Stratus Consulting

Benefit Analysis for National Oceanic and Atmospheric Administration High-Performance Computing System for Research Applications

Final Report

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Exhibits

Acronyms

ADDS	Aviation Digital Data Service
AMS	American Meteorological Society
ASA	Atmospheric Science Advisors, LLC
ASOS	Automated Surface Observing Stations
ATM	Air Traffic Management
AWC	Aviation Weather Center
AWIPS	Advanced Weather Interactive Processing System
AWRP	Aviation Weather Research Program
BoM	Bureau of Meteorology
CDD	cooling degree days
CPC	Climate Prediction Center
DOE	U.S. Department of Energy
DTC	Developmental Testbed Center
ENSO	El Niño/Southern Oscillation
FAA	Federal Aviation Administration
FSL	Forecast Systems Laboratory
FY	fiscal year
GFDL	Geophysical Fluid Dynamics Laboratory
GPS	global positioning system
HDD	heating degree days
HPCS	high-performance computing systems
IFR	instrument flight rules
IIDA	Integrated Icing Diagnostic Algorithm
ITS	Information and Technology Services
ITWS	Integrated Terminal Weather System
LAPS	Local Analysis and Prediction System
LAX	Los Angeles International Airport
MIT	Massachusetts Institute of Technology

NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NHRA	NOAA High Performance Computing System for Research Applications
NITRD	Networking and Information Technology Research and Development
NOAA	National Oceanic and Atmospheric Administration
NWP	numerical weather prediction
NWS	National Weather Service
PI	perfect information
PRM	parallel runway monitoring
RAP	Research Applications Program
R&D	research and development
RUC	Rapid Update Cycle
SEA	Seattle-Tacoma International Airport
SFO	San Francisco International Airport
SOIA	Simultaneous Operation with Independent Approaches
TCWF	Terminal Convective Weather Forecast
TCWS	Tropical Cyclone Warning System
TDWR	Terminal Doppler Weather Radar
TF	teraflop
VSL	value of statistical life
WRF	Weather Research and Forecasting
WSP	Weather System Processor
WTA	willingness to accept
WTP	willingness to pay

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Executive Summary

Purpose

This benefit analysis assesses the potential economic benefits of purchasing new supercomputing equipment for the NOAA High Performance Computing System for Research Applications (NHRA) in Boulder, Colorado, to serve the computing needs of NOAA and associated entities.

Approach

In this analysis, we identify economic sectors that currently benefit from weather forecasts and that would realize increased benefits from the acquisition of a new NHRA supercomputer and the associated improvements in weather forecasts. Personnel at NOAA's Forecasting Systems Laboratory (FSL), which will operate the NHRA, supplied input on the technical aspects of potential weather forecasting improvements. For this study, we reviewed the literature that places value on short-term weather forecasts from the perspectives of various sectors of the economy, including households, agriculture, aviation, and the energy industry. Exhibit S.1 shows the conceptual relationship between the purchase of a new supercomputer and the benefits to various sectors as a result of this investment

Using conservative assumptions about the contribution of a new NHRA supercomputer to the potential overall improvement in weather forecasting, we conducted an economic analysis that focused on household values. Households are most likely the largest end user of NOAA's weather forecasting services, and a recent economic analysis (Stratus Consulting, 2002) resulted in the most direct estimates of improved weather forecasting benefits. We also separately quantified potential benefits to a limited number of agricultural crops, estimated the potential value of reduced weather-related fatalities, and examined the literature on values to portions of the energy industry and the commercial aviation industry.

Results

The economic analysis conducted here indicates that the potential societal benefits from the purchase of a new NHRA supercomputer are great. The estimated present value of benefits to the household sector for improvements in ordinary day-to-day (i.e., not including severe weather) weather forecasts alone are estimated at $69 million. A sensitivity analysis of the assumptions underlying this derivation indicates a range of values to the household sector of between $34 million and $232 million.

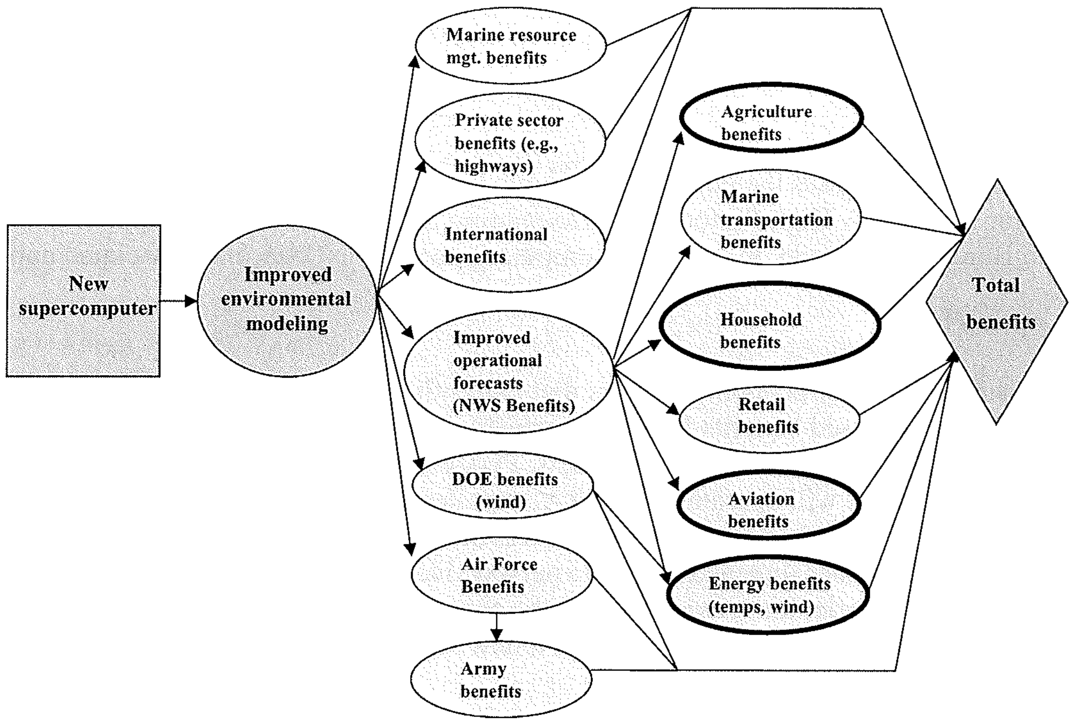

Exhibit S.1. Benefits of improved weather modeling.
(NWS = National Weather Service; DOE = U.S. Department of Energy)

Calculated benefits to certain segments of the agricultural economy (some orchards, winter wheat, and alfalfa) are estimated at a present value of about $26 million. The present value of potentially avoided weather-related fatalities is estimated at $21 million.

Exhibit S.2 summarizes the base case present values for these three areas. Although a significant amount of additional research would be needed to refine these estimates, the benefits from this small subset of the economy appear significant.

Exhibit S.2. Summary of present value of benefits in 2003 (million $, 2002)

Household sector	69
Orchards, winter wheat alfalfa	26
Avoided weather-related fatalities	21

We should note that, in general, we made very conservative assumptions in deriving these benefit estimates. These assumptions include the evaluation of the time period over which benefits may accrue to different sectors and how many of those benefits may be attributable to the research and development that a new supercomputer would allow. In addition, the analysis includes values to parts of two sectors only (households and agriculture) and thus does not include value estimates from numerous other sectors. Our brief literature review indicated that at least the aviation and energy industries could realize potentially significant economic benefits.

Conclusions

This work presents a lower bound estimate of the value of improved weather forecasting made possible by NOAA's acquisition of a new NHRA supercomputer (i.e., the potential benefits to society are likely to be significantly larger than just those included in this analysis). This information can be used in NOAA's benefit-cost analysis of a new supercomputer, and may be useful to policy makers as well.

Future work could better identify all end users of the supercomputer outputs and determine more completely how NOAA's supercomputers have contributed to the progress of forecast accuracy (and how further upgrades will continue to do so). Because of the potentially significant societal benefits from improved weather forecast research, and the lack of reliable economic information quantifying these benefits, future work could also explore the values to other sectors of the economy not evaluated in this report, and offer additional insight into individual uses, perceptions, and values of weather forecasts.

1. Introduction

Approximately 20% of the U.S. economy, or $2 trillion per year, is weather sensitive (Dutton, 2001). Each year, the United States loses billions of dollars in terms of lost time, property and crop damage, and avoidance measures, along with many human lives to adverse weather and environmental conditions. Examples include:

- In the commercial aviation community, weather is responsible for approximately two-thirds of air carrier delays, representing a cost of $4 billion per year, $1.7 billion of which is avoidable (NASA, 2003).
- Utility operational costs are associated with the start-up and shutdown of generation units, which can result from errors in short-term hourly temperature forecasts. A conservative annual estimate of weather error costs associated with start-up and shutdown of generation units is $8 million for Duke Power in North and South Carolina alone (Keener, 1997).
- In 2000, $9 billion in crop damage was caused by weather (e.g., floods, convective weather, winter storms, drought, and fire weather; National Weather Service [NWS], 2001).
- Between 1996 and 2002, an average of 602 people in the United States died each year in weather-related incidents.[1]

NOAA, which is part of the U.S. Department of Commerce, has the stated mission to "understand and predict changes in the Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs."[2] One of NOAA's four mission goals through 2008 is to "serve society's needs for weather and water information." To fulfill this need, NOAA's strategies include:

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1. It is not clear from this information source whether this includes weather-related aviation fatalities. Even if aviation fatalities are included in this number, they likely represent only a small portion of the annual weather-related fatalities in the United States. As stated in the 2002 Natural Hazard Statistics summary report, "As in the previous 4 years, extreme heat ranked as the number one weather killer in the United States. The 10-year average for heat-related deaths is 235; for cold, 26. The 30-year average (1973-2002) for floods is 110; lightning, 69; tornadoes, 66; and hurricanes, 14" (NWS, 1996-2002, pg. 2).

2. This statement and the quotes that follow in this introduction are from NOAA's "New Priorities for the 21st Century: NOAA's Strategic Vision" (n.d.).

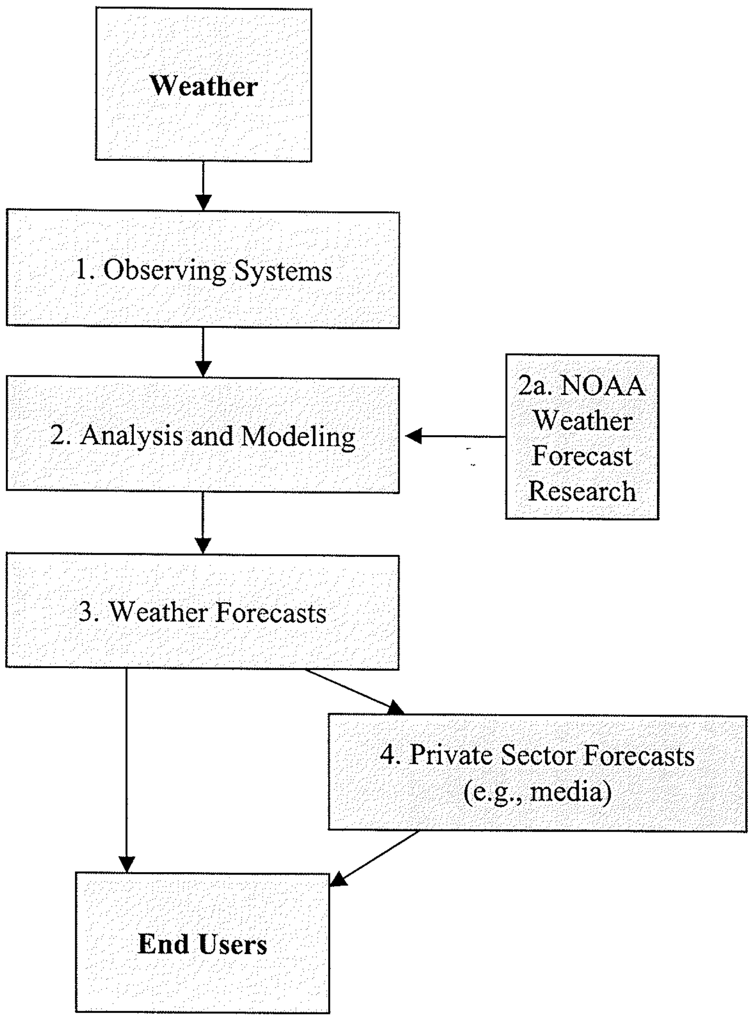
- investment "in new technologies, techniques, and weather and water forecast modeling to improve the accuracy and timeliness of our prediction capabilities and services"
- "improve the performance of our suite of weather and water, air quality, and space weather prediction capabilities."

This includes a commitment to "maintain and improve our technology infrastructure to enhance our scientific productivity through seamless sets of observational and forecast products, advanced high-bandwidth networks, supercomputing capabilities, and actions to improve our customers' use of e-government to receive 24 7 service — 24 hours a day, 7 days a week." As NOAA's strategy statements indicate, improved supercomputing capabilities are essential to the agency's mission.

1.1 Background

The flow chart in Exhibit 1.1 shows how weather information is collected, analyzed, and delivered to users. The flow chart also illustrates how the NOAA weather forecast research and its computing capabilities contribute to the process. NOAA weather forecast research, of which the Forecast Systems Laboratory (FSL) is a critical element, improves the analysis and modeling methods that are used to generate weather forecasts. This information is then transmitted directly or indirectly (e.g., through the media or private sector forecasters) to end users. Because weather forecasts are a quasi-public good,[3] there is no developed market for intermediate weather forecast products and thus no market data on the value of these products. There are numerous steps between the point at which weather forecast research work enters the forecasting system and the point at which the end users receive forecasts and make decisions. Exhibit 1.1, then, also suggests that even if the specific contribution of research and development (R&D) work in weather forecast research is identified, it may be difficult to translate into changes in forecast products that benefit end users.

3. See Section 3.1 of this report and Stratus Consulting (2002) for further discussion of the public good nature of weather forecasts.



1. Satellites, weather balloons, ground stations, and other equipment collect data from around the world.

2. These data are then put into computers and analyzed to predict the weather in the near future.

2a. NOAA weather forecast research resources (supercomputing and other leading technologies) are used to conduct applied meteorological R&D.

3. Weather forecasts are issued (as well as watches or warnings).

4. Weather forecasts are provided to end users such as the aviation or energy industries and the public by the NWS and private services (e.g., the media).

Exhibit 1.1. How weather information is collected, analyzed, and delivered.

1.2 Objectives

The objective of this report and analysis is to assess the potential economic benefits of the purchase of new supercomputing equipment for the NOAA High Performance Computing System for Research Applications (NHRA) in Boulder, Colorado, to serve the computing needs of NOAA and other associated entities.

1.3 Outline

In Chapter 2, we discuss the background of supercomputing at NOAA and the functions and capabilities of NOAA's three centers that operate supercomputers. Chapter 3 covers the concepts involved in valuing weather information and presents an overview of the value of R&D. In Chapter 4, we identify the sectors that would likely benefit from NOAA's acquisition of a new supercomputer and review the available literature on weather forecast values for four sectors (households, aviation, agriculture, and energy). The economic analysis, presented in Chapter 5, focuses primarily on the economic benefits stemming from the household sector. This discussion outlines the estimated household economic values for improvements in weather forecasts, and quantifies how much a new supercomputer would contribute to improvements. In Chapter 6, we offer concluding remarks. The appendices include more extensive information on the literature reviewed for this benefits assessment and a discussion of the omissions, biases, and uncertainties involved in the analysis.

2. NOAA Supercomputing and Weather Forecasting Research

2.1 Supercomputing at NOAA

NOAA is dedicated to enhancing economic security and national safety by predicting and conducting research on weather- and climate-related events, along with providing environmental stewardship of the nation's coastal and marine resources. NOAA participates in the Information Technology Research and Development Program[1] both as a user of high-end computing, with its global change and weather forecasting modeling applications, and as a proponent of expanded information dissemination through the Internet. NOAA's primary role in the national program is as an early adopter of advanced technology.[2]

NOAA conducts real-world testing of advanced concepts such as scalable parallel computing, high-bandwidth networking, and advanced information and dissemination technologies. NOAA's research in climate prediction and weather forecasting is critical to its mission of describing and predicting changes in the earth's environment, managing the nation's ocean and coastal resources, and promoting global stewardship of the world's oceans and atmosphere. This research depends on advances in high-end computing; on the collection and dissemination of environmental data; on the ability to visualize and analyze vast quantities of data; and on the ability of NOAA researchers to collaborate effectively, efficiently, and easily with colleagues throughout the agency, the nation, and the world.

Each day, the supercomputers use more than 2 million atmospheric and oceanic observations collected from the ground, the air, the sea, and space. From these observations, the models predict changes that could occur in the atmosphere and the resulting weather. Crucial guidance, given under strict timetables, enables forecasters to predict events such as hurricanes, floods, and winter storms days in advance.

Increased computing power enables higher resolution in models of the earth's atmosphere-ocean system. Increased resolution permits key features such as weather fronts and ocean eddies to be more accurately represented, and reduces distortions that result from clouds. More accurate

1. The Interagency Working Group on Information Technology Research and Development, which coordinates the Federal information technology R&D programs, is part of the multiagency Federal Networking and Information Technology Research and Development (NITRD) Program.

2. See: http://www.cio.noaa.gov/hpcc/relation.html.

NOAA models improve the understanding of the behavior of climate and weather systems, allowing government and industry representatives to make better decisions on issues that affect both the environment and the economy.

The three organizations within NOAA that maintain supercomputing facilities and of which at least a portion is devoted to R&D of weather forecasting capabilities follow:

- the National Centers for Environmental Prediction (NCEP)
- the Geophysical Fluid Dynamics Laboratory (GFDL)
- the Forecast Systems Laboratory (FSL).

2.1.1 National Centers for Environmental Prediction

NCEP delivers national and global weather; water, climate, and space weather guidance; forecasts; warnings; and analyses. NCEP, an arm of NOAA's NWS, makes a wide variety of national and international weather guidance products available to NWS field offices, government agencies, emergency managers, private sector meteorologists, and meteorological organizations and societies throughout the world.[3]

NCEP Central Operations sustains and executes the operational suite of the numerical analysis and forecast models and prepares NCEP products for dissemination. The Networking and Communications Branch of Central Operations maintains system administration and other user support services on a 24-hour basis for NCEP computing and communications systems including high-performance computing systems (HPCS). This branch is responsible for the overall planning, design, development, implementation, and assessment of NCEP computing and communications capabilities, as well as for the facilities and infrastructure that support the relevant technology. This responsibility includes coordinating network and communications issues between NCEP and other parts of NOAA as well as between NCEP and other agencies.

In addition, NCEP's Environmental Modeling Center develops and improves numerical weather, climate, hydrological, and oceanic predictions through programs of applied research in data analysis, modeling, and product development in partnership with the broader research community.

3. For more on NCEP, see http://www.ncep.noaa.gov.

2.1.2 Geophysical Fluid Dynamics Laboratory

The GFDL is engaged in comprehensive, long-lead-time research that is fundamental to NOAA's mission.[4] The goal of this research is to expand the scientific understanding of the physical processes that govern the behavior of the atmosphere and the oceans as complex fluid systems. These systems can then be modeled mathematically and computer simulation methods can be used to study their phenomenology. The Technical Services Branch of GFDL maintains a computational facility to support research conducted at GFDL with emphasis on supercomputing and networked desktop systems for developing, running, and analyzing results from numerical models.

2.1.3 Forecast Systems Laboratory

Established in 1988, FSL conducts applied meteorological R&D to improve and create short-term warning and weather forecast systems, models, and observing technology. Supercomputing and other leading-edge technologies are used in these applications. FSL then transfers the new scientific and technological advances to its clients, which include NOAA's NWS, the commercial and general aviation communities, the U.S. Air Force, many foreign weather forecasting offices, various private interests, and others. Section 2.2 gives more detail on FSL and the laboratory's supercomputing capabilities.[5]

2.2 Forecast Systems Laboratory

FSL's mission is to transfer technology and research findings in the atmospheric, oceanic, and hydrologic sciences to NOAA operations, other federal organizations, industry, and virtually any users of environmental information. Major research interests center on short-range numerical weather prediction and its applications to daily commerce. The laboratory's researchers work to anticipate the science and technology that the nation's operational weather services will need in the next 5 to 15 years. More than ever, the rapid pace of technological change and the need for sound science to support more advanced services dictate the importance of FSL's endeavors.

FSL has six divisions that carry out research and systems development activities. Under the Office of the Director, Information and Technology Services (ITS) supports these six divisions. ITS is responsible for managing the computers, communications, data networks, and associated peripherals that the FSL staff uses. The central facility houses a wide variety of meteorological

4. For more information on GFDL, see: http://www.gfdl.gov.

5. For more information on FSL, see: http://www.fsl.noaa.gov/.

data-ingest interfaces, storage devices, local- and wide-area networks, communications links to external networks, and display devices. It comprises dozens of computers, ranging from workstations and servers to a supercomputer manufactured by High Performance Technologies, Inc. (Reston, Virginia).[6]

The research and technology activities at FSL cover four major themes: 1) bringing new atmospheric observing systems to maturity, 2) assimilating and modeling to improve short-range weather predictions, 3) investigating computer architectures as a vehicle for handling the computational demands of environmental models, and 4) developing environmental information systems for customers both inside and outside of NOAA. FSL's research efforts have brought about numerous advances in weather forecasting technologies and methods, including:

- The laboratory spearheaded efforts to make wind profiling and ground-based global positioning system (GPS) moisture observations a staple in regional prediction. The NOAA Profiler Network provides reliable hourly observations of winds from the surface to the lower stratosphere, revealing details not available from other observing systems.
- FSL's 20-km Rapid Update Cycle (RUC) model, one of NOAA's operational Numerical Weather Prediction (NWP) models, was a multiyear development project that has set the stage for assimilation of new satellite and radar data sets in the future.
- The laboratory is collaborating on a multiagency Developmental Test Center in Boulder, Colorado, which will focus on developing the Weather Research and Forecasting Model.[7] This model will serve as both an operational model and a research vehicle for the larger modeling community.
- FSL's Local Analysis and Prediction System (LAPS) has been deployed to supply higher resolution analyses and forecasts of all weather variables to support space-vehicle launches and routine space operations at Cape Canaveral and at Vandenberg Air Force Base.
- FSL supports the U.S. Forest Service with high-resolution graphic and point-specific products specially configured to give fire officials a variety of information, including fire indices and ventilation potential.
- In collaboration with the NOAA Ocean Service and the NOAA NWS, the laboratory's researchers set up a demonstration system to bring on-site analysis and modeling to the

6. For more on FSL supercomputing, see http://www.supercomputingonline.com/print.php?sid = 4883.

7. See http://www.wrf-model.org/PRESENTATIONS/2000_06_23_klemp/sld002.htm for information on the collaborators in this multiagency project.

Jacksonville, Florida, Warning and Forecast Office. This system includes real-time analysis of local data using LAPS and forecasts generated by the new Weather Research and Forecasting (WRF) model.

- More timely and accurate warnings and forecasts require continued improvements to the Advanced Weather Interactive Processing System (AWIPS), the backbone of the modernized NOAA NWS. AWIPS was built on technology that FSL developed.

- In collaboration with the Federal Highway Administration and other organizations, FSL generates meteorological fields from an ensemble of mesoscale models. The complex weather information that goes into the resulting maintenance decision support system allows clear decisions to be made about a number of transportation issues, including snowplow deployment, chemical application, and weather-threatened locations.

- The laboratory has partnered in the development of the Aviation Digital Data Service (ADDS), now implemented at the NOAA Aviation Weather Center, to furnish pilots with current preflight planning information on the status of the national airspace. ADDS is a joint effort of NCAR Research Applications Program (RAP), NOAA Forecast Systems Laboratory (FSL), and the National Centers for Environmental Prediction (NCEP) Aviation Weather Center (AWC).

- Prototypes of two other aviation products are being implemented: the Tactical Convective Hazard Product and an initial version of the Volcanic Ash Coordination Tool.

As a leader in high-performance computing, FSL houses the essential infrastructure for weather and other environmental research, and allows future observing systems to be tested through repeated model simulations that require extraordinary processing power. The laboratory's HPCS comprises 768 nodes with dual Intel Pentium processors rated at 2.2 GHz. An upgrade in November 2002 merited a ranking of number 8 (at that time) on the Top 500 List of the World's Fastest Computers (http://www.top500.org/dlist/2002/11/). As of November 2003, this system was ranked 17th in the world (http://www.top500.org/dlist/2003/11/).

FSL supplies the computational capability for numerous environmental modeling efforts that are carried out by FSL and non-FSL researchers, NCEP, several NOAA laboratories, and numerous joint institutes. FSL's Advanced Computing Branch enables advancements in atmospheric and oceanic sciences by making HPCS easier to use (i.e., through development of the Scalable Modeling System) and by exploiting the advanced capacities of high-speed networks and technologies.

To perform computer-intensive tasks, FSL acquired an Intel Paragon XP/S-15-208-processor massively parallel computer 9 years ago.[8] When the Paragon reached the end of its life about 6 years ago, the laboratory leased an interim 32-processor SGI Origin 2000 machine. Because FSL and NOAA needed to increase the spatial and temporal resolution of the models it runs, an HPCS was procured. Improved computing power permits more detailed models covering larger geographic areas to be developed and tested. FSL has acquired a commodity-based cluster with an initial peak speed of approximately 0.34 teraflop (TF) and a 10%-20% sustainable performance for running finite-difference models of the atmosphere and ocean. In fiscal year (FY) 2001, the peak speed was increased to 0.8 TF. In FY 2003, the peak speed was increased to 14.2 TF.

The FSL HPCS's LINPACK performance of 3.3 TF/s was sufficient to place 11th in the May 2003 ranking of the world's fastest supercomputers (http://www.top500.org/list/2003/06/?page). Although it is only one-tenth as powerful as the Japanese Earth Simulator (which comprises NEC SX-6 vector platforms), LINPACK's price/performance is $1.5 million/TF compared to $11 million/TF for the Earth Simulator. FSL's environmental models scale to use the available computing power. The system is currently in the midst of a new procurement cycle. Experts anticipate that cost per teraflop will continue to fall, providing the government with a more powerful system. As more computing power becomes available, the resolution of the model and the complexity of the physics within the model are increased to use the computing resources.

2.3 NOAA Proposal to Expand Supercomputing Capabilities

NOAA seeks to acquire an HPCS to meet its research and development needs in 2004. The desired new system will replace several GNU/Linux-based clusters within FSL's computing facilities. The system known as the NOAA HPCS for Research Applications (NHRA) will be used to sustain geophysical research programs such as the Developmental Testbed Center (DTC), development and testing of National- and Global-scale observing systems, air quality modeling, ocean modeling, and climate modeling as well as parallel processing research as applied to real-time numerical weather prediction (NWP).

8. See http://www-fd.fsl.noaa.gov/papers/pm_ams94.htm for an early history of FSL supercomputing (accessed December 1, 2003).

The NHRA is one of the technology components in the current NOAA Strategic Plan and is critical to achieve NOAA's four strategic goals. Many specific environmental modeling and forecast goals for the years 2004 through 2009 as identified in the current NOAA Strategic Plan are dependent upon the timely acquisition of the NHRA.[9]

NOAA's purchase of a new HPCS for installation in Boulder, Colorado, would double current computing capabilities. It would also enable doubling of the spatial and temporal resolutions of environmental models currently run by NOAA, including finite-difference models of the atmosphere and ocean.

This analysis is designed to quantify the potential benefit of the proposed procurement.

9. See http://nhra.fsl.noaa.gov/nhraPA_team1.html (accessed December 1, 2003).

3. The Value of Weather Forecasts and R&D to Improve Weather Forecasts

3.1 Value of Weather Forecasts

Many authors discuss weather forecasts as public goods (e.g., Anaman and Lellyett, 1996; Johnson and Holt, 1997; Freebairn and Zillman, n.d. [a], n.d. [b]). Public goods are goods or services that are "nonrival" and "nonexcludable." Nonrival means that one person's consumption of the good does not diminish the ability of others to consume the good (e.g., one person knowing the weather forecast does not diminish anyone else's ability to benefit from knowing the forecast).[1] Nonexcludable means that once the good is provided, no one can be excluded from using the good. The excludable characteristic of weather forecasts forms the basis for private weather forecasting services. Consequently, weather forecasts are better defined as "quasi-public" goods because of the potential for exclusion. Because the NWS has not excluded the public from the services it offers, weather forecasts have been furnished as a free good.

Given the quasi-public good nature of weather forecasts, the economic value of most weather forecasting services is not directly observed in the market. For this reason, it is difficult to determine the economic value of the changes in these services that are provided as a result of NOAA programs to improve weather forecasting. However, this is exactly what benefit-cost analyses require.

In categorizing valuation approaches, Murphy (1994) distinguishes between prescriptive approaches (behavior in accordance with normative principles such as utility maximization or loss minimization) and descriptive studies (focusing on actual behavior, as in decision making or information processing; see also Freebairn and Zillman, n.d. [a]). Most prescriptive studies posit a loss function or its inverse, a payoff function (e.g., Davis and Nnaji, 1982; Ehrendorfer and Murphy, 1992).

Hundreds of studies have been done on the value of weather, but fewer studies have examined the value of weather information. Using Murphy's terminology, most studies of the value of weather information are prescriptive in terms of examining idealized behavior given a change in the information available to the decision maker. Johnson and Holt (1997) and Wilks (1997) review several such studies, mainly in the agriculture sector. Murphy (1994) includes an

1. "Nonrivalry also often characterizes the benefits from . . . weather monitoring stations . . ." (Cornes and Sandler, 1996, p. 8).

annotated bibliography of studies of the value of forecasts indicating approach/method, type/range of forecasts, and sector of application.

3.2 Value of Information and R&D

In economic terms, improved weather forecasts can be thought of as improved information. R&D undertaken to improve weather forecasts, including the use of higher performance computing systems, can be conceptualized in terms of economic approaches to understanding the value of information and R&D.

Most organizations, governmental as well as private, make significant investments in R&D in the hopes of developing successful new products. These products may be tangible, such as bioengineered pharmaceuticals, or intangible, such as improved scientific information. Assessing the value of R&D is a challenging endeavor because of the uncertainty, complexity, and long time horizons typically associated with R&D programs. Moreover, the immediate results of R&D are rarely useful on their own; instead, transforming promising R&D results into end-user value requires additional development, commercialization, and marketing activities, all of which involve further uncertainty, complexity, and time. Matheson (1983) offers an excellent overview of the challenges of managing R&D activities.

In contrast to corporate R&D, where each company receives the benefits of its own successful efforts, government-sponsored R&D creates public research results on which various user groups may or may not capitalize. In this context, calculating the value of R&D requires an economic evaluation of all potential public benefits. Ideally, areas of greatest potential public benefit would be used to guide the selection of R&D activities. In other words, even though the flow of benefits from R&D starts with the sponsoring organization and moves outward to users, the optimal management of R&D should quantify benefits in the opposite direction: first, where are the greatest potential benefits from R&D, and then, what R&D activities are most likely to produce those benefits? Menke (1981) outlines a detailed methodology and gives an example of quantifying the value of basic research.

As noted above, basic information — as opposed to new technology — is often the result of R&D. Intuitively, it would seem that additional information would always have value. Is this true, and if not, under what conditions does it hold? When does better information have value, and how is it quantified?

Quantifying the economic value of information is a relatively new concept, dating back to the 1960s when the field of decision analysis was created (Raiffa and Schlaifer, 1961; Howard, 1966). Decision analysis merges statistical decision theory with systems analysis to form a methodology for analyzing large, complex, and uncertain decisions. The process involves structuring a decision problem to clarify its alternatives, information, and values. A mathematical model is built to quantify the value of each alternative according to the information and value objectives of the decision maker. Important uncertainties in the information are represented stochastically, and a final probability distribution over the potential outcomes for each alternative is determined.

In the prescriptive framework of decision analysis, new information has value if it has the potential to change the decision maker's preferred alternative.[2] A key assumption of many prescriptive models is that decision makers are acting to maximize profit and minimize losses. An extensive literature exists on the psychology of decision making (see Tverksy and Kahneman, 1974, 1981). These works point out flaws in prescriptive decision-making models, primarily in the areas of preference modeling and judgments about uncertain information. Decision analysis incorporates the use of utility functions to address risk attitudes (Howard, 1970) and enhanced methods for subjective probability assessment to address subconscious informational biases (Spetzler and von Holstein, 1972).

Decision analysis offers a means to determine the value of both perfect and imperfect information to the decision maker. "Perfect" information is always correct, hardly a realistic concept, but one that is very useful when trying to determine an upper bound on the value of additional information. Because it is a relatively straightforward calculation, the value of perfect information is helpful for ranking R&D activities.

In the context of weather forecasting, a perfect forecast would be one that allows the decision maker to maximize her weather-related benefits and minimize her weather-related costs. For example, consider a hypothetical case of an orange grower whose crop can be damaged by frost. Assume that on a given night she must decide whether to operate a frost protection device, such as a heating system. Exhibit 3.1 illustrates her decision problem (in the absence of any forecast) with a decision tree, which shows the sequence of events from left to right. First, she must make her decision to frost protect or not (the decision node, shown by the branches emanating from the square). Then, she must await the outcome (whether the frost occurs or not; the probability node, shown by the branches emanating from the circle; the sum of these probabilities must be 1.0). In the language of probability theory, this probability distribution is known as the underlying state of nature, or the prior state of information.

2. We emphasize the word "potential" here, because new information does not have to actually change decisions in order to have value. Thus, there do not have to be observable differences in decision making (ex post) as a result of better information, even though the improvement in information has positive value.

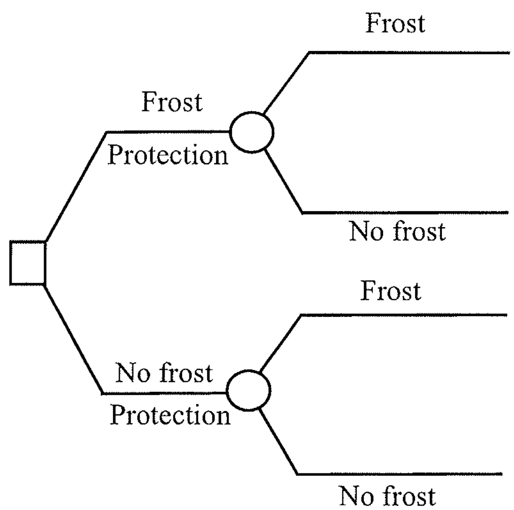


Exhibit 3.1. Decision tree for orange grower.

Applying hypothetical values to the situation shown in Exhibit 3.1, we can calculate the optimal decision for the grower. Assume that the cost of frost protection is 25, and the value of the crop with no frost damage is 100. If frost occurs and she has no frost protection, she has a total loss, 0. If frost occurs but she has frost protection, she still has crop damage but it is limited to 25, and her net loss is 50. If there is no frost, but she has installed frost protection anyway, her potential value of 100 is reduced by the cost of frost protection to 75. Finally, by applying a hypothetical discrete probability distribution for the likelihood of frost (40% chance of frost; 60% chance of no frost), we can calculate the expected (i.e., probability-weighted) value of each alternative as follows:

$$\text{Expected value with frost protection} = (0.4) \times 50 + (0.6) \times 75 = 65$$

$$\text{Expected value with no frost protection} = (0.4) \times 0 + (0.6) \times 100 = 60$$

In the absence of additional information, then, her best decision is to frost protect, with an expected value of 65. Exhibit 3.2 shows the decision tree incorporating these hypothetical values and results. The arrow highlights the preferred alternative.

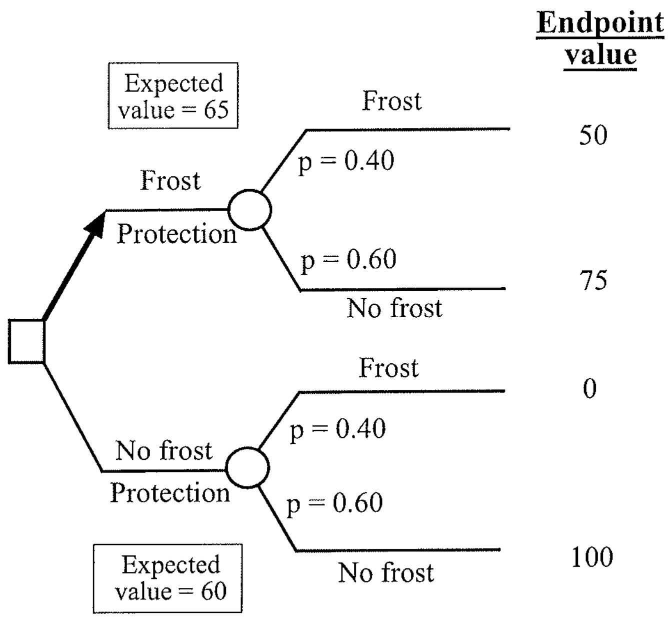


Exhibit 3.2. Orange grower's decision tree with expected values.

(p = probability)

What is the value of additional information, such as a forecast, in this situation? Before determining the value of a weather forecast or an improved weather forecast, however, consider the value of perfect information about frost (i.e., a perfect frost forecast). This is a comparatively straightforward calculation and, as noted above, determines an upper bound on the willingness to pay (WTP) for imperfect information. Exhibit 3.3 illustrates this calculation. Perfect information is represented by switching the time sequence of events in the decision tree, placing the uncertainty node before the decision node. In other words, the decision maker will know if frost will occur or not before she makes her decision on frost protection.

If she knows that frost will occur (which will happen 40% of the time), she will choose to frost protect, with a value of 50. If she knows that frost will not occur (60% frequency), she will not choose to incur frost protection costs and her value will be 100. Therefore, the expected value of this situation is

$$(0.4) \times 50 + (0.6) \times 100 = 80$$

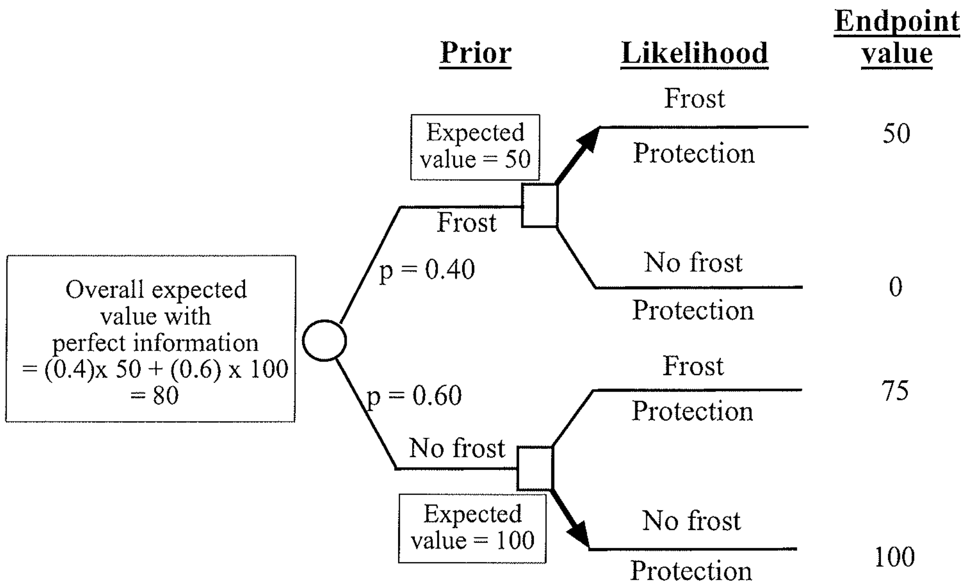


Exhibit 3.3. Decision tree with perfect information about frost.

The value of perfect information is the difference between the expected values of the two situations, with and without perfect information. Without perfect information, her expected value is 65. With perfect information, her expected value is 80, and the value of perfect information is 15. Thus, any weather forecast (i.e., imperfect information) will have a value less than 15. Note the reason that perfect information has value: without it, her best alternative is to protect; with it, 60% of the time she would *change her decision* to no frost protection and would increase her value from 75 to 100 (60% of 25 is 15).

Imperfect information is the real-world norm, and is often thought of in terms of a forecast. For example, a frost forecast has a certain degree of accuracy associated with it. Given this forecast, how should we update our probability distribution on frost? The Reverend Thomas Bayes (1702-1761) developed a theorem, called Bayes' Rule, to update a prior probability distribution given new information:

> If the events $E_1, E_2, \ldots, E_k$ partition a sample space, and if B is any other event for which $P(B) > 0$, the conditional probability of any partitioning event E_i given that B has occurred is

$$P(E_i \mid B) = \frac{P(E_i)P(B \mid E_i)}{\sum_{j=1}^{k} P(E_j)P(B \mid E_i)}, \; i = 1, 2, \ldots, k$$

The term on the left is known as the "posterior" distribution; that is, the updated probability on the state of information (i.e., the prior) given the new information. The two probability expressions in the numerator of the right-hand term are the "prior "and the "likelihood" distributions, respectively. The denominator is known as the "preposterior" distribution.

This process is most clearly explained using an example, such as that of our orange grower. Assume that a frost forecasting method that is 80% accurate exists. In other words, if a frost occurs, the method would predict frost 80% of the time and be wrong 20% of the time. Similarly, if a frost does not occur, the method would predict no frost 80% of the time. Exhibit 3.4 shows a probability tree of the possible forecasts (the likelihood function) given that a frost will or will not occur (the prior). The probabilities shown at the end of each path through the tree are called "joint" probabilities, and are the product of the probabilities along each branch.

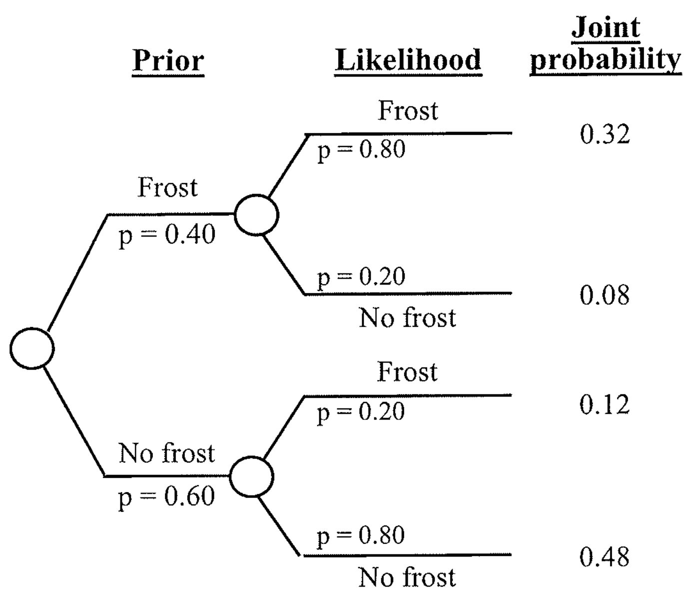


Exhibit 3.4. Probability tree of forecast accuracy.

To determine the value of this forecast to the orange grower, the information is needed in the reverse order to follow the time sequence of events. In other words, what is the probability of frost given the forecast? Applying Bayes' Rule in the decision-tree format requires reversing the order of the probability nodes and calculating the updated probabilities as shown in Exhibit 3.5. By adding up the appropriate joint (i.e., end point) probabilities from Exhibit 3.4, the overall probability that the forecast predicts frost is 0.44. The overall probability that the forecast foretells no frost is 0.56 (the preposterior). This is shown in the first node in Exhibit 3.5.

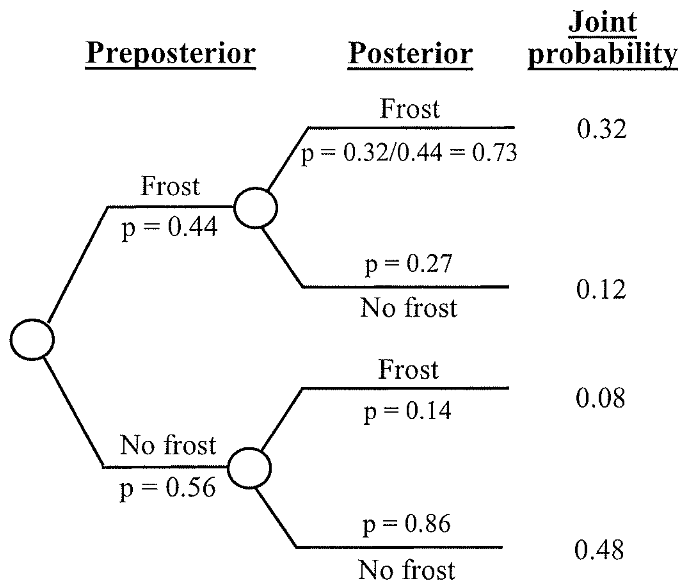


Exhibit 3.5. Result of applying Bayes' Rule.

Following the top path through the probability tree, the joint probability that the forecast indicates frost and that frost occurs is 0.32, the same joint probability of these two events as shown in Exhibit 3.4. When we apply Bayes' Rule, the updated probability of frost given the forecast (i.e., the second node in the tree) is 0.32/0.44 = 0.73 (the posterior probability). Similar calculations produce the remaining probabilities shown in Exhibit 3.5.

Exhibit 3.6 shows the orange grower's decision tree when this new information is incorporated with the proper time sequence (i.e., the forecast occurring before the frost protection decision and then the updated probability distribution on frost). In the case where the forecast predicts frost, the best alternative remains to frost protect with an expected value of 56.75. In the case where the forecast indicates no frost, the best alternative changes to no frost protection, with an expected value of 86. The overall expected value of the decision situation with the forecast is computed by weighting these results by the probabilities that the forecast predicts frost or no frost. The result is:

$$(0.44) \times (56.75) + (0.56) \times (86) = 73.13$$

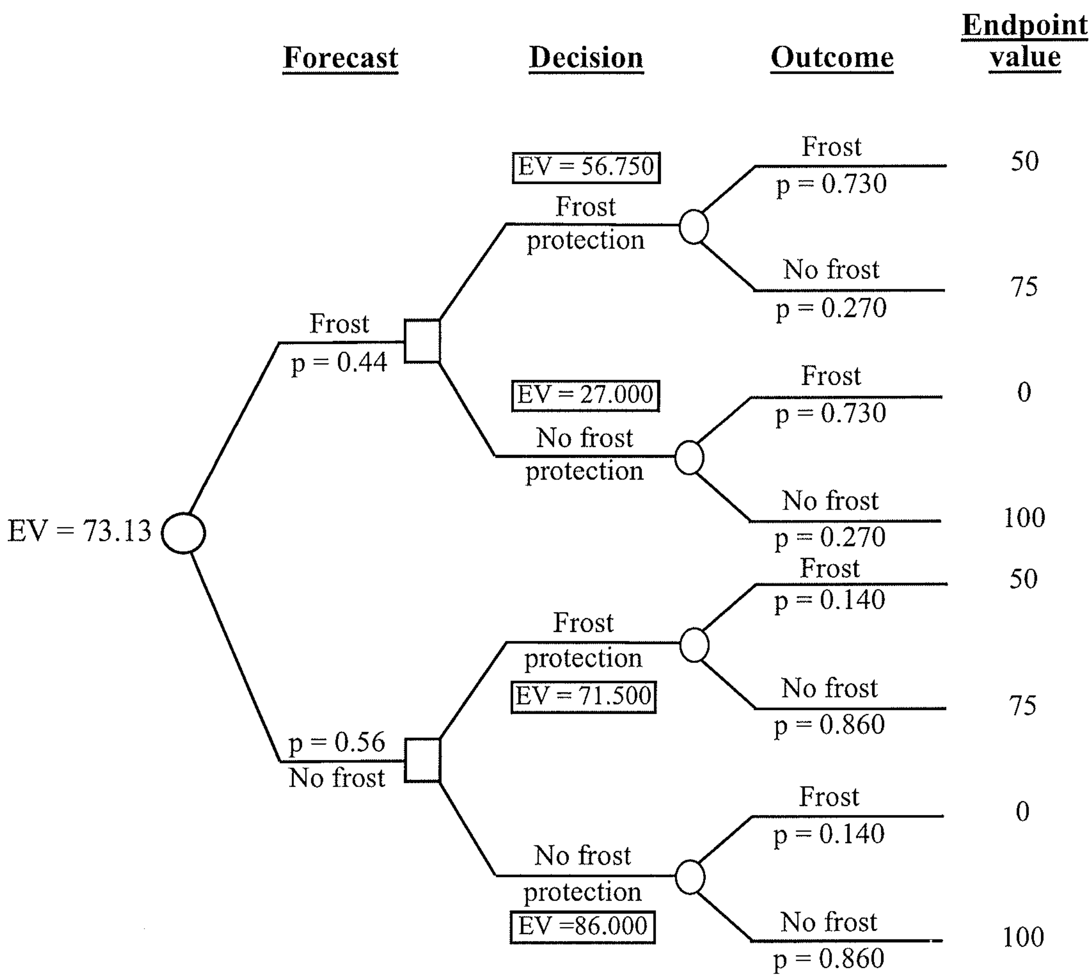


Exhibit 3.6. Expected value with 80% accurate forecast.

Finally, the value of the forecast itself (i.e., the value of imperfect information) is the difference between the decision maker's expected value with and without the information:

Value of the 80% accurate forecast = 73.13 – 65 = 8.13

As we would expect, this value is less than the value of perfect information, which was 15.

In this situation, what would be the value of an improved forecast such as might result from a new R&D effort? Suppose the improved forecast has an accuracy of 90%. Following the same process as shown in Exhibits 3.4, 3.5, and 3.6 and applying Bayes' Rule, we arrive at the new decision tree for the orange grower, shown in Exhibit 3.7. The overall expected value rises to 76.5 as a result of the improved accuracy. The value of the 90% accurate forecast, then, is 11.5 compared to no new information and 3.37 compared to the 80% accurate forecast.

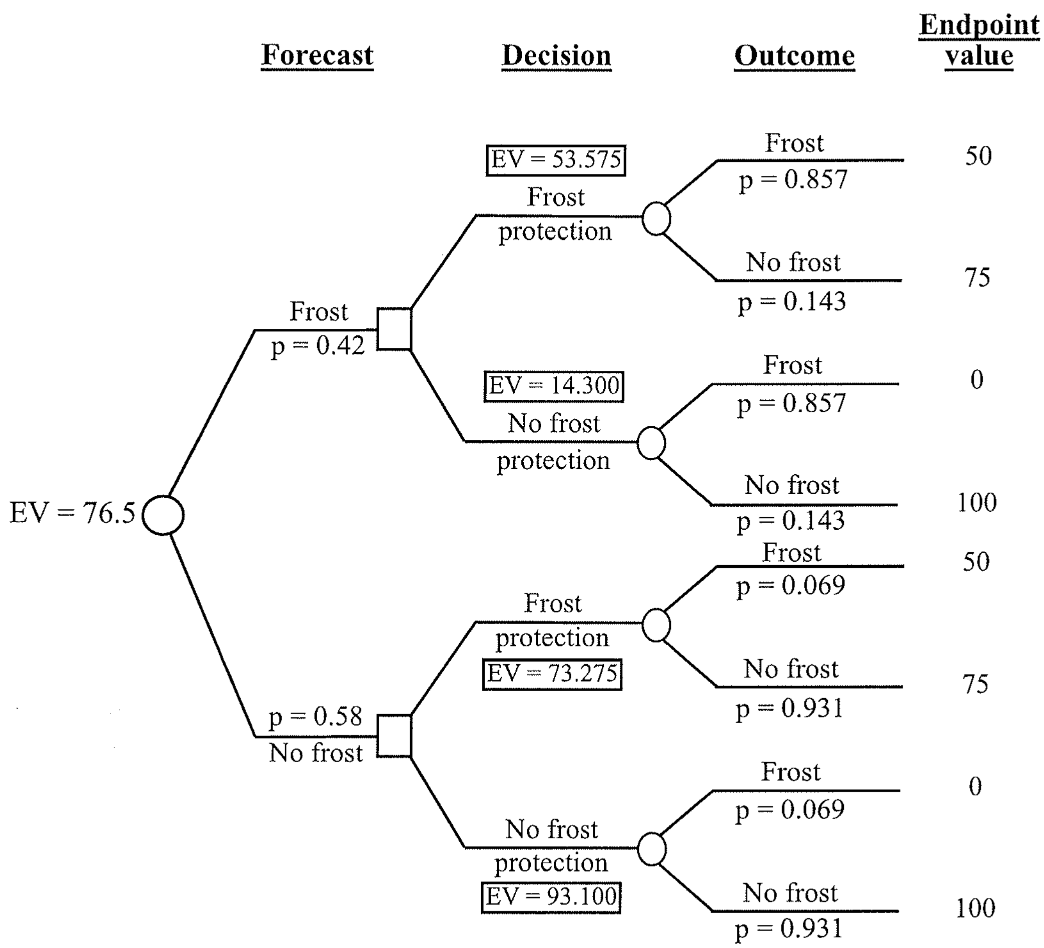


Exhibit 3.7. Expected value with 90% accurate forecast.

In summary, methods exist to determine the value of information to decision makers even if it is imperfect, as in the case of weather forecasting. This value can in turn be used to assess the benefits of R&D efforts that will yield better information.

4. Assessment of Benefits of Improved Weather Forecasts

The improvements in computing and modeling capabilities derived from the acquisition of a new supercomputer may lead to various economic benefits as illustrated in the influence diagram in Exhibit 4.1. In an influence diagram, square icons represent decisions; circles represent uncertain data or events, or both; and diamonds represent the decision criteria. The direction of the arrows indicates the influences. Exhibit 4.1 shows the decision to purchase a new supercomputer (a square) leading to improved environmental (including weather) modeling (a circle). Improved weather modeling, in turn, has the potential to lead directly to an array of benefits in the following sectors (also in circles):

- NWS operational forecasts
- marine resource management
- private sector (e.g., highways)
- international benefits
- wind-related sectors of the U.S. Department of Energy (DOE)
- U.S. Air Force, which also provides forecasts to the U.S. Army.

Exhibit 4.1 also illustrates that additional economic benefits are possible from the sectors utilizing NWS forecasts, either directly or as inputs to sector-specific weather forecast models:

- agriculture
- marine transportation
- households
  - ordinary weather forecasts
  - weather-related fatalities
- retail businesses
- aviation
- energy.

Combining all the direct and indirect benefits of improved weather modeling will lead to the total benefits of acquiring a new supercomputer, as shown by the arrows leading into the diamond icon. Note that Exhibit 4.1 is intended to represent the majority of the possible benefits of a new NOAA supercomputer; it is not meant to be exhaustive.

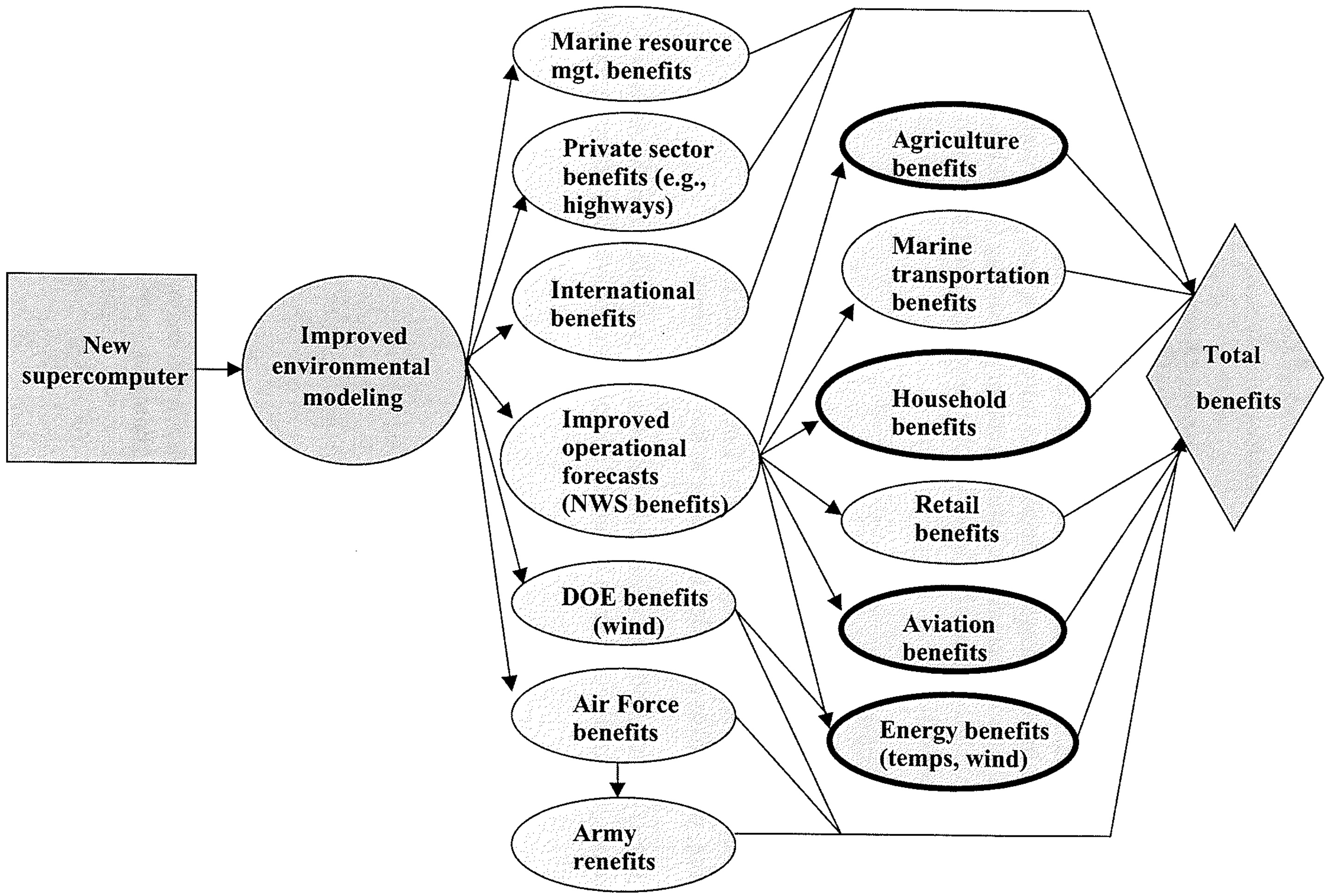


Exhibit 4.1. Benefits of improved weather modeling.

(NWS = National Weather Service; DOE = U.S. Department of Energy)

Exhibit 4.2 presents a similar taxonomy in tabular form, where we can see that improvements in weather forecasting will entail numerous economic benefits, resulting from the ability of the data users to improve their operational decision making. For example, airlines will make safer and more efficient routing decisions, the agricultural sector can make crop selection decisions and realize irrigation efficiencies, the utilities can improve the accuracy of their energy load forecasting decisions, and individuals can make better decisions to lessen the loss of life and personal property (NOAA, 2002). Exhibit 4.2 lists the categories of potential economic benefits by benefit type and application area.

Exhibit 4.2. Taxonomy of potential beneficiaries of weather information

Benefit type	Application area	
Social benefits	**Household values — everyday decisions based on weather**	
Loss of life, injury, and property damage	Severe storm	Tornadoes
		High winds
		Snow
		Tropical storms
	Flood	Coastal
		River
	Droughts	
	Heat waves	
	Lightning	
Economic activity	**Agriculture**	
	Fisheries	
	Forestry	
	Range management	
	Energy production	
	Manufacturing	
	Construction	
	Transportation	**Air**
		Ocean
		Land
		Space
	Utilities	**Electric**
		Water
		Natural gas
		Communication
	Recreation	
	Finance	
	Insurance	
	Commodities	
	Weather (as industry)	

Exhibit 4.2. Taxonomy of potential beneficiaries of weather information (cont.)

Benefit type	Application area
Public policy; understanding Earth	Earth processes Model evaluation Global change

Source: NOAA, 2002.

For the purposes of this study, we selected for analysis the sectors likely to show the greatest potential economic benefits or those for which making quantitative assessments of the relationship between improved forecast quality and improved weather modeling appears most feasible. The benefits of the four application areas listed in Exhibit 4.2 (in bold type) are discussed in further detail in this analysis: 1) households, 2) agriculture, 3) aviation, and 4) utilities (electric and natural gas).The benefits to these sectors are examined both qualitatively and quantitatively. We obtained information on economic benefits (primarily costs avoided by the increased forecast accuracy) via interviews with NOAA personnel and from published and unpublished literature.

This analysis attempts to quantify some of the expected benefits to just a few of the 33 application areas identified in Exhibit 4.2. Thus, notwithstanding the limitations of the estimation techniques used, these estimates represent a lower bound to the true dollar value for potential benefits.

The remaining sections in this chapter briefly summarizes the literature on the value of weather forecasts and improved weather forecasts in each of these four sectors. Appendix A includes more detailed summaries of the literature we reviewed.

4.1 Households

Future weather inherently involves risk and uncertainty, concepts that have been addressed in many forms in economic theory and modeling. Weather forecasts are made up of information about future events, which may or may not be of use to individuals or groups in dealing with the risk and uncertainty of future weather conditions. Although weather outcomes have real impacts on behavior and economic consequences, information about potential weather outcomes may also have value. We focus here on the *value* of information in dealing with risk and uncertainty of future weather outcomes. The value of information then relates to how individuals, or "economic agents," can or will react to changes in the information available when they face a "weather risk." Exhibit 4.3 shows that improvements in many weather forecast products have potential decision-making values to households.

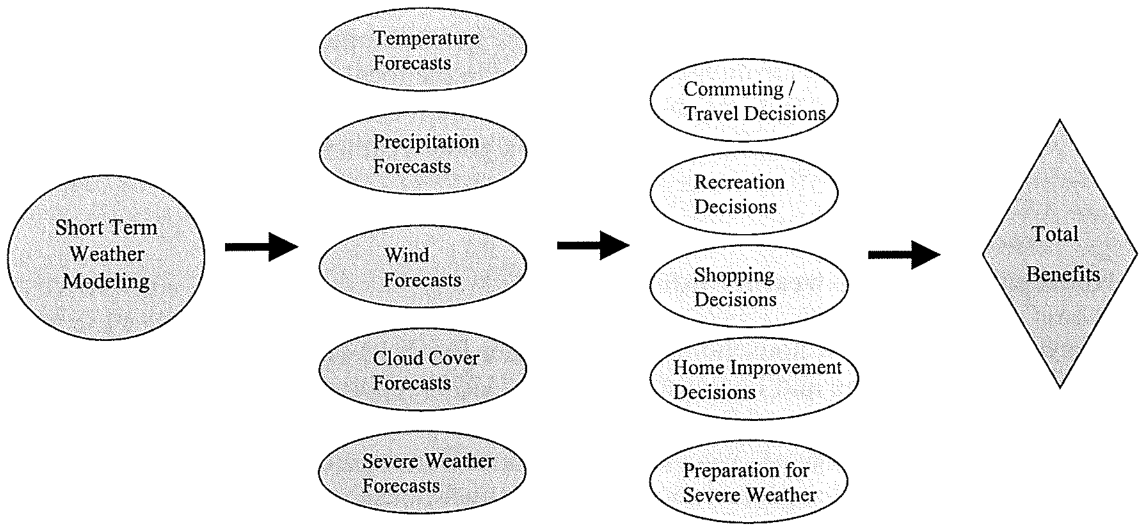


Exhibit 4.3. Flow chart of household benefits from short-term weather forecasts.

4.1.1 Household perceptions and uses of weather information

In general, the importance of communication in the valuation process has not been thoroughly examined. Studies have generally addressed specific aspects of weather forecasts. Understanding household perception of weather information involves the *receiving* part of communication, and few studies have examined how individuals perceive and use weather information. We are not aware of any consistent or determined effort to examine the communication of weather information to households.

Murphy et al. (1980) report on an examination of how laypeople understand probabilities in terms of precipitation forecasts. Results indicate that individuals misunderstand the event more so than the probabilities and that they prefer information presented as percentages. MSI Services Incorporated (1981) reports on a national telephone survey of 1,300 households' use of and need for weather forecast information, but this work did not elicit reliable economic estimates of the value for current or improved forecasts. Murphy and Brown (1983) discuss the use of terminology in verbal public weather forecasts and what can be done to improve the transfer of information. They conclude that studies have found that, in general, temperature and precipitation are the most important part of the forecast message. Curtis and Murphy (1985) discuss a survey implemented through a newspaper in Seattle examining individual interpretations of various terms used in weather forecasts. Similar to previous findings, precipitation and temperature information was more important than cloud cover or wind. Pope

(1992) conducted a 48-question survey in 10 U.S. cities and towns exploring individual use, understanding, and perceptions of weather forecasts. The general topics examined were weather information sources, quality and attributes of importance in the local forecast, and understanding of severe weather. Colman (1997) discusses a survey of a small convenience sample of weather forecasters who were asked the question "What makes a good weather forecast for the general public?"

4.1.2 Household values for weather information

Few studies have explored how households value weather forecasts or improved forecasts. The Prototype Regional Observing and Forecasting Service (1979) reports on research conducted by J.E. Haas and R.B. Rinkle of Human Ecology Research Services in Boulder, Colorado. Values for improved local weather forecasts were elicited from 95 Denver urban area households. Estimated aggregate benefits for perfect forecasts for Denver households were $31 million (1979$) based on estimated annual per capita benefits of $44 for commuting, $17 for recreation, and $23 for shopping weighted by the number of activities undertaken. The MSI Services Incorporated national telephone survey (1981) included a valuation question on what value individuals place on their weather information. Depending on how the upper bound of the highest category is treated, the mean WTP is between $20.72 and $27.20 per year.

Anaman et al. (1995, 1997, 1998) and Anaman and Lellyett (1996) describe two projects that used stated value methods to elicit values for weather information. One project elicited Sydney area residents' values for Bureau of Meteorology (BoM) services and another project elicited household values for the Tropical Cyclone Warning System (TCWS) in Queensland. Anaman and Lellyett (1996) report on a short telephone stated-value survey administered to 524 adults in Sydney eliciting values for the Australian public weather service. Average monthly WTP was AU$2.00, with 62.5% reporting zero WTP. Chapman (1992) prepared a benefit-cost analysis of the (then) proposed NWS modernization, including a sensitivity analysis. The benefit estimate relies heavily on a value derived from the MSI Services Incorporated (1981) report. Cavlovic et al. (n.d. [a]) value Environment Canada's Weatherline Automated Telephone Answering Device weather information service, focusing specifically on business callers from the Toronto area. Cavlovic et al. estimate a mean WTP per call of CA$1.20, which varies depending on the type of business using the information. Cavlovic et al. (n.d. [b]) surveyed 624 individuals to elicit values for Weatheradio in Canada. Weatheradio, run by Environment Canada, provides weather warnings along the Atlantic Coast of Canada with an aggregate value of slightly more than CA$2 million annually.

Stratus Consulting (2002) represents the only recent study designed to elicit household values for current and improved weather forecasts using accepted economic approaches. Because this work is the basis for the benefit analysis in this report, we discuss this study in more detail in the following section.

4.1.3 Stratus Consulting (2002)

Stratus Consulting (2002) examined the benefits to households of potential improvements in weather forecasting services, as well as how the public values current forecast services. The rest of this section discusses the methods used in and the results from this study.

The study focused primarily on household values for potential improvements in "day-to-day" weather forecasts. To elicit these values, the study developed a survey instrument through a series of focus groups, one-on-one interviews, a pilot study in Denver, and external review by survey research experts. Atmospheric Science Advisors, LLC (ASA; Silver Spring, Maryland) supplied input on the technical aspects of potential weather forecasting improvements. Data were collected with individual self-administered surveys conducted at survey centers in nine locations across the United States in October 2001. In all, 381 individuals participated.

The survey used stated-preference nonmarket valuation approaches to elicit household values for current or improved weather forecasting services. Stated-preference valuation includes stated choice methods (similar to conjoint analysis used in marketing research) and stated-WTP methods. The study used stated-choice methods to examine values for potential changes in attributes of day-to-day weather forecast information — frequency of updates, accuracy of 1-day forecasts, accuracy of multiday forecasts, and geographic detail (resolution). Exhibit 4.4 shows the baseline levels of these forecast attributes and levels of potential improvements considered by respondents.

Exhibit 4.4. Attribute levels for storm survey

Attribute level	Frequency of updates (times per day)	Accuracy of 1-day forecasts (%)	Accuracy of multiday forecasts (days)	Geographic detail (miles)
Baseline	4	80	5	30
Minimal improvement	6	85	7	15
Medium improvement	9	90	10	7
Maximum improvement	12	95	14	3

Individuals were also asked their WTP for a specific program that would improve weather forecast attributes. The improvement in forecast attributes was varied across the 20 versions of the survey. Several follow-up questions to the WTP questions helped to assess the reliability and validity of the value statements. Third, individuals were asked if the current weather forecast services were worth what they were currently paying in taxes for these services. By varying the amount individuals were told they currently paid, this question functions similarly to a referendum WTP question.

Analysis of the responses to the stated-choice questions indicates that improving the accuracy of 1-day forecasts is valued most, followed by improving the accuracy of multiday forecasts and geographic detail. Overall, individuals appear to have little value for increasing the frequency of weather forecast updates. Although this holds for the day-to-day forecasts examined in this study, the frequency of updates may be very crucial in situations such as severe weather (e.g., tornadoes or floods), which was not addressed. Using the marginal values estimated for changes in the attribute levels, the study calculated that individuals' values for a program that would increase all attributes to their maximum level was between $12 and $17 a year per household with a best estimate of $16.48.

Exhibit 4.5 presents this study's best estimates of annual per household values for improved and current weather forecasts. Based on Census estimates of about 105 million U.S. households, total annual national values for improving weather forecasts to the maximum levels proposed in the survey are estimated to be $1.73 billion per year. The study also calculated an annual national value of $11.4 billion for current weather forecast services (which includes the value of all weather forecast information services from public and private sectors).

Exhibit 4.5. Best estimate of annual values for improved and current weather forecast services (2001$)

Value	Annual value per household	Total national value[a]
Value for improving all forecast attributes to their maximum level (as described in Exhibit 4.4)	16.48	1.73 billion
Value for current weather forecast services[b]	109.00	11.4 billion

a. Based on approximately 105 million U.S. households (U.S. Census, 2000).
b. This aggregation takes the median value ($109) as representative of household values for current forecast services.

4.2 Aviation

Between 70% and 75% of recorded commercial flight delays were caused by weather over the last decade, and approximately 35% of commercial aviation fatalities occur in weather-related accidents. Delays and accidents can be caused by turbulence, icing, low-level wind shear, fog, low visibility, lightning strikes, and other factors. Accidents also can be caused by volcanic ash damaging airframes, engines, or instruments. For example, one Boeing 747 lost power in all four engines while flying through a cloud of volcanic ash over Alaska. The pilot was able to restart the engines and land safely, but all four engines had to be replaced and damages totaled $30 million. Weather is the cause of 80% of accidents in general aviation, and 83.3% of fatal accidents among private fliers (American Meteorological Society [AMS] Newsletter, 2000).

When weather events occur, flights may be delayed substantially, the capacity of the system may be greatly reduced, and aircraft and crews may not be available when needed. Improvements in forecasting weather en route and at the airport can lower costs for fuel, lower crew labor costs as more flights operate closer to the scheduled times, reduce passenger reaccommodation costs because fewer connections are missed, and lower costs from repositioning aircraft to serve later flights. For some airlines that do not have an automatic policy of carrying extra fuel to allow for all contingencies, accurate forecasts can allow aircraft to avoid carrying extra fuel that might be needed for safety, reducing weight and saving on fuel costs. Reduced delays or cancellations can also produce higher revenue because more passengers complete their trips as planned (and are not rebooked on other carriers when flights are cancelled or connections are missed), and generate less "ill will" toward the carrier or the carrier's hub airport because passengers will have better flight experiences (Sinnott et al., 2002).

Exhibit 4.6 summarizes some of the potential weather impacts on aviation and shows where improved weather forecasts may generate benefits.

Aviation weather information and products serve the Air Traffic Management (ATM) system operated by the Federal Aviation Administration (FAA). This system has taken decades to develop to its current capabilities. The NWS works closely with the FAA and the U.S. Department of Defense to provide aviation weather products. Much of the effort to increase scientific understanding of atmospheric conditions that cause dangerous weather is being coordinated through the FAA's Aviation Weather Research Program (AWRP). The research is aimed at producing more accurate and accessible weather observations, warnings, and forecasts. Partner agencies including NOAA, the National Center for Atmospheric Research (NCAR), the Massachusetts Institute of Technology's (MIT) Lincoln Laboratory, and the Naval Research Laboratory have worked with the AWRP to conduct the research.

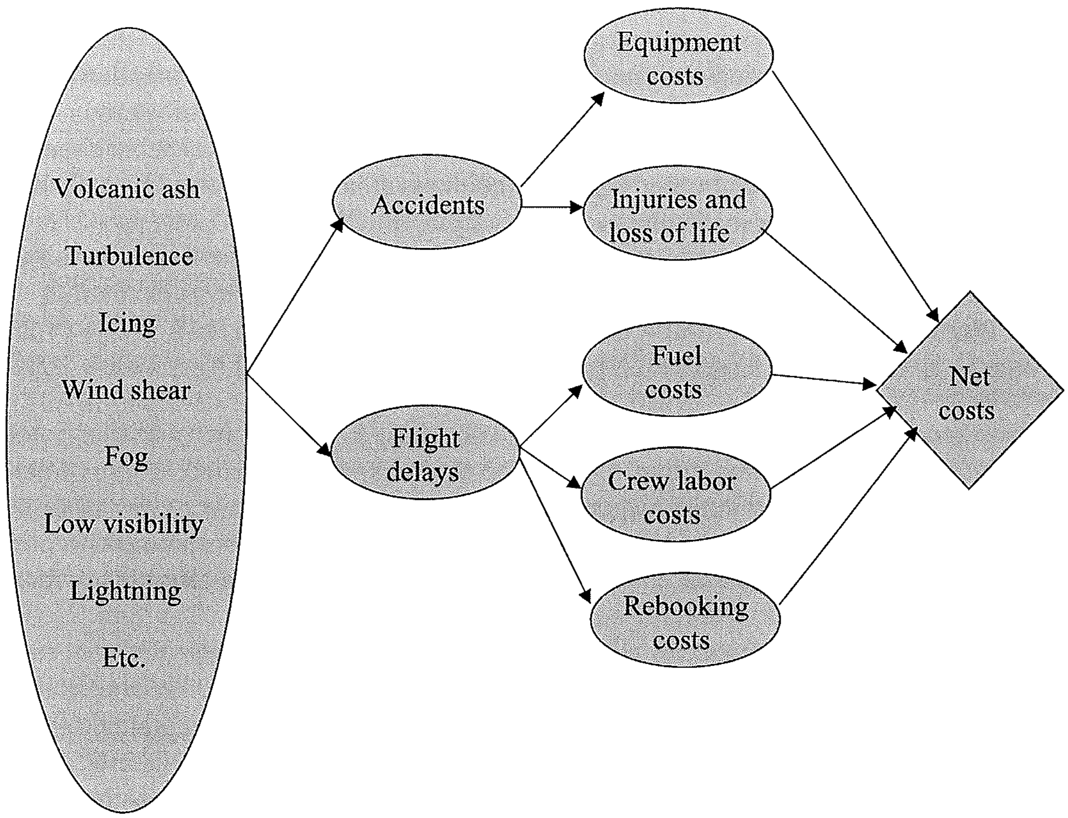


Exhibit 4.6. Influence diagram of weather impacts on aviation.

Estimates from the literature of the benefits of improvements in weather forecasts and the technology that produces them vary greatly according to the areas of forecasting examined and the system evaluated. The value of improvements in satellite technology that is used to produce weather forecasts and volcanic ash plume notifications is estimated to be $55 million in marginal annual benefits, and $205 million in discounted present value benefits from the time frame 2012-2027 (NOAA, 2002). A study from the national deployment of the Weather System Processor (WSP) assessed delay-reduction benefits in terms of aircraft delay-hour reductions. The benefits are expected to be $21 million per year based on expected year 2000 traffic counts at the planned WSP airports (Rhoda and Weber, 1996). Based on the latest estimates, national delay-reduction benefits from implementing the Integrated Terminal Weather System (ITWS) totals $521.6 million per year. Benefits from additional deployment of ITWS at three West Coast airports (San Francisco International Airport [SFO], Seattle-Tacoma International Airport [SEA], and Los Angeles International Airport [LAX]) are estimated to total $56.8 million from reduced delays resulting from improved merging and sequencing of aircraft. In addition, benefits from Simultaneous Operation with Independent Approaches (SOIA) at SFO are estimated to be $84.3 million per year (Evans et al., 1999). Estimates of the benefits of ITWS application at New York area airports also show substantial benefits from avoided delays in specific convective weather events (Allan et al., 2001). A study of the benefits of Terminal Convective Weather Forecast (TCWF) implementation for the ITWS estimates the benefits of national implementation of TCWF to be $545.2 million annually because of avoided delays from convective weather events (Sunderlin and Paull, 2001). A study of potential benefits from implementation of the Integrated Icing Diagnostic Algorithm (IIDA) estimates an average annual benefit of $31.7 million accruing from avoided in-flight accidents caused by icing (Paull, 2001). Another study showed the value of improved forecasts to an Australian airline in fuel savings to be approximately $11 million per year. The value of a hypothetical 1% increase in forecast accuracy was valued at $0.85 million (Leigh, 1995).

4.3 Agriculture

4.3.1 Introduction

Agricultural activities are very sensitive to climate and weather conditions. Both short-term and long-term forecasts are essential in planning agricultural production. Short-term and daily forecasts relate to daily weather up to 10 days ahead; seasonal forecasts relate to climate over 3- to 6-month periods with lead times of 1-12 or more months. Short-term weather forecasts, such as daily temperature and precipitation predictions, help producers to make better decisions on irrigation and crop-weather relationships such as frost protection and timing of optimal harvests. Long-term climate forecasts are useful to producers for managing land use, selecting plants and breeds of animals, and implementing crop production practices such as irrigation and pest and disease control. Farmers also benefit from severe weather forecasts. Severe weather causes crop damage averaging $2.5 million each year, and this figure would be even higher if the forecasts did not give farmers time to prepare and protect their property.

In this section, the discussion focuses on the benefits from short-term weather forecasts, because most of NOAA FSL's supercomputing capabilities benefit those forecasts. However, we include a brief discussion of seasonal climate forecasts because these types of forecasts are also generated using the current capabilities, but to a lesser extent.

Short-term forecasts include forecasts for less than 1 day, showing location, movement, and intensity of regional and local rainfall, and displaying current weather conditions as well as derived variables. Daily weather forecasts include forecasts up to 10 days in advance, and outputs are produced for 12 hourly or daily intervals. Variable forecasts, which are important to agriculture, include rainfall, temperature, winds, frost, and all types of severe weather forecasts.

The flow chart in Exhibit 4.7 displays these weather forecasts and shows which agricultural decisions are based on these forecast variables. Planting, irrigation, fertilization, pesticide application, harvesting, and drying decisions are all affected by weather, and harvest yield can be greatly influenced by the decisions made by producers and by the weather that follows.

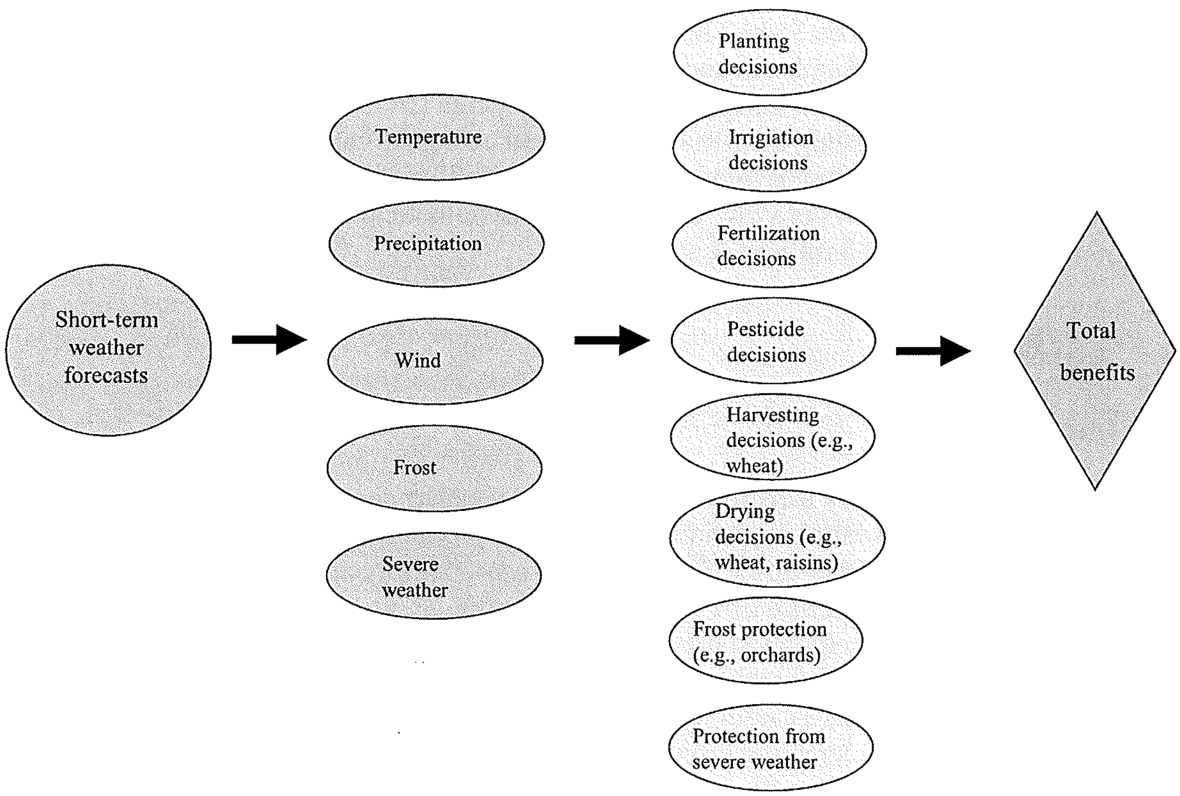


Exhibit 4.7. Flow chart of the agricultural benefits of short-term weather forecasts.

4.3.2 Value of weather forecasts to agriculture

The value of short-term weather forecasts to agriculture materializes when producers have the flexibility to adjust production responses to the new information as it comes in and make decisions that improve harvest levels (increase profits) or reduce damage (decrease costs). Forecasts also are used to help producers decide whether or not to buy crop insurance.

Several studies have estimated the economic benefits of weather forecasts. Some have done so by determining the benefit per unit of farmland (most commonly per hectare), and some have examined a lump sum improvement across a region or a nation per year. We discuss a few studies applicable to the purposes of this research here, and the appendices contain a more complete listing of studies and the values that have been estimated for various short-term weather forecasts.

Katz et al. (1982) examined the relationships between temperature, bud loss, and yield loss, and used optimal decision models to estimate the value of the meteorological information to apple, pear, and peach growers in central Washington. The per acre values estimates (1977$) were $808 for apples, $492 for pears, and $270 for peaches. These amounts account for 66%, 63%, and 47%, respectively, of the economic value that an orchardist whose decisions were based on perfect information would realize. Wilks et al. (1993) examined how alfalfa producers used daily precipitation, temperature, and evaporation forecasts in making their day-to-day harvest decisions. Wilks and colleagues modeled the daily cutting decisions over a growing season, allowing the model to prescribe both the number and timing of cuttings. Temperature forecasts were included in the model to control plant yield and maturity, and as input to the derived evaporation forecasts. The study concluded that perfect weather forecasts are worth $140 per hectare per year to alfalfa growers (1991$). For wheat, precipitation forecast information, as with alfalfa, is most valuable at harvest time because grain quality deteriorates when rain delays the wheat harvest. Fox et al. (1999a) found that the value of perfect weather information averaged $100 per hectare per year (1994 CA$). Fox and coworkers also found that the level of the farmers' risk aversion was an important determinant of the value of weather forecast information.

4.3.3 Literature on the value of seasonal climate forecasts to agriculture

Substantial advances in climate forecasting in recent years have given farmers access to a growing number of seasonal outlooks. These longer term forecasts may be useful for decisions on land use and management, selection of plants and breeds of animals, and crop production practices such as irrigation, fertilizer application, and pest and disease control.

One study of the Corn Belt region found that perfect long-term forecasts for precipitation, temperature, and radiation were worth from $1.3 billion to $2.9 billion over a 10-year horizon to farmers making decisions about fertilizer application, planting date and density, hybrid selection, and harvest date (Mjelde and Penson, 2000). Adams et al. (1995) assessed the economic returns from improved El Niño/Southern Oscillation (ENSO) forecasts (precipitation and temperature) to various crop yields 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 $200 million per year. The value of imperfect but improved forecasts is $132 million. Solow et al. (1998) found perfect ENSO information to be worth more than $320 million per year to U.S. agriculture as a whole. This forecast value was based on expected economic surplus (the sum of consumer and producer welfare). It used teleconnection between ENSO events and minimum and maximum temperature and precipitation in the United States. Appendix A reviews several more studies on the benefits of seasonal forecasts to agriculture.

4.3.4 Estimation of value to three crop sectors of improvements in weather forecasts

Applying a few of the estimates explained in Section 4.3.2 to the nation can yield some insight as to what national agricultural values of perfect weather information might be. Exhibit 4.8 displays the forecast values for three different crops: orchards (apples, peaches, and pears); alfalfa; and winter wheat. The values are listed per acre and are then multiplied by various amounts of land.[1] For illustrative purposes, the per-acre values are first applied to the total amount of land planted for that crop. We then show varying percentages of these because it is believed that the studies were likely focused on lands where the value of the weather information is high. We calculated these values over a range of 5% to 20% of the total cropland.

Exhibit 4.8. Annual value of improvement to perfect information

	Orchards (apples, peaches, and pears)	Alfalfa	Winter wheat	Total for these crops
Value of improvement to perfect information (PI) per acre of farmland[a]	$1,403	$75	$35	$65.19[b]
Acres of farmland[c]	828,460	23,541,000	44,349,000	68,718,460
Value of PI for 100% of land	$1.16 billion	$1.77 billion	$1.55 billion	$4.48 billion
Value of PI for 20% of land	$232 million	$354 million	$310 million	$896 million
Value of PI for 10% of land	$116 million	$177 million	$155 million	$448 million
Value of PI for 5% of land	$58 million	$89 million	$77 million	$224 million

a. Midpoint was used when a range of values was given.
b. Average per acre.
c. Source: Census of Agriculture (1997).
Sources: orchards: Katz et al. (1982); alfalfa: Wilks et al. (1993); winter wheat: Fox et al. (1999b).

1. We converted value per hectare to value per acre as appropriate in order to aggregate using information about the number of acres harvested.

Applying the per-acre value of weather information to orchards to just 10% of all orchard land (for apples, peaches, and pears) indicates an annual benefits of $116 million. Alfalfa and winter wheat values for weather information on just 10% of total acres planted indicates benefits of $177 million and $155 million, respectively. The final column of Exhibit 4.8 shows the total benefits of perfect information for these crops for the percent of land included. For instance, perfect short-term weather forecasts on just 10% of the cropland of only five crops generates a total benefit of $448 million each year.

4.4 Energy

Reliability is arguably the highest priority of electric companies. Roughly two-thirds of power outages are weather-related, and some of these could be avoided if more accurate weather data were available. Although the analysis of the recent (August 14, 2003) blackout in the Northeast is still being completed, and early indications are that this particular widespread outage was caused more by a breakdown in human-computer communications than weather, the cost of this outage alone has been estimated between $4 and $6 billion (Dukart, 2003).

Hot weather causes air-conditioning equipment to operate at higher capacity, increasing the need for power suppliers to produce electricity, and thus requiring less economically efficient generating units to run. This, in turn, increases peak loads on the nation's electric transmission grid, and as power demands surge, equipment becomes overloaded and can fail and cause outages. The primary equipment failures typically involve transformers, which themselves are heat producers that fail when they become overheated. Transmission lines sag when they heat, and if they sag so far that they touch trees, they will short to the ground and automated controls will switch them off from the transmission grid. A number of high-profile outages in recent years have been caused by one of these two mechanisms, although it is unclear exactly how many outages could be prevented by increasing the accuracy of weather data. The increased power demands also increase the level of air pollution emitted by generating facilities. Outages and other heat-related system problems affect power generators, electricity and gas traders, regional transmission operators, and local populations.

Short-term load forecasts of power needs depend on a number of weather variables, including temperature, humidity, wind speed, cloud cover, and extreme events. Temperature is the leading factor in most situations, and more accurate hourly temperature predictions would increase the accuracy of load forecasts, reducing the impacts on the nation's power system (Fan and McDonald, 1994).

In addition to these weather-related impacts, both short-term forecasts and seasonal weather information drive business decisions within the energy sector. Utility companies typically cite weather as a major determinant of earnings performance in their annual reports, and most state utility commissions permit utilities to adjust rates based on a weather-normalization clause. Seasonal forecasts of heating degree days (HDD) and cooling degree days (CDD) are now used by third-party companies, who sell "hedge" products to utilities that insure them against the risk to profits associated with above- or below-normal weather conditions. In 2000, nearly 1,400 weather-risk contracts were in place in the United States, with an estimated value of weather risk transferred of $1.8 billion (Nathan, 2001). Temperatures from the Automated Surface Observing Stations (ASOS) are the most widely used data for the weather-risk industry.

Other uses of weather data in the energy sector include:

- DOE accumulates ASOS data to derive renewable power resource assessments of solar and wind potential across the country. These assessments, in turn, are a key determinant in investment decisions by developers of renewable energy.
- Natural gas suppliers and industrial consumers use longer term forecasts to optimize investments in gas storage, primarily for winter use. Store too much gas for the weather conditions and capital is diverted from other profitable investments. Store too little gas and be forced to purchase on the spot market at prohibitive prices (although in the past few years, gas prices have also heavily influenced electricity prices because gas-fired combustion turbines used to produce power at peak times have become significant users of natural gas, and they rely on short-term forecasts).
- In the case of severe weather, utilities can minimize downtime, and thus revenue loss, by predicting when and where crews will be needed to repair downed lines or blown transformers.

Although summing the various end uses for weather data and accurately predicting the value of marginal increases in accuracy of the weather data would be difficult, the value of the marginal benefits of improved short-term forecasts to electric and gas suppliers has been estimated at $500 million per year (Williamson et al., 2002).

Exhibit 4.9 summarizes the relationship between forecasts and costs in the energy industry.

4.5 Weather-Related Fatalities

Significant numbers of people are killed or injured each year in weather-related incidents. Although not all of these are likely to be preventable with improved weather forecasts, some portion of the total could likely be reduced with improved forecasts, warning systems, and changes in behavior on the part of the people receiving this information.

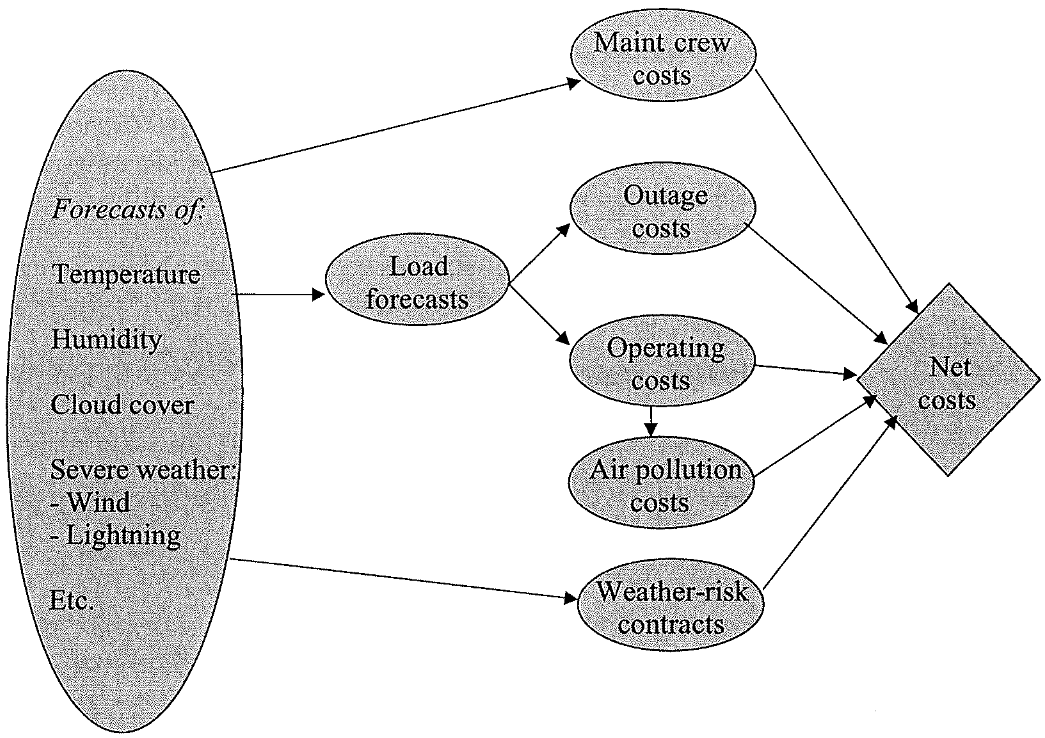


Exhibit 4.9. Influence diagram of weather impacts on energy industry.

One approach to valuing the benefits of better weather forecasts would be to determine the number of reduced deaths and injuries and put a value on these. The "value of statistical life" (VSL) approach is commonly used in determining the value of mortality reductions in public policy decision making.[2] Deriving individual WTP to reduce the risk of death is used to calculate the VSL.

An extensive body of literature exists on individual WTP to reduce mortality risks. Many studies, using either revealed-preference or stated-preference approaches, have estimated average WTP or willingness to accept (WTA) for small changes in risks of accidental death. These studies are being used as the basis for monetary valuation of mortality risk in assessments of the potential benefits of policy decisions. The works that discuss these types of applications include Fisher et al. (1989), Miller (1989), Cropper and Freeman (1991), and Viscusi (1992, 1993).

2. See Kenkel (2001) for a discussion of the use of VSL statistics in policy decision making.

Although all of the VSL estimates used in policy assessments have been drawn from basically the same underlying literature, there have been some differences in the specific VSL numbers that different offices have selected for use (Chestnut et al. 1997). Most have selected a central point estimate VSL and many have also used a range. Selected VSL point estimates have generally been between $5 million and $8 million. Selected ranges also vary. The range used has often been within $2 million to $14 million, but some assessments have used a range of as much as $0.5 million to $20 million. A common point estimate for the VSL is $6 million.

Exhibit 4.10 shows the number of weather-related fatalities each year for the last 7 years and the "cost" to society of these fatalities using standard VSL estimates.

Exhibit 4.10. Weather-related fatalities and VSL estimates

Year	Fatalities	Fatalities — value[a]
1996	540	$3,240,000,000
1997	600	$3,600,000,000
1998	687	$4,122,000,000
1999	908	$5,448,000,000
2000	476	$2,856,000,000
2001	464	$2,784,000,000
2002	540	$3,240,000,000
Average annual	602	$3,613,000,000

a. Calculated as $6 million per fatality.

Source: NWS (1996-2002).

5. Economic Analysis

The economic benefits of improved weather forecasting are potentially huge. As shown in Exhibit 4.1 in the previous chapter, the investment in a new NOAA supercomputer will affect many sectors of society, including other government agencies, private industry, and individual households. In this chapter, we report on an economic analysis of the societal benefits of a new NOAA supercomputer in three areas:

- the household sector
- a limited number of agricultural crops
- weather-related fatalities.

At this time we have not included a calculation of the present benefits in the aviation or energy sectors. Noting the magnitude of the benefits suggested in these other industries, however, we feel the analysis described here represents a lower bound to total benefits. Even though these areas represent only a fraction of all the potential benefits of the new supercomputer, the present value of the benefits from each of these areas individually is in the tens of millions of dollars, even using conservative assumptions.[1]

Determining these benefits requires linking the use of the new supercomputer to overall improvements in weather forecasting and then linking these forecasting improvements to economic benefits. Because these linkages have never been formally quantified, Stratus Consulting facilitated an assessment with NOAA staff. According to NOAA, improvements in forecasting are a function of three factors: observation, understanding, and computing, as shown in Exhibit 5.1. NOAA estimates that each of these factors make roughly equal contributions.

NCEP, GFDL, and NHRA make these contributions to computing, which NOAA estimates at 60%, 20%, and 20%, respectively.[2]

The final step is to estimate the new supercomputer's contribution to improvements in weather forecasting generated by NOAA researchers over the expected likely 5-year life of the new computer. NOAA estimates this contribution at 75%. In other words, without the proposed

1. Throughout this work we attempted to make "conservative" assumptions at any point where a subjective judgement was necessary. By conservative we mean erring on the side of *understating* the final benefit estimates instead of potentially overstating the benefits.

2. As discussed in chapter 2, the proposed new supercomputer will replace several GNU/Linux-based clusters within FSL's computing facilities and will be known as the NOAA HPCS for Research Applications (NHRA). We thus refer to this as NHRA here rather than as FSL.

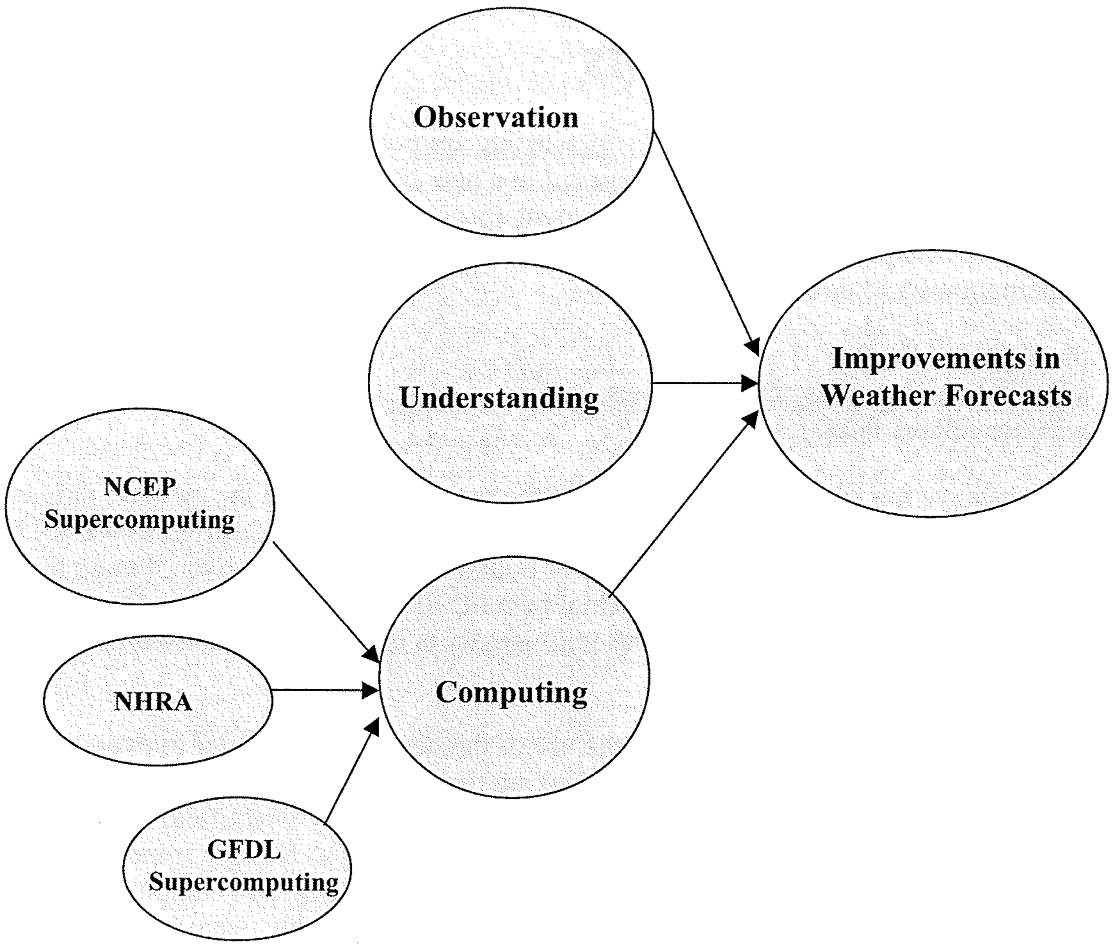


Exhibit 5.1. Contributions to improving weather forecasts.

NHRA supercomputing capabilities, advances in weather forecasting research and development at FSL and other NOAA laboratories to which this computer contribute are expected to be only about one-fourth of what they would be with the increased computing capabilities.

Combining these contributions results in an overall contribution from the new NOAA supercomputer of:

$$33\% \times 20\% \times 75\% = 5\%$$

This 5% contribution will be applied to the economic benefits in the household, agriculture, and weather-related fatalities segments that are expected to result from improved environmental modeling. The details of the analysis for each area follow.

5.1 Household Sector Benefits for Improved Weather Forecasts

In contrast to the often anecdotal research available in other sectors, Stratus Consulting recently completed an extensive economic analysis for NOAA that links specific improvements in weather forecast accuracy to social benefits: *Economic Value of Current and Improved Weather Forecasts in the U.S. Household Sector* (Stratus Consulting, 2002).

As described in Section 4.1.3, the Stratus Consulting household study determined that the average household would be willing to pay about $16 (2001$) per year to have forecast quality improved to the maximum technically feasible level. The aggregate national benefit is $1.73 billion per year. The forecast improvements were in the categories of 1-day forecasts, multiday forecasts, geographic details, and update frequency, and they focused on temperature and precipitation. Study participants assumed that current forecasts were 80% accurate and that the maximum technically feasible level is 95%. Since the study was completed, forecasts have continued to improve and are currently estimated to be 85% accurate.[3] The total potential household benefit of improving forecasts to 95% accuracy is therefore reduced by one-third to $1.15 billion (2001$) for the purposes of *this* analysis.

The percent improvement in overall weather forecasting over the analysis period is highly uncertain because of the complexity of the problem and the multiple parties involved in R&D and technology transfer. For the purposes of this study, we used a conservative range of percent improvements in overall weather forecasting over current accuracy so as not to overestimate the benefits of the new NOAA supercomputer. The range chosen is from 2.5% to 10.0%, with a base case value of 4.25%. This range represents the total (not annual) improvement in weather forecast accuracy that accrues over a 5-year period from all sources of R&D (i.e., improvements in observation, understanding, and computing). Once this total benefit accrues, we assume that it remains an annual benefit to society in perpetuity.

We used the financial assumptions shown in Exhibit 5.2 to compute the present value of benefits to the household sector.

3. This conservative assumption is made to ensure that we account for improvements in weather forecasting that may have occurred since the study was conducted in 2001.

Exhibit 5.2. Financial assumptions for base case present value calculations

Real social discount rate[a]	3%
Decision to purchase supercomputer	2004
First year of operation	2005
Number of years until benefits begin	2
Number of years in which benefits accrue	5
Time horizon for accrued benefits	Infinite

a. We are using a real rate of discount.

We derived these assumptions as follows:

- Decision to purchase supercomputer: We assume that the decision to undertake the purchase of the new supercomputer is made during FY 2004.
- First year of operation: We assume that it takes 1 year from the time the purchase decision is made to the time when the new equipment is in place and operational for use in R&D activities.
- Number of years until benefits begin: We assume a 2-year time lag between the time when R&D makes progress in weather forecasting and the time when the new system is fully operational and the end users of weather forecasts are seeing the benefits.
- Number of years in which benefits accrue: We assume that once benefits begin, they continue to accrue over a 5-year time frame.
- Time horizon for accrued benefits: We assume that once R&D leads to improved quality or accuracy of weather forecasting, these improvements will not be lost. In other words, the incremental improvement in weather forecasting quality that occurs as a result of R&D efforts during this time period will accrue to future generations as long as they continue to use and build on the body of weather forecast knowledge.

Combining these financial assumptions with the contribution of the new NOAA supercomputer to improved forecasting (5%), the base case percent improvement in current accuracy (4.25%),[4] and the total potential household benefits ($1.15 billion) produces a base case present value of benefits in 2003 of $69 million (2002$).

Because of the uncertainty in many of the variables in the present value calculation, we performed a sensitivity analysis. Exhibit 5.3 shows the uncertainty ranges that we considered and the variation in present value that we obtained. The uncertainty with the largest impact is the discount rate, followed by the assumptions for the percent improvement in forecast accuracy, the contribution of the supercomputer to improvements, and the dollar-per-household value.

Because the benefits of improved forecasting are assumed to accrue in perpetuity, the choice of discount rate will have a large effect on present value. Even with a relatively high real social discount rate of 5%, however, the present value of benefits is still $37 million. The uncertainty in the percent improvement in current forecasting accuracy causes the second largest swing in present value. Still, the present value with only a 2.5% increase in accuracy is $34 million. The low assumptions for the supercomputer's contribution and the dollar-per-household value result in $35 million and $58 million in present value, respectively.

Exhibit 5.3. Household benefits sensitivity analysis results (base case present value = $69 million; 2002$)

		Low	High	Range in present value (millions)
Real social discount rate	Input value (%)	5	1	195
	Present value (millions)	37	232	
Percent improvement	Input value (%)	2.5	10	104
	Present value (millions)	34	138	
Supercomputer contribution	Input value (%)	2.5	7.5	69
	Present value (millions)	35	104	
Household value ($/household)[a]	Input value	14.13	19.84	24
	Present value (millions)	58	82	

a. 95% confidence interval from Stratus Consulting (2002) pp. 5-6.

In summary, using conservative estimates for the uncertain assumptions still produces a large present value of benefits to the household sector, in the tens of millions of dollars.

4. This translates into an improvement from 85% accuracy as described in the Stratus Consulting 2002 report, to 85.425% accuracy [0.85 + ((0.95 - 0.85) × 0.0425)] as a result of *all* R&D weather forecasting efforts (not just that associated with NHRA).

5.2 Agricultural Benefits from Improved Weather Forecasts

As described in detail in Section 4.3, a variety of studies exist quantifying the benefits of improved and perfect weather forecasting for specific situations in the agriculture sector. Although the benefits to agriculture appear to be potentially large, little comprehensive research exists that directly links improvements in forecast accuracy to the sector as a whole. As a result, this analysis is illustrative only, but does indicate the potential magnitude of the benefits to agriculture.

For this illustrative analysis, we use the benefits reported in Section 4.3 for orchard land (apples, pears, and peaches); alfalfa; and winter wheat. As Exhibit 4.8 showed, assuming perfect information on the weather and 10% of all land, the benefits to orchard land, alfalfa, and winter wheat crops are $116 million, $177 million, and $155 million per year, respectively. The total value, then, for these three crops under conditions of perfect information for 10% of cropland is $448 million per year. This value is analogous to the household value of $1.15 billion for increasing weather forecasting levels to 95% accuracy ("almost" perfect information).

The benefits to these three crops are therefore calculated in parallel fashion to that for the household sector, using the same financial assumptions (see Exhibit 5.2), the assumptions for percent improvement in current forecasting accuracy (4.25%), and the contribution of the new NOAA supercomputer (5%) to improved weather forecasting. The resulting present value of benefits to these crops potentially attributable to a new NOAA supercomputer is $26 million.

5.3 Avoided Weather-Related Fatalities Resulting from Improved Weather Forecasts

As we reported in Section 4.5, the average social cost of weather-related fatalities is $3.6 billion per year. To our knowledge, no comprehensive study exists that correlates weather forecast accuracy with weather-related loss of life, although improvements in accuracy, especially for severe weather, can be expected to prevent some loss of life. As for the agriculture sector, this analysis is illustrative only and uses conservative assumptions to result in a reasonable lower bound on the benefits accruing from a new NOAA supercomputer. For example, assume that just 10% of weather-related fatalities are preventable if perfect information were available. This puts the potential benefit at $360 million per year. Again, this value is analogous to the potential benefits under perfect information obtained earlier for households and the agricultural crops. Applying the same financial model and conservative assumptions, we arrive at a present value of avoided weather-related fatalities of $21 million because of the new NOAA supercomputer.

The Stratus Consulting (2002) household study described earlier in this report focuses on household values for day-to-day (i.e., ordinary) weather forecasts. Because weather-related fatalities are generally associated with severe weather or extreme weather-related events (e.g., tornadoes, floods, lightning, heat waves), these values should largely be separate from those of the Stratus study. However, because of the small potential for double counting, we currently do not add the values of reduced mortality to the household sector values.

5.4 Summary

In summary, the potential societal benefits from the purchase of a new NOAA supercomputer are very large. If the benefits were seen in the household sector alone, the present value ranges from $34 million to $232 million, depending on assumptions. The benefits to certain segments of the agriculture economy appear to be of the same order of magnitude, as does the potential for avoided weather-related fatalities. Exhibit 5.4 summarizes the base case present values for these three areas.

Exhibit 5.4. Summary of present value of benefits in 2003 (millions, 2002$)

Household sector	69
Orchards, winter wheat, alfalfa	26
Avoided weather-related fatalities	21

6. Conclusions

With a significant portion of the U.S. economy being weather sensitive, and some portion of weather losses being preventable, public investments in R&D that lead to improvements in weather forecast accuracy will likely result in significant benefits to society. NOAA's strategic plan states a commitment to "maintain and improve our technology infrastructure" including "supercomputing capabilities." This report assesses the potential economic benefits of the purchase of new supercomputing equipment for the NHRA in Boulder, Colorado, to serve the computing needs of NOAA and other associated entities.

Exhibit 6.1 gives the estimates of the present value of benefits in millions of dollars for the sectors for which our analysis quantified these benefits. Given that these represent only a fraction of the sectors that would likely realize economic benefits from improved weather forecasts, and given that we used conservative assumptions to derive these benefit estimates, these should be considered lower bound estimates.

Exhibit 6.1. Summary of present value of benefits in 2003 (millions, 2002$)

Household sector	69
Orchards, winter wheat, alfalfa	26
Avoided weather-related fatalities	21

Our sensitivity analysis of several of the key assumptions for just the household values for ordinary weather forecasts indicates a range of present value benefit estimates from $34 million to $232 million. Appendix B covers some of the omissions, biases, and uncertainties that are unresolved in this analysis and the likely effect (if identifiable) on benefit estimates if these uncertainties were reduced. In general, adjustments to the present value estimates made by reducing the uncertainties in this analysis would lead to higher present value estimates than those presented in this report.

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A. Literature Review by Sector

A.1 Households

A.1.1 Perceptions of weather forecasts

Murphy, A.H., S. Lichtenstein, B. Fischhoff, and R.L. Winkler. 1980. "Misinterpretations of Precipitation Probability Forecasts." ***Bulletin of the American Meteorological Society*** **61:695-701.**

Murphy et al. (1980) report on an examination of laypeople's understanding of probability of precipitation forecasts in which 79 student subjects' preferences for numerical versus verbal information in precipitation forecasts were elicited in an 11-question survey. The questions distinguish between the subjects' understanding of the forecast event (likelihood of precipitation stated in a given forecast) and their understanding of probabilities (e.g., 70%). Results indicate that individuals misunderstand the event more so than the probabilities and that they have a preference for information stated in terms of percentages.

MSI Services Incorporated. 1981. Public Requirements for Weather Information and Attitudes Concerning Weather Service. Prepared for the National Weather Service.

MSI Services Incorporated (1981) reports on a national telephone survey of 1,300 households' use of and need for weather forecast information. The survey was designed to answer eight general questions of interest to the NWS:

1. What types of weather information does the public use?
2. Does the public understand the information they are currently receiving?
3. What types of weather information does the public want?
4. How does the public obtain their weather information now and what method is preferred?
5. How often does the public want weather information?
6. How does the public feel about the value of the weather information they receive?
7. For what purpose does the public use weather information?
8. Is there a relationship between how close a person lives to a National Weather Service Office and how he/she perceives the service he/she is receiving?

Murphy, A.H. and B.G. Brown. 1983. "Forecast Terminology: Composition and Interpretation of Public Weather Forecasts." ***Bulletin of the American Meteorological Society*** **64:13-22.**

Murphy and Brown (1983) discuss the use of terminology in verbal public weather forecasts and what can be done to improve the transfer of information. Focusing on short-term weather forecasts, they define and consider 1) events, 2) terminology, 3) words versus numbers, 4) uncertainty, 5) amount of information, and 6) content and format of public forecasts and how these affect information transfer. Murphy and Brown suggest that individuals have a limited capacity to absorb and retain information and thus it is unnecessary for forecasts to provide excessive information:

> . . . In determining the amount of information to include in a weather forecast, it appears that considerations related to . . . the recipient's ability to absorb, process, and recall information dominate considerations related to . . . the amount of information desired by the recipient" (p. 17).

They further conclude that studies have found that, in general, temperature and precipitation are the most important part of the forecast message. Research recommendations include more study of public perception, use of, and understanding of public weather forecasts.

Curtis, J.C. and A.H. Murphy. 1985. "Public Interpretation and Understanding of Forecast Terminology: Some Results of a Newspaper Survey in Seattle, Washington." ***Bulletin of the American Meteorological Society*** **66:810-819.**

Curtis and Murphy (1985) discuss responses to a survey implemented through a newspaper in Seattle examining individual interpretations of various terms used in weather forecasts. The survey was a self-administered newspaper questionnaire with more than 2,000 responses. The results were compared with those from two questionnaires administered to college students in Oregon. Similar to prior findings, precipitation and temperature information was more important than cloud cover or wind. Numerical probability statements were preferred to verbal probability statements. Overall the results reported did not seem to indicate any significant misinterpretation of weather terminology by the public. There is no discussion in Curtis and Murphy of whether the interpretation of different weather terminology has any direct importance or how it may affect behavior.

Pope, C.A. 1992. Viewer Perceptions of Severe Weather and Broadcast Meteorologists, Vol. II. Masters thesis, Mississippi State University, Starkville.

Pope (1992) conducted a 48-question survey in 10 U.S. cities and towns exploring individual use, understanding, and perceptions of weather forecasts. The general topics examined were weather information sources, quality and attributes of importance in the local forecaster, and understanding of severe weather. Location-specific differences were found that generally seemed to correlate with the locations' weather. Respondents used TV as the primary weather forecast source (70.5%). Pope found that current, today's, and the next day's forecasts were the most important meteorological data displayed by local weather forecasters, over other data such as local radar, national weather, extended forecasts, satellite images, and jet stream maps. Individuals were generally indifferent between temperature being presented as a range versus a point description, but were generally in favor of percentage terminology rather than a descriptive term to indicate probability of precipitation. Similar to Murphy et al. (1980), Pope found general misinterpretation of "the event." In this case a "50% chance of rain" was interpreted as meaning any one place in the forecasting area will have a 50% chance of rain (as opposed to the "correct" interpretation of only one specific place in the forecasting area will have a 50% chance of rain).

Colman, B. 1997. "What Is a Good Weather Forecast? in the Eyes of a Forecaster." Presented at the Workshop on the Social and Economic Impacts of Weather, April 2-4, Boulder, CO.

Colman (1997) discusses briefly what makes a good weather forecast for the public. A small convenience sample of weather forecasters was asked the question, and a majority answered that a good forecast was determined by the public's response and perception of the forecast rather than by skill measures of accuracy: ". . . forecasters are concerned about public perception and the action the forecast instills" (p. 2). Colman provides two examples of similar forecasts of high wind warnings for the Seattle area, one that did not receive much public reaction and one that did, but the author does not offer any reasons for this difference. Similar to the issues raised by Hooke and Pielke, Colman discusses that modernization has developed the technology for highly detailed weather forecasts but that the "technology" to best communicate forecasts to the public has not been developed. Several of the issues raised about communication and public perception are closely related to the risk perception literature (e.g., trust and credibility issues), but this literature is not specifically mentioned.

A.1.2 Studies on household values for weather forecasts

Prototype Regional Observing and Forecasting Service. 1979. Report of a Study to Estimate Economic and Convenience Benefits of Improved Local Weather Forecasts. NOAA Technical Memorandum ERL PROFS-1. NOAA Environmental Research Laboratory, Boulder, CO.

Prototype Regional Observing and Forecasting Service (1979) reports on research conducted by J.E. Haas and R.B. Rinkle of Human Ecology Research Services in Boulder, Colorado. Values for improved local weather forecasts were elicited from 95 Denver urban area households.

Residents were interviewed to examine their use of forecasts for various work and recreation activities. After discussing forecasts for different weather conditions with different lead times, individuals were asked to estimate benefits from improved or perfect weather forecasts. Values were elicited in terms of their savings in undertaking different activities such as recreation, commuting, or shopping. The majority of subjects were unable or unwilling to make a value statement. Treating nonresponses as zero value, values were estimated on a per forecast basis for type of forecast (e.g., hail, snow, rain). Estimated aggregate benefits for perfect forecasts for Denver households were $31 million (1979$) based on estimated annual per capita benefits of $44 for commuting, $17 for recreation, and $23 for shopping weighted by the number of activities undertaken.

MSI Services Incorporated. 1981. Public Requirements for Weather Information and Attitudes Concerning Weather Service. Prepared for the National Weather Service.

MSI Services Incorporated (1981) reports on a national telephone survey of 1,300 households' use of and needs for weather forecast information. The survey included a valuation question on what individuals think the value of their weather information is: "If you had to put a dollar value per year on weather information you receive, what would it be?" Depending on how the upper bound of the highest category is treated, the mean WTP is between $20.72 a year and $27.20 a year. Given reasonable practices in stated value studies, the value estimate derived from this report is of questionable use — the question was the 51st question in a 59-question telephone survey; the commodity being valued, "weather information you receive," is extremely vague even given the preceding questions; and the valuation scenario did not identify a payment mechanism, discuss complements or substitutes, or check for validity or reliability of responses.

Anaman, K.A. and S.C. Lellyett. 1996. "Contingent Valuation Study of the Public Weather Service in the Sydney Metropolitan Area." ***Economic Papers*** **15(3):64-77.**

Anaman, K.A., D.J. Thampapillai, A. Henderson-Sellers, P.F. Noar, and P.J. Sullivan. 1995. "Methods for Assessing the Benefits of Meteorological Services in Australia." ***Meteorological Applications*** **2:17-19.**

Anaman, K.A., S.C. Lellyett, L. Drake, R.J. Leigh, A. Henderson-Sellers, P.F. Noar, P.J. Sullivan, and D.J. Thampapillai. 1997. ***Economics and Social Benefits of Meteorological Services Provided by the Australian Bureau of Meteorology: Final Project Report.*** **MacQuarie University, Bureau of Meteorology, Sydney.**

Anaman, K.A., S.C. Lellyett, L. Drake, R.J. Leigh, A. Henderson-Sellers, P.F. Noar, P.J. Sullivan, and D.J. Thampapillai. 1998. "Benefits of Meteorological Services: Evidence from Recent Research in Australia." ***Meteorological Applications*** **5(2):103-115.**

Anaman et al. (1995, 1997, 1998) and Anaman and Lellyett (1996) describe a seven-project, multiyear study of various aspects of the value of weather information services provided by the Bureau of Meteorology (BoM) of Australia. Two of the seven projects used stated-value methods to elicit values for weather information; Project 1 elicited Sydney area residents' values for BoM services and Project 7 elicited household values for the Tropical Cyclone Warning System (TCWS) in Queensland. Anaman and Lellyett (1996) report on a short telephone stated-value survey administered to 524 adults in Sydney eliciting values for the Australian public weather service. Average monthly WTP was AU$2.00, with 62.5% reporting zero WTP. A logistic regression indicated lower WTP from older people, higher WTP from more frequent users and from those judging the information to be of higher quality, and no significant relationship for the additional use of weather information in business as well as personal use. The logistic regression modeled WTP as 0 for zero WTP and 1 for positive WTP.

Chapman, R.E. 1992. ***Benefit-Cost Analysis for the Modernization and Associated Restructuring of the National Weather Service.*** **NISTIR 4867. Report to the U.S. Department of Commerce, National Institute of Standards and Technology. Washington, D.C.**

Chapman (1992) prepared a benefit-cost analysis of the (then) proposed NWS modernization, including a sensitivity analysis. In general, Chapman found strong support for the modernization using any criteria (benefit-cost ratio or net present value). The benefit estimate relies heavily on a value derived from the 1981 MSI Services report "Public Requirements for Weather Information and Attitudes Concerning Weather Service." The per capita value from the MSI Services study was translated to $35.50 per year (1992$). Even given adjustments made to the MSI Services study values for use in the benefit-cost analysis of the weather service modernization, there is nothing in the MSI Services study that would indicate a specific relationship between values for current services (as elicited in the MSI Services study) and values for changes in services (as required for benefit-cost analysis of the modernization).

Cavlovic, A., J. Forkes, and K. Rollins. No date (a). ***Economic Value of Environment Canada's ATAD Service for Business Users in the Greater Toronto Area.*** **Unpublished report submitted to The Policy Program and International Affairs Directorate, Atmospheric Environment Service, Environment Canada.**

Cavlovic et al. (n.d. [a]) value Environment Canada's Weatherline Automated Telephone Answering Device (ATAD) weather information service, focusing specifically on business callers from the Toronto area. Cavlovic et al. estimate a mean WTP per call of CA$1.20, which varies depending on the type of business using the information.

Cavlovic, A., J. Forkes, and K. Rollins. No date (b). Economic Value of Environment Canada's Weatheradio Service for Users in Maritime Communities of Atlantic Canada. Unpublished report submitted to The Policy Program and International Affairs Directorate, Atmospheric Environment Service, Environment Canada.

Cavlovic et al. (n.d. [b]) surveyed 624 individuals to elicit values for Weatheradio in Canada. Weatheradio, run by Environment Canada, provides weather warnings along the Atlantic coast of Canada and thus is primarily a weather warning system. A telephone-administered, double-bounded dichotomous choice contingent valuation survey was used. The survey also elicited information on other sources and uses of weather information and preferences for improvements to Weatheradio. Average annual WTP for Weatheradio was derived for residents of New Brunswick (CA $96.27 per user, business or personal), Nova Scotia (CA$76.47), and Prince Edward Island (CA$93.12) for an aggregate value of slightly more than CA $2 million annually.

A.2 Aviation

Sunderlin, J. and G. Paull. 2001. FAA Terminal Convective Weather Forecast Benefits Analysis. Prepared for the FAA by MCR Federal, Inc. Bedford, MA.

The study estimated the benefits of the Terminal Convective Weather Forecast (TCWF) product. The product is being developed as part of the Federal Aviation Administration (FAA) Aviation Weather Research Program (AWRP). TCWF is an implementation product for the Integrated Terminal Weather System (ITWS). ITWS forecasts are sometimes erroneous because they do not account for storm evolution, and the current prediction window is limited to 10 to 20 minutes. TCWF addresses these shortcomings. TWCF was demonstrated at Dallas-Fort Worth, Orlando, Jacksonville, and New York airports. Benefits were estimated for these locations and extrapolated to the national level. Current ITWS benefits were estimated to be $573.5 million. Benefits were estimated for the TCWF based on interviews with traffic management personnel. Delay reduction benefits were extrapolated to yearly savings using linear extrapolation and a queuing model. The percentage of respondents expressing that they saw benefits from using the product were used to develop confidence intervals around the estimate. Total national benefits were estimated to be $545.2 million annually at a confidence level of 55%-60%. This estimate ranges from $461.2 million at the 80% confidence level to $687.2 million at the 20% confidence level. Estimated TCWF savings are approximately 3% of the delay baseline. Also, TCWF savings is approximately 6% of weather delay at the TCWF sites, assuming that weather delay is approximately 40% of all delays.

Paull, G. 2001. Integrated Icing Diagnostic Algorithm (IIDA) Safety Benefits Analysis Accident Case Studies. Prepared for the FAA by MCR Federal, Inc. Bedford, MA.

This study estimated the benefits of the Integrated Icing Diagnostic Algorithm (IIDA), and the related product the Integrated Icing Forecast Algorithm (IIFA). The majority of estimated benefits apply to general aviation operations, with the remainder from commuter and air taxi operations. Air carrier benefits were excluded because of the limited number of historical in-flight icing accidents. Six recent in-flight accidents were selected for review as to the likelihood the IIDA product would have prevented the event. Excluding air carriers, the average annual cost of in-flight icing accidents is $100 million. The effectiveness of IIDA in reducing accident risk was estimated to range from 26% to 62%. Accidents occurring within the CONUS were 90% of total accidents, and 80% of all noncarrier accidents involved known icing conditions where the pilot received a weather briefing. Thus the historical baseline was limited to 72% (90% * 80%) of the historical baseline. Therefore, the accident pool that IIDA may affect totals $72 in annual costs. The potential safety benefit from IIDA was estimated to range from $18.7 million to $44.7 million, with an average benefit of $31.7 million. Benefits for Alaska were excluded because IIDA is not projected to cover Alaska until 2002. This result assumes that the proportion of pilots who currently receive weather briefings will utilize IIDA, have established confidence in the product, and do not benefit in situations where icing conditions were not forecast. The ability to disseminate information to pilots in a timely manner is still of concern. Until IIDA is easily accessible to pilots and pilots build confidence in the product, the benefits potential estimated will not be fully realized.

Leigh, R.J. 1995. "Economic Benefits of Terminal Aerodrome Forecasts (TAFs) for Sydney Airport, Australia." *Meteorological Applications* 2:239-247.

This study analyzed the economic value to Quantas Airlines of improvements in Terminal Aerodrome Forecast (TAF) information. The value to the airline derives from avoidance of carrying extra fuel on board that might have been required in bad weather conditions to divert to an alternate airport or account for other contingencies. A hypothetical increase in TAF accuracy of 1% is valued at $0.85 million. The average value to Quantas of TAF service at the Sydney airport is $4.9 million. This is more than the value that Quantas pays indirectly to Australian Bureau of Meteorology for all aviation weather services ($4.2 million). When extrapolated to all international Quantas flights this is about $11 million per year. These values do not consider the social value of reduced air pollution (carbon dioxide, nitrogen oxides, etc.). Quantas policy allows for making the decision on how much fuel to carry after factoring in weather forecasts. Many other airlines require carrying extra fuel regardless of the weather forecast, so this value to Quantas is not widely applicable to other airlines.

Evans, J.E. 1995. "Measuring the Economic Value of Aviation Meteorological Products." Paper presented at the 14th Conference on Weather Analysis and Forecasting. January 15-20. Dallas, TX.

This study reviews safety and delay reduction in regard to aviation weather forecasting — specifically the benefit of wind shear detection systems and delay reduction resulting from improved weather information. Assessing the benefits of wind shear impact reduction systems is difficult because of the small number of wind shear incidents in history to study, and the limited amount of wind shear data at some airports depending on the variability of thunderstorm events between years. It is also difficult to determine the effect of warning systems that alert only when a plane is already encountering a microburst. Pilot reaction to these rare warnings is a key factor. Regarding delays, in another study delay results were extrapolated from Chicago O'Hare to other major airports based on differences in traffic into the airport. Thunderstorms, heavy fog, and low visibility were considered. Thunderstorms accounted for approximately 50% of the delay. Downstream effects of a delay are generally considered to be 4 times the initial weather delay, although one study showed the downstream affected passengers to be 27 times the initial delay. A queuing model study suggests a modest reduction in weather event effective duration (e.g., from 3.0 hours to 2.5 hours) by predicting the event end time can produce substantial changes in delay (e.g., 20%-35%), and that relatively small changes in system capacity (e.g., 10%) can produce much larger proportional reductions in accumulated delay (e.g., 20% to 50%).

NOAA. 2002. Geostationary Operational Environmental Satellite System (GOES) GOES-R Sounder and Imager Cost/Benefit Analysis (CBA). Prepared for the Department of Commerce by NOAA, National Environmental Satellite, Data, and Information Service (NESDIS), Office of Systems Development. November 15. Silver Spring, MD: NOAA/NESDIS.

Two main products from the GEOS-R satellite system are an advanced imager and sounder. These will provide greater Earth coverage and weather and environmental information and predictive capability. There are two main sources of value to aviation from improvements in the satellite — avoided delays from better weather information, and detection of volcanic ash plumes to avoid catastrophic aircraft failure or damage to engines, instruments, and airframes. With advanced sounder data, forecasters looking 1 to 2 hours in advance will likely be able to reduce the watch area by approximately 90%. This will result in more efficient use of air space by reducing weather related flight delays. It will also provide more information about the intensity and rate of development of convective weather. Estimated benefits are $55 million marginal annual benefits, and $205 million in discounted present value benefits from the time frame from 2012 to 2027. Of this amount, $38 million annually and $103.3 million in present value terms will come from avoided delays from better weather information; the rest comes from avoiding volcanic ash plumes.

Allan, S.S., S.G. Gaddy, and J.E. Evans. 2001. ***Delay Causality and Reduction at the New York City Airports Using Terminal Weather Information Systems.*** **Lexington, MA: MIT Lincoln Laboratory.**

This study examines initial benefits from a pilot project to provide Integrated Terminal Weather System services to New York. In the late summer of 1999, the initial ITWS capability was extended to include 30- to 60-minute predictions of convective storms generated by the Terminal Convective Weather Forecast (TCWF) algorithm. One key benefit is improved traffic management decision making during convective weather. Traffic managers were able to reduce airport gridlock by releasing several additional departures each hour by properly timing the arrival and impact of lines of convective weather. In the second example, terminal wind information is used to correctly set arrival rates and merge/sequence aircraft during a time of strong vertical wind shear. Because New York winters are especially vulnerable to vertical wind shear, accurate knowledge of terminal winds is critical for traffic managers. Study of these two types of benefit using an MIT-developed queuing model shows that nearly $2,080,000 was saved at Newark International Airport through the use of ITWS during the convective weather event. It also reveals that use of the terminal wind product led to savings of at least $156,000 on the strong vertical wind shear day. Improved decision making by New York FAA users of ITWS results in more than $156 million in benefits per year. A case study showed additional possible benefits from providing storm decay predictions (more than $1,560,000 for one day), and substantial benefits ($499,200 per event) from providing correct timing of the onset and ending of capacity-limiting events such as low ceilings or high surface winds.

Evans, J.E., T.J. Dacey, D.A. Rhoda, R.E. Cole, F.W. Wilson, E.R. Williams. 1999. "Weather Sensing and Data Fusion to Improve Safety and Reduce Delays at Major West Coast Airports." Lexington, MA: MIT Lincoln Laboratory.

This study analyzes the weather sensing and forecasting required to improve safety and reduce delays at West Coast airports currently not scheduled to receive an Integrated Terminal Weather System (ITWS). This report considers the Los Angeles (LAX), San Francisco (SFO), Seattle (SEA), and Portland (PDX) international airports. There are three basic approaches for reducing delays: 1) use a parallel runway monitoring (PRM) system with a wake vortex encounter avoidance system to permit use of closely spaced runways in instrument flight rules (IFR) conditions; 2) increase the number of aircraft landed per hour per runway; and 3) match the traffic flow to the time-varying airport capacity (i.e., traffic flow management optimization). Delay reduction benefit for the West Coast airports would come from use of terminal winds information. National delay-reduction benefits from ITWS implementation based on latest estimates totals $521.6 million per year. Reduced SFO delays resulting from improved merging and sequencing of aircraft is estimated to be $21.1 million. In addition, benefits from Simultaneous Operation with Independent Approaches (SOIA) at SFO are estimated to be $84.3

million per year. Merging and sequencing improvements at LAX are projected to be worth $22.7 million. Benefits at SEA are projected to be $14.8 million.

Rhoda, D.A. and M.E. Weber. 1996. "Assessment of Delay Aversion Benefits of the Airport Surveillance Radar (ASR) Weather Systems Processor (WSP) — Project Report." Lexington, MA: MIT Lincoln Laboratory.

Testing of the Weather Systems Processor (WSP) modification to existing Airport Surveillance Radars (ASR-9) and related terminal areas hazardous weather detection systems (Terminal Doppler Weather Radar (TDWR) and the Integrated Terminal Weather System (ITWS) have been shown to reduce the risk of wind shear induced aircraft accidents during landing or takeoff and significantly aid terminal air traffic management during adverse weather. Delay benefits from national deployment of the WSP are assessed in terms of aircraft delay-hour reductions. Benefits are expected to be $21 million per year based on expected year 2000 traffic counts at the planned WSP airports.

A.3 Agriculture

Katz, R.W., A.H. Murphy, and R.L. Winkler. 1982. "Assessing the Value of Frost Forecasts to Orchardists: A Dynamic Decision-Analytic Problem." ***Journal of Applied Meteorology*** **21: 518-531.**

Katz et al.(1982) found that daily minimum temperature forecasts were valuable to apple, pear, and peach orchardists in central Washington. Deciduous fruit trees become particularly susceptible to damage from freezing temperatures, or frost, in the spring when the buds begin to develop into blossoms. Frost can damage or kills buds, and extremely low temperatures can damage trees. To minimize damage caused by low temperatures, many fruit growers employ devices such as heaters, wind machines, and overhead sprinklers to protect their orchards. Because the use of protective devices involves considerable expense, the producer must decide if it makes economic sense to use these devices if just a slight chance of frost exists. To aid in these decisions, the area's NWS office disseminates minimum temperature forecasts to the orchardists each evening. The value of these forecasts to a fruit grower is measured by the ability of the forecasts to reduce the uncertainty under which the decision is made, resulting in turn in a reduction in the orchardist's expected expenses. The study examined the relationships between temperature, bud loss, and yield loss, and used a class of models to determine the optimal actions and to estimate the value of the meteorological information. Over the entire frost-protection season, these values estimates (1977$) were $808 per acre for apples, $492 per acre for pears, and $270 per acre for peaches. These amounts account for 66%, 63%, and 47%, respectively, of the economic value that would be realized by an orchardist whose decisions were based on perfect information.

Wilks, D.S., R.E. Pitt, and G.W. Fick 1993. "Modeling Optimal Alfalfa Harvest Scheduling Using Short-Range Weather Forecasts." ***Agricultural Systems*** **42:277-305.**

Wilks et al. (1993) examined how alfalfa producers used daily precipitation, temperature, and evaporation forecasts in making their day-to-day harvest decisions. Forage preservation is another agricultural process where weather forecasts are important inputs. Alfalfa is usually preserved for livestock feed at a later date. Good weather is needed for drying the harvest several days in the field, as rain can damage the harvest and extend the drying period, exposing the forage to the potential for further damage. The problem is complicated by the fact that the quality, and thus value, of the undamaged product decreases as harvests are delayed, so that the farmer cannot wait indefinitely for a very high probability of good drying weather. The Wilks et al. (1993) study modeled the daily cutting decisions over a growing season, allowing the model to prescribe both the number and timing of cuttings. Temperature forecasts were included in the model to control plant yield and maturity, and as input to the derived evaporation forecasts. The study concluded that the perfect weather forecasts are worth $140 per hectare per year to alfalfa growers (in 1991 dollars).

Fox, G., J. Turner, and T. Gillespie. 1999a. "The Value of Precipitation Forecast Information in Winter Wheat Production." ***Agricultural and Forest Meteorology*** **95:99-111.**

Fox et al. (1999a) explored that fact that weather forecast information is also an important for timing winter wheat planting, spraying, fertilizing, and harvesting. Precipitation forecast information, as with alfalfa, is most valuable at harvest time as grain quality deteriorates when rain delays wheat harvest. Fox et al. (1999a) found that the value of perfect weather information averaged $100 per hectare per year (CA 1994$). The study also found that the level of risk aversion was an important determinant of the value of weather forecast information.

Additional literature

There is a large set of literature that examines the value of weather forecasts to various agricultural commodities. Exhibit A.1 lists some of this literature and the estimated values for short-term forecasts to various crops. Exhibit A.2 lists some of the values estimated for longer term forecasts such as seasonal forecasts

Exhibit A.1. Value of short-term weather forecasts to agriculture

Study	Value source	Estimate
Anaman and Lellyett (1996)	Value of temperature, wind, and precipitation forecasts to cotton producers in Australia	VOI[a] imperfect: $397,150/yr (AU 1995$)
Baquet et al. (1976)	Value of frost forecast to pear orchard managers	VOI, imperfect: $798/ha-yr; VOI perfect: $1,270/ha-yr (1976$)
Fox et al. (1999a)	Value of precipitation forecast information in winter wheat production in Canada	VOI, imperfect: -$153 – +$364/ha-yr; VOI, perfect: $0 – $364/ha-yr (CA 1999$)
Fox et al. (1999b)	Value of precipitation forecast information in alfalfa dry hay production in Ontario	VOI, imperfect: -$6 – +$36/acre-year; VOI, perfect: $4 – $73/acre-year (CA 1999$)
Hammer et al. (1996)	Value of precipitation and frost timing forecasts for wheat crop management in Australia	VOI, imperfect: up to 20% increase in profit; VOI, perfect: 15% of value of perfect forecasts is achieved by present forecasts (1996$)
Luo et al. (1994)	Value of temperature forecasts to U.S. corn producers deciding whether to buy crop insurance	VOI, imperfect: $0.30-$0.86/dollar of insurance premium (1994$)
Wilks and Wolfe (1998)	Value of temperature and precipitation forecasts for lettuce irrigation timing in a humid climate in the United States	VOI, imperfect: $900-$1000/ha-yr (1998$)

a. Value of information.

Exhibit A.2. Value of long term climate forecasts to agriculture

Abawi et al. (1995)	Value of precipitation forecasts in implementing wheat harvest strategies such as early harvesting, drying, and contract harvesting	VOI, imperfect: $12/ha-yr; VOI, perfect: $20/ha-yr (AU 1995$)
Adams et al. (1995)	Value of improved El Nino-Southern Oscillation forecasts (precipitation and temperature) to various crop yields in the southeastern United States	VOI, perfect: $200 million/yr; VOI, imperfect: $132 million/yr (1994$)
Bowman et al. (1995)	Value of precipitation and temperature forecasts to wool-producers in Victoria, Australia	VOI, imperfect: $890-$2,390; VOI, perfect: $1,380-$2,940 (AU 1995$)
Chen et al. (2002)	Agricultural value of ENSO information	VOI, imperfect: $399-$754 million; VOI, perfect: $1390 million (1996$)
Hill et al. (1999)	Value of precipitation, temperature, and radiation forecasts for Texan aggregate sorghum production	VOI, imperfect: $0-$90/ha (1999$)

Exhibit A.2. Value of long term climate forecasts to agriculture (cont.)

Hill et al. (2000)	Value of precipitation, temperature, and radiation forecasts for planning fertilizer applications on U.S. and Canadian wheat fields	VOI, imperfect: $0-$10/ha-yr; VOI, perfect: $9-$52/ha-yr (2000$)
Jochec et al. (2001)	Value of temperature and precipitation forecasts to livestock ranchers in Texas	VOI, imperfect: -$149-$5/section-yr; VOI, perfect: -$46 to $121/section-yr (2001$)
Messina et al. (1999)	Value of maximum and minimum temperature, precipitation, and radiation forecasts to corn, soybean, sunflower, and wheat producers in Argentina	VOI, imperfect: $5-$15/ha-yr (1999$)
Mjelde and Penson (2000)	Value of precipitation, temperature, and radiation forecasts in making fertilizer application decisions in the Corn Belt region	VOI, perfect: $1.3-$2.9 billion over 10 years (2000$)
Mjelde et al. (1996)	Value of precipitation forecasts on the following decisions: type of crop, amount of nitrogen applied, the farmer's participation in the Federal Farm Program, and whether to buy crop insurance	VOI, imperfect: $974-$12,085/farm; VOI, perfect: $16,567/farm (1996$)
Mjelde et al. (1997)	Value of precipitation forecasts on the following decisions: fertilizer application level, planting date, and seeding rate	VOI, imperfect: $1-$2/acre (1997$)
Solow et al. (1998)	Value of improved ENSO prediction to U.S. agriculture (various crops)	VOI, imperfect: $240-$266 million/yr; VOI, perfect: $323 million/yr (1995$)

A.4 Energy

Changnon, S.A., J.M. Changnon, and D. Changnon. 1995. "Uses and Applications of Climate Forecasts for Power Utilities." ***Bulletin of the American Meteorological Society*** **76(5):711-720.**

This paper looks specifically at climate forecasting use by power utilities, and focuses on the *type and quality* of information most useful to this business type. Changnon et al. (1995) surveyed 56 decision makers at six utilities in the Midwest. A key finding was that only 3 out of the 56 decision makers surveyed used 30- and 90-day NWS outlooks for seasonal load planning (a usage level much lower than agribusiness). One of the reasons given for low usage of these forecasts was the format of the information received, which was not area-specific, and was also text-based only at that time. Given changes in utility market structure in the last 8 years, one would expect the use of the data for load forecasting purposes to be much higher today — and the majority of respondents did use climate forecasts in other forms. When queried about the type of data he/she was interested in receiving in the future, interest centered on temperature and extreme temperature data. There was also a significant interest in the accuracy of weather data, including the accuracy trends of recent forecasts — and a comfort level with the use of probabilities as a means of expressing uncertainty of forecasts. As most of the utilities are summer-peaking, the utility representatives were most interested in summer climate forecasts.

The paper discusses the value of climate forecasts. A majority (25 of 44 respondents) set the value of using climate forecasts as >$100,000 for their individual task area. The energy traders and fuel acquisition specialists in the sample *all* valued the information higher than this threshold. If we extrapolate these findings using the simple assumption that each electricity utility in the country would achieve similar value from climate forecasts, given the more than 3000 investor-owned and public utilities in the United States, the resulting value would be in the range of $300 million.

Murnane, R. J., M. Crowe, A. Eustis, S. Howard, J. Koepsell, R. Leffler, and R. Livezey. 2002. "The Weather Risk Management Industry's Climate Forecast and Data Needs: A Workshop Report." ***Bulletin of the American Meteorological Society*** **83(8):1193-1198.**

This paper reports on a workshop held in 2001 — cosponsored by NOAA, the Weather Risk Management Association, and the Risk Prediction Index. The workshop was not focused entirely on energy, but did include energy participants, including Enron. The group determined that NOAA's forecasts and climate data were "key elements of the weather risk market." The key factor in growing this market was that forecasts evolve and become easier to understand and use. The most widely used data sources are the Automated Surface Observing System (ASOS) and the Cooperative Observer Program (COOP). This paper does not provide dollar values associated with data accuracy, and participants stated they do not really use long-range forecasts — but acknowledged that contract prices change after forecasts are issued.

Dempsey, C. L., K. W. Howard, R. A. Maddox, and D. H. Phillips. 1998. "Developing Advanced Weather Technologies for the Power Industry." ***Bulletin of the American Meteorological Society*** **79(6):1019-1035.**

This paper reports on a tailored collaboration between the Electric Power Research Institute (EPRI) and the Salt River Project (SRP) that explored the use of NWS nonweather data into operational decision making. It focused on the impacts of extreme weather events (thunderstorms, lightning, high winds, sudden temperature changes, and winter precipitation) on daily operations. A number of outage situations were investigated, but they were not assigned an economic value. A key finding of this study was the benefits of the use of NowCasts, short-term detailed forecasts typically valid for 30-120 minutes — produced by the NWS WSR-88D observing system. The paper summarizes postanalysis conducted on weather events during the summer of 1994 (the study period), and the expected megawatt-hour savings that could have been realized through the use of NowCasts. Even though the summer monsoon was less active than normal that year, the findings point to potential savings of well over 1000 MWh. At an average market price of $30/MW, this would have resulted in $30,000 savings. Savings were based primarily on the cost of purchased energy that could have been avoided, had advance knowledge of storm effects (lower temperatures, and thus lower air conditioning loads) been utilized.

Additional Notes: Two recent articles in *Transmission and Distribution World* (Q4, 2003) contain the following additional information on costs and causes of power outages in the United States — 67% of power outages are weather-related (this comes from an Edison Electric Institute (EEI) 1999 reliability report that surveyed 62 investor-owned utilities). The articles do not define "weather-related," but extreme heat is often cited as the cause of system overload, a primary outage factor. A second article in the same Q4 2003 issue cites the costs of the August 14, 2003, outage in the upper Midwest and along the East Coast at between $4 and $6 billion. It is unclear how much more accurate the weather data would have needed to be to reduce the likelihood of this outage.

Cogan, J. 1998. "What is Weather Risk?" Originally published by *PMA Online Magazine,* May, 1998. Downloaded October 28, 2003, from http://www.retailenergy.com/articles/weather.htm.

This article reports on a survey of 200 top utility company annual reports, 80% of which cite weather as a major determinant of earnings performance. About half the companies claimed that weather was responsible for poorer than expected financial performance. The article is written by the president of Natsource, Inc., a weather hedging service. Weather hedging is based on a risk mitigation strategy for energy companies that basically buy insurance against abnormal levels of heating or cooling degree days, or precipitation. This is a relatively new business that has grown in deregulated energy markets. The article cites some examples of various weather risk products, but does not provide dollar estimates of savings to the industry.

Dischel, B. 2001. "Seasonal Weather Forecasts and Derivative Valuation." Available at http://www.financewise.com/public/edit/energy/weather00/wthr00-forecast.htm. Accessed December 1, 2003.

This article looks at the value of short- and long-term forecasts in weather-derivative products. The article states that there is limited value in short-term forecasts, as they provide only a few days of information, with the uncertainty of the data declining rapidly after the first few days. Long-range forecasts, however, make use of factors including atmospheric and oceanic conditions and are based on average weather — not specific events. The article advocates for future forecasts that "quantify the probability of each possible weather outcome throughout the full range of possibilities." The article reviews several tools available from the Climate

Prediction Center (CPC), including the seasonal forecasts for distribution of temperature, precipitation, and the error envelopes of each.

The article goes on to provide an example of weather-contingent revenue estimation at a gas supply company. As with the Cogan article, weather risk products are advocated to reduce the value at risk associated with uncertainty of the weather. The example provided indicates a significant upside (up to 100% revenue increase at certain degree day levels) for an energy provider that hedges against the possibility of warmer or cooler than average weather. No concrete dollar values are included.

Fan, J.Y. and J. D. McDonald. 1994. "A Real-Time Implementation of Short-Term Load Forecasting for Distribution Power Systems." ***IEEE Transactions on Power Systems*** **9(2):988-994.**

This paper presents a model for short-term forecasting of electrical loads by correlating weather data and other factors to system loads. The key weather factors used in the algorithm developed are temperature, dry bulb temperature, relative humidity, and wind speed. The study demonstrates that weather impacts electrical loads in a nonlinear manner (usually taking a "bathtub-like" relationship, which dips from cooler temperatures until about 60°F is reached, and then rises a bit steeper until it flattens out somewhere above 100°F). Temperature is clearly the primary determinant.

Hackney, J. 2002. "Increasing the Value of Weather Information in the Operation of the Electric Power System – Workshop Report." November 6-7, Boulder, CO. Sponsored by the United States Weather Research Program (USWRP). Available online at http://www.esig.ucar.edu/electricity/workshop/. Accessed December 1, 2003.

This workshop report provides highlights from a meeting held at NCAR, which included 35 experts from the electric power industry and the meteorological sciences community. It focuses on the information needs of the electricity sector. Although the workshop report does not contain dollar values associated with improved information, one presenter (Frank Monforte) highlighted a regression study indicating that daily electrical load prediction errors could be reduced from roughly 3.00% to about 1.33% through the use of average dry bulb temperatures.

B. Omissions, Biases, and Uncertainties

Exhibit B.1 lists some potential omissions, biases, and uncertainties in the present value estimates for the benefits of a new supercomputer. These might affect the final benefit estimates if better information were available. "Positive" impact suggests that including better information on this aspect of the analysis would *increase* the present value estimates above those given in Exhibit 5.4. "Negative" impact suggests that including better information on this aspect of the analysis would *lower* the present value estimates below those given in Exhibit 5.4.

Exhibit B.1. Omissions, biases, and uncertainties in the present value estimates for the benefits of a new supercomputer

Issue	Impact on present value estimates	Comments
Omitted benefits from other agricultural sectors benefiting from improved weather forecasts	Positive (actual present value may be higher than estimated)	Estimated benefit estimates do not include benefits to agriculture other than those derived for orchards, winter wheat, and alfalfa.
Omitted benefits from all sectors where existing literature indicates significant benefits from improved weather forecasts	Positive (actual present value may be higher than estimated)	Estimated benefits estimates do not include benefits to: ▸ aviation ▸ energy. The literature reviewed in this report indicates significant potential positive benefits in these two sectors that are not included in this economic analysis.
Omitted benefits from all other sectors benefiting from improved weather forecasts	Positive (actual present value may be higher than estimated)	Estimated benefits estimates do not include benefits to: ▸ marine transportation ▸ retail businesses ▸ marine resources ▸ private sector (e.g., highways) ▸ international weather bureaus ▸ military ▸ others not identified in this report.

Exhibit B.1. Omissions, biases, and uncertainties in the present value estimates for the benefits of a new supercomputer (cont.)

Issue	Impact on present value estimates	Comments
Timing of benefits	Uncertain	Timing of benefits is assumed to begin 2 years after the new supercomputer is installed. Benefits would be experienced in full in 5 years, some occur sooner or later.
Appropriate discount rate	Uncertain	Some might argue that a 0% discount rate is applicable for activities that span across generations; others might argue that rates greater than 3% should apply to reflect real opportunity costs of capital in the near term.
Portion of weather forecast improvements attributable to the supercomputer	Uncertain	It is uncertain that the applied percent of improvement resulting from the supercomputer is the true percent. The true percent could be higher or lower (see sensitivity analysis in Section 5.1 for more information).
Percent improvement in weather forecast	Uncertain	It is uncertain that the applied percent of improvement expected in weather forecasts is the true percent. The true percent could be higher or lower (see sensitivity analysis in Section 5.1 for more information).
Omitted benefits to other applications besides weather forecasting	Positive (actual present value may be higher than estimated)	Estimated benefits do not include benefits to other laboratories and entities that will use the supercomputer (e.g., for climate and flood forecasting). We approximate that 80% of the supercomputer use will be for the weather forecasts discussed in this report.
Population growth and wealth growth	Positive (actual present value may be higher than estimated)	The benefit estimates derived in this report implicitly assume a constant population at current levels of real wealth. As population increases and real wealth increases, the aggregate value of improved weather forecasts to future generations will be higher.
Link between improved forecast and specific type of use benefit	Uncertain, but likely negative	The model used in the study is simplified and omits critical factors such as: 1) effective dissemination of the forecast; 2) articulation of the forecast in a way that is both comprehensible and realistically actionable to the target user; and 3) absence of other confounding factors that might limit or constrain use of the improved information.