The distinction is that compensating variation uses an "after-price change" base, while equivalent variation uses a "before-price change" base. Willig (1976) has illustrated under very general conditions that Marshallian consumers' surplus closely approximates compensating variation. This fact, coupled with ease of application, has resulted in the continued use of Marshallian surplus measures in empirical valuation studies (a classic reference is Hayami and Peterson, 1972).

An additional complication arises, however, if price is a random variable. The most common approach in this instance is to recognize that the surplus measures are also random variables and that their expectations will provide an indication of average benefits accruing to an individual (Waugh, 1944). It has been shown recently, though, that these concepts must be modified if the information valuation problem is to be viewed *ex ante*. In particular, it has been demonstrated that expected Marshallian consumers' surplus (and, consequently, expected compensating variation) is a valid welfare measure only in the special case when marginal utility of income does not depend on price (Turnovsky, Shalit, and Schmitz, 1980; Rogerson, 1980). Even with these clear conceptual problems, expected Marshallian consumers' surplus is widely used (e.g., Burt, Koo, and Dudley, 1980; Taylor and Talpaz, 1979).

Several authors have proposed measures to determine correctly the consumer benefits in a stochastic setting. Specifically, Anderson (1979a) and Helms (1985) have argued that *ex ante* compensating and equivalent variations are improved measures of consumer benefits when price is a random variable. These *ex ante* measures are appropriate in the present context for evaluating weather information. The relevant compensation experiment is to determine how much income the potential user would be willing to forgo in exchange for the information service before the outcome is known.

In previous value-of-information studies, expectations of Marshallian consumers' surplus measures have typically been applied to assess the economic benefits of information (i.e., Bradford and Kelajian, 1977). As indicated in the preceding discussion, however, Marshallian consumers' surplus measures are inappropriate if the valuation problem involves stochastic prices, and is thus *ex ante*. Furthermore, because expected compensating variation employs an after-price change base, it is the amount of monetary income necessary, on average, to compensate a consumer for facing prices in a no-information environment if the compensation is paid *after* the random price is observed. Clearly, this measure does not reflect the willingness of the individual to pay for an information service before observing the actual price outcome.

Although *ex ante* compensating and equivalent variations are appropriate welfare measures in a stochastic price setting, these measures are of limited practical value. They require information about risk attitudes of consumers and about properties of the direct utility function that are difficult to obtain. These limitations may explain the continued use of expected consumer's surplus measures in empirical valuation studies. Alternatively, Hausman (1981) has shown that compensating and equivalent variation measures — and consequently the expected values of these measures — can be recovered from many common forms of estimable demand functions (e.g., linear, double logarithmic, etc.). Choi and Johnson (1987) have provided further justification for the use of expected equivalent variation in empirical applications. They show that expected equivalent variation and *ex ante* equivalent variation are identical if the individual is risk neutral. More important, they demonstrate that expected equivalent variation provides a lower bound for *ex ante* equivalent variation when individuals are risk averse in income. These favorable aspects of expected equivalent variation suggest it will be more widely applied in future studies of information value.

3. Review of selected value-of-information studies

In recent years, a number of studies have attempted to value the weather information system, as well as particular weather information collection and dissemination systems. Studies examining these and related issues are too numerous to allow a complete enumeration here. Our objective is to highlight briefly selected studies illustrative of the kinds of issues examined and the methods used to value weather information. In addition, emphasis is placed on the studies that have provided actual value estimates of improved weather information. As already indicated, the literature on the value of weather information generally falls into two broad categories: (i) the value of weather information to individual decision makers; and (ii) the value of weather information at the market level. Examples of studies conducted under both of these categories are presented here; more examples and further details on studies under category (i) can be found in Chapter 4 of this volume.

3.1. Individual decision applications

Of the two areas, primary research emphasis has been placed on valuing weather information at the individual decision-making level. As discussed in Section 2.1, individual valuation studies are generally couched in a decision-analytic framework. Many of these studies involve a "cost–loss situation," in which a decision maker must choose one of two actions: protect an activity or operation at a known cost or face the risk of, perhaps catastrophic, loss. Upon receipt of the forecast information, initial probabilities for each state of nature can then be revised in accordance with Bayes' theorem. See Section 2.1 and, specifically, Bayes' theorem as presented in equation (3.3), for additional details. In all cases, the decision maker is assumed to choose the action maximizing expected return (minimizing expected expense) or maximizing expected utility.

Table 3.1 summarizes a number of applied studies that have examined the value of weather information for individual decision-making units. Studies that have used a Bayesian framework for analyzing the value of weather information include those by Baquet, Halter, and Conklin (1976), Katz, Murphy, and Winkler

(1982), Stewart, Katz, and Murphy (1984), Mjelde et al. (1988), Hashemi and Decker (1972), and Byerlee and Anderson (1969). Note that the Baquet et al. study relied on the more general demand value measure of the value of information mentioned earlier. Other Bayesian decision-analytic studies are reviewed in Chapter 4 of this volume. Anderson (1979b), Lave (1963), and Sonka, Changnon, and Hofing (1988) have used a "cost–loss" approach in valuing weather information. Additional studies have determined the value of weather information to individual decision-making units by using less structured subjective measures. These studies typically involve surveys of users in which the respondents are asked to estimate subjectively the value of an information service. One example is the survey by Ewalt, Wiersma, and Miller (1973). See also Chapter 5 of this volume for a more detailed discussion of the survey approach.

3.2. Market applications

While studies investigating information value to individuals are numerous, far fewer inquiries into the social value of weather information have been made. Most studies assessing the social value of information use *ex post* Marshallian surplus or benefits measures. It is assumed that producers and/or consumers make economic decisions with uncertainty about the possible outcomes. The benefits of information result either because markets have a temporal dimension (i.e., inventory levels are adjusted) or because economic agents have flexibility to adjust to new (more current) information.

Figure 3.2 illustrates how the Marshallian framework is typically applied to estimate the social returns from improved weather information when markets are temporally linked. Holders of storage (i.e., arbitragers) decide the level of inventories to carry forward from period 1 on the basis of expectations about production in the second period. If it were known that quantity Q_1 would be produced in the first period and quantity Q_2 in the second period, then social value would be maximized by choosing an inventory level equating prices in the two periods (in the absence of storage costs and time preference for money). That is, with identical linear demands, the optimal inventory divides total output $(Q_1 + Q_2)$ equally between the two periods. Now, suppose agents do not know Q_2 — perhaps it depends on stochastic climate conditions

Table 3.1. Summary of selected value-of-information studies: individual decision applications

Investigators	Subject	Weather Characteristics	Weather Impact Variables	Information Concept	Value System	Valuation Method	Conclusion
Baquet et al. (1976)	Value of frost fore. to pear orchard managers	Temp.	Bud damage & yield loss	Daily min. temp. fore., hist. wea. info.	Individual	Bayesian, expected utility max.	US NWS frost fore. had approx. value of $13.32/ha-day for risk averse decision makers.
Katz et al. (1982)	Value of frost fore. to orchardists in Yakima Valley	Temp.	Bud damage & yield loss	Daily min. temp. fore., hist. wea. info.	Individual	Bayesian, expected cost min., Markov decision process	Value ranged from $667 to $1,997/ha-yr.
Stewart et al. (1984)	Value of frost fore. to apple orchardists in Yakima Valley	Temp., dew pt.	Bud damage & yield loss	Daily min. temp. fore. & post fore. temp. & dew pt.	Individual	Bayesian, expected cost min.	Approx. $1,885/ha-yr.
Wilks & Murphy (1985)	Value of prec. fore. for haying/pasturing decisions in west. Oregon	Prec., temp.	Net income from pasturing or haymaking; hay quality	Seasonal prec. fore.	Individual	Bayesian, expected utility max.	Value of current fore. ranges from $0.00 to $1.41/ha-day.
Hashemi & Decker (1972)	Irrigation scheduling in corn prod.	Prec.	Irrigation freq.	Prec. prob. fore.	Individual	Bayesian	Reduction in magnitude & freq. of supplemental irrigation.

Ewalt et al. (1973)	Value of prec. & field condition fore. to Indiana farmers	Prec., field conditions	None	Prec. & field condition fore.	Individual	Survey (subjective)	Value of fore. positively related to soil types. Highest values obtained for spring mos.
Lave (1963)	Value of better wea. info. to raisin industry	Prec., deg. days	Grape yields & uses (i.e., raisins, crushing, etc.)	Perfect prec. fore.	Individual, market	Cost–loss & impact on industry profits	Value of perfect 3-week fore. is $225/ha. Partial equilibrium analysis shows industry profits fall with improved wea. fore.
McQuigg & Thompson (1966)	Natural gas demand in Columbia, MO	Heating deg. days	Demand for natural gas	Fore. of heating deg. days	Individual	Loss function	Value of wea. info. depends on ability of user to translate effectively such info. into economic terms.
Tice & Clouser (1982)	Value of wea. info. to individual corn producers	Min. & max. soil & air temp. & daily prec.	Corn & soybean yields	Prob. knowledge of wea. indices	Individual	Accounting, expected profit max.	Utilizing current wea. info. & prob. of future wea. events results in increased returns of $3.66 to $9.86/ha.
Anderson (1979b)	Value of extended-period wea. fore. in pea prod. & logging	Temp., prec.	Ripening date for peas. Road improvement costs for logging	Prob. knowledge of wea. data	Individual	Cost–loss	Savings level varies depending on conditional prob. of "bad" outcome given that unfavorable outcome has been predicted.

Table 3.1 continued.

Investigators	Subject	Weather Characteristics	Weather Impact Variables	Information Concept	Value System	Valuation Method	Conclusion
Byerlee & Anderson (1969)	Value of prec. predictors in wheat yield response functions	Prec.	Wheat yield through nitrogen, prec., soil moisture interactions	Prediction of annual prec. trends	Individual (*ex ante*)	Bayesian, expected profit max.	Values of prec. predictors ranged from 0.7 to 89.0 cents/ha.
Brown et al. (1986)	Value of seasonal wea. fore. to wheat farmers in Great Plains	Prec., soil moisture	Wheat yields	Clim. info. & imperfect fore. of wea. conditions	Individual	Expected profit max.	Value of current & perfect fore. estimated between $0.00 & $196.62/ha, resp.
Sonka et al. (1987)	Value of seasonal wea. fore. to Illinois corn producers	Temp., prec., solar radiation	Corn yields	Hist. freq. of clim. conditions	Individual	Expected profit max.	Value of perfect annual fore. varies from $21.20 to $45.99/ha-yr. Fore. for early summer crop stage were most valuable.
Bosch & Eidman (1987)	Value of soil moisture & wea. info. to irrigators	Temp., prec., solar radiation	Irrigation schedule	Perfect fore. of prec. & evapotranspiration for 3-day horizons	Individual	Expected profit, generalization stochastic dominance	Value of perfect wea. & soil info. varies from $2.47 to $40.28/ha, depending on degree of risk aversion.

Mjelde & Cochran (1988)	Bounds on wea. info. value to corn producers	Temp., prec., solar radiation, wind	Corn yields	Perfect fore. of seasonal clim. indices	Individual	Net returns, stochastic dominance	Value of perfect fore. varies between \$0.00 & \$218.00/ha-yr, depending on prior knowledge & deg. of risk aversion.
Mjelde et al. (1988)	Value of seasonal wea. fore. to corn producers	Temp., prec., solar radiation, wind	Corn yields	Seasonal wea. fore. at various crop stages	Individual	Bayesian, expected net returns max.	Expected value of perfect fore. varies from \$17.95 to \$28.46/ha-yr, for different levels of prior knowledge.
Sonka et al. (1988)	Value of wea. fore. to major seed corn producing firm in Midwest	Temp., prec.	Corn yields	Seasonal temp. & prec. fore.	Individual	Cost–loss	Savings from perfect info. between 2 & 5% of production cost. Fore. of adverse conditions, accurate only 50% of time, had 2/3 value of perfect fore.
McGuckin et al. (1992)	Value of field clim. info. to irrigators	Temp., prec., soil moisture	Corn yields	Soil moisture as function of temp., prec., & soil type	Individual	Av. cost reduction	Moisture sensors can improve technical efficiency by 3.9% on av. Value of info. depends on producer's technical efficiency, & ranges from \$40 to \$58/ha.

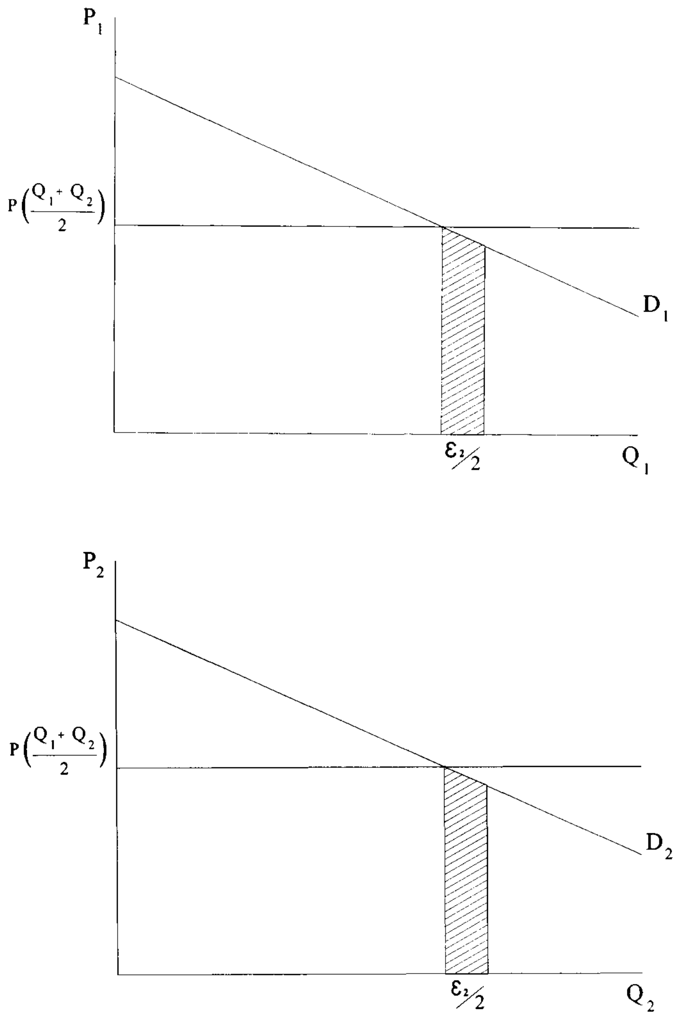

Figure 3.2. Welfare effect of forecast error: (top) period 1 consumption; (bottom) period 2 consumption.

— and instead use $Q_{2,1}$, which differs from Q_2 by a forecast error ε_2. Arbitragers will then hold in inventory an amount equal to $(Q_1 - Q_{2,1} - \varepsilon_2)/2$, which is $\varepsilon_2/2$ less than the amount $(Q_1 - Q_2)/2$. That is, if ε_2 is positive, too little inventory is held relative to a situation of perfect foresight.

The dollar loss in consumption in period 2 is given by the hatched trapezoid in Figure 3.2 (bottom). This area shows the extra consumption value attached to perfect foresight. Period 1 consumption is correspondingly larger than it otherwise would have been, with the resulting dollar gain due to the additional consumption equal to the hatched area in Figure 3.2 (top). Since demand is nonrandom, the net loss in value relative to what would have occurred with a perfect forecast is given by the area of the rectangle with base $\varepsilon_2/2$ and height $\beta\varepsilon_2/2$, where $-\beta$ is the slope of the (linear) inverse demand function. Thus, the net social loss is $\beta\varepsilon_2^2/4$. An analogous argument holds when ε_2 is negative. Assuming that $E(\varepsilon_2) = 0$, the expected value of the social loss is given by $\beta\sigma^2/4$, where σ^2 represents the forecast error variance.

Increasing the accuracy of the forecast (i.e., reducing the forecast error variance) can be evaluated to determine the marginal social benefit of improvements in forecasting accuracy. A similar framework can be used to evaluate the social benefit of improved intraseasonal forecasts when producers have the flexibility to adjust production responses to the new information. Various forms of the above approach have been used to value information for crop and livestock forecasting systems; for example, Hayami and Peterson (1972), Bradford and Kelajian (1977, 1978), Freebairn (1976), and more recently Adams et al. (1995) (see Table 3.2).

Only a few studies have attempted to estimate directly the social value of weather forecasting per se. Furthermore, the only studies conducted to date in a rational expectations framework are by Antonovitz and Roe (1984) and Babcock (1990), although in neither case did the analysis focus on public policy aspects of improved forecast performance. Lave (1963) examined the potential worth of improved forecasts for the raisin industry, but his conclusion was limited to the argument that better forecasts would result in larger output and, because of the inelastic nature of raisin demand, prices and revenues would fall. He did not, for example, directly estimate consumer benefit. One recent attempt to assess the economic returns from improved weather forecasts was undertaken by Adams et al. (1995). Their study focused on estimating the value of improved El Niño–Southern Oscillation forecasts to the agricultural sector in the southeastern United States. The results indicated that, under a free-market setting (i.e., in the absence of farm programs), the value of perfect forecasts is \$145 million (in 1990 dollars), while the value of imperfect but improved forecasts is \$96 million (again, in 1990 dollars).

Table 3.2. Summary of selected value-of-information studies: market applications

Investigators	Subject	Weather Characteristics	Weather Impact Variables	Information Concept	Value System	Valuation Method	Conclusion
Lave (1963)	Value of better wea. info. to raisin industry	Prec., deg. days	Grape yields & uses (i.e., raisins, crushing, etc.)	Perfect prec. fore.	Individual, market	Cost–loss & impact on industry profits	Value of perfect 3-week fore. is $225/ha. Partial equilibrium analysis shows industry profits fall with improved wea. fore.
Freebairn (1976)	Value of commodity price outlook info.	—	Supply response is function of producer price fore. in previous periods	Improvement in accuracy of commodity price fore.	Market	Marshallian surplus	Potential gross benefits for wool, lamb, wheat, barley, & potato markets in Australia was at least 1% of gross value of commodity.
Antonovitz & Roe (1984)	Value of rational expectations fore. in fed. beef market	—	Supply response is function of expected mean & variance of price	Fore. of mean and variance of market price	Market	Marshallian surplus	Av. *ex ante* value of rational expectations fore. vs. ARIMA fore. was $0.21 per cwt. over 1970–80 in 1972 $.
Bradford & Kelajian (1978)	Value of wheat crop fore. infor. in US	—	Wheat inventory adjustments	Wheat crop fore.	Market	Marshallian surplus	Point estimate of annual loss to US economy of less than perfect wheat crop fore. is $64 million (1975 $).
Hayami & Peterson (1972)	Marginal social returns to improved crop & livestock statistics	—	Prod. & inventory adjustments	Reduced sampling error contained in USDA survey	Market	Marshallian surplus	Marginal benefit–cost ratios associated with 0.5% reduction in sampling error found to be between 600 to 9 & 100 to 9.
Adams et al. (1995)	Value of improvements in El Niño fore. to US agriculture	Prec. & temp.	Various crop yields	Improvements in accuracy of fore. relative to perfect info.	Market–regional	Marshallian surplus	Free-market value of perfect info. is $144.5 million and of improved fore. $96 million (1990 $).

Clearly, considerable scope exists for improving estimates of the social worth of weather information. In addition to the theoretical problems identified in previous sections, market valuation studies have been hampered by the fact that weather information is a publicly available good, and that diverse groups typically use the same types of weather information. This means that it is frequently difficult to account for all the benefits that result from even a single weather-related prediction.

4. Valuation puzzles

The review of selected empirical value-of-weather information studies and the brief sketch of the theory have suggested several problems or puzzles. If resolved, they represent opportunities for improving the design of weather information systems. The discussion of these puzzles or issues is not intended to imply that the process of providing a more systematic basis for valuing weather information is beyond reach, but instead that there is a broad opportunity for improvement. Of course, in any decision context the objective is to proceed with the best available data and theoretical concepts. They will never be free from uncertainties and assumptions. Changes in the perceptions of the valuation problem, the institutional setting, available technology, and many other critical factors will keep valuation analysis in a constant state of transition.

4.1. Valuation and information processing

From the brief survey of applied valuation studies, it is apparent that weather information is rarely used in the form observed, reported, or even necessarily intended. That is, the weather data as observed and recorded and forecasts as communicated have time and space dimensions. Frequently, transfer functions are applied to these data and forecasts to process them into a form consistent with individual information requirements. Examples include crop yield models, wind chill indices, short-term and long-term forecasts, degree days, soil moisture, and soil temperature. In assigning a value to weather information, it is important to recognize that there can be a confounding of the "information" implicit in the transfer functions with that of the observed or partially processed weather data provided by the system under study. That is, the value of weather information includes the value of the raw observations as well as the value of the information that underlies the various processes used to transform the data into a usable form. In fact, it may be impossible to disentangle the value of the original or unrefined information from the value of the transformation processes themselves.

Who should assume responsibility for the development of these transfer functions or information processing models, and how are the priorities for developing these functions to be determined? In a related vein, are the transfer functions necessary because the system has been designed for purposes other than those of the present users? These and other questions are important for valuing weather information and for developing an appropriate scope for both public and private weather information services.

Presently, it appears, for example, that the U.S. weather information system follows a middle of the road approach in regard to these questions. That is, some processing of information and developmental work on transfer functions aimed at particular clients is accepted as the responsibility of the public agency. Alternatively, there are a number of individuals, organizations, and firms privately processing data provided by public information agencies to make it more useful in specific decision contexts. Public organizations, including state-supported universities, also play a role in processing weather information for specific public uses. Clearly, decisions about public and private responsibility for transfer function development and primary data collection will continue to have an important effect on assessments of the value of information, as well as on the design of the national weather information system.

4.2. Ex ante versus ex post valuations

It is necessary to determine prior to investing in an information system whether the benefit will be greater than the cost. The readily available data on market response to weather information, however, are largely *ex post*. Obtaining appropriate (*ex ante*) valuation calculations will be difficult at best, because the majority of applied valuation studies rely on passively generated data (i.e., data not obtained in an experimentally controlled environment).

Common forms of surplus measures (Hayami and Peterson, 1972; Bradford and Kelajian, 1978) ignore obvious problems associated with using *ex post* secondary data to infer value. It is well understood that actions ranked on the basis of *ex post* measures of consumer and producer surplus cannot be similarly ranked by applying the same measures *ex ante* (Anderson, 1979a; Helms, 1985). These observations on valuation at the market level render many of the existing empirical results on the value of weather information questionable.

Implications of this *ex post* versus *ex ante* conflict are, however, not all negative. Instead, the concepts suggest more constructive ways of proceeding with applied research into the valuation problem. Subjective probabilities regarding plausible states of nature should be elicited from potential users. A new set of subjective probabilities should then be elicited, after the respondents have altered their initial beliefs on the basis of new or additional information. If the message to be received is uncertain, then probabilities associated with possible messages should be estimated as well. In short, problems with *ex ante* valuation simply suggest the use of different types of data and different modeling approaches. These data, in general, cannot be obtained from secondary sources. Investigations using passively generated data are inexpensive but, as is becoming increasingly apparent, provide valuation estimates that are flawed.

4.3. Utility and expected utility maximization

Most applied studies that value weather information in an individual decision context use Bayesian decision-analytic methods (see Section 2.1). Oftentimes such studies have relied upon restrictive utility concepts (e.g., linear utility functions). This is, of course, not a limitation of the Bayesian decision-analytic approach; rather, it reflects the fact that in valuing weather information, utility functions that do not incorporate these restrictive assumptions about attitudes toward uncertainty have only rarely been applied (see Chapter 4 of this volume for some exceptions). There is reason to believe that individuals are generally risk averse (i.e., that utility functions should be concave). Taking into account risk aversion may be an important factor in obtaining more realistic estimates of the value of information. In particular, a risk averse decision maker would not necessarily select the action with the highest expected profit, but rather might prefer another action with lower profit variability. A problem for applied work that attempts to estimate accurately the value of weather information is that if risk aversion is not incorporated, the information may be undervalued (although this is not necessarily the case in general, see Hilton, 1981). Thus, it is necessary to evaluate implications of improved weather information for risk averse decision makers.

4.4. Short- and long-term valuations

Much of the extant theory, as well as the applied work on information valuation, has concentrated on short-term decisions. As is becoming increasingly apparent, though, an important benefit of the weather information system is to provide a capacity for anticipating longer-term events.

The long-term valuation of information is more difficult even within the present theoretical framework. Present versus future trade-offs of benefits and costs provide an especially difficult problem when decisions are made under uncertainty (Chavas, Kristjanson, and Matlon, 1991). For instance, an important problem is to determine appropriate social discount factors. Whose discount factors should be used — those of the present generation or those of future generations? Under what conditions is it possible to aggregate over individual decision-making units to obtain a social discount factor? What is the exact nature of the sequential decision-making process, as well as the associated technological and institutional arrangements, that would allow for long-run adjustments? These and other questions related to the methodology for valuing long-term weather information will lead to a new agenda for theoretical and applied research.

4.5. Distributional effects

Decisions about the public production and dissemination of weather information frequently incorporate distributional concerns. For instance, individuals in agricultural markets serviced by weather information systems may benefit relative to other less well-informed participants. On what basis can society determine the relative utility of benefits generated by the supply of weather information among individuals, as well as among groups of individuals? These are very complicated questions that cannot be easily resolved within the context of the existing economic framework. Many of the individual benefits of information may, in fact, cancel from a societal standpoint. Having better-informed groups of market participants, for example, may simply result in a redistribution of income, leaving total social well-being unaffected. The whole area of social welfare and distributional effects continues to be a prickly issue in economic thought. But for policy decisions, particularly in the design of public services, such problems cannot be dismissed without inviting future difficulties.

4.6. Public versus private information systems

The design of many existing weather information systems is the result of a number of deliberate decisions, natural crises, and other more or less random factors. Current and future discussions will continue to be concerned with the appropriate division between private and public responsibility. These questions on public versus private responsibility are usually evaluated by economists on the basis of efficiency. That is, can public agencies provide information more efficiently than individuals or firms in the private sector? When does the market system fail, resulting in a welfare gain from public intervention? Having established the market, which, if any, components of the public sector's responsibility should be transferred to the private sector? Given the changing technology for sensing and recording weather data and for distributing forecasts from the weather system, these issues will continue to evolve.

The difficulty in determining the appropriate division of private and public responsibility is also related to the transfer function question. All individuals or groups of individuals who are users of weather information must, in one fashion or another, specialize the information to their individual decision needs. These individuals may develop their own personalistic transfer functions or invest in transfer and data processing technology that can be shared. To what extent can this specialization be accommodated given the public–private split in responsibility for weather information services?

5. Concluding observations

Our objective has been to review and assess the results concerning the valuation of weather information and the methods currently used for developing these valuation measures. The first conclusion is that, in both instances, the refinements and extensions in economic decision theory under uncertainty present an opportunity for making important advances in the valuation problem. These advances may lead to workable structures and methods for developing measures of value from a market or societal perspective. From an economic standpoint, these valuation measures require assumptions that are only beginning to be fully understood. A flurry of activity in the market valuation area is likely as the uncertainty and rational expectations theories are more fully merged into information valuation studies.

A second conclusion concerns the measure of information and, perhaps more important, the way data and forecasts from the weather information system find their way into use in economic and social activities. Much of the work on the value of weather information is implicitly related to the value of this information as an input into transfer functions — functions or processes that include extensive types of prior and empirical information not related to weather; for example, plant simulation models. Thus, if an improved basis for valuing the system is to be provided, the role of these transfer functions and their implicit information content must be more clearly recognized and incorporated. The explicit introduction of transfer functions into valuation analysis becomes especially difficult when private versus public information generation and delivery systems are contemplated.

The information valuation problem is difficult. However, the costs of not addressing it directly can be high, both for economists and scientists from other fields, who must ultimately advance the theory of information, and for those directly involved in designing and implementing improved weather information systems.

Acknowledgments

An earlier version of this chapter was presented at the Seminar on the Policy Aspects of Climate Forecasting, jointly sponsored by the National Climate Program Office, NOAA; the National Center for Food and Agricultural Policy, Resources for the Future; and the National Academy of Sciences, Washington, DC.

References

Adams, R.M., Bryant, K.S., McCarl, B.A., Legler, D.M., O'Brien, J., Solow, A. & Weiher, R. (1995). Value of improved long-range weather information. *Contemporary Economic Policy*, **XIII**, 10–19.

Anderson, J.E. (1979a). On the measurement of welfare costs under uncertainty. *Southern Economic Journal*, **45**, 1160–1171.

Anderson, L.G. (1979b). The economics of extended-term weather forecasting. *Monthly Weather Review*, **101**, 115–125.

Antonovitz, F. & Roe, T. (1984). The value of a rational expectations forecast in a risky market: a theoretical and empirical approach. *American Journal of Agricultural Economics*, **66**, 717–723.

Arrow, K.J. (1965). *Aspects of the Theory of Risk-Bearing.* Helsinki: Yrjo Jahnssonin Saatio.

Babcock, B.A. (1990). The value of weather information in market equilibrium. *American Journal of Agricultural Economics*, **72**, 63–72.

Baquet, A.E., Halter, A.N. & Conklin, F.S. (1976). The value of frost forecasting: a Bayesian appraisal. *American Journal of Agricultural Economics*, **58**, 511–520.

Baron, D. (1970). Price uncertainty, utility, and industry equilibrium in pure competition. *International Economic Review*, **11**, 463–480.

Blackwell, D. (1953). Equivalent comparisons of experiments. *Annals of Mathematical Statistics*, **24**, 265–272.

Blackwell, D. & Girshick, A. (1954). *Theory of Games and Statistical Decisions.* New York: Wiley.

Bosch, D.J. & Eidman, V.R. (1987). Valuing information when risk preferences are nonneutral: an application to irrigation scheduling. *American Journal of Agricultural Economics*, **69**, 658–666.

Bradford, D.F. & Kelajian, H.H. (1977). The value of information for crop forecasting in a market system: some theoretical issues. *Review of Economic Studies*, **44**, 519–531.

Bradford, D.F. & Kelajian, H.H. (1978). The value of information for crop forecasting with Bayesian speculators: theory and empirical results. *The Bell Journal of Economics*, **9**, 123–144.

Brown, B.G., Katz, R.W. & Murphy, A.H. (1986). On the economic value of seasonal-precipitation forecasts: the fallowing/planting problem. *Bulletin of the American Meteorological Society*, **67**, 833–841.

Burt, O.R., Koo, W.W. & Dudley, N.J. (1980). Optimal stochastic control of U.S. wheat stocks and exports. *American Journal of Agricultural Economics*, **62**, 172–187.

Byerlee, D.R. & Anderson, J.R. (1969). Value of predictors of uncontrolled factors in response functions. *Australian Journal of Agricultural Economics*, **13**, 118–127.

Chavas, J.-P. & Johnson, S.R. (1983). Rational expectations in econometric models. In *New Directions in Econometric Modeling and Forecasting in U.S. Agriculture*, ed. C.R. Rausser, 205–224. New York: Elsevier–North Holland.

Chavas, J.-P., Kristjanson, P.M. & Matlon, P. (1991). On the role of information in decision making. *Journal of Development Economics*, **35**, 261–280.

Choi, E.K. & Johnson, S.R. (1987). Consumer's surplus and price uncertainty. *International Economic Review*, **28**, 407–411.

Choi, E.K. & Johnson, S.R. (1991). Uncertainty, price stabilization, and welfare. *Southern Economic Journal*, **57**, 789–797.

DeGroot, M.H. (1970). *Optimal Statistical Decisions.* New York: McGraw-Hill.

Ewalt, R.E., Wiersma, D. & Miller, W.L. (1973). Operational value of weather information in relation to soil management. *Agronomy Journal*, **65**, 437–439.

Fama, E.F. (1970). Efficient capital markets: a review of theory and empirical work. *Journal of Finance*, **25**, 383–417.

Freebairn, J.W. (1976). The value and distribution of the benefits of commodity price outlook information. *The Economic Record*, **52**, 199–212.

Gould, J.P. (1974). Risk, stochastic preference, and the value of information. *Journal of Economic Theory*, **8**, 64–84.

Grossman, S.J. & Stiglitz, J.E. (1976). Information and competitive price systems. *American Economic Review*, **66**, 246–253.

Hashemi, F. & Decker, W. (1972). Using climatic information and weather forecast for decisions in economizing irrigation water. *Agricultural Meteorology*, **6**, 245–257.

Hausman, J.A. (1981). Exact consumer's surplus and deadweight loss. *American Economic Review*, **71**, 662–676.

Hayami, Y. & Peterson, W. (1972). Social returns to public information services: statistical reporting of U.S. farm commodities. *American Economic Review*, **62**, 119–130.

Hayek, F.A. (1945). The use of knowledge in society. *American Economic Review*, **35**, 519–530.

Helms, L.J. (1985). Errors in numerical assessment of the benefits of price stabilization. *American Journal of Agricultural Economics*, **67**, 93–100.

Hess, J. (1982). Risk and the gain from information. *Journal of Economic Theory*, **27**, 231–238.

Hilton, R.W. (1981). The determinants of information value: synthesizing some general results. *Management Science*, **27**, 57–64.

Hirshleifer, J. (1971). The private and social value of information and the reward to incentive activity. *American Economic Review*, **61**, 561–574.

Hirshleifer, J. (1989). *Time, Uncertainty, and Information.* Oxford: Basil Blackwell.

Hirshleifer, J. & Riley, J.G. (1979). The analysis of uncertainty and information. *Journal of Economic Literature*, **17**, 1375–1421.

Hirshleifer, J. & Riley, J.G. (1992). *The Analysis of Information and Uncertainty*. Cambridge: Cambridge University Press.

Innes, R. (1990). Uncertainty, incomplete markets, and government farm programs. *Southern Economic Journal*, **57**, 47–65.

Katz, R.W., Murphy, A.H. & Winkler, R.L. (1982). Assessing the value of frost forecasts to orchardists: a dynamic decision-analytic approach. *Journal of Applied Meteorology*, **21**, 518–531.

Kunkel, J.G. (1982). Sufficient conditions for public information to have social value in a production and exchange economy. *Journal of Finance*, **37**, 1005–1013.

Lave, L.B. (1963). The value of better weather information to the raisin industry. *Econometrica*, **31**, 151–164.

Leland, H.E. (1972). The theory of the firm facing uncertain demand. *American Economic Review*, **62**, 278–291.

Malinvaud, E. (1971). A planning approach to the public good problem. *Swedish Journal of Economics*, **73**, 96–112.

Marschak, J. (1971). Economics of information systems. In *Frontiers of Quantitative Economics*, ed. M.D. Intriligator, 32–107. Amsterdam: North-Holland.

McCall, J.J. (1965). The economics of information and optimal stopping rules. *Journal of Business*, **38**, 300–317.

McGuckin, J.T., Gollehon, N. & Ghosh, S. (1992). Water conservation in irrigated agriculture: a stochastic production frontier model. *Water Resources Research*, **28**, 305–312.

McQuigg, J.D. & Thompson, R.G. (1966). Economic value of improved methods of translating weather information into operational terms. *Monthly Weather Review*, **94**, 83–87.

Mjelde, J.W. & Cochran, M.J. (1988). Obtaining lower and upper bounds on the value of seasonal climate forecasts as a function of risk preferences. *Western Journal of Agricultural Economics*, **13**, 285–293.

Mjelde, J.W., Sonka, S.T., Dixon, B.L. & Lamb, P.J. (1988). Valuing forecast characteristics in a dynamic agricultural production system. *American Journal of Agricultural Economics*, **70**, 674–684.

Muth, J.F. (1961). Rational expectations and the theory of price movements. *Econometrica*, **29**, 315–335.

Newberry, D.M.G. & Stiglitz, J.E. (1981). *The Theory of Commodity Price Stabilization*. Oxford: Oxford University Press.

Pesaran, M.H. (1987). *The Limits to Rational Expectations*. Oxford: Basil Blackwell.

Pope, R.D., Chavas, J.P. & Just, R.E. (1983). Economic welfare evaluation for producers under uncertainty. *American Journal of Agricultural Economics*, **65**, 98–107.

Pratt, J.W. (1964). Risk aversion in the small and in the large. *Econometrica*, **32**, 122–136.

Raiffa, H. (1968). *Decision Analysis*. Reading, MA.: Addison-Wesley.

Riley, J.G. (1979). Informational equilibrium. *Econometrica*, **47**, 331–359.

Rogerson, W.P. (1980). Aggregate expected consumer surplus as a welfare index with an application to price stabilization. *Econometrica*, **48**, 423–436.

Roll, R. (1984). Orange juice and weather. *American Economic Review*, **74**, 861–880.

Rothschild, M. & Stiglitz, J.E. (1970). Increasing risk. I: a definition. *Journal of Economic Theory*, **2**, 225–243.

Sandmo, A. (1971). On the theory of the competitive firm under price uncertainty. *American Economic Review*, **61**, 65–73.

Sonka, S.T., Changnon, S.A. & Hofing, S. (1988). Assessing climate information use in agribusiness. II: decision experiments to estimate economic value. *Journal of Climate*, **1**, 766–774.

Sonka, S.T., Mjelde, J.W., Lamb, P.J., Hollinger, S.E. & Dixon, B.L. (1987). Valuing climate forecast information. *Journal of Climate and Applied Meteorology*, **26**, 1080–1091.

Stewart, R.T., Katz, R.W. & Murphy, A.H. (1984). Value of weather information: a descriptive study of the fruit-frost problem. *Bulletin of the American Meteorological Society*, **65**, 126–137.

Stigler, G.J. (1961). The economics of information. *Journal of Political Economy*, **69**, 213–225.

Taylor, C.R. & Talpaz, H. (1979). Approximately optimal carryover levels for wheat in the United States. *American Journal of Agricultural Economics*, **61**, 32–40.

Tice, T.F. & Clouser, R.L. (1982). Determination of the value of weather information to individual corn producers. *Journal of Applied Meteorology*, **21**, 447–452.

Turnovsky, S.J., Shalit, H. & Schmitz, A. (1980). Consumer's surplus, price instability, and consumer welfare. *Econometrica*, **48**, 135–152.

von Neumann, J. & Morgenstern, O. (1944). *Theory of Games and Economic Behavior*. Princeton: Princeton University Press.

Waugh, F.V. (1944). Does the consumer benefit from price instability? *Quarterly Journal of Economics*, **58**, 602–614.

Wilks, D.S. & Murphy, A.H. (1985). On the value of seasonal precipitation forecasts in a haying/pasturing problem in western Oregon. *Monthly Weather Review*, **113**, 1738–1745.

Willig, R.D. (1976). Consumer's surplus without apology. *American Economic Review*, **66**, 589–597.

Winkler, R.L. (1972). *An Introduction to Bayesian Inference and Decision*. New York: Holt, Rinehart and Winston.

Wright, B.D. (1979). The effects of ideal production stabilization: a welfare analysis under rational behavior. *Journal of Political Economy*, **87**, 1011–1033.