ECONOMIC BENEFITS AND COSTS OF DEVELOPING AND DEPLOYING A SPACE-BASED WIND LIDAR

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1. INTRODUCTION

The National Weather Service (NWS) provides a number of valuable services to the Nation. These include collecting and analyzing environmental data, preparing weather and climate forecasts and watches and warnings for severe weather, and disseminating this information to the public, to other government agencies, and to private concerns.

These activities provide a range of economic benefits. Accurate information about potential weather hazards allows the government and private citizens to take preventive actions that reduce the losses to property, life, and limb that can accompany adverse weather. Information about weather conditions also generally helps individual citizens to plan their daily activities, and is a key element in the decisions of businesses in sectors such as agriculture and aviation, whose daily operations are affected by weather. These tangible benefits can be substantial. [1]

Investing in obtaining high-quality weather information also provides important, although less tangible benefits, in the form of scientific and technical knowledge about our physical environment. Such knowledge has value in its own right. It is also becoming increasingly clear that improved knowledge of the atmosphere is important in the design and implementation of environmental policies, which are having an increasing effect on the American economy.

Although the National Weather Service has made great progress through its modernization efforts in providing more accurate forecast products and services, additional opportunities remain. One of the most significant is the potential improvement in the understanding and prediction of weather and climate that would be possible with global wind measurements. [2] Pilotless aircraft could, in theory, be used to obtain such measurements. But, for reasons discussed below, this is not a realistic alternative. Thus, the capability for obtaining global wind measurements must be provided from space; and studies have concluded that it is

[1] Robert E. Chapman, July 1992: *Benefit-Cost Analysis for the Modernization and Associated Restructuring of the National Weather Service.* National Institute of Standards and Technology. Report prepared for the National Oceanic and Atmospheric Administration, National Weather Service.

[2] Wayman Baker, *et al.,* in press 1995: "Lidar Measured Winds From Space: A Key Component for Weather and Climate Prediction," *Bulletin of the American Meteorological Society.*

possible to measure tropospheric winds from space with current Doppler lidar technology.

This study identifies the tangible as well as some of the intangible benefits that would be provided by a space-based Doppler wind lidar, and presents a formal analysis that compares estimates of the tangible benefits with the costs of implementing a wind lidar system. The next section outlines the principles and advantages of measuring winds by lidar. This is followed by a discussion of the current sources of wind information in Section 3. The scientific benefits of lidar wind measurements are briefly reviewed in Section 4, and the estimated costs of making a space-based wind lidar operational are discussed in Section 5. The study then examines ways in which a wind lidar would benefit the U.S. economy, and presents baseline estimates of the principal economic benefits that could reasonably be expected to be provided by a wind lidar (Section 6). Estimated benefits and costs of the wind lidar are then compared in a formal benefit-cost analysis in Section 7. Because these estimates are subject to some uncertainty, Section 8 of the study examines the sensitivity of the main results of the benefit-cost analysis to variations in benefits and costs above and below their baseline values. The main conclusions of the analysis are summarized in Section 9.

2. PRINCIPLES AND ADVANTAGES OF DOPPLER LIDAR

A Doppler wind lidar system would significantly improve the quality of global wind data in two ways. It would significantly expand the amount of wind data that are available ill what are now data-sparse areas, and it would measure wind speed and direction directly and accurately.

A Doppler lidar operates much like Doppler radar. A satellite, deployed in polar (sun-

3 R.M. Huffaker, 1978: *Feasibility Study of Satellite-Borne Lidar Global Wind Monitoring System.* NOAA Technical Memorandum, ERL WPL-37; R.M. Huffaker, et al., 1980: *Feasibility Study of Satellite-Borne Lidar Global Wind Monitoring System, Part II.* NOAA Technical Memorandum, ERL WPL-63; R.M. Huffaker, et al., 1984: "Feasibility Studies for a Global Wind Measuring Satellite System (WINDSAT): Analysis of simulated performance," *Applied Opt.*, 22, 1655-1665; Menzies, R.T., 1986: "Doppler lidar atmospheric sensors: A comparative performance evaluation for global measurement applications from earth orbit," *Applied Opt.,* 25, 2546-2553; National Aeronautics and Space Administration, 1979: *Shuttle atmospheric lidar research program. Final report of Atmospheric Lidar Working Group SP-433.* [Available from NASA, Washington, D.C. 20546; National Aeronautics and Space Administration, 1982: *Feasibility assessment: Satellite Doppler lidar wind measuring system.* NASA Report MSFC-MOSD-146; [available from NASA Marshall Space Flight Center, Huntsville AL 35812]; National Aeronautics and Space Administration, 1987: *Laser Atmospheric wind sounder.* Earth observing system panel report, Vol IIg. Satellite Doppler lidar wind measuring system. NASA Report MSFC-MOSD-146; [Available from NASA, Washington, D.C. 20546].

synchronous) orbit, would transmit pulses of light from a laser to earth. These pulses of light would be reflected from the earth' s surface and be received by a telescope which would act as an optical antenna much as radio waves returned from earth are received by a radio antenna in the Doppler radar system. Pulses of light returned to the lidar would be spectrally analyzed to recover the Doppler shifts caused by the movement of the airborne targets (e.g., clouds, aerosols).

The principal difference between lidar and radar is that lidar can sense and transmit signals for much smaller airborne targets than can radar because lidar has much shorter wavelengths (<10 microns for lidar vs. 100 microns for radar). This feature of lidar makes it possible to measure a true wind using naturally occurring targets that are as small as cloud particles and aerosols, because these targets move at approximately the speed of the wind.

3. CURRENT SOURCES OF WIND DATA

At present, estimates of the speed and direction of global winds come from several different sources. These include measurements obtained from in-flight-tracking of winds by commercial airliners as well as from data gathered by balloons sent aloft that are equipped with instruments to measure winds (rawinsondes). Wind speed and direction are also obtained indirectly from satellite-retrieved measurements of temperature, from tracking the motions of clouds by satellite, from profilers, and are provided by a space-based scatterometer, buoys, and ships over the ocean surface.

The methods that are used to estimate wind speed and direction are varied and complex. In some cases, scientific relationships provide a basis for inferring the direction and speed of global winds based on observations of other variables. For example, the geostrophic relationship assumes that the geostrophic wind has a direction and speed given by the gradient in the atmospheric mass field and the latitude. [4] In other cases, wind speed and direction may be inferred by observing the speed and direction of atmospheric tracers, such as clouds, which move approximately with the environmental wind under certain conditions.

In the past decade, advances in scientific knowledge and modeling of weather and climate have significantly improved the quality of forecasts that use wind data obtained from the above sources. [5] Although further enhancements to numerical models and in the analysis of existing

[4] For a useful explanation see Robert C. McNeill, 1991: *Understanding the Weather: An explanation for everyone, particularly for flyers and students of meteorology.* Arbor Publishers, Las Vegas, Nevada.

[5] For a discussion see G. White, J. Alpert, C. Vlcek, and P. Julian, "The Skill of the NMC Global Model in Analyzing and Forecasting Upper-Level Global Winds," unpublished and undated.

data will certainly improve forecast skill, there is considerable agreement that there could be at least as great a payoff from efforts aimed at providing accurate global wind data.

An important limitation of existing data, and hence of the models that rely on these data, is that wind observations are relatively sparse, especially in some remote regions of the world (see Figure 1, for example, in Baker, et al., 1995). To a large extent, this reflects the present reliance on airborne and surface-based platforms to gather wind observations. In some cases, observations obtained from these sources provide data that are fairly complete and timely. For example, commercial air traffic over the United States provides accurate measurements of wind direction and speed at flight level in most cases. In most other areas, observations are more limited because there are fewer opportunities to use airborne and surface-based platforms. Over the oceans, wind data are measured only at flight level, and are heavily biased depending on the flight direction, since the airlines try to avoid or take advantage of the jet stream for west or east-bound flights, respectively. Even over the United States, wind data tend to be more sparse in areas of the West, as well as at certain times of day, such as the early morning hours, because there is less air traffic at that time. Because there are fewer opportunities to take needed measurements, there are less wind data over the oceans. Wind measurements in the Southern hemisphere are completely inadequate.

4. SCIENTIFIC BENEFITS

A Doppler wind lidar is the only instrument available that can provide direct measurement of the tropospheric wind field. Pilotless aircraft have been proposed, but the logistical and safety issues associated with launching such aircraft are formidable, especially outside of nearby U.S. coastal waters.

Global wind measurements from a Doppler lidar would provide data that are fundamental to advancing the understanding and prediction of possible climate change and would significantly increase the skill of numerical weather forecasts, as briefly summarized below.

4.1 Aerosols and the Carbon Cycle

It is widely recognized that aerosols, which are fine solid or liquid particles suspended in the atmosphere, play an important role in influencing the earth's climate through their radiational cooling effect. Production of these aerosols by human activities and natural processes is widely dispersed around the globe, and their transport is influenced by the speed and direction of the wind field.

Improved knowledge of the transport of aerosols would help to better understand the earth's carbon cycle. Research into processes governing the carbon cycle has focused on searching for a "missing sink" of approximately 1.0 to 2.0 gigatons of carbon per year. [6] Because the wind field is poorly measured over critical source/sink regions, such as tropical rain forests and boreal systems, refinement in transport estimates via lidar wind measurements would be an important contribution to narrowing the uncertainties in the carbon cycle.

4.2 Aerosols, Trace Gases and the Biogeochemical Cycle

Varying degrees of concern have been raised in recent years about the prospect of major global climate changes. These concerns have been prompted, in part, by observed increases in the atmospheric concentration of elements such as carbon dioxide, methane, oxides of nitrogen, and sulfur, as well as chlorofluorocarbons, (IPCC, 1990).

There is, however, considerable disagreement about the extent and the pace of possible future global climate changes that may be foreshadowed by greater atmospheric concentrations of the aforementioned elements. Concerns about the increased concentrations of some elements such as chlorofluorocarbons, have led to international efforts to regulate economic activities that contribute to such increased concentrations. But in general, there is a wide range of scientific opinion about the likely prospects of future climate change. Improved knowledge of the global wind field is critical to the accurate estimation of the long-range transport of trace gases and aerosols.

4.3 Numerical Weather Prediction

Accurate global wind measurements would be as valuable for weather forecasting as they would be for climate studies. The relatively advanced state of atmospheric general circulation models now available for coupling with those of the ocean and biosphere is due in large part to the advances in numeric weather prediction (NWP), for which atmospheric general circulation models are now widely used. In addition, improvement in NWP is essential for improving the validation of climate models, as our perception of the evolution of the atmospheric component of climate is ultimately based on the continuous assimilation of data into NWP systems. A number of observing system simulation experiments, where simulated Doppler lidar winds have been used in general circulation models, have consistently indicated that a dramatic improvement in weather forecasting skill would occur with the addition of lidar winds in data-sparse regions. [7] In addition to the obvious fact that accurate observations in data sparse regions will always be useful, one can mention at least two independent reasons for such improvement.

[6] IPCC, 1990: *Climate Change:* The *IPCC Scientific Assessment.* WMO/UNEP Intergovernmental Panel on Climate Change; [Available from WMO].

[7] Atlas, R., *et al.,* 1985: "Observing system simulation experiments at GSFC," *Proceedings of the NASA Symposium on Global Wind Measurements,* Columbia, Md., NASA, 256 pp. [out of print].

First, even if mass observations are available, which can lead to wind estimates through the geostrophic relationship, those estimates cannot be expected to be as accurate as the direct measurement of the wind. This is especially true because the process of differentiation worsens the estimates from noisy observations. Since the geostrophic relationship relates the wind to the horizontal pressure gradient, this is a major cause of error in the estimation of the wind field. [8] Second, at low latitudes the geostrophic relationship is invalid, and at small scales at higher latitudes, the geostrophic relationship is often not accurate. The next generation NWP models (in the time frame of the first space-based wind lidar) will reach high-enough resolution to include significantly non-geostrophic scales. Thus winds will become an increasingly more important measure of the atmospheric state.

5. SYSTEM COSTS

Making a wind lidar system fully operational requires several steps. The first step is to build upon results of R&D that is completed or in progress by developing and deploying a small satellite prototype, utilizing a *2µm* solid state lidar. Such an instrument would provide wind data from aerosols in the planetary boundary layer and cloud returns. If approved, this phase of the project would commence in FY 1997 (Oct. 1996) and continue until FY 2002 (Oct. 2001). Based on the results obtained from the prototype, it is anticipated that work needed to develop and deploy a fully operational lidar could commence in FY 1999 (Oct. 1998) and continue until FY 2004 (Oct. 2003). The first operational wind lidar satellite would then be ready for launch by FY 2005 (Oct. 2004). Maintaining a global wind monitoring system in polar sun- synchronous orbit would then require launching a "replacement" every five years. Based on experience with other weather satellite systems (i.e., TIROS-N), it is reasonable to assume that once developed, the same lidar technology would be used operationally for 20 years.

Table 1 shows estimated costs, in constant FY 1994 dollars, for each phase of the development and eventual operation of a wind lidar. Figure 1 shows the profile of these costs over the assumed 28-year period of development and deployment of the lidar system. If the same lidar technology is assumed to be utilized for 20 years after initial launch, estimated annual outlays needed to develop, launch, and operate the proposed system sum to more than $900 million. Almost half of this total ($440 million) consists of "fixed" costs that would be incurred to develop the system to the point where it would become operational, with the balance attributable to costs of launching and operating the lidar once it is fully developed. [9]

[8] Kalnay, E., Jusem, J.C., and Pfaendtner, J., 1985: "The relative importance of mass and wind data in the present observing system," *Proceedings of the NASA Symposium on Global Wind Measurements,* Columbia, Md., NASA, 256 pp., [out of print].

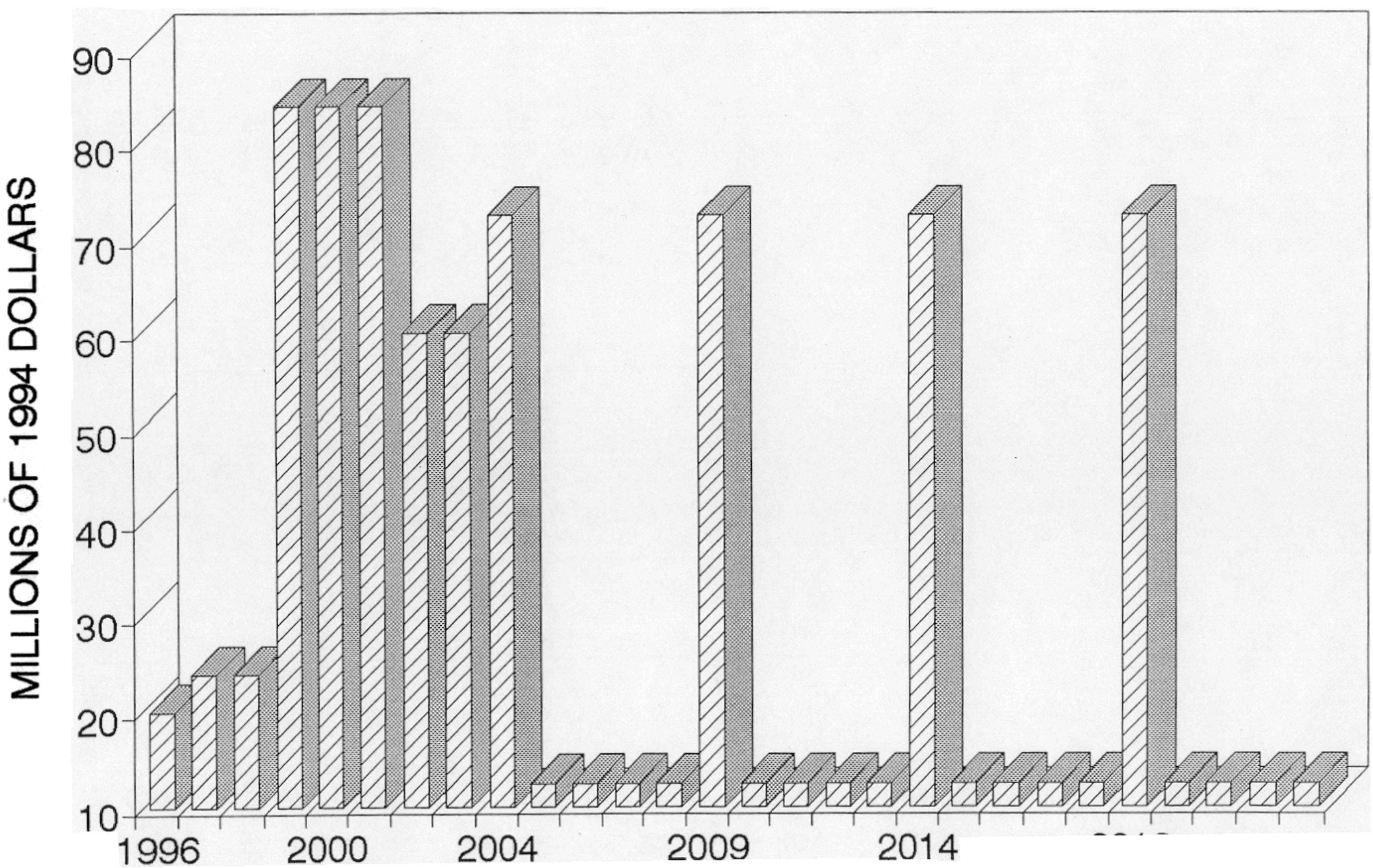
[0] The totals reported here are not discounted to reflect the time value of money; and hence, do not equal the *present value* of the costs of a wind lidar shown in Table 6 and Figure 5.

PROJECTED ANNUAL COSTS OF LIDAR IN 1994 $S

YEAR	R&D	Develop/Deploy Prototype	Develop & Deploy Operational Version	Launch Lidar	Operate Lidar	Total
through 1996	$20,000,000	N.A.	N.A.	N.A.	N.A.	$20,000,000
1997	N.A.	$24,000,000	N.A.	N.A.	N.A.	$24,000,000
1998	N.A.	$24,000,000	N.A.	N.A.	N.A.	$24,000,000
1999	N.A.	$24,000,000	$60,000,000	N.A.	N.A.	$84,000,000
2000	N.A.	$24,000,000	$60,000,000	N.A.	N.A.	$84,000,000
2001	N.A.	$24,000,000	$60,000,000	N.A.	N.A.	$84,000,000
2002	N.A.	N.A.	$60,000,000	N.A.	N.A.	$60,000,000
2003	N.A.	N.A.	$60,000,000	N.A.	N.A.	$60,000,000
2004	N.A.	N.A.	N.A.	$60,000,000	$12,500,000	$72,500,000
2005	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2006	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2007	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2008	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2009	N.A.	N.A.	N.A.	$60,000,000	$12,500,000	$72,500,000
2010	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2011	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2012	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2013	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2014	N.A.	N.A.	N.A.	$60,000,000	$12,500,000	$72,500,000
2015	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2016	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2017	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2018	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2019	N.A.	N.A.	N.A.	$60,000,000	$12,500,000	$72,500,000
2020	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2021	N..A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2022	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
2023	N.A.	N.A.	N.A.	N.A.	$12,500,000	$12,500,000
TOTAL	$20,000,000	$120,000,000	$300,000,000	$240,000,000	$250,000,000	$930,000,000

IGURE 1

ANNUAL COSTS OF L DAR



The cost estimates shown in Table 1 and Figure 1 are conservative estimates in the sense that actual costs may well be lower than those shown. Development and launch costs for the operational lidar are likely to be significantly lower than assumed in this study because of recent advances in small satellite technology.

6. ECONOMIC BENEFITS

In addition to the real, though intangible, value of the scientific knowledge that would be gained, developing, deploying, and operating a wind lidar would provide a number of potential economic benefits. Improved understanding and prediction of climate made possible by global wind data can benefit the economy by helping reduce the uncertainty about the scope and the pace of possible future climate changes. Improvements in numerical weather forecasting can help to reduce the size of preventable losses caused by adverse weather. Finally, improved measurements of the wind field would be of direct benefit to air carriers who use forecast information on wind speed and direction to plan and conduct their daily operations.

6.1 Climate Change

Although the precise order of magnitude cannot be quantified, reducing uncertainty about the scope and the pace of possible future climate change provides real benefits. Several studies have shown that the potential economic costs caused by significant global warming plus the costs of adapting existing economic activities to mitigate its effects would be substantial. These studies also show that the costs of future global warming can be reduced significantly if steps are taken soon enough to modify economic activities that might give rise to such warming.

The possibility of climate change poses a challenge to policymakers because there are potential costs to action as well as inaction. On the one hand, steps can be undertaken to reduce emissions that are the potential cause of climate change. But, taking these steps will be economically costly. For example, several different analyses imply that the economic costs of simply stabilizing the level of CO2 emissions at 1990 levels would be on the order of one-half of one percent of Gross Domestic Product, or roughly $3 billion, while the costs of reducing CO2 emissions by 20% from current levels would be roughly twice as large. For this reason, there is understandable caution in embracing such measures unless there is adequate evidence that the prospects of significant global warming are real. [10]

On the other hand, if steps are not undertaken to reduce worldwide emissions of CO2 and

[10] Darius W. Gaskins, Jr. and John P. Weyant, May 1993: "Model Comparisons of the Costs of Reducing CO2 Emissions," *American Economic Review.* William B. Nordhaus, May 1993: "Optimal Greenhouse-Gas Reductions and Tax Policy in the "DICE" Model," *American Economic Review;* and John Reilly and Neil Hohmann, May 1993: "Climate Change and Agriculture: The Role of International Trade," *American Economic Review.*

other gases, and significant global warming does take place, measures may need to be taken to quickly stabilize and reduce these emissions. The short-run costs of the behavioral changes that would be required to achieve such adjustments would be higher than if such changes had been encouraged sooner and took place over a longer period of time.

In each case, better information about climate would be of economic value to policymakers because it would reduce the present range of uncertainty about the scope and pace of possible climate change. Lowering the level of uncertainty would reduce the likelihood of taking steps to reduce global warming which later prove unnecessary because the risk of significant global warming fails to materialize. It would also reduce the likelihood of failing to act in the face of a real threat. In short, information about the process of climate change, which would be enhanced by data provided by a wind lidar, could help lower the economic costs associated with both unwarranted action and inaction in the face of possible, though uncertain global climate change.

6.2 Numerical Weather Prediction

Adverse weather conditions, such as that caused by tropical storms, can impose substantial economic losses in the form of property damage, loss of life and limb, and interrupted business activities. Accurate information about potentially adverse weather conditions is economically valuable because it gives individuals and companies the chance to take actions that can reduce these economic losses.

6.2.1 A SimQle Model

If people and companies are economically rational, they should undertake actions to reduce the affects of adverse weather whenever the expected benefit of doing so –measured by the expected losses that are saved –exceeds the costs. [11] Thus, if we define P to be the predicted probability of adverse weather, L to be the economic loss associated with adverse weather, and C to be the cost of measures undertaken to reduce such economic losses a forecast of adverse weather will prompt loss-reduction activities when $P\ L \geq C$, where P L is the expected economic benefit possible from loss reduction activities. [12]

[11] This discussion follows that presented in J.C. Thompson, Sept. 1972: The *Potential Economic Benefits of Improvements in Weather Forecasting.* Final report submitted to the National Aeronautics and Space Administration. See also Richard W. Katz and Allan H. Murphy, 1990: "Quality/Value Relationships for Imperfect Weather Forecasts in a Prototype Multistage Decision-Making Model," *Journal of Forecasting,* Vol. 9, 75-86.

[12] If the chance of an adverse weather event is 60%, there is a 60% chance of suffering loss L, (P = 0.60) and a 40% chance of no loss ([1-P] = 0.40). The expected benefit from actions that reduce the loss, if the adverse weather event occurs, equals 0.60 L + 0.40 O = 0.60 L = P L.

An alternative way of stating the same criterion is to note that, if people make rational decisions in response to probability information about adverse weather, they would undertake corrective actions when the projected probability of adverse weather was at or above some threshold value $P^* = C/L$. In the analysis that follows, it is assumed that $C < L$, so that loss-reduction activities would always become economically rational at some forecast probability of adverse weather. [13]

If a series of N forecasts are made about the probability of adverse weather, the contingency table below illustrates how people would react to such information. For example, if the forecasts indicated that the probability of adverse weather was below the threshold that would prompt corrective action [(a+c)/N]% of the time, there would be a times when people "correctly" took no action, and c times when, in hindsight, loss reduction activities should have been undertaken, but were not. [14] Similarly, when such forecasts indicated that the probability of adverse weather was above the threshold [(b+d)/N]% of the time, there would be d times when people correctly took preventive actions, and b times when, in hindsight, loss-reduction activities were undertaken unnecessarily. Given such behavior, the total economic costs resulting from adverse weather would be given by $E_f = c\,L + d\,C + b\,C$, where C is the cost of loss-reducing activities.

Predicted Probability or Adverse Weather

	Take No Action ($P < P^* = C/L$)	***Take Action*** ($P > P^* = C/L$)	***Total***
Actual Weather			
Not Adverse	a	b	(a + b)
Adverse	c	d	(c + d)
Total	(a + c)	(b + d)	N

[13] Note that when C > L it is economically rational to "do nothing" in the face of adverse weather, even if the occurrence of such an event is known with certainty. This is no doubt a possibility in some cases. Ignoring it does not affect the basic conclusions of the analysis.

[14] This is SO when the cost of reducing losses, C, is less than the losses avoided, L.

To determine the costs of imperfect forecasts, it is useful to consider how people would behave if all N forecasts contained scientifically perfect information about weather events. In that case, armed with perfect foreknowledge of weather, businesses and individuals would not spend resources on loss-reducing activities when there was no adverse weather, and would spend resources on such activities in all cases when adverse weather occurred. The economic costs of adverse weather, given perfect information about its occurrence, would be $E_p = c\,C + d\,C$.

The difference between the economic costs suffered from adverse weather when information is imperfect (E_f) and when it is perfect (E_p) define the maximum potential economic value of obtaining more accurate forecasts. This difference is given by equation (1).

(1) $$[E_f - E_p] = c\,(L - C) + b\,C$$

Equation (1) has a straightforward interpretation. The first term on the right-hand side of (1) is the net economic payoff from undertaking loss-reduction activities that should be undertaken, but which are not when there is imperfect information. The second term is the economic savings from not undertaking loss-reduction activities when they are not necessary.

6.3 Improving Forecast Accuracy by Measuring Global Winds

Because accurate global winds measured by a space-based Doppler wind lidar will improve weather forecasts, the economic benefits of the general type described in (1) will occur.

6.3.1 Improved Forecasts of Hurricanes

The global wind field has a particularly important influence on both the intensity and the path of hurricanes. These storms, which regularly strike coastal regions of the United States, impose a variety of economic costs.

Direct Damage. While current forecasting capabilities have done much to provide communities with advance warning of the onset of hurricanes, direct damage from major hurricanes has been substantial, as shown in Table 2. [15] Although much of this damage –such as destruction of structures –may not preventable, even if the landfall of hurricanes could be predicted with greater accuracy further in advance, it is widely believed that roughly 15-20% of the damage from hurricanes can be prevented, when there is sufficient advance warning. [16] Providing the capability to predict the path and intensity of hurricanes further in advance, with greater

[15] The data in Table 2 were provided by the National Climatic Data Center to the NWS in August 1993. The Table does not include the costs attributable to landfalling storms which are not" major" hurricanes.

[16] Personal communication from the Hurricane Research Division, NOAA, to the National Weather Service, August 1993.

precision would lower the cost of taking preventive actions, thereby increasing the range of preventive actions that would be undertaken.

Simulations of the effects of having accurate global wind measurements on the scale of hurricanes suggest that it would be possible to improve forecast accuracy by approximately 17%. Roughly speaking, this would enable a 29-hour forecast to be as accurate as the current 24-hour forecasts. If one assumes that the benefits from preventable property damage that would result is proportional to the improvement in forecast accuracy and warning time, then improving the ability to forecast hurricanes by a factor of 17% would help reduce preventable losses by roughly 2 to 3 percent (e.g.. 0.17 X 15% is a 2.5 percentage point reduction in preventable loss).

The 13-year average of damage from the storms listed in Table 2, (excluding the exceptional damage from Hurricane Andrew) equals $1.2 billion per year. These orders of magnitude suggest that global wind measurements would provide real annual economic benefits of roughly $24 million to $36 million per year in the form of preventable property damage from "typical hurricanes" that can be expected to strike the United States.

<u>Loss of Life and Limb.</u> As shown in Table 2, hurricanes also exact a toll in lives lost. It is difficult to know how many additional lives, if any, would be saved by the increase in forecast accuracy indicated above. It is harder still, and somewhat controversial to attach an economic value to any lives that could be saved. Nonetheless, the potential for reducing losses of life and limb should be counted qualitatively, if not quantitatively, as an economic benefit of improvements in the ability to forecast the severity and direction of hurricanes.

<u>Reduced Overwarning.</u> Based on current forecasting capabilities, the National Hurricane Center issues warnings to areas that are likely (though not certain) to be struck by hurricanes. It has been estimated that the costs of preparing for a possible hurricane landfall is roughly *$90,000/km.* Because of current uncertainties about the precise direction and onset of hurricanes, it has also been estimated that a typical landfall warning area is 550 km in length, even though the coastal area that is ultimately affected by hurricane once it hits land is only 200 km. This implies that the costs of undertaking preventive actions that ultimately prove to be unnecessary are on the order of $32 million *($90,000/km* X 350 km) for a typical hurricane. [17]

If one assumes that a 17% improvement in forecasting skill would allow the overwarned area to be reduced proportionately by 17%, accurate measurement of global winds would provide annual savings of $5.4 million for a typical storm landfall. Since an average of two such storms strike U.S. coast lines each year, annual savings from reduced overwarning would be approximately $11 million per year.

[17] James L. Franklin and Mark DeMaria, March 1992: "The Impact of Omega Dropwindsonde Observations on Barotropic Hurricane Track Forecasts," *Monthly Weather Review,* p. 390; and R.C. Sheets, 1990: "The National Hurricane Center -- past, present, and future," *Weather Forecasting.*

TABLE 2

LOSSES FROM HURRICANES [1]

YEAR	HURRICANE NAME	ESTIMATED DAMAGES	NUMBER OF DEATHS
1992	lniki	$1.8 billion	5
1992	Andrew	$25.0 billion	58
1991	Bob	$1.5 billion	18
1989	Hugo	$7.1 billion	57
1985	Juan	$1.5 billion	63
1985	Elena	$1.3 billion	4
1983	Alicia	$2.0 billion	21
13- Year Average (Including Andrew)	N.A.	$3.7 billion	17
	N.A.	$1.2 billion	14

[1] The number of "typical" landfalling storms that affect U.S. coastlines each year is larger than the number of major hurricanes listed in this table.

6.3.2 Improvements in General Forecasting Abilities

Although the accurate measurement of global winds would be especially useful in forecasting hurricanes, such measurements would enhance the quality of numerical weather forecasts in general. Chapman has estimated that the modernization of the National Weather Service would provide potential gains from scientific advances in numerical weather forecasts of roughly $1.2 billion in 1994 dollars. [18] If it is assumed that better measurements of global winds would provide benefits from improved forecast accuracy equal to 5% of those attributable to an across-the-board modernization of the entire forecast system, implementation of wind lidar would provide roughly $60 million per year in economic benefits in addition to those associated with specific improvements in the ability to forecast hurricanes.

6.4 Improved Efficiency of Business Operations

Forecasts of the wind speed and direction is a key factor in flight-planning by commercial airlines. Accurate wind measurements would enable airlines to more accurately gauge the amount of fuel needed on flights for a variety of reasons. First, the speed and direction of wind encountered in-flight affects the amount of fuel that is consumed. Simulation studies done by the FAA in the early 1980s show that a 50 knot headwind decreases the nautical miles covered per each thousand pounds of fuel by 11%. A 50 knot tailwind increases fuel consumption efficiency by a comparable amount. [19]

Wind information can also affect fuel efficiency indirectly through its effect on "tankering," which is the use of fuel to carry extra fuel. For example, if headwinds are expected, prudent flight planning requires that extra fuel be carried on board. But this extra fuel adds to the weight of the flight, which reduces the efficiency of each unit of fuel that is used. Accordingly, if headwinds are expected, but not actually encountered, a certain amount of fuel will be wasted because of the extra weight of the fuel that must be carried on the flight.

It has long been recognized that providing airlines with more accurate forecast information on wind speed and direction would enable them to do a better job of planning fuel consumption. Although the amount of such fuel savings are somewhat speculative, evidence from a simulation study are useful for gauging the order of magnitude of fuel savings that could be achieved from more accurate wind forecasts.

The study, which was done in the early 1980s, compared the minimum time-tracks for flights between New York and London that were computed from "old" data based on a 24-hour forecast provided by NWS, with "current" data derived from information provided in "real time"

[18] Chapman, *ibid.*

[19] David E. Winer, and John E. Wesler, "Meteorological Impact on Aviation Fuel Efficiency, Federal Aviation Agency, unpublished and undated.

by aircraft in flight. The results indicated that using more accurate wind information cut flight times by roughly 4.2%. [20]

It is not possible, for several reasons, to extrapolate directly from this result to estimate the size of fuel savings that might be achieved if airlines had access to forecasts based on the type of wind measurements that would be provided by the proposed wind lidar. Although reduced flying times generally translate into reduced fuel consumption, the relationship may not be directly proportional. Since the early 1980s, the NWS forecast products have also improved significantly. Thus, in some cases, average improvements in flight times that are likely to result from wind measurements obtained from lidar are likely to be smaller than 4.2% .For example, while the lidar wind measurements would no doubt improve the forecasts for all regions of the globe, the improvement would be smaller over the continental United States, where there is now considerable wind data available in real time, than it would be elsewhere.

Nonetheless, the simulated reductions in flight time suggest that it would not be unrealistic to expect that better wind measurements would enable U .S. carriers to reduce fuel consumption by (at least) 0.5% on domestic flights, and 1.0% on international flights. Table 3 presents projections of future jet fuel consumption based on FAA data. These projections indicate that permanent annual reductions in fuel consumption of these magnitudes would translate into annual dollar savings of on the order of $100 to $200 million per year over the assumed 20=year period of wind lidar operations. From the year 2011 onward, the largest share of these savings would come from fuel savings on international flights, which are projected to increase at a more rapid rate than domestic flights. [21]

6.5 Overall Economic Benefits

Figure 2 and Table 4 summarize the economic benefits that can reasonably be assumed from accurately measuring global winds provided by a Doppler wind lidar. Over its 20-year assumed operating life, annual tangible benefits from the wind lidar are estimated to total some $4.9 billion. [22] The main source of tangible benefits is airline fuel savings which are estimated to total almost $3.1 billion. Accurate measurement of the global wind field can also be expected to provide real, though intangible, economic benefits by helping to reduce uncertainties about the scope and pace of possible climate change, as well as loss of life and limb from hurricanes.

[20] Robert Steinberg, April 1981: "Airline Flight Planning: The Weather Connection," National Aeronautics and Space Administration, unpublished paper, presented at the Symposium on Commercial Aviation Energy Conservation Strategies, Washington D.C.

[21] It should be noted that all fuel projections are based on tropospheric subsonic flight operations. The potential savings might be reduced if a transition to stratospheric, supersonic operations occurred during the period that the lidar is operational.

[22] This total is the *undiscounted* sum of the annual benefits, and hence should not be confused with the *present value* of benefits shown in Table 6 and Figure 5.

TABLE 3

PROJECTED JET FUEL CONSUMPTION BY U.S. COMMERCIAL AIR CARRIERS [1]

YEAR	GALLONS OF DOMESTIC JET FUEL MILLION GAL.	COST OF DOMESTIC JET FUEL MILLION 1.994$	GALLONS OF INTERNATL. JET FUEL MILLION GAL.	COST OF INTERNATL. JET FUEL MILLION 1994$
2004	16607	$10,502	7455	$4,570
2005	17163	$10,796	7823	$4,795
2006	17678	$11,119	8292	$5.083
2007	18208	$11,453	8790	$5,388
2008	18754	$11,797	9317	$5,712
2009	19317	$12,150	9876	$6054
2010	19897	$12,515	10469	$6417
2011	20494	$12,890	11097	$6,803
2012	21108	$13,277	11763	$7,211
2013	21742	$13,675	12469	$7,643
2014	22394	$14,086	13217	$8.102
2015	23066	$14,508	14010	$8,588
2016	23758	$14,944	14850	$9,103
2017	24470	$15,392	15741	$9,649
2018	25204	$15.854	16686	$10,228
2019	25961	$16.329	17687	$10,842
2020	26739	$16,819	18748	$11,493
2021	27542	$17,324	19873	$12,182
2022	28368	$17,843	21066	$12,913
2023	29219	$18,379	22329	$13,688

[1] Data from 1996-2004 are based on projections published by the Federal Aviation Administration. Fuel consumption estimates from 2004 onward assume that international fuel consumption will grow at a rate of 6%, and domestic fuel consumption at a rate of 3%, which were the average growth rates used by the FAA in making their own projections through 2004. The real price per gallon of jet fuel is assumed to remain constant at $0.63 per gallon for fuel consumed on domestic flights, and at $0.61 for jet fuel consumed on international flights.

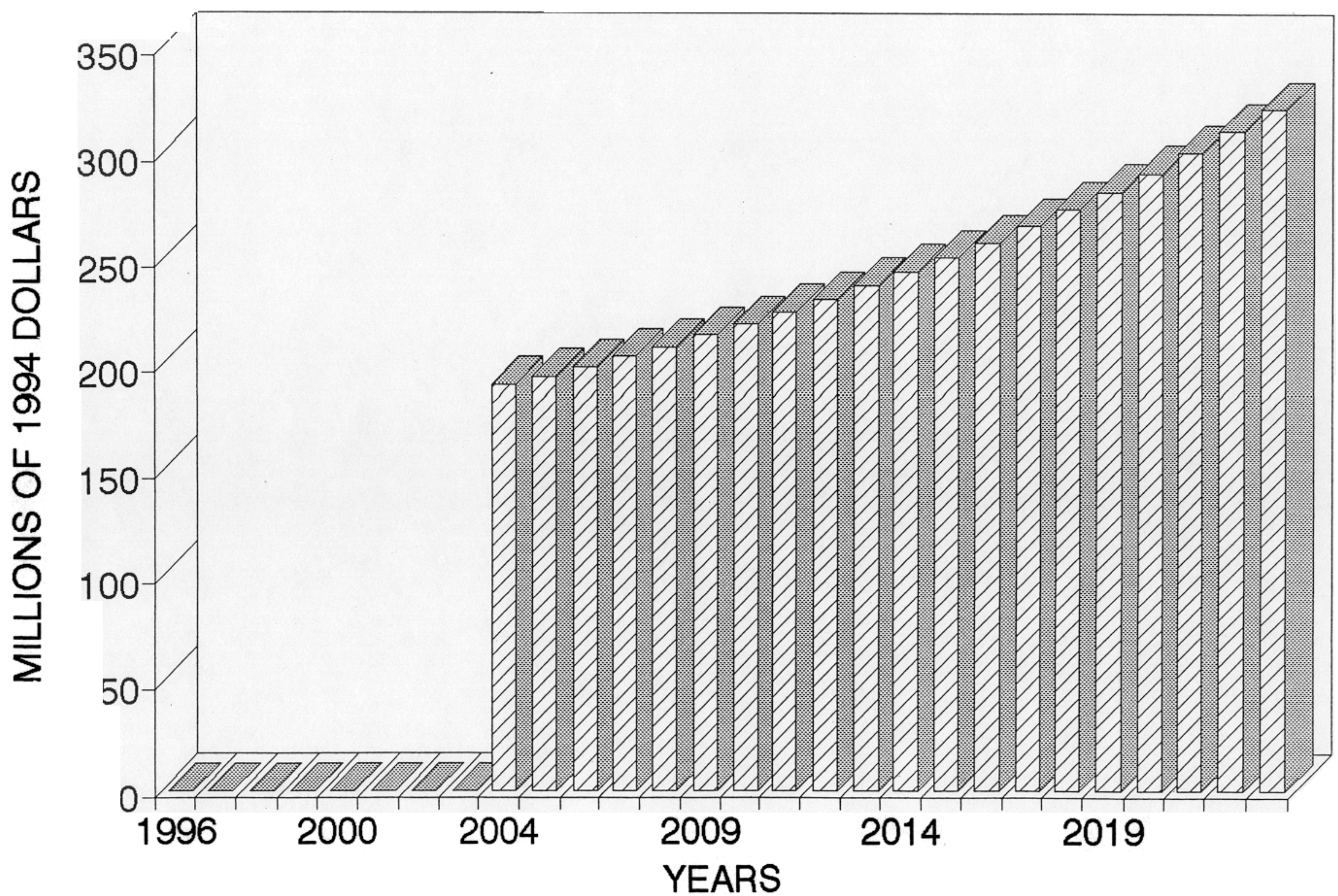
TABLE 4

PROJECTED ANNUAL BENEFITS OF LIDAR IN 1994 $S

YEAR	Reduced Economic Costs from Hurricanes	Reduced Loss of Life and Limb	Improved Weather Forecasts	Airline Fuel Savings	Better Forecasts of Climate Change	Total[1]
1996	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
1997	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
1998	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
1999	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2000	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2001	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2002	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2003	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2004	$33,000,000	+	$60.000,000	$99,000,000	+	$191,000,000
2005	$33,000,000	+	$60,000,000	$102,000,000	+	$195,000,000
2006	$33,000,000	+	$60,000,000	$107,000,000	+	$199,000,000
2007	$33,000,000	+	$60,000,000	$111,000,000	+	$204,000,000
2008	$33,000,000	+	$60,000,000	$116,000,000	+	$209,000,000
2009	$33,000,000	+	$60,000,000	$122,000,000	+	$214,000,000
2010	$33,000,000	+	$60,000,000	$127,000,000	+	$220,000,000
2011	$33,000,000	+	$60,000,000	$132,000,000	+	$225,000,000
2012	$33,000,000	+	$60,000,000	$138,000,000	+	$231,000,000
2013	$33,000,000	+	$60,000,000	$144,000,000	+	$238,000,000
2014	$33,000,000	+	$60,000,000	$151,000,000	+	$244,000,000
2015	$33,000,000	+	$60,000,000	$159,000,000	+	$251,000,000
2016	$33,000,000	+	$60,000,000	$166,000,000	+	$259,000,000
2017	$33,000,000	+	$60,000,000	$173,000,000	+	$266,000,000
2018	$33,000,000	+	$60,000,000	$181,000,000	+	$275,000,000
2019	$33,000,000	+	$60,000,000	$190,000,000	+	$283,000,000
2020	$33,000,000	+	$60,000,000	$199,000,000	+	$292,000,000
2021	$33,000,000	+	$60,000,000	$209,000,000	+	$301,000,000
2022	$33,000,000	+	$60,000,000	$218,000,000	+	$311,000,000
2023	$33,000,000	+	$60,000,000	$229,000,000	+	$322,000,000

[1] Totals may differ from the sums of individual columns due to rounding.

FIGURE 2
ANNUAL BENEFITS OF LIDAR



7. BENEFIT COST ANALYSIS

Figure 3 presents the estimates of annual costs, shown in Table 1, along with the estimates of tangible annual benefits shown in Table 4 and Figure 2. The issue is whether the stream of measured economic benefits shown in Figure 3 justifies incurring the stream of annual outlays required to develop and implement an operational wind lidar that are shown in the same figure.

The question can be usefully restated in terms of Table 5 and Figure 4, which show annual estimates of the *net benefits and/or costs* of a wind lidar. The economic decision to proceed with the deployment of a wind lidar turns on whether it is economically worthwhile, from society's point of view, to incur the (net) costs of implementing the wind lidar between 1996 and 2003, in exchange for the stream of net benefits that the wind lidar system is projected to provide between the years 2004 and 2023.

7.1 Concept of Present Value

Because individuals and businesses who make up society place more value on a dollar of cost incurred and/or benefit received in the present than in the future, the appropriate measures for comparing the benefit and cost streams shown in Figure 3 and the net benefit and cost streams shown in Figure 4 are the present values of these streams, as indicated by equation (2), in the case of Figure 3,

(2) $$NPV = \sum_{t=1}^{t=T} \frac{\overline{B_t}}{(1+i)^t} - \sum_{t=1}^{t=T} \frac{\overline{C_t}}{(}$$

where T is the length of the project, or equivalently by equation (3), in the case of Figure 4:

(3) $$NPV = \sum_{t=1}^{t=T} \frac{(B_t - C_t)}{(1+i)^t}$$

where B_t and C_t are the annual net cost/benefits in Figure 3, (B_t - C_t) are the annual net costs/benefits in Figure 4, and i is the discount rate used to calculate present values.

F GURE 3
ANNUAL BENEF TS AND COSTS OF L DAR

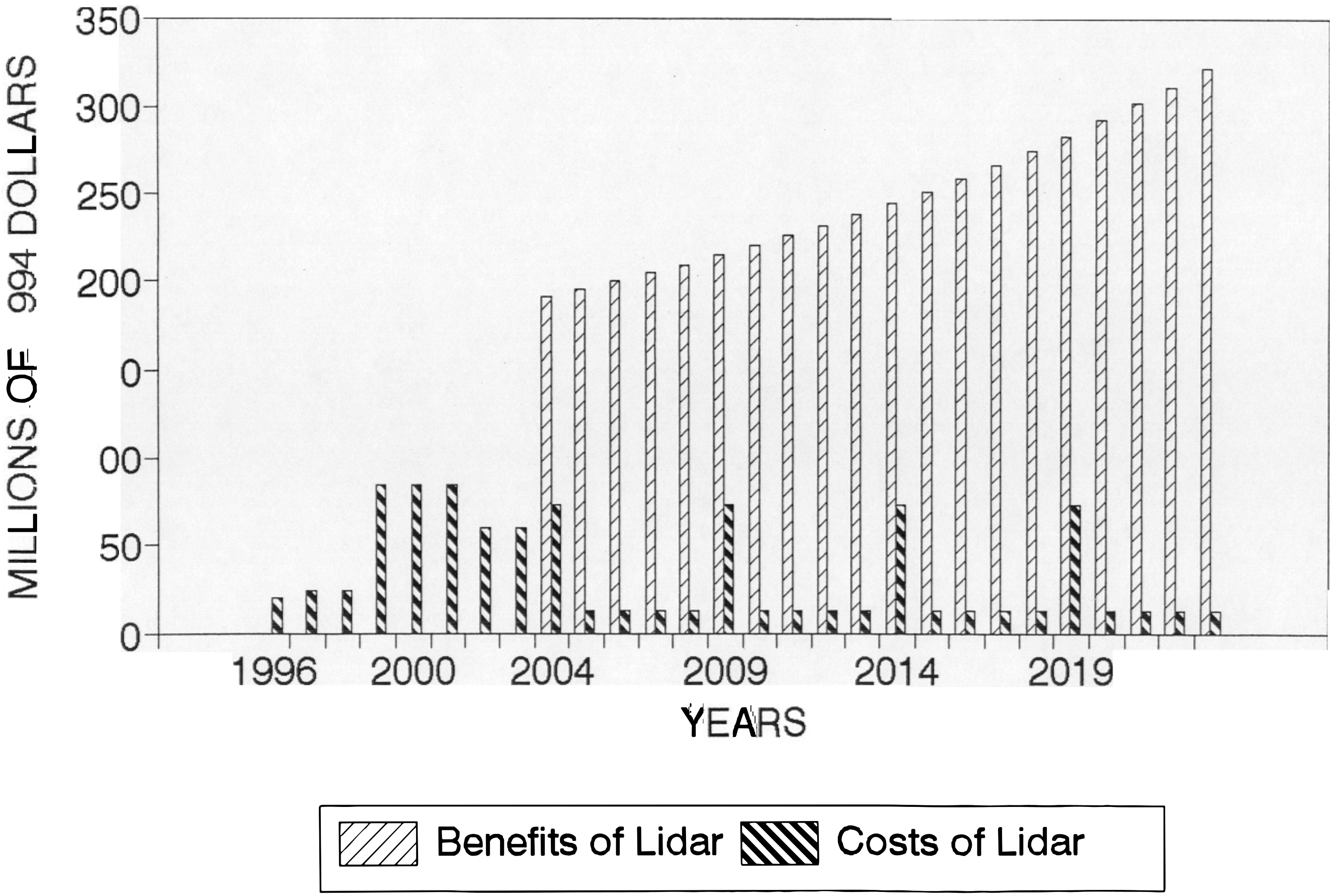


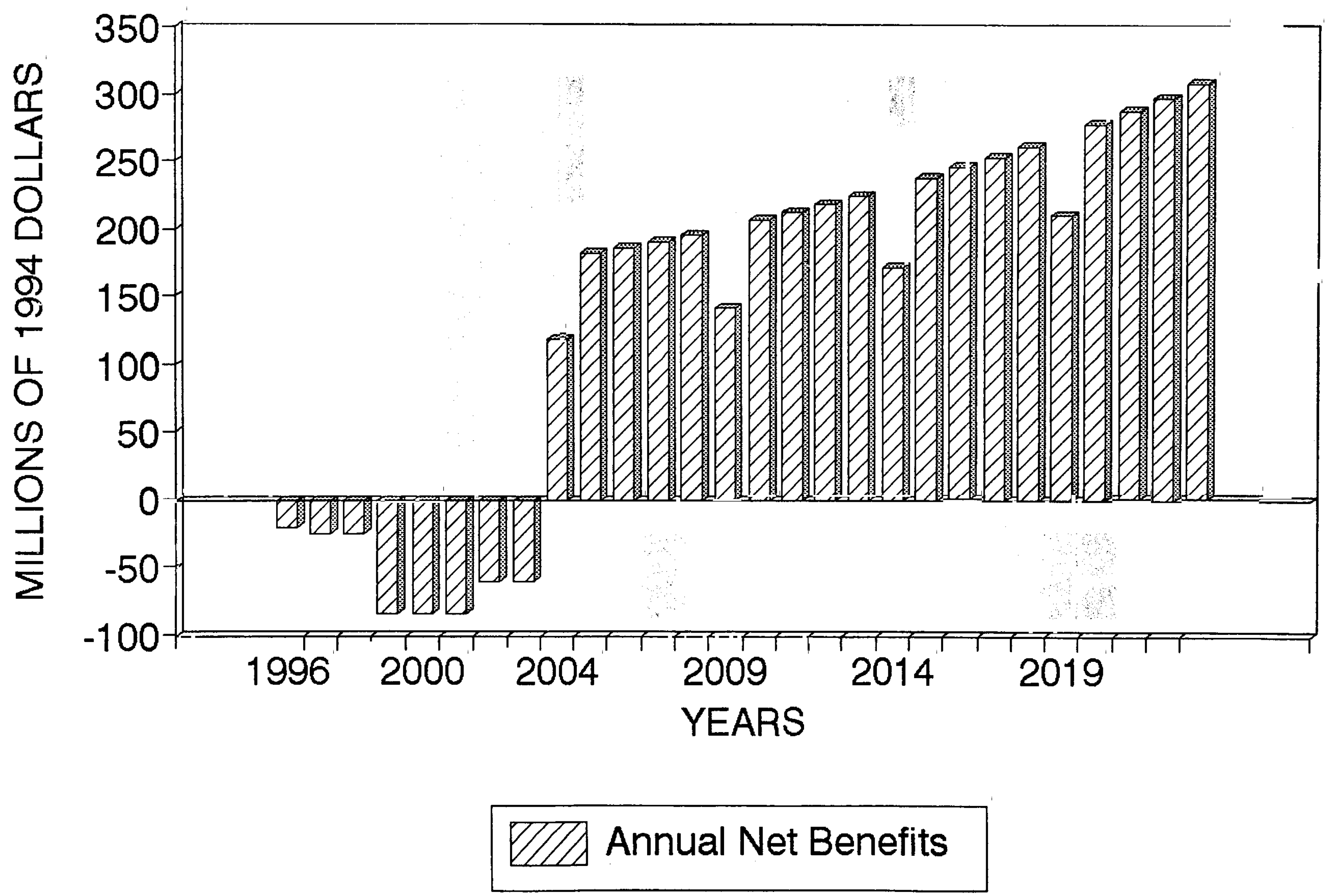
TABLE 5

PROJECTED ANNUAL NET BENEFITS OF LIDAR IN 1994 $S[1]

YEAR	Total Annual Costs	Total Annual Benefits	Benefits-Costs
1996	$20,000,000	$0	$(20,000,000)
1997	$24,000,000	$0	$(24,000,000)
1998	$24,000,000	$0	$(24,000,000)
1999	$84,000,000	$0	$(84,000,000)
2000	$84,000,000	$0	$(84,000,000)
2001	$84,000,000	$0	$(84,000,000)
2002	$60,000,000	$0	$(60,000,000)
2003	$60,000,000	$0	$(60,000,000)
2004	$72,500,000	$191,000,000	$118,500,000
2005	$12,500,000	$195,000,000	$182,500,000
2006	$12,500,000	$199,000,000	$186,500,000
2007	$12,500,000	$204,000,000	$191,500,000
2008	$12,500,000	$209,000,000	$196,500,000
2009	$72,500,000	$214,000,000	$141,500,000
2010	$12,500,000	$220,000,000	$207 500,000
2011	$12,500,000	$225,000,000	$212,500,000
2012	$12,500,000	$231,000,000	$218,500,000
2013	$12,500,000	$238,000,000	$225,500,000
2014	$72,500,000	$244,000,000	$171,500,000
2015	$12,500,000	$251,000,000	$238,500,000
2016	$12,500,000	$259,000,000	$246,500,000
2017	$12,500,000	$266,000,000	$253,500,000
2018	$12,500,000	$275,000,000	$262,500,000
2019	$72,500,000	$283,000,000	$210,500,000
2020	$12,500,000	$292,000,000	$279,500,000
2021	$12,500,000	$301,000,000	$288,500,000
2022	$12,500,000	$311,000,000	$298,500,000
2023	$12,500,000	$322,000,000	$309,500,000

[1] Totals may differ from the sums of individual columns due to rounding.

FIGURE 4
ANNUAL NET BENEFITS OF LIDAR



7.1.1 Choice of Discount Rate

The present values in (2) and (3) depend on the choice of the discount rate, i. Although there is a range of views about how to choose the discount rate, the Office of Management and Budget has instructed agencies to use a real, ("inflation-adjusted") discount rate of 7%. Because the benefits and costs in Figures 3 and 4 are expressed in constant 1994 dollars, the OMB-recommended real discount rate of 7% is used to estimate the benefit-cost estimates. [23]

7.2 Results

Table 6, and the accompanying Figure 5, show the estimated present value of the benefits and costs of the proposed wind lidar system. [24] Given the assumptions that have been made about benefits and projected costs, the present value of measured benefits from a wind lidar are estimated to exceed the present value of the projected costs by $958 million, which represents a ratio of benefits to costs of just over 3 to 1. Table 6 also shows that it would take roughly four years for an operational wind lidar to produce net payoffs equal, in present value terms, to the initial costs of developing and deploying the system.

[23] One question is whether to use a "nominal" discount rate, which includes the effects of inflation, or a "real" rate which measures the time value of money in a world in which there is no inflation. Present-value calculations will not be affected by which of these discount rates is used, provided that the underlying benefits and costs are also consistently measured. The rule is to use a nominal discount rate when benefits and costs are expressed in current (inflation-unadjusted) dollars; and a real discount rate when benefits and costs are expressed in constant (inflation-adjusted) dollars. For a discussion of this point, as well as of views on how to choose the discount rate, see Richard 0. Zerbe and Richard D. Dively, 1994: *Benefit-CostAnalysis In Theory and Practice,* Harper-Collins.

[24] Note that the present value formulas in (2) and (3) discount a future dollar of benefit, cost, or net benefit by a factor of [l/(l+i)]t. For example, $1 of net benefit received 20 years in the future, discounted at a rate of 7% has a value today (its *present value)* of [1/(1.07)]20, or $0.26. Thus, the *present values* presented in Table 6, and shown in Figure 5 are *weighted sums* of the corresponding annual amounts shown in Tables 1, 4, and 5 and Figures 1-4, where the weights decline the further out in time the benefit is received, or the cost is incurred. Hence, the amounts reported in Table 6 and Figure 5 will be less than the simple (undiscounted) sum of the annual amounts shown in Tables 1,4,and 5, and Figures 1-4.

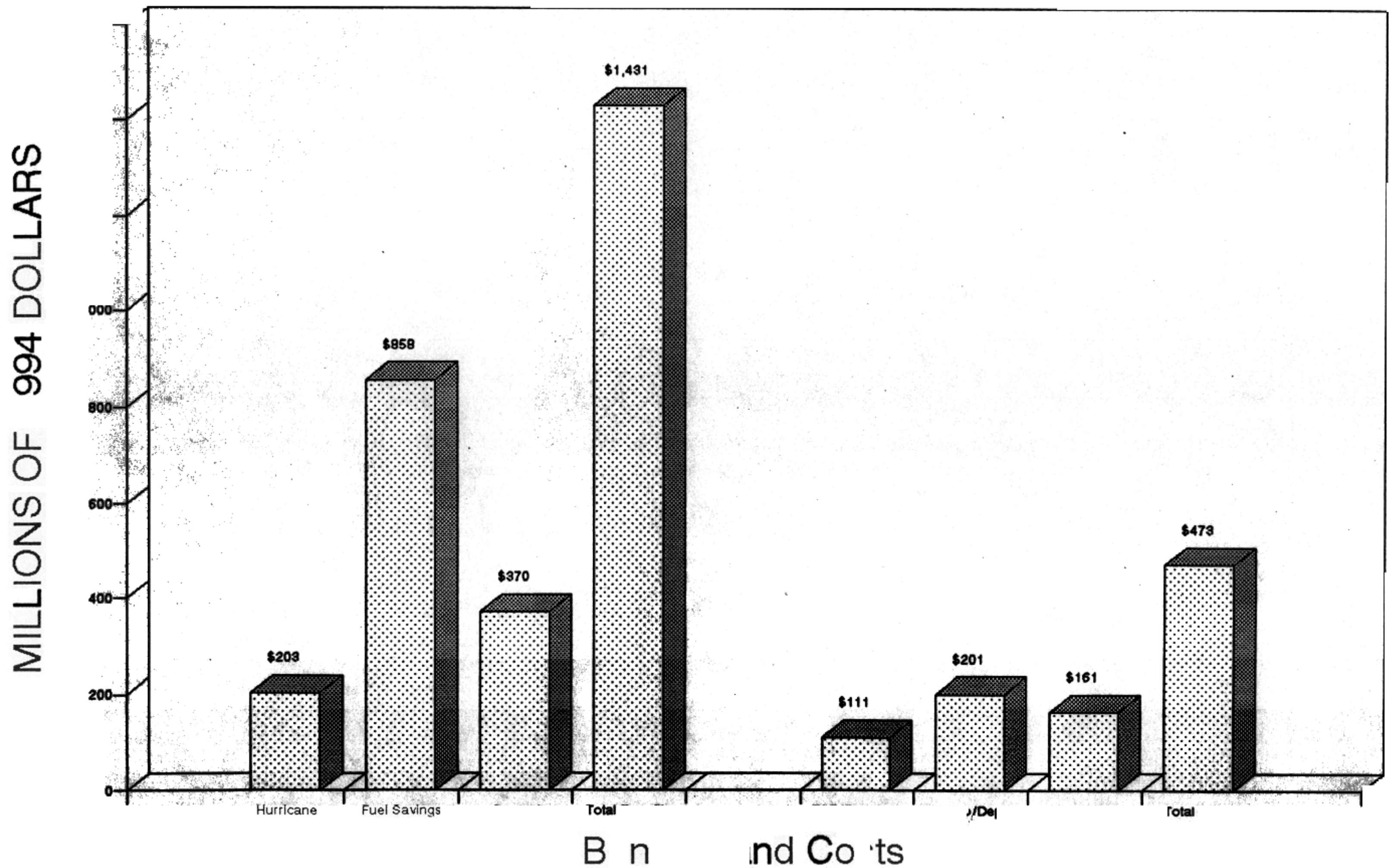
TABLE 6

NET BENEFITS AND COSTS OF WIND LIDAR SYSTEM

PRESENT VALUE OF BENEFITS	**$1,431,000,000**
Reduced Hurricane Damage	$203,000,000
General Weather Forecasting	$370,000,000
Airline Fuel Savings	$858,000,000
PRESENT VALUE OF COSTS	$473,000,000
R&D and Prototype	$111,000,000
Development and Deployment	$201,000,000
Operating	$161,000,000
NET PRESENT VALUE	$958,000,000
BENEFIT-TO-COST RATIO	3.03
PAYBACK PERIOD	4 Years

F GURE 5

PRESENT VALUE OF L DAR BENEF TS & COSTS



8. SENSITIVITY ANALYSIS

Although the estimates presented above are based on reasonable judgements about the projected costs and measured benefits of a wind lidar, there is also uncertainty about their true magnitude. For example, the cost estimates presented in Table 1 assume that the costs of operating a wind lidar would remain constant in real dollars over the assumed 20-year period of operations. Actual costs of deploying wind lidar could be lower than these projected costs if technological change made it easier to launch and operate future wind lidar satellites. On the other hand, the costs of developing wind lidar could be higher than those projected. Similarly, although the assumptions that underlie the estimates of the economic benefits of wind lidar are plausible, they could either overstate or understate the actual economic benefits.

8.1 Specifying Ranges of Variables

To explore how such uncertainty might affect the results of the analysis, this section presents a structured sensitivity analysis similar to that presented in Chapman. [25] The first step in the analysis is to identify the variables to be included in the analysis. These are: (1) program cost (COST); (2) benefits from reduced hurricane damage (HURRICANE); (3) benefits from general improvements in weather forecasting skill (GENERAL); (4) percentage annual fuel savings on domestic flights (PCT. DOMESTIC FUEL); and (5) percentage annual fuel savings on international flights (PCT. INTERNATL. FUEL). [26]

The second step is to specify ranges that establish bounds for the minimum and the maximum values of each variable. These ranges are described in Table 7; and Table 8 shows the values of each variable that correspond to these ranges along with the baseline values.

8.2 Structuring the Analysis

The minimum and maximum values of the variables shown in Tables 7 and 8 form the basis for the structured sensitivity analysis. In this analysis, it is assumed that the extreme values of each variable characterize a uniform probability distribution of possible values for the variable. An attractive property of a uniform distribution is that all values between the minimum and the maximum value are equally likely, so that the cumulative distribution function (CDF) of each variable can be described in terms of the range of values shown in Table 9, which shows odd percentiles (i.e., the 1st, 3rd,...,99th) of the possible values for each of the variables.

For example, the sensitivity analysis assumes that the actual value of the present value

[25] Chapman, *op.cit.,* Section 7.

[26] Because annual expenditures by commercial airlines on fuel consumption are projected to increase from year to year, the relevant parameter to be varied in the sensitivity analysis is the annual percentage by which these expenditures would be reduced by deploying a wind lidar.

of the costs of developing and deploying a wind lidar can take on a range of equally likely values bounded at the lower end by ($315.33 million, equal to 2/3rds of the baseline estimate of $473 million), and at the high-end by ($630.67 million, equal to 4/3rds of the baseline estimate). Table 9 then shows that if the true value of the costs is assumed to be drawn from a uniform probability distribution with minimum and maximum values of $315.33 million and $630.67 million, respectively, there is a 25% chance that the present value of costs will be greater than $315.33 million, but less than $394.1 million, a 75% chance that the present value of costs will be greater than $315.33 million, but less than $551.6 million, and so forth.

8.2.1 Latin Hyuercube Samuling Design

The final step is to specify a mechanism for "sampling" from the assumed probability distributions of values for costs and benefits that are shown in Table 9. The technique that is used for this purpose is that of a Latin hypercube sampling experiment, which randomly selects percentiles (rows in Table 9) from the CDF of each variable in a way that ensures that a given value (row/percentile) appears only once in each row and in each column.[27]

Using this approach, Table 10 specifies 50 different simulations corresponding to 50 different random draws of values from the probability distributions of each of the variables analyzed in the sensitivity analysis. Thus, for example, the first row in Table 10 can be viewed as a "simulation" in which the annual real benefits from reduced hurricane damage equals the 19th percentile value in Table 9 (row 10), annual real benefits from general improvements in forecasting skill equal the 29th percentile value in Table 9 (row 15), annual savings in international fuel consumption equal the 9th percentile value in Table 9 (row 21), and the present value of costs equals the 63rd percentile value in Table 9 (row 32). The other rows in Table 10 have analogous interpretations.

[27] The assistance of Robert Chapman in providing the Latin Hypercube used to choose the simulations is gratefully acknowledged.

TABLE 7

Upper and Lower Bounds of Key Variables

	RANGE BETWEEN LOWER AND UPPER BOUND VALUES
PROGRAM COST	-33% to +33% of baseline annual real system costs
PROGRAM BENEFIT VARIABLES	
HURRICANE	-33% to +33% of estimated annual real benefits from reduced costs of hurricanes
GENERAL	-33% to +33% of baseline annual real benefits from general improvements in forecasting skill
PCT. DOMESTIC FUEL	-50% to +50% of baseline annual percentage reduction in fuel consumption on domestic flights
PCT. INTL. FUEL	-50% to +50% of baseline annual percentage reduction in fuel consumption on international flights

TABLE 8

Baseline and Extreme Values Used in the Structured Sensitivity Analysis

	BASELINE VALUE	MINIMUM VALUE	MAXIMUM VALUE
PROGRAM COST	$473 million	$315 million	$631 million
PROGRAM BENEFIT VARIABLES			
HURRICANE	$33 million	$21 million	$44 million
GENERAL	$60 million	$40 million	$80 million
PCT. DOMESTIC FUEL	0.50%	0.25%	0.75%
PCT. INTL. FUEL	1.0%	0.5%	1.5%

TABLE 9

RANGES OF VALUES OF BENEFIT AND COST VARIABLES USED IN SENSITIVITY ANALYSIS

Row Number	Percentile	Hurricane Savings (Million $ Per Year)	Improved Forecasting Skill (Million $ Per Year)	Domestic Fuel Savings (Percent Per Year)	Internatl. Fuel Savings (Percent Per Year)	Present Value of System Costs (Million $)
1	1st	$22.22	$40.40	0.255%	0.51%	$318.5
2	3rd	$22.66	$41.20	0.27%	0.53%	$324.8
3	5th	$23.10	$42.00	0.28%	0.55%	$331.1
4	7th	$23.54	$42.80	0.29%	0.57%	$337.4
5	9th	$23.98	$43.60	0.30%	0.59%	$343.7
6	11th	$24.42	$44.40	0.31%	0.61%	$350.0
7	13th	$24.86	$45.20	0.32%	0.63%	$356.3
8	15th	$25.30	$46.00	0.33%	0.65%	$362.6
9	17th	$25.74	$46.80	0.34%	0.67%	$368.9
10	19th	$26.18	$47.60	0.35%	0.69%	$375.2
11	21st	$26.62	$48.40	0.36%	0.71%	$381.5
12	23rd	$27.06	$49.20	0.37%	0.73%	$387.8
13	25th	$27.50	$50.00	0.38%	0.75%	$394.1
14	27th	$27.94	$50.80	0.39%	0.77%	$400.4
15	29th	$28.38	$51.60	0.40%	0.79%	$406.7
16	31st	$28.82	$52.40	0.41%	0.81%	$413.0
17	33rd	$29.26	$53.20	0.42%	0.83%	$419.3
18	35th	$29.70	$54.00	0.43%	0.85%	$425.6
19	37th	$30.14	$54.80	0.44%	0.87%	$431.9
20	39th	$30.58	$55.60	0.45%	0.89%	$438.2
21	41st	$31.02	$56.40	0.46%	0.91%	$444.5
22	43rd	$31.46	$57.20	0.47%	0.93%	$450.8
23	45th	$31.90	$58.00	0.48%	0.95%	$457.1
24	47th	$32.34	$58.80	0.49%	0.97%	$463.4
25	49th	$32.78	$59.60	0.50%	0.99%	$469.7

TABLE 9 (Continued)

RANGES OF VALUES OF BENEFIT AND COST VARIABLES USED IN SENSITIVITY ANALYSIS

Row Number	Percentile	Hurricane Savings (Million $ Per Year)	Improved Forecasting Skill (Million $ Per Year)	Domestic Fuel Savings (Percent Per Year)	Internatl. Fuel Savings (Percent Per Year)	Present Value of System Costs (Million $)
26	51st	$33.22	$60.40	0.51%	1.01%	$476.0
27	53rd	$33.66	$61.20	0.52%	1.03%	$482.3
28	55th	$34.10	$62.00	0.53%	1.05%	$488.6
29	57th	$34.54	$62.80	0.54%	1.07%	$494.9
30	59th	$34.98	$63.60	0.55%	1.09%	$501.2
31	61st	$35.42	$64.40	0.56%	1.11%	$507.5
32	63rd	$35.86	$65.20	0.57%	1.13%	$513.8
33	65th	$36.30	$66.00	0.58%	1.15%	$520.1
34	67th	$36.74	$66.80	0.59%	1.17%	$526.4
35	69th	$37.18	$67.60	0.60%	1.19%	$532.7
36	71st	$37.62	$68.40	0.61%	1.21%	$539.0
37	73rd	$38.06	$69.20	0.62%	1.23%	$545.3
38	75th	$38.50	$70.00	0.63%	1.25%	$551.6
39	77th	$38.94	$70.80	0.64%	1.27%	$557.9
40	79th	$39.38	$71.60	0.65%	1.29%	$564.2
41	81st	$39.82	$72.40	0.66%	1.31%	$570.5
42	83rd	$40.26	$73.20	0.67%	1.33%	$576.8
43	85th	$40.70	$74.00	0.68%	1.35%	$583.1
44	87th	$41.14	$74.80	0.69%	1.37%	$589.4
45	89th	$41.58	$75.60	0.70%	1.39%	$595.7
46	91st	$42.02	$76.40	0.71%	1.41%	$602.0
47	93rd	$42.46	$77.20	0.72%	1.43%	$608.3
48	95th	$42.90	$78.00	0.73%	1.45%	$614.6
49	97th	$43.34	$78.80	0.74%	1.47%	$620.9
50	99th	$43.78	$79.60	0.75%	1.49%	$627.2

TABLE 10

SIMULATIONS BASED ON LATIN HYPERCUBE SAMPLING DESIGN

Simulation Number	Hurricane Savings (Table 9 Row)	Improved Forecasting Skill (Table 9 Row)	Percent Domestic Fuel Savings (Table 9 Row)	Percent Internatl. Fuel Savings (Table 9 Row)	Present Value of System Costs (Table 9 Row)
1	10	15	5	21	32
2	21	7	10	8	28
3	44	42	24	32	5
4	20	31	37	12	17
5	50	14	12	23	15
6	34	48	33	19	8
7	1	30	35	50	22
8	23	12	47	11	20
9	32	18	38	44	27
10	13	27	19	10	12
11	33	43	26	29	21
12	38	1	50	4	37
13	25	29	32	3	35
14	36	34	17	43	6
15	43	21	16	37	39
16	39	32	42	45	26
17	3	2	48	49	34
18	46	16	44	47	14
19	22	3	27	35	19
20	6	45	8	40	44
21	14	6	9	34	4
22	40	49	20	22	38
23	41	33	6	14	50
24	27	5	31	38	42
25	47	41	46	6	7

TABLE 10 (Continued)

SIMULATIONS BASED ON LATIN HYPERCUBE SAMPLING DESIGN

Simulation Number	Hurricane Savings (Table 9 Row)	Improved Forecasting Skill (Table 9 Row)	Percent Domestic Fuel Savings (Table 9 Row)	Percent Internatl. Fuel Savings (Table 9 Row)	Present Value of System Costs (Table 9 Row)
26	9	46	23	2	24
27	12	25	14	7	11
28	26	19	41	33	36
29	11	39	21	9	46
30	5	28	2	17	29
31	24	4	25	42	23
32	30	17	39	48	18
33	35	23	49	16	43
34	31	13	22	18	45
35	19	44	18	1	9
36	15	35	4	20	40
37	28	26	40	27	30
38	37	8	29	26	49
39	45	47	7	31	3
40	18	20	13	46	31
41	48	9	45	24	13
42	17	38	11	39	2
43	16	11	1	36	41
44	7	10	36	25	16
45	4	36	30	41	1
46	42	37	3	28	33
47	8	50	43	30	25
48	2	40	34	13	47
49	29	24	15	5	10
50	4	22	28	15	48

8.3 Results

Table 11 presents the minimum, maximum, and average values, and the standard deviations of the present value of net benefits and of the benefit-to-cost ratios that were calculated in the 50 different simulations described in Table 10. [28] Figures 6 and 7 show the frequency distribution of the present value of net benefits and of the benefit-to-cost ratio. In the 50 simulations, the estimated net present value of developing and deploying a wind lidar range from a low of $561 million to a high of $1.4 billion dollars, while the ratio of benefits to costs ranges from a low of 2.0 to just under 5.0.

TABLE II
RESULTS OF SENSITIVITY ANALYSIS

Variable	Minimum Simulated Value	Maximum Simulated Value	Average of Simulated Values	Std. Deviation of Simulated Values
Present Value of Net Benefits	$561 million	$1.4 billion	$962.5 million	$217 million
Benefit/Cost Ratio	2.00	4.99	3.17	.88

[28] Note that the average of the simulated values of net benefits and the benefit/cost ratio are close, but not identical to, baseline estimates of these magnitudes. This is to be expected since the ranges of values of the variables in the sensitivity analysis are centered around the values used to calculate the baseline estimates of benefits and costs.

FIGURE 6

SIMULATED NET BENEFITS OF WIND LIDAR

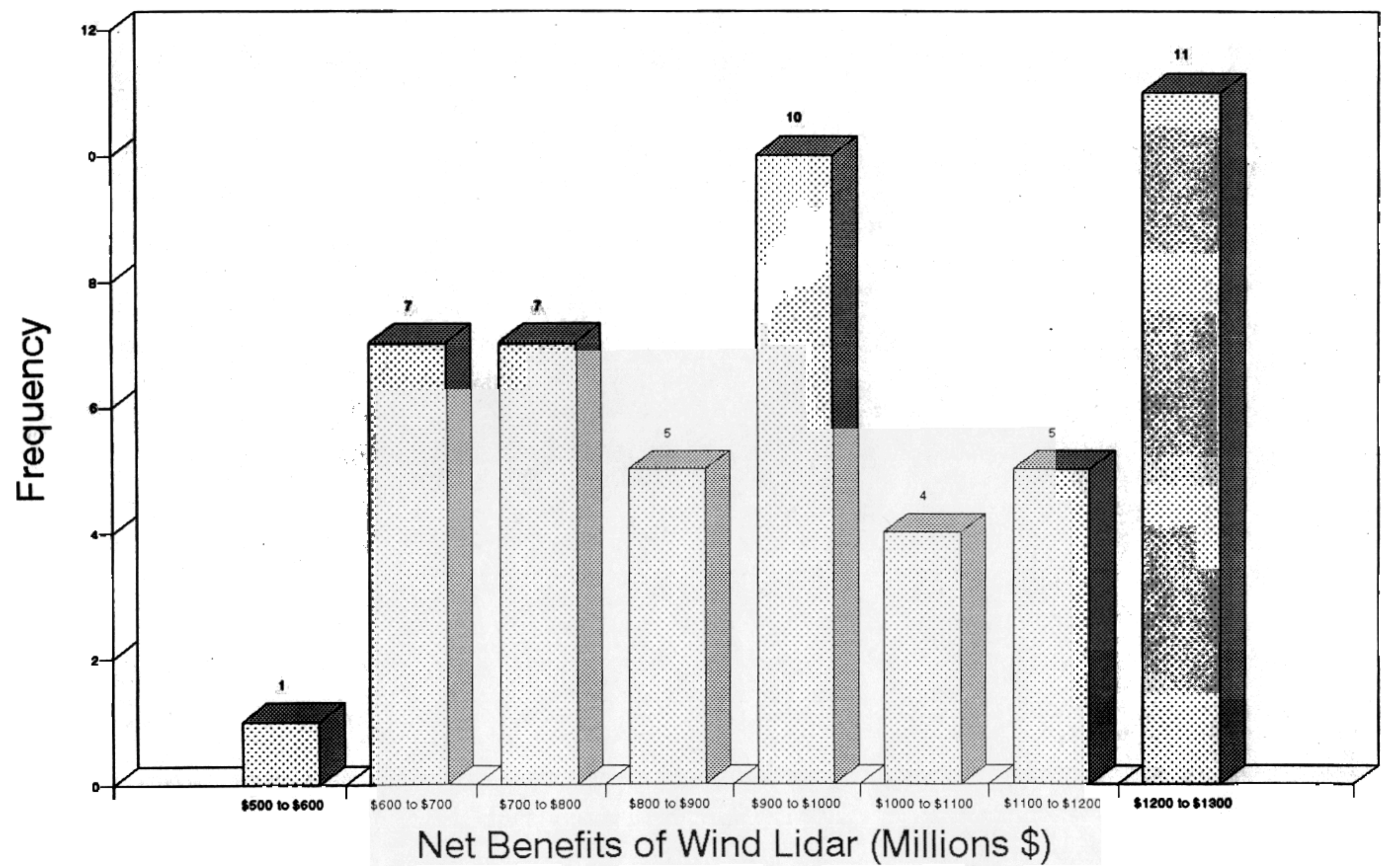
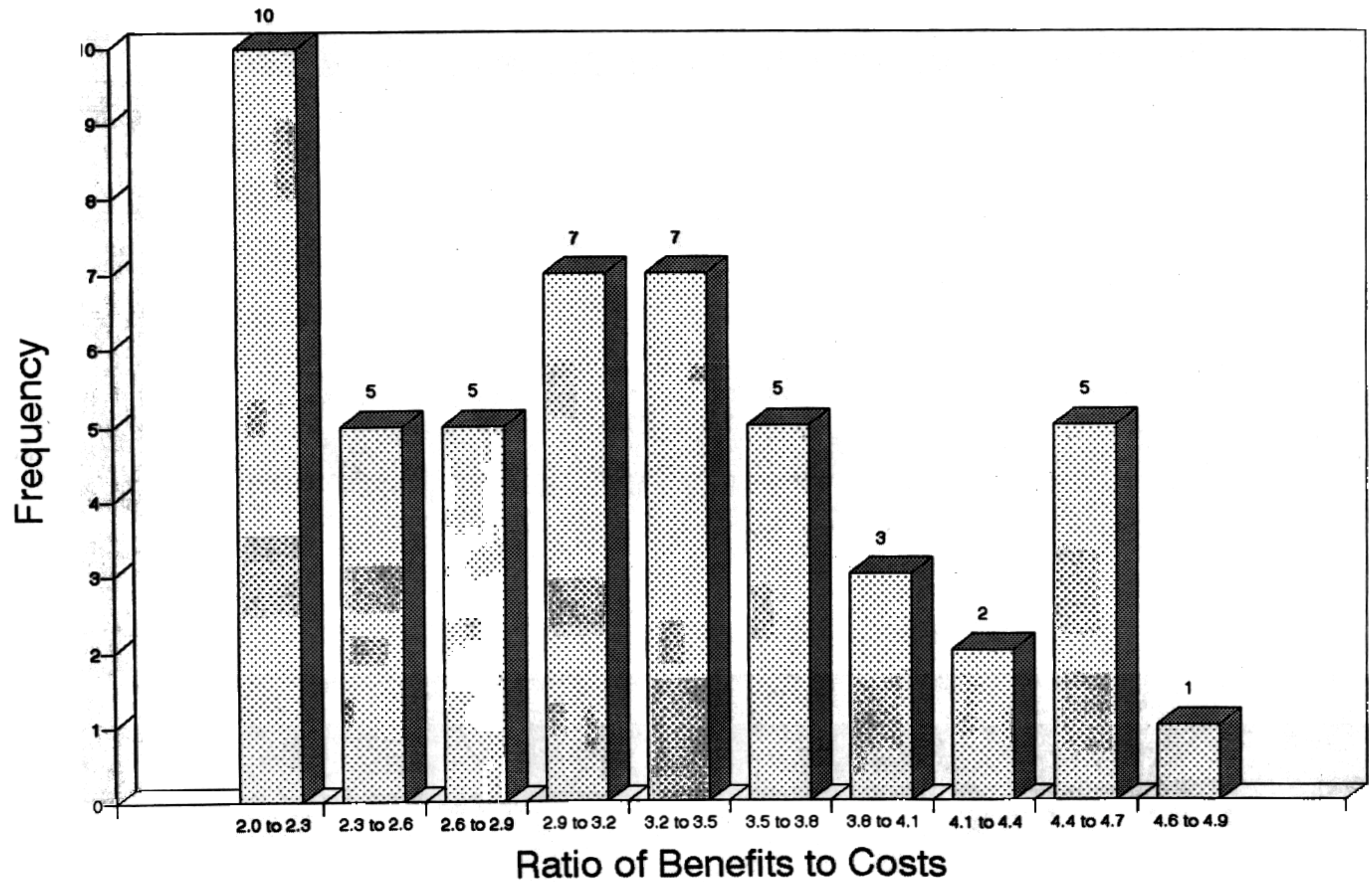


FIGURE 7
SIMULATED BENEFIT/COST RATIOS



9. CONCLUSIONS

Developing the capacity for making accurate global wind measurements has the potential to significantly improve the understanding and prediction of weather and climate. Such a capability must be provided from space; and studies have concluded that it is possible to measure tropospheric winds from space with current Doppler lidar technology.

This study has identified the tangible as well as the intangible benefits that would be provided by a space-based Doppler wind lidar, and presented a formal analysis that compares estimates of the tangible benefits with the costs of developing and deploying a wind lidar. These estimates, based on reasonable assumptions about both the costs and tangible economics benefits of developing and deploying a wind lidar system, indicate that:

- Developing and deploying such a system will require a projected public investment equal to $473 million in present value over an assumed system life of 20 years, while providing tangible economic benefits with an estimated present value just over $1.4 billion.

- The estimated net benefits from developing and deploying a wind lidar system are $958 million, and the estimated ratio of benefits to costs is just over 3.029.

These results indicate that developing and deploying a wind lidar will provide projected tangible economic benefits well in excess of projected costs. Moreover, the results of the structured sensitivity analysis show that this broad conclusion is relatively unaffected by a fairly wide range of alternative assumptions about the magnitudes of both costs and tangible economic benefits.

[29] Note again that the *baseline estimates* differ somewhat from the *average simulated values* calculated in the sensitivity analysis and presented in Table 11.

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