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Economic Value of Hurricane Forecasts: An Overview and Research Needs

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Abstract: Hurricane forecasting is in part an economic problem, because it commits scarce resources to save lives, reduce injuries, and lessen economic impacts. New sensing, recording, and reporting technologies, as well as the increased number of clients and their changing needs, have heightened the need to economically justify the hurricane warning system. Estimating forecast value can help show if improved forecast provision and dissemination would offer more benefit to society than alternative public investments such as infrastructure or forecasts of other hazards. We review research that has estimated the economic value of the hurricane forecast and warning system and the value of improving forecast quality. We recommend developing a comprehensive theoretical understanding of economic value of hurricane forecasts to diverse stakeholders across all time scales. This improved, basic understanding would involve a more in-depth discussion of the value of information as well as a broader knowledge of actual (or created) distinctions between adaptation, mitigation, and response to hurricane risks.

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Introduction

Hurricane Forecasting as an Economic Problem

Hurricane forecasting is in part an economic problem, because it commits scarce resources to save lives, reduce injuries, and lessen economic impacts. In 2005, three major hurricanes—Katrina, Rita, and Wilma—struck the U.S. Gulf Coast. For victims of Katrina and Rita, Congress has provided $\$110.6 \times 10^9$ for rescue, relief, reconstruction, and recovery operations—more than all the federal aid for the September 11, 2001 terrorist attacks, 2004's four hurricanes, and Hurricane Andrew combined (USDHS 2006). In the 14 months from Aug. 2004–Oct. 2005, in terms of insured losses, seven of the ten most expensive hurricanes in U.S. history occurred: Katrina, Rita, Wilma, Charley, Ivan, Frances, and Jeanne (Insurance Information Institute 2006).

The human tragedy wrought by these storms raises many important questions. Among them is the economic question of whether improved hurricane forecasts are a good way to prevent a recurrence of anything approaching the destructive scale of the 2004–2005 hurricane seasons. New sensing, recording, and reporting technologies, as well as the increased number of clients and their changing needs, have heightened the need to economically justify the hurricane warning system (Jarrell 1999). This paper reviews research that has estimated the economic value of the hurricane forecast and warning system and the value of improving forecast quality. We define that system to include the writing and dissemination of advisory products by the National Weather Service, and their interpretation and responses by users, from the time the forecast track first threatens U.S. mainland or territories through landfall; what is not part of the process are largely passive measures that might limit damage or shape the recovery independently of the content of National Weather Service products or users' response to them (H. E. Willoughby, private communication, November 19, 2004). We intend this review to inform the process of identifying priorities for ongoing and future social science research (including economics) on the hurricane forecast and warning system. Our review also considers how economic value considerations can guide future improvements in forecasts. We also describe different models used by economists for discussing and exploring the value of information.

What Economics May Contribute to the Hurricane Warning System

Information about the weather has economic value only in terms of how it affects or potentially affects human behavior. One challenge in assessing the economic value of hurricane forecasts is that it is inherently a multidisciplinary endeavor, drawing not only from meteorology and statistics but from the entire spectrum of social sciences. Social systems are highly complicated, and, as Mileti (1999) warns, engineering or scientific approaches to natural hazards can sometimes exacerbate their impact. Assessing the economic value of improved forecasts thus requires that we examine not only the value of improved meteorological forecasting, but also the value of improvements in forecast communication, comprehension, and response.

How does economics fit in? Developing and issuing hurricane

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Nat. Hazards Rev., 2007, 8(3): 78-86

forecasts is hardly free, and attaching a monetary value to these publicly available goods helps public officials determine if investing in forecast improvements is worthwhile. Improving our knowledge of economic values informs policy making by identifying or at least approximating what may be the best choice between alternative investment options. The value of hurricane forecasts has become an important public policy concern. The public sector often provides or subsidizes meteorological research, data, forecasts and technical assistance (Pielke and Carbone 2002). Whether meteorological services such as hurricane forecasts should be provided by the public sector has been a longstanding and contentious debate (Smith 1995; Rosenfeld 2000; NRC 2003). Estimating forecast value can help show if improved forecast provision and dissemination would offer more benefit to society than alternative public investments such as infrastructure or forecasts of other hazards. Assessing the value of improved forecasts can help inform decisions about how best to prepare for hurricanes. Economics offers methods for quantifying changes in social welfare resulting from changes in the condition or availability of resources. Economists use market and nonmarket information to assess options and suggest priorities for decision makers. Economics can also help identify indirect, counterintuitive consequences of hurricane forecasts, such as the increased vulnerability that might arise from an incorrect forecast.

Forecasts versus Mitigation

At least one caveat is in order. Economists have studied many aspects of hurricanes, including the impact of and recovery from hurricanes (see Guimaraes et al. 1993; West and Lenze 1994; Ewing and Kruse 2002; Carbone et al. 2006; Hallstrom and Smith 2005; V. Smith et al. 2006), the determinants of property damage (Fronstin and Holtman 1994), and evacuation costs (Whitehead 2003). Although these studies help us understand the societal impacts of hurricanes, they are not necessarily relevant to the *valuation* of hurricane forecasts.

Society takes numerous actions to reduce the impact of natural hazards, and these actions can be broadly considered mitigation. Economists and other social scientists have examined the value of mitigation, decisions by individuals and governments to mitigate (or not), and the role of insurance and disaster relief in encouraging or discouraging mitigation. Although all self-protective measures could be considered mitigation, a useful distinction can be made between actions that must be taken in advance of a specific hurricane threat and actions that can be undertaken quickly as a hurricane approaches a coast. Generally the term mitigation is reserved for irreversible actions that must be taken well in advance of a hurricane threat; as Mileti (1999, p. 23) puts it, "These [mitigation] measures generally are in place before a disaster occurs." Thus hurricane mitigation typically involves measures like strengthened building construction, land use planning to restrict coastal development, and the siting of critical facilities and infrastructure. Climatological data on the probability and intensity of landfalling hurricanes along different coastlines would be needed to inform mitigation decisions. Consequently mitigation is not based on the issuance of a hurricane watch or warning, which in turn means that the value of mitigation is not a part of the (shorter-term) value of a hurricane forecast.

This review focuses on the *value* of hurricane forecasts, which we assume to be (somewhat) distinct from mitigation as a way to reduce the societal cost of hurricanes. Although a useful fiction for our purposes, in reality evacuation responses do affect the costs and benefits of mitigation and vice versa. At least three interesting issues fall outside our current focus but can be the subject of future research. First, the line between mitigation and temporary loss reduction is not fixed over time and depends on the quality and lead time of hurricane forecasts. If a loss reduction measure requires four weeks to implement, a sufficiently reliable forecast must be available a month ahead of time if this action is to be taken in advance of an approaching storm. Without such a forecast, this action falls within the category of mitigation. But if forecasts became available on a monthly or even a seasonal time scale or longer (e.g., Klotzbach and Gray 2006), the measure could be taken prior to a forecasted hurricane. The optimal forecast response strategy in those situations will likely be some mix of evacuation and mitigation.

Second, improved forecasts could weaken incentives for mitigation or produce a behavioral response that offsets the value of mitigation. If reliable forecasts allow for evacuation before a hurricane, the value of strengthened construction, for example, is reduced because residents and some of their possessions will be out of harm's way. Also, improved forecasts lower the cost of living in vulnerable areas and may result in more property at risk and higher damages (Sadowski and Sutter 2005). Because citizens have the right to evacuate on their own accord, policy officials should consider evacuation responses when making mitigation policy. Otherwise, mitigation policy will be more costly than necessary, with no attendant reduction in risk.

Third, widespread mitigation can reduce the value of a hurricane forecast. If land use planning succeeded in preventing building in areas subject to storm surge, fewer residents would need to evacuate, yet evacuation decisions are what provide the primary value for the forecast. Society can select its level of risk avoidance through a mix of mitigation and evacuation. An endogenous risk avoidance model (e.g., Kane and Shogren 2000) would consider the joint selection of risk reduction strategies—evacuation and mitigation—and examine how their interplay affects the level of risk and the costs of risk reduction. Such a model could examine how small changes in mitigation would affect the marginal productivity of evacuation and vice versa but is beyond our scope here. Of course, focusing on parts and assuming separability has its price—artificial separation of mitigation and evacuation carries over to the research agenda, and the research investment into the behavioral component of hurricane risk reduction has historically been small.

Economics and the Value of Information

Problem Statement

In economics, information such as a hurricane forecast acts as a decision aid to reduce uncertainty. If we think of uncertainty as the dispersion of individuals' subjective probability distributions over possible states of the world, then information consists of events tending to change those probability distributions (Hirschleifer 1973). Here we offer a stylized individual decision model to illustrate the central concepts of the economic theory of information value.

Economists assume that an individual's utility or well being is a function of commodities that the individual consumes (with consumption very broadly defined). The individual is assumed to be rational and an expected utility *maximizer*. The utility function allows for any type of preferences. The expected utility framework can be applied either to an individual or to society as a whole. At the individual level, the payoffs would be framed in

Nat. Hazards Rev., 2007, 8(3): 78-86

terms of expected utilities and would take into account the potential for injury if a hurricane occurs without evacuation as well as the cost of evacuation. At the societal level the framework could be used to estimate the value to society of a hurricane forecast or an improvement in forecast quality. For purposes of this description, utility is a function of consumption of commodities, X. The level of utility is also dependent on the quality of hurricane forecast information that the individual uses to make decisions, FQ:

$$U = U(X,\mathrm{FQ})$$

The individual has a certain income, Y; faces a vector of commodity prices, which we assume constant and therefore suppress in our notation; and has a given level of forecast quality, FQ_1. The person will choose the level and composition of X that maximizes utility. The optimal level of utility that the individual can achieve given these constraints, U^*, can thus be written as a function of income and forecast quality:

$$U^* = V(Y,\mathrm{FQ}_1)$$

The term V indicates that utility is now measured as a function of income and forecast quality using what economists call an *indirect utility function*, rather than a *direct utility function*, U, which is a function of the consumption of commodities, X.

Given the option between different levels of forecast quality, FQ_1 and FQ_2, where we assume FQ_2 to be a higher quality forecast, we can define willingness to pay (WTP) as the maximum amount an individual is willing to pay to ensure that a welfare-increasing activity takes place, or the maximum the person is willing to pay to prevent a welfare-decreasing activity from being implemented:

$$U^* = V(Y,\mathrm{FQ}_1) = V(Y - \mathrm{WTP},\mathrm{FQ}_2)$$

In other words, it is the amount of money that can be taken away from income, Y, given the fixed and exogenous prices, while keeping the individual at the same level of utility, U^*, that he had before forecast quality was improved from FQ_1 to FQ_2.

So far, our economic model does not include hurricane risk, our motivating concern. Forecast users, unless they are at risk, are unlikely to value hurricane forecasts at all. So, forecast value is appropriately defined in ex ante terms, that is, prior to knowing what the forecasts will say or whether or not a hurricane will strike. To introduce hurricane risk into our basic model, let the variable H indicate whether or not a hurricane occurs, so that $H = H^*$ represents occurrence while $H=0$ represents the absence of a hurricane. Let H take the value H^* with the probability p_H and take on the value 0 with the probability $1-p_H$. Finally, let D represent the monetary value of damages caused by the hurricane, given that the hurricane has occurred:

$$V(Y,\mathrm{FQ},H^*) = V(Y - D,\mathrm{FQ},0)$$

Thus exposed to hurricane risk, the individual maximizes indirect expected utility:

$$E(U)^* = p_H V(Y,\mathrm{FQ},H^*) + (1 - p_H)V(Y,\mathrm{FQ},0)$$

Given the option between FQ_1 and FQ_2, we can derive the ex ante willingness to pay:

$$\begin{aligned} E(U)^* &= p_H V(Y,\mathrm{FQ}_1,H^*) + (1 - p_H)V(Y,\mathrm{FQ}_1,0) \\ &= p_H V(Y - \mathrm{WTP},\mathrm{FQ}_2,H^*) + (1 - p_H)V(Y - \mathrm{WTP},\mathrm{FQ}_2,0) \end{aligned}$$

In general, the ex ante WTP measure of forecast value will not equal $p_H D$, the expected monetary damages from a hurricane. For a risk averse (seeking) individual, forecast value may well exceed (be less than) expected damages. Note also that economic value and hurricane forecast skill are not the same metric, and that a more skillful forecast is not necessarily more valuable.

The close association between forecast skill and value has led to some confusion, as noted by Murphy (1993). Decision makers may elect not to use forecasts for many reasons. One concern may be forecast quality, or the degree to which the forecast corresponds to subsequent observations. To be useful, a forecast must offer higher skill or quality than that of a naïve forecasting system, such as the average conditions over many years for that location and time of year (i.e., climatology). Although forecast value depends partly on skill, the two concepts differ in important ways, as Hartmann et al. (2002) and Meinke and Stone (2005) clarify: a highly skillful forecast could have no value, and one of modest skill could have value if applied well under the right circumstances. As Sarewitz et al. (2000, p. 366) note, "comparing a prediction with actual events does not provide sufficient information to evaluate its performance." Other influences on forecast value warrant attention, especially those that are random and region or application specific (Wilks 1997; Hartmann et al. 2002).

Although the expected utility model has considerable analytical power, it may or may not accurately describe how individuals actually make decisions based on a hurricane forecast. The expected utility model is prescriptive in that it specifies how individuals or policy makers *should* act if they wish to maximize expected utility or value (Freeman 1993). Unfortunately prescriptive models may seem irrelevant if their idealized decision makers do not resemble actual forecast users. Describing hurricane warning decision processes is and should be a focus of social science research but is outside our scope here. Stewart (1997, p. 155) notes that although "in principle, a descriptive model could be used to estimate the monetary value of forecasts, this process has rarely been completed." Ideally, researchers would integrate the descriptive and prescriptive approaches, allowing local knowledge and scientific expertise to inform one another, and at least two studies have tried to do so. Sonka et al. (1988) used a gaming approach to elicit information about forecast value, deriving actual decisions albeit in a hypothetical setting. Jochec et al. (2001) combine decision rules derived from focus groups with ecological and economic models to simulate forecast value.

Economics offers many conceptual models to choose from, and several alternatives are available to explore the value of forecasts, depending on the purposes of the analysis. For example, to capture the temporal dimension of hurricane warnings, we could use a Bayesian framework, in which forecast information becomes available only gradually. Following the Bayesian approach, (e.g., Kite-Powell and Solow 1994, Johnson and Holt 1997), the users' previous expectations of hurricane strike probabilities (i.e., their "priors") are updated after additional forecasts are released. Still another approach is to use dynamic modeling to characterize evacuation decision processes as an optimal stopping problem, where the users decide in each advisory period whether to evacuate or to wait another time period for a revised advisory (Czajkowski 2007).

As guidance for empirical estimation, we note that our problem statement may be limited by observational difficulties. Although ex ante WTP is the conceptually appropriate measure of forecast value, it can be prohibitively expensive to elicit. One alternative is to measure avoided costs of evacuation. Broadly speaking, forecast value is derived from the actions people take upon receipt of the forecast or warning. For hurricanes, the main action clearly is evacuation. Tropical cyclone evacuation orders or warnings are expensive, regardless of whether the hurricane actu-

Nat. Hazards Rev., 2007, 8(3): 78-86

Table 1. Benefits Captured by Cost-of-Evacuation and WTP Measures

Affected group	Examples of potential benefits of improved hurricane forecasts	Cost-of-evacuation measure	WTP measure
Individual	Reduced cost of unnecessary evacuations (gas, hotels, etc.)	✓	✓
	Reduced avoidable property damage (paid out of pocket)		✓
	Reduced health risks (reduced morbidity and mortality)	Partially	✓
	Altruistic concern for family or community		✓
	Lost personal time (vacation time or leisure time)		✓
	Reduced risk exposure (i.e., risk aversion)		✓
Business	Reduced property damage	✓	
	Reductions in lost business	✓	
	Reduced costs of making insurance payouts		
Society	Avoided damage to infrastructure (roads, utilities, etc.)	Possibly	Possibly
	Reduced public expenditures on hurricane emergency responses and evacuations	Possibly	Possibly
	Reduced expenditures on emergency assistance, damages and public health costs (paid for by government expenditures)	Possibly	Possibly

ally hits the alerted area. Depending on development in the area, the cost-of-evacuation approach estimates that tropical cyclone warnings can cost from \$0.5 million to \$1 million per mile of shoreline for lost productivity, safeguarding of homes and businesses, evacuation of aircraft and vessels, and canceled vacations. Whitehead (2003) argues, however, that $\$1 \times 10^6/\mathrm{mi}$ evacuation cost is a gross overestimate. The costs associated with warnings alone, which extend 300–400 mi and are issued an average of three times per hurricane season, total $\$787.5 \times 10^6/\mathrm{year}$ (HRD 2001).

The cost-of-evacuation approach assumes residents choose to incur the cost of evacuation (instead of risking life and limb by remaining in their homes or continuing their vacations) any time a tropical system threatens their section of the coast. An improved hurricane forecast reduces the incidence of false alarms or the extent of evacuation and thus reduces the number of miles of coast which need to be evacuated to avoid hurricane casualties. The resulting reduction in evacuation costs then provides a measure of the value of the forecast improvement.

Reduced evacuation costs are but one element of the total value of forecast improvements, however. The cost-of-evacuation measures capture only some of the marginal market costs (out of pocket) of the resources used and productivity lost in evacuations. Whitehead (2003, p. 2) states that "this measure is clearly not an opportunity cost as it is tied to a physical variable." In other words, the cost of evacuation is not a correct measure of the value to the individual because it is tied to miles of coastline and not to individual decision making. The cost per mile of evacuation is taken to be the same whether anyone lives anywhere near that mile of coastline or whether it is a mile of Miami Beach. Although reduced evacuation costs are a benefit to society, they do not include the total value of improved hurricane forecasts. The total value to society, as measured by its willingness to pay, could be considerably more than just the market costs of reducing unwarranted evacuations.

Empirical Approaches

A variety of estimation methods may be used to gauge empirical magnitudes for the value of hurricane forecasts. In general, economics offers two classes of methods for the empirical estimation of values for public goods, such as hurricane forecasts. The first, revealed preference (RP) methods, generally relies on observations of actual behavior either directly in markets (e.g., buying a hamburger) or indirectly in decisions that reveal preferences (e.g., paying more for a house with a great view than for an identical house without the view implies the revealed value of the scenic view). The second empirical approach, stated preference (SP) methods, attempts to directly measure individual's WTP for a commodity (such as improved hurricane forecasting) without necessarily having to rely on a complete model of the individuals' utility function. SP methods are generally survey-based approaches that ask individuals to make choices in hypothetical situations that either directly or indirectly indicate the individual's values for a commodity or commodity characteristic (where commodities is broadly defined to include everything from "normal" market goods such as cars and coffee cups, to environmental commodities such as endangered species, to preferences in terms of health outcomes, to hurricane warnings and forecasts).

Each empirical approach has its strengths and weaknesses. SP approaches can also allow the individual to state his benefits from the change without the researcher limiting these benefits by preconceived constraints on the individual values. The WTP approach, when combined with an SP method, thus attempts to capture all of the values for all potential impacts on the individual. SP valuation is necessary (as opposed to RP valuation) when there are no observable market values for a commodity or no behavioral trails that permit RP approaches to be used. SP methods can also be used for valuing hypothetical commodities such as improved hurricane forecasts (commodities for which there will be no market or RP data).

Partial Taxonomy of Forecast Benefits

Having seen how economists define and measure forecast value, we now turn to the evidence on how valuable hurricane warnings are or might be. In short, that evidence relies heavily on what we know about how individuals, businesses, and society as a whole make decisions when confronted with hurricane risk. The value of a hurricane forecast ultimately depends on the action(s) that can be taken based on the forecast, and how these actions reduce hurricane losses. A weather event might be costly, but forecasts of the event may not be similarly valuable if nothing can be done to reduce losses. Also, individuals may fail to evacuate because they misjudge the quality of the forecast, or because they do not make decisions according to the expected utility model, or because they place a low value on safety or high cost on evacuation.

Table 1 shows a variety of benefits from improved hurricane

Nat. Hazards Rev., 2007, 8(3): 78-86

forecasts. Improved hurricane forecasts allow people to make preparations to reduce or prevent physical damage from hurricanes on three different levels: individual, business, and societal (discussed in the sections that follow). The two right-hand columns indicate which of these benefits may be captured by the cost of evacuation and the WTP valuation approaches.

Individuals

Individuals are affected by hurricanes in various ways, and only some of these are related to evacuation decisions. Cost-of-evacuation measurements will most likely capture only the out-of-pocket expenses that individuals pay when they actually evacuate. More comprehensive cost-of-evacuation approaches (such as those using values of statistical life estimates) could include values for reduced mortality risks. Morbidity impacts, though, are less often measured and thus are more likely to be missing from cost-of-evacuation benefit estimates.

Because they elicit values directly from individuals, WTP methods are more likely to capture the whole range of potential benefits to the individual from improved hurricane forecasts. WTP measures can capture all economic surplus associated with the household benefit from improved forecasts. This benefit can include market values—including some of those suggested by the cost-of-evacuation approach—as well as nonmarket values that individuals place on improved hurricane forecasts. The WTP measures will also capture values that arise from individuals' risk aversion or from their perceived risks (as opposed to "true" objective risks). Further, the household WTP approach will capture individuals' implicit values for changes in potential risks to life and limb (e.g., mortality and morbidity) associated with changes in the quality of hurricane forecasts. All of these represent economically valid benefits from improved hurricane forecasts that have not been measured previously.

Whitehead (2003) uses both RP and SP methods to evaluate the hurricane evacuation decisions of households in North Carolina in response to the Hurricane Bonnie warnings in 1998. The data were collected by surveying residents in eight North Carolina counties four months after the hurricane made landfall. A random effects probit model was used to estimate the predicted probabilities of evacuation by households conditional on intensity of the hurricane, travel cost, time cost, voluntary or mandatory evacuation orders, mobile homes, wind risk, flood risk, and other demographic parameters. The study confirms the hypothesis that as the hurricane intensity increases from Category 1 to Category 5, the probability of evacuation also increases. In addition, the study finds that in general, the stated hurricane evacuation cost of $\$1 \times 10^6/\mathrm{mi}$ of evacuated coastline is an overstatement. The cost of the evacuation increases with increasing severity of the hurricane, ranging from $\$5.7 \times 10^6$ for a Category 3 storm to $\$27.2 \times 10^6$ for a Category 5 storm under voluntary evacuation orders.

In a follow-up paper, Whitehead (2005) attempts to evaluate SP validity in the context of hurricane forecast use, specifically for evacuation behavior. In this paper, Whitehead conducts predictive validity tests using revealed and stated behavior data from a panel survey of North Carolina coastal households. Predictive validity is the extent to which a stated response predicts subsequent behavior. In two of three nonparametric tests of stated and actual behavior, he finds evidence of predictive validity. Using predictions from random effects probit models, he finds evidence that out-of-sample forecasts from combined revealed and stated behavior models correctly predict over 70% actual evacuation behavior with small forecast error.

Businesses

Benefits to businesses are more directly measurable using market valuation methods and are likely to be captured by the cost-of-evacuation approach (and in cost–loss models or decision models). In essence, these benefits are not just direct impacts on businesses but are incurred by the business (e.g., market) sector. One potential benefit of improved hurricane forecasts—most likely not captured by the cost-of-evacuation approach—is reductions in the costs of insurance payments as a result of actions taken to avoid or minimize hurricane impacts. Although individuals are certainly affected by property damage, insurance and reinsurance companies often pay such costs. The insurance payments themselves are simply transfer payments (captured as monetized damages using the cost-of-evacuation approach), and the expenses associated with making the payments are not measured as part of the cost of evacuation.

A cost-of-evacuation to business example is Considine et al. (2004), which estimates the value of both existing and more accurate hurricane forecast information to crude oil and natural gas producers in the Gulf of Mexico. More accurate hurricane forecasts would result in fewer false alarms, preventing unnecessary evacuations and disruptions in production. A probabilistic cost/loss model is used to estimate the incremental value of hurricane forecast information for oil and gas leases over the past two decades. Estimates indicate that the value of existing 48-h hurricane forecast information to oil and gas producers averaged roughly $\$8 \times 10^6/\mathrm{year}$ during the 1990s, which substantially exceeds the operating budget of the National Hurricane Center. From an industry perspective, however, these values are a small fraction of drilling and production costs. However, Considine et al. (2004) appeared before Katrina, and could not consider that storm, which was a costly one for energy companies. Although recent hurricane forecast accuracy is improving, it has not been sufficient to create significant value to this industry. On the other hand, forecast value dramatically increases with improvements in accuracy, rising by more than $\$15 \times 10^6/\mathrm{year}$ with a simulated 50% improvement in 48-h forecast accuracy.

Society

When more sophisticated approaches are undertaken, costs paid by society as a whole may be captured by the cost-of-evacuation measure, although we were unable to find published examples. Societal benefits are largely those that may result from avoided damage to public sector assets (e.g., roads) and reduced public expenditures on unnecessary evacuations. Societal costs may also include instances where individuals or businesses shift costs to society (e.g., under some conditions of publicly funded emergency assistance or public health costs).

Societal impacts may also be captured in part by the WTP measure, depending on how individuals perceive their responsibility for funding societal activities (despite the merits of this approach, we were unable to find published examples). Individuals who see societal expenditures as ultimately coming from their own tax dollars may indicate a WTP to reduce these societal expenditures. The WTP approach may capture the values that some individuals may place on improved hurricane forecasts because of an altruistic concern for the welfare of others and the benefits that improved hurricane forecasts bring to other people or communities. Societal costs are shifted to individuals in the form of direct and indirect taxes to rebuild the damaged infrastructure. The complexity arises when the federal government taxes low-

Nat. Hazards Rev., 2007, 8(3): 78-86

hurricane-risk individuals to subsidize the infrastructure maintenance in the high-hurricane-risk areas. Low-risk individuals may not be necessarily acting out of altruism to pay for high-risk individuals. On the other hand, federal government intervention permits the spread of the risk to the entire society.

The most frequent approach to estimating societal benefits has been the examination of temporal trends, which though less sophisticated can be insightful. In an early example, Sugg (1967) assessed a mean trend of hurricane damages and projected damages over the period from 1965 to 1975. The study estimated that hurricanes were causing an annualized average damage of $\$309.55 \times 10^6$ (in 1965 US$). More recently, Jamieson and Drury (1997) used property loss and loss-of-life data between 1900 and 1990 to show that the property loss resulting from hurricanes exponentially increased and the loss of life exponentially decreased during that period. The reduction in the loss of life is attributed to better forecast and evacuation plans. Most importantly, the paper outlined a risk assessment tool, called HAZUS, developed by FEMA to assess and manage the loss of property resulting from hurricanes in the United States. In an effort to highlight the obstacles posed by poverty, O'Hare (2001) used both historical cyclone/hurricane incidence data and qualitative interviews and newspaper reports to assess the damage wreaked by Hurricane 07B along India's eastern Bay of Bengal Coast. The casualty rate from hurricanes (and other natural hazards) is extremely high in developing countries compared to developed countries because of pervasive poverty, missing infrastructure, and income inequality (Kahn 2005). In addition, hurricane forecasts are not heeded by the vulnerable populations, either because they are not communicated in time, because there are too many false warnings, or because individuals have no viable response options (e.g., no where to evacuate to).

Yet another vein of the societal benefits literature argues that rising coastal populations and real estate values have fundamentally altered the economics of hurricanes. Pielke (1997) argues that the conventional framing of the hurricane problem to the minimization of loss of life and property should be replaced with an alternative problem definition such as reduction of the societal vulnerability to the incidence and exposure of hurricanes. The vulnerability of the U.S. East and Gulf Coasts to hurricane incidence and exposure is presented at the coastal county level for the period from 1900 to 1995. Hurricane incidence is modeled as a function of hurricane intensity, occurrence, and landfall frequency. Hurricane exposure is modeled as a function of human population at risk, property at risk, and emergency preparedness. Pielke concludes that the reframing of the U.S. hurricane problem in terms of societal vulnerability leads to several insights, including the fact that few systematic data are available to measure vulnerability to hurricanes in the United States. Similarly, Pielke and Landsea (1998) calculate U.S. hurricane damages using a normalization of the damages and taking inflation and changes in coastal population and wealth into account. They find that in recent decades, the trend of increasing damage amounts has disappeared. Instead, substantial multidecadal variations in normalized damages are observed, with the 1970s and 1980s incurring less damage than was seen in the preceding few decades, and the early 1990s approaching the high level of impact seen from the 1940s through the 1960s. The average annual impact of damages in the continental United States is about $\$4.8 \times 10^9$ (1995 US$)—substantially more than previous estimates—with more than 83% accounted for by the intense hurricanes (rated Categories 3, 4, and 5 on the Saffir–Simpson scale). Hurricanes of these categories make up only 21% of the tropical cyclones that make landfall in the United States. Finally, Katz (2002) proposes using a stochastic Poisson distribution model both to estimate the probability of hurricane occurrence and to specify the damage associated with the hurricane landfalls. Katz uses an inflation-, wealth-, and population-normalized hurricane damage data set that covers the period from 1925 to 1995 (the same data used by Pielke and Landsea in 1998) to test the proposed Poisson distribution model. Katz also discusses extensions of the model, such as the effect of El Niño and La Niña events on hurricane damages.

As these studies show, hurricanes have significant economic and societal impacts. These damages have changed over time and are related to changes in hurricane forecasting and mitigation (although it is not clear how much can be attributed to forecasting and how much to mitigation). Our review also suggests that there is little, if any, literature on the value of current or improved hurricane forecasts that would be useful for policy making.

Conclusions

Hurricanes pose enormous economic questions, highlighted most recently by the catastrophic 2004 and 2005 seasons. As individuals and citizens, we have difficult choices to make as to how to protect ourselves from hurricanes. Among them is the economic question of whether improved hurricane forecasts are a good way to reduce hurricane risk. Economics can contribute to this important, multidisciplinary discussion, as suggested by the literature we have reviewed here. Because resources available for hurricane hazard reduction are limited, the design of a hurricane forecasting system is partly an economic problem. A systemic economic framework helps organize how we think about an optimal mix of strategies to reduce hurricane vulnerability and how new information about predictive capabilities and risk exposures may affect that mix.

Assessing the economic value of improved forecasts requires that we examine not only the value of improved meteorological forecasting, but also the value of improvements in forecast communication, comprehension, and response (Sarewitz et al. 2000; National Research Council 2006). Interpreting the hurricane warning process thusly may reveal potential sources of additional forecast value. For example, expanding the range of choice among forecast responses (e.g., hurricane shelters that will accept pets) can also increase forecast value. Policy officials may wish to compare whether investments in forecast generation, communication, or response would be most effective at the margin in reducing property loss and mortality.

Spending money on one prospective forecast improvement means not spending those same funds elsewhere. Comparing the different ways of improving hurricane forecasts requires that we consider some of the more subtle aspects of forecast quality only implied in how forecasts are currently issued. The multidimensionality of hurricane warnings (e.g., location, intensity, forward speed, storm surge, etc.) suggests that hurricane forecasts might be improved in many ways. So, for example, both additional lead time and a narrower 5-day forecast window would qualify as improvements. Yet one sort of improvement may create a greater value than the other, and meteorologists may find one sort of improvement easier to produce. From the point of view of forecast users and providers, trade-offs likely exist between these dimensions of forecast quality. Evaluating these trade-offs can yield important information to forecast providers, forecast users, and policy makers. The variety of ways that can be used to reduce

Nat. Hazards Rev., 2007, 8(3): 78-86

hurricane risk is one indication of the advantages of a coordinated strategy.

Some trade-offs are geographic in nature. For example, forecast landfall probabilities are based on the geographic area included in the forecast and the warning lead time required for loss-reducing action. Refining the geographic areas (a finer partition of the coast) covered by different forecast and evacuation decisions, although costly for the forecasting and emergency management community, would provide a way to value more precise warnings. So, if all or most of Florida is covered by one forecast and therefore one evacuation decision, the costs for the whole state would likely be large. In contrast, with separate forecasts for each coastal county, the evacuation cost for each would be lower, and only those counties in the hurricane's path would need a warning issued. The attendant reduction in evacuation cost in this case would yield a means for estimating the value of geographically refined warnings.

Other trade-offs are temporal. For example, the lead time of the warning is often implicitly set by the amount of time required to take the protective action in question. For evacuation, then, the lead time on the forecast must be sufficient to allow the relevant area to be evacuated. Evacuation times will differ for different coastal areas; in more populated areas the previously described analysis might need a 48-h instead of a 24-h lead time. In addition, the characteristics of the population in a given area might affect the time required for an evacuation. An area with a large disabled, nonambulatory, or elderly population might need extra time for evacuation, requiring that the evacuation forecast be issued earlier. And the amount of time required for protecting property might differ from that for evacuation, potentially leading to using forecasts with different lead times for different actions.

Economics provides a set of tools for evaluating trade-offs in how we might improve hurricane forecasts. Available economic modeling approaches represent good ways with which to value marginal (i.e., small) improvements in forecast quality, meaning changes in forecast ability for which society would take the same protective actions as we currently do, only more effectively given the better forecast. Improvements in forecast, however, can create the potential for society to undertake radically different and new loss-reducing actions. If a skilled forecast becomes available with seven or 14 days of lead time, for example, residents might be able to take completely different actions to reduce hurricane losses. With enough lead time it might be possible to install hurricane shutters on some buildings, or for businesses to back up computer systems or records. To take an example from another hazard, if tornado warning lead times of 30 min or more become common, it might be feasible to consider evacuating people from the tornado's path instead of merely taking cover. In such cases, a potential response may act as a spur for forecast improvements, and here too economic analysis plays an important role. Another way to approach the question of hurricane forecast value is to ask how hurricane losses could be more effectively reduced and then determine the type of forecast that would be necessary to implement this loss-reducing action. An important component of the economic analysis should be to engage in such "out-of-the-box" thinking and to consider new responses that might become feasible with sufficiently improved forecasts. Refining or expanding the range of choice among forecast responses can be an important source of increased forecast value.

A few caveats are in order. First, economists, as do any researchers, have difficulty anticipating all of the changes in behavior that result from the availability of new information. That is, we did not know how bar codes, Post-Its, or electricity would change our lives until they were introduced. Similarly, improved hurricane forecasts could change the timing of activities during hurricane season, or the placement of productive capacity for weather sensitive infrastructure. One might imagine, for example, new portable energy collection mechanisms to capture and reuse wind energy. Consequently, economics will never be able to list and value all the benefits of an improved forecast because even residents or businesses may not be able to anticipate all the adjustments they would make with better hurricane forecasts. And the initial adjustments by some parties could lead to second- and third-round adjustments. Forecast improvements may turn out to be more valuable than can be estimated ahead of time.

Second, the wide variety of storms and threatened resources will prove challenging to our efforts. The cost of evacuation and the hurricane losses avoided are unlikely to be the same for all parts of a coastline or for all categories of hurricanes. Similarly, the optimal hit and false alarm probabilities will differ, so the same warning approach is unlikely to be optimal for all parts of the U.S. coast or for all categories of hurricanes. Losses avoidable with a forecast will depend on the population in coastal flooding zones. In a particularly low-lying coastal area (e.g., New Orleans as was evidenced during Katrina), for example, the number of deaths and injuries without evacuation is likely to be particularly high. Avoidable losses will likely be lower with weaker hurricanes, but evacuation costs may be similar for hurricanes of differing categories. A lower false alarm probability, then, should likely be optimal for weaker hurricanes.

Finally, the question of how to make the hurricane forecasting system more valuable depends perhaps most critically on what forecast users actually need. Public policy questions such as this one should reflect an understanding of the public's values. Making better decisions about hurricane hazard reduction is clearly about more than making better forecasts. Although the weather community has developed highly sophisticated methods for evaluating and verifying parts of the forecast process, it has not placed similar attention on evaluating the process as a whole. As a consequence, when the weather community evaluates forecasts, the answers typically do not necessarily address what policy makers and society more generally consider to be most important. Such knowledge gaps suggest directions for further research.

We recommend that economics and social science in general should be a committed and integral part of hurricane forecast research. The alarming events of the 2004–2005 seasons offer graphic evidence that what we do not know about the economic value of hurricane forecasts can indeed hurt us. In broad terms, we suggest developing a comprehensive theoretical understanding of economic value of hurricane forecasts to diverse stakeholders across all time scales. This improved, basic understanding would involve a more in-depth discussion of the value of information as well as a broader knowledge of actual (or created) distinctions between adaptation, mitigation, and response to hurricane risks. For example, a rigorous theoretical model of the cost of evacuation (backed up by state-of-the-art empirical studies) would offer guidance on the ongoing use of this model as the primary metric of the value of hurricane forecasts.

In addition, we see a significant need for reliable and detailed studies of the value of hurricane forecasts to help inform policy discussions, and to make available quantitative economic information in support of current forecast programs and ongoing forecast improvement research. This knowledge gap suggests that a diversity of economic valuation studies is needed to encompass: different methods (e.g., stated and revealed preference, Bayesian decision models, cost–loss models, cost minimization studies);

different spatial scales (e.g., city to national studies); different temporal scales (e.g., hourly-to-decadal decision modeling); and a range of stakeholders (e.g., general public, aviation, tourism, emergency managers, oil and gas industry). For instance, a significant, unmet need exists for understanding how current hurricane forecasts and warning communication and comprehension are valued. In addition, a whole new area of research is needed to evaluate the potential communication, comprehension, use, and value of probabilistic hurricane forecasts.

Finally, we recommend that economic studies be integrated with the physical and other social sciences. One example would be using experimental economics methods in conjunction with risk communication research to evaluate preferences for probabilistic forecast information. Further integration with other social science research methods is important because each paradigm has the potential for enhancing societal goals of reducing injuries and loss of life and reducing property losses through better preparedness and improved forecasting, warning, and response. Integrating economic theory and methods with those of sociology, psychology, hazards research, communication, and other disciplines in an end-to-end-to-end approach offers new avenues of understanding to meet societal objectives.

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Notation

The following symbols are used in this paper:

- D = monetary damages;
- E = expectations;
- FQ = forecast quality;
- H = hurricane strike binary variable;
- p_H = hurricane strike probability;
- RP = revealed preference;
- SP = stated preference;
- U = utility;
- V = indirect utility;
- WTP = willingness to pay;
- X = consumption goods; and
- Y = income.

References

Carbone, J., Hallstrom, D., and Smith, V. (2006). "Can natural experiments measure behavioral responses to environmental risk?" *Environ. Resour. Econ.*, 33, 273–297.

Considine, T., Jablonowski, C., Posner, B., and Bishop, C. (2004). "Value of hurricane forecasts to oil and gas producers in the Gulf of Mexico." *J. Appl. Meteorol.*, 43, 1270–1281.

Czajkowski, J. (2007). "Is it time to go yet? Dynamically modeling hurricane evacuation decisions." *Tech. Rep.*, International Hurricane Research Center, Florida International Univ., Miami.

Ewing, B., and Kruse, J. (2002). "The impact of Project Impact." *Pub. Fin. Rev.*, 30, 296–309.

Freeman, A. (1993). *The measurement of environmental and resource values*, Resources for the Future, Washington, D.C.

Fronstin, P., and Holtman, A. (1994). "The determinants of residential property damage from Hurricane Andrew." *Sou. Econ. J.*, 61(2), 387–397.

Guimaraes, P., Hefner, F., and Woodward, D. (1993). "Wealth and income effects of natural disasters: An analysis of Hurricane Hugo." *Rev. Region. Stud.*, 23, 97–114.

Hallstrom, D., and Smith, V. (2005). "Market responses to hurricanes." *J. Envir. Econom. Manage.*, 50, 541–561.

Hartmann, H., Pagano, T., Sorooshian, S., and Bales, R. (2002). "Confidence builders: Evaluating seasonal climate forecasts from user perspectives." *Bull. Am. Meteorol. Soc.*, 83, 683–698.

Hirschleifer, J. (1973). "Economics of information." *Am. Econ. Rev.*, 63(2), 31–39.

HRD (NOAA/AOML/Hurricane Research Division). (2001). "Hurricanes and tropical meteorology." ⟨http://www.aoml.noaa.gov/general/WWW000/nhurr00.html⟩ (Mar. 31, 2006).

Insurance Information Institute. (2006). "Hurricane facts and statistics." ⟨http://www.iii.org/media/facts/statsbyissue/hurricanes/⟩ (Dec. 11, 2006).

Jamieson, G., and Drury, C. (1997). *Hurricane mitigation efforts at the U.S. Federal Emergency Management Agency*, FEMA, Washington, D.C.

Jarrell, J. (1999). "What does the National Hurricane Center need from social scientists?" *WeatherZine*, ⟨http://sciencepolicy.colorado.edu/zine/archives/1-29/15.html#2⟩.

Jochec, K., Mjelde, J., Lee, A., and Conner, J. (2001). "Use of seasonal climate forecasts in rangeland-based livestock operations in west Texas." *J. Appl. Meteorol.*, 40(9), 1629–1639.

Johnson, S., and Holt, M. (1997). "Value of weather information." *Economic value of weather and climate forecasts*, R. Katz and A. Murphy, eds., Cambridge University Press, New York, 75–107.

Kahn, M. (2005). "Death toll from natural disasters: Income, geography, and institutions." *Rev. Econ. Stat.*, 87, 271–284.

Kane, S., and Shogren, J. (2000). "Linking adaptation and mitigation in climate change policy." *Clim. Change*, 45, 75–102.

Katz, R. (2002). "Stochastic modeling of hurricane damage." *J. Appl. Meteorol.*, 41, 754–762.

Kite-Powell, H., and Solow, A. (1994). "A Bayesian approach to estimating benefits of improved forecasts." *Meteorol. Appl.*, 1, 351–354.

Klotzbach, P., and Gray, W. (2006). "Extended range forecast for 2007." ⟨http://hurricane.atmos.colostate.edu/forecasts/2006/dec2006/⟩ (Dec. 11, 2006).

Mileti, D. (1999). *Disaster by design: A reassessment of natural hazards in the United States*, Joseph Henry Press, Washington, D.C.

Meinke, H., and Stone, R. (2005). "Seasonal climate forecasts: increasing preparedness to climate variability and change in agricultural planning and operations." *Clim. Change*, 70, 221–253.

Murphy, A. (1993). "What is a good forecast?" *Weather Forecast.*, 8, 281–293.

National Research Council (NRC). (2003). *Fair weather: Effective partnerships in weather and climate services*, National Academy of Sciences, Washington, D.C.

National Research Council (NRC). (2006). *Completing the forecast: Characterizing and communicating uncertainty for better decisions*, National Academy of Sciences, Washington, D.C.

O'Hare, G. (2001). "Hurricane 07B in the Godavari Delta, Andhra Pradesh, India: Vulnerability, mitigation, and the spatial impact." *The Geographical J.*, 167(1), 23–38.

Pielke, R., Jr. (1997). "Reframing the US hurricane problem." *Soc. Nat. Resour.*, 10, 485–499.

Pielke, R., Jr., and Carbone, R. (2002). "Weather impacts, forecasts, and policy." *Bull. Am. Meteorol. Soc.*, 83(3), 393–403.

Pielke, R., Jr., and Landsea, C. (1998). "Normalized hurricane damages in the US: 1925–95." *Weather Forecast.*, 13, 621–631.

Rosenfeld, J. (2000). "Do we need the national weather service?" *Scientific American Presents: Weather*, 11(1), 28–31.

Nat. Hazards Rev., 2007, 8(3): 78-86

Sarewitz, D., Pielke, R. Jr., and Byerly, R. Jr. (2000). “Decision making and the future of nature.” *Prediction: Science, decision making and the future of nature*, Chap. 18, D. Sarewitz, R. Pielke, Jr., and R. Byerly, Jr., eds., Island Press, Washington, D.C., 361–387.

Sadowski, N., and Sutter, D. (2005). “Hurricane fatalities and hurricane damages: Are safer hurricanes more damaging?” *Sou. Econ. J.*, 72(2), 422–432.

Smith, J. (1995). *Testimony before the Senate Government Affairs Committee on the elimination of the Department of Commerce*, Commercial Weather Services Association.

Smith, V., Carbone, J., Hallstrom, D., Pope, J. and Darden, M. (2006). “Adjusting to natural disasters.” *J. Risk and Uncertainty*, 33(1–2), 37–54

Sonka, S., Changnon, S., and Hofing, S. (1988). “Assessing climate information use in agribusiness. II: Decision experiments to estimate economic value.” *J. Clim.*, 1, 766–774.

Stewart, T. (1997). “Forecast value: Descriptive decision studies.” *Economic value of weather and climate forecasts*, R. Katz and A. Murphy, eds., Cambridge University Press, New York, 147–181.

Sugg, A. (1967). “Economic aspects of hurricanes.” *Mon. Weather Rev.*, 95(3), 143–146.

U.S. Dept. of Homeland Security (USDHS). (2006). “Hurricane Katrina: What government is doing.” ⟨http://www.dhs.gov/xprepresp/programs/gc_1157649340100.shtm⟩, (Dec. 11, 2006).

West, C., and Lenze, D. (1994). “Modeling the regional impact of natural disaster and recovery.” *Int. Region. Sci. Rev.*, 17, 121–150.

Whitehead, J. (2003). “One million dollars a mile? The opportunity costs of hurricane evacuation.” *Int. Region. Sci. Rev.*, 46, 1069–1089.

Whitehead, J. (2005). “Environmental risk and averting behavior: Predictive validity of revealed and stated preference data.” *Environ. Resour. Econ.*, 32, 301–316.

Wilks, D. (1997). “Forecast value: Prescriptive decision studies.” *Economic value of weather and climate forecasts*, R. Katz and A. Murphy, eds., Cambridge University Press, New York, 109–145.

Nat. Hazards Rev., 2007, 8(3): 78-86