The Socio-Economic Value of Improved Weather and Climate Information

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EXECUTIVE SUMMARY

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Virtually all economic sectors and many public and private activities are affected in some measure by changes in weather and climate. Uncertainties in the scope and severity of these changes pose financial and social risks for individuals, businesses, and government agencies. Hence, achieving more accurate weather and climate forecasts contributes to well being and the economy by reducing risk and creating new opportunities.

Over the past four decades the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) have made considerable scientific progress towards enhancing the accuracy of weather and climate predictions. Improved predictions made possible by global satellite data have led to numerous social and economic benefits, including more effective management of energy resources; enhanced natural disaster planning, mitigation, and response; cost savings in aviation, agriculture, and other industries; and in the effectiveness of the U.S. military. Sophisticated instruments on future observation satellites will continue the trend toward achieving a better understanding of Earth's climate and establishing a continuing basis for expanding domestic and global socio-economic benefits.

Yet scientific understanding is only the beginning of the process of developing socio-economic benefits from satellite data. The data must be analyzed, combined with information obtained from other sources, placed into appropriate models of the behavior of global weather and climate, and turned into information to be disseminated at the right time in useable forms to individuals and organizations that put the information to practical use. The paths from space data to decisions capable of generating economic benefits are complex; they vary with each application and cross several institutional boundaries. They also require myriad information linkages. At times, potential benefits are unrealized as a result of inadequate or untimely data transfers.

Thus, increases in *scientific* information about weather and climate do not automatically create information that is of *economic* or *social* value. This implies that the mix of funded research projects could change over time depending on how considerations of economic value are weighed along with the scientific merits of earth sensing activities.

Reducing uncertainties results in enhanced benefits for:

- ***Improving civil government and military planning:*** Weather conditions have a major role in government planning for administering forests, grasslands, and other lands under federal management. Military operations, also, whether in war or peacetime, are affected by weather conditions. More accurate weather information reduces risk to personnel and gives them an information edge over adversaries. In peacetime, applying weather forecasts to logistics and field operations reduces operational costs by improving routing and timing of deliveries.
- ***Improving natural hazard mitigation, response, and recover****:* More accurate prediction of severe weather can help substantially reduce the costs to society of weather-related disasters. Better information induces governments, businesses, and individuals to invest in loss-reduction activities; it can also reduce economic costs from *unnecessary* loss-

reduction activities that derive from uncertainty about adverse weather (e.g., evacuations during hurricanes).

- ***Improving industrial planning:*** Reduced uncertainty translates directly into better use of scarce productive resources, as well as dampened fluctuations in prices and quantities of commodities affected by weather and climate.
- ***Hedging against uncertainty***. Providing better information about the probabilities of weather-related events also enables the emergence of specialized markets that help mitigate the economic and financial consequences of uncertainty, such as insurance, trading in commodities futures, and weather derivatives.

Estimating Socioeconomic Value

This study has examined a range of studies of the economic value of weather forecasts, concluding that savings and benefits are real, but extremely difficult to measure on a national or global scale. The best studies examine a component of an industry or sector, estimating economic value very narrowly. Since these studies have been done at different times by different researchers, using different methodologies, the results cannot be combined into one summary statistic. Nevertheless, these studies show in a general way the potential socio-economic value of investments in Earth science research.

Some studies have examined the value of short-term weather predictions, e.g.,

- Savings to oil drilling companies in the Gulf of Mexico from avoiding unnecessary drill rig evacuations could equal $18 million per year, given a 50% reduction in hurricane forecast error.
- Improved fueling decisions at Australian airports resulting from better forecasts could save companies some $6-7 million per year.
- More accurate short term forecasts can save U.S. agriculture an additional $40 million dollars per year in avoided irrigation costs.
- Improving short-term forecasts could result in marginal benefits of $500 million per year for electric energy and gas power producers.
- Better hurricane forecasts for the Atlantic Coast over the past 100 years have resulted in major reductions in yearly deaths from hurricane activity.

Other studies have focused on the effects of seasonal climatic change. For example, the worldwide socio-economic effects of El Niño and the Southern Oscillation (ENSO) can equal billions of dollars in a severe El Niño season. However, these effects can be positive as well as negative, requiring detailed analysis of their *net* benefits for any region and ENSO event.

Current and Foreseeable Improvements in Weather and Climate Predictions

Measurements from several new NASA instruments are well poised to contribute to improvements in weather and climate prediction. For severe weather conditions, especially, the additional information that synoptic, global satellite data provide, if properly integrated into appropriate forecast models and effectively communicated to the public, can save lives, reduce costs, and improve the quality of life in affected areas.

Most recently, several scientific studies show how data from NASA's TRMM and Quikscat research satellites can be incorporated into the weather forecasting process, improving knowledge of the paths and force of tropical cyclones and other severe weather. Some data products from future missions such as the NPOESS Preparatory Project (NPP), Global Precipitation Mission (GPM), and the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) will not only advance the science of global weather and climate research, but will also feed directly into operational forecasts.

Transforming Research Results into Valuable Information Products

As noted, the process of moving from research to useful applications is complex, involving various institutions. Unfortunately, U.S. science and technology institutional structures tend to treat the transfer process as a linear one, where the results of scientific research flow through a series of steps from basic research to an application generating socioeconomic benefits. In reality, the process generally incorporates multiple flow impedances and feedback loops. Hence, the *details* of this process are especially important, because small impedances in the process flow, when added up, can result in large barriers to implementation and great difficulty in providing the optimum type and quality of information to users.

NASA therefore faces a number of challenges in assuring that its research programs result in economic benefits to the U.S. economy. Not only is the process of knowledge transfer complex, but also many decisions regarding the *applications* of information derived from NASA's technology and research are out of NASA's direct control. They may reside either in other government agencies or in the private sector.

Findings

Our research reached a number of conclusions, the most important of which are summarized below:

Finding One: Although the marginal value of additional information in a given economic sphere may appear relatively small as a percentage, they may translate into very large potential economic effects. Because of the economic magnitude of sectors affected, the total socioeconomic effects of both short-term weather variations as well as long-term climate changes are very large. These effects are especially noticeable when measured on a regional or local level.

Finding Two: Information from NASA's Earth observations research and development provide significant scientific and research knowledge, but economic methodology and studies generally have not been adequate for measuring the value of this type of information.

Finding Three: Although large benefits have been associated with predictive capability for weather and climate, the value is dependent on the timeliness and appropriate use of the data. The potential for greater benefits depends not only on new research instruments and predictive capability, but also on the effective transmission of this information to end-users. Therefore, without sustained and persistent NASA involvement in the task of turning research into useful information, the transfer of knowledge and technology is not likely to be as successful as it could be.

Finding Four: NASA therefore has a major responsibility for assuring that promised economic benefits of Earth science research from space are actually achieved in practice. Infusing the results of NASA's Earth science research into useful applications and decision support tools will require NASA to work closely with other Federal, state, and local agencies. It will also require that NOAA, and other federal agencies making use of information products derived from this research focus more of their effort on ensuring that these products meet the needs of information consumers and that they are delivered in formats that fit the user's needs.

Recommendations:

1. **NASA should expend sustained resources on improving the two-way flow of information from the scientist to the application end user and back to the scientist.** The economic value of new data and information is effectively zero until the information is used productively in an application that actually brings economic benefit to an end user. Hence, NASA should focus on developing an integrated perspective concerning improvements in prediction, involving other agencies and institutions in the process.
2. **NASA should conduct a detailed analysis of the research to applications process for several specific cases, in order to achieve the best return on investment in Earth science research.** By understanding the details of the applications process more fully, NASA scientists could help design data products that are of greater utility to the modelers, the users of the models, and the customers of those users In other words, quantifiable socioeconomic benefits should be an intended part of the mission, not merely a residual outcome.
3. **NASA could improve the long-term economic value of its Earth science investments by investing a small percentage of each mission's funds on identifying potential future user communities and potential barriers to information transfer.** To reap these additional benefits from Earth science research, it will also be important for NASA to experiment with inserting new types of data into applied models during the research phase, such as has been done with the precipitation data from TRMM, and to ensure that if successful, the data stream will advance from research to operations.

The Socio-Economic Value of Improved Weather and Climate Information

INTRODUCTION

Over the past four decades of operation of Earth observation satellites, the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) have made considerable scientific progress towards improving the accuracy of weather and climate predictions.[1] These improved predictions have led to numerous social and economic benefits, including more effective management of energy resources; enhanced natural disaster planning, mitigation, and response; cost savings in aviation and many other industries affected by the weather; and in the effectiveness of the U.S. military. New and more sophisticated instruments on future observation satellites will continue the trend toward achieving a better understanding of Earth's climate which, in turn, will provide a basis for achieving additional socio-economic benefits, both in the United States and globally.

The data gathered from satellite observations are extremely important for understanding the biophysical mechanisms that generate changes in weather and climate. Yet scientific understanding is only the beginning of the process of developing socio-economic benefits from satellite data. The data must be analyzed, combined with information obtained from other sources, placed into appropriate models of the behavior of global weather and climatic conditions, and then disseminated at the right time in useable forms to individuals and organizations that can put the information to practical use. The paths from space data to decisions that generate economic benefits are complex and vary with each application. They also require myriad additional information linkages. At times, potential benefits are unrealized as a result of inadequate or untimely data transfers.

With support from NASA, the Space Policy Institute at the George Washington University has been engaged in an analysis of potential future benefits expected from the continued progress in weather and climate prediction over the next 25 years. An initial report[2] examined the use of such information for U.S. natural disasters. This final report of the project is based in part on a workshop the Institute convened in March 2002 in order to gain a better understanding of the possible scale of these benefits. The workshop brought together scientists, economists, emergency disaster managers, and policymakers to explore the scientific underpinnings of improved weather and climate predictions and how scientific results are translated into information useful to society (Appendix A).

The workshop focused on understanding the current state of the art in weather and climate prediction and the role that NASA's research satellites might play in the development of improved weather and climate predictions. We chose as examples the currently op-

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[1] Note: for purposes of brevity, in this report, "weather and climate" are generally grouped together, but the two phenomena follow wildly different time and spatial scales, and therefore present very different modeling and forecasting challenges.

[2] See for example, Ray A. Williamson, Henry R. Hertzfeld, Joseph Cordes, and John M. Logsdon, "The Socio-economic Benefits of Earth Science and Applications Research: Reducing the Risks and Costs of Natural Disasters in the USA," *Space Policy* 18: 57-65, 2002.

erating Tropical Rainfall Measuring Mission (TRMM) and the several planned future missions, including the Global Precipitation Measurement Mission (GPM), the National Polar-Orbiting Environmental Satellite System (NPOESS)[3] Preparatory Project (NPP), and the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) in order to examine the following important issues:

- What elements of weather and climate predictions can be improved most effectively using data from NASA/NOAA instruments and the vantage point of space?
- How is improved predictive information used to create socioeconomic benefits?
- What barriers are there to achieving significant benefits in the path from research to routine applications of new data to weather and climate prediction?

Lasting economic benefits accrue only from the use of the data.[4] Without a clear path from the "production" of the data to the consumer/end user of the information there is ample opportunity for data to be ignored, lost, or not used in a timely fashion to maximize their useful potential. Therefore, not only did the workshop focus on what data would be most valuable to users in the future, but also how the organization and coordination of the weather prediction system can provide a path for the maximum efficient use of new information.

A list of the economic sectors that would benefit in some way from better weather and climate information and forecasts would include virtually every sector and firm in business. It would also include families and individuals who base decisions about their everyday activities on the daily weather forecast. Such decisions range from which routes to choose for the workday to planning a weekend picnic. All have economic consequences for themselves, their employers, and for the businesses from which they purchase goods and services.

Not all industries are equally affected by weather; Table 1 below identifies some of the sectors that are most affected by weather and climate. Firms within these sectors attempt to mitigate weather-related variations by hedging their risks in futures markets, employing meteorologists, and otherwise investing time and funds in weather prediction.

Table 1: Representative Industries For Which Weather Predictions Have An Important Financial Impact

Major Industry	Examples of Specific Applications
Agriculture	• Crop management • Irrigation decisions • Prevention of weather-related diseases
Energy	• Planning purchases of gas and electric power • Managing responses in emergency situations • Managing capacity & resources
Aviation/Transportation	• Optimizing flight patterns • Reducing wait times on runways • Avoidance of sudden volcanic plumes
Tourism/Recreation	• Improving ski slope demand/production of artificial snow • Marine forecasts/warnings

[3] NPOESS is a joint program of NOAA, the Department of Defense, and NASA.

[4] Some economic activity is generated by the sale of data, which can also be an indicator of future use. But long-run productivity gains come from the benefits accrued from industrial, governmental, and consumer uses of data and information services.

Table 2 summarizes some of the uses of weather and climate data in the public sector. Often, the economic and social values of these uses are very difficult to estimate because they are spread throughout the economy and through a wide variety of entities, including local communities, families, and diverse businesses.

Table 2. Uses of Weather and Climate Data in the Public Sector and by Individuals

Entity	Examples
Federal, State, Local Government	• Managing public resources • Managing assistance programs • Managing disasters, emergencies • More efficient emergency evacuation • Reducing operational costs • Improving operational capacity and safety of U.S. military forces
Citizens	• Improving safety • Managing daily choice of activities • Improving quality of life • Reducing lives lost

Although the workshop focused primarily on weather and climate prediction, NASA is involved in generating data and information that are useful for predicting and mitigating the effects of other types of natural disasters such as earthquakes, volcanic activity, and the spread of vector-borne diseases. Improving the understanding of these types of natural events will assist in the development of better policies aimed at mitigating their effects, which will have a significant impact on the economy and on the way people live.

NASA has a major interest in reducing the negative effects of natural disasters in the United States. However modeling of weather and climatic conditions cannot be limited to one nation. Nearly all major weather and climatic changes can be traced to global phenomena, for which the vantage point of Earth-circling satellites is especially advantageous. Hence, NASA's employment of satellite sensors assists in understanding global changes,[5] which in turn lead to better predictions of local and regional weather patterns. Further, the development of weather and climate predictive tools also assists other countries to improve their ability to mitigate the destructive effects of natural disasters and to respond effectively. Many countries, especially the less developed ones, have much less access than the United States to these contemporary information tools.

THE VALUE OF INFORMATION AND KNOWLEDGE TRANSFER

Measuring the economic value of information from weather and climate research satellites is neither straightforward nor easy. The creation and distribution of accurate weather forecasts involves several elements, beginning with scientific research and continuing through to the delivery of information to government agencies, businesses, and consumers.

[5] Other information sources, of course, are equally important in this effort, but only satellite information can provide timely, uniform, and calibrated data on a worldwide basis.

The process can be viewed both over time (i.e. research results may precede actual use of information by end-users) and at a given point in time (the institutional system structure of information delivery). Measuring the value of information therefore requires evaluating a complex process and has typically only been attempted through studies of specific, isolated examples. It may not even be possible to develop a measure of the entire system.

The March workshop was designed to examine NASA's role in the process of turning Earth science research into socio-economic benefits for the American public. Yet workshop discussions ranged far beyond direct research impacts, covering downstream topics that feed back to the research effort and which are also instrumental in the process of integrating research information into economically useful products.

NASA's Earth Science Enterprise conducts fundamental scientific research into climate and weather phenomena and other Earth science topics. The output of this research is new knowledge about how Earth's complex biophysical systems function and how they interact with each other. Much of this knowledge will be useful in constructing more accurate weather and climate forecast models as well as directly assisting forecasting.

Benefits to society derive from public investment in increasing the amount and the quality of information about natural processes such as weather and climate. Increased scientific knowledge *per se* generates real benefits. For example, better observations of the geophysical processes that influence weather and climate help advance scientific knowledge directly, or indirectly by providing better data for calibrating scientific models and/or testing scientific hypotheses. However, despite considerable research on the topic, no accurate metrics exist that enable economists to determine *both* the quality and the future monetary value of economic benefits that may arise from acquiring new knowledge. Indeed, even the use of peer review and other methods of selecting future scientific missions cannot predict with accuracy the success of such scientific pursuits.

Reducing Uncertainty

Nevertheless, better information about weather and climate provides tangible socio-economic pay-offs that, at least in principle, lend themselves to quantification. These benefits derive from the fact that weather and climate information can help reduce uncertainty in several ways:

- **Improved Civil Government and Military Planning** Weather conditions have a major role in government planning for such tasks as administering forests, grasslands, and other lands under federal management. The 2000 fire in Los Alamos, New Mexico, provides an instructive example. In that case, a fire that was deliberately set by federal officials to reduce the load of dry underbrush raged out of control when the winds turned unfavorable. Better local weather forecasts of wind conditions[6] might have prevented the devastating effects of that fire, reducing or eliminating the severe social and economic effects of that experience. Weather forecasts at airports can reduce operational costs. A 1995 Australian study found savings of $6-7 million per year from improved fueling decisions.[7]

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[6] Keith Easthouse, "Park Service Unfairly Scapegoated for Los Alamos Fire," *Forest Magazine*, April 2001, accessed at http://www.forestmag.com/losalamosfire-update.cfm.
[7] Roy J. Leigh, "Economic Benefits of Terminal Aerodrome Forecasts (TAFs) for Sydney Airport, Australia," Meterological Applications, Volume 2, 1995, pp.239-247.

Military operations, whether in war or peacetime, are affected by weather conditions. The military services need accurate weather information in order to increase personnel safety and to gain an information edge over adversaries. Accurate weather forecasts can reduce operational costs by allowing commanders to make better decisions regarding movements and deployments of troops. For example, accurate information regarding winds, sea state, and ocean currents can enable ships to follow more cost effective courses than would be possible without such information.

- **Responding to Natural Hazards** The unexpected and severe flooding of the many major rivers in Europe and China in the summer of 2002 and the 1998 devastation of Central America from Hurricane Mitch serve as reminders of the potentially huge economic costs of natural hazards. Better prediction of weather and climate cannot reduce the likelihood that severe weather events will occur, but can help substantially lower the costs to society of such events. These cost savings come in two forms: 1) people are more likely to invest in loss-reduction activities when better information is available; 2) Better information can also reduce economic costs that arise when uncertainty about adverse weather causes government authorities, people, and business to "err on the side of caution" and undertake what later turn out to be unnecessary loss-reduction activities.
- **Improved Industrial Planning** Reducing uncertainty about weather and climate facilitates the process of planning in a variety of industrial sectors. More accurate predictions about future weather and climate enable farmers and agribusinesses to estimate future crop yields, leading to reduced uncertainty about yields and prices. In economic terms, such reduced uncertainty translates directly into better use of scarce productive resources, as well as dampening the fluctuations in prices of agricultural products. Similarly in the energy generation industry, improving the predictive ability of forecasts by an average of only one degree can result in more efficient use of power generating resources and mean hundreds of thousands of dollars saved each year for electric utilities.[8] Many utilities employ their own forecasters at a high annual cost because of these potential large savings. Airports use weather forecasts to reduce operational costs.
- **Insurance and Hedging Against Uncertainty** Finally, providing better information concerning the probabilities of weather-related events also enables the emergence of markets that help mitigate the economic and financial consequences of uncertainty. These markets, which allow the consequences of uncertainties to be "priced" in the form of insurance and hedge contracts, are able to function because information about weather and climate makes it possible to attach probabilities to uncertain events.

In each of these instances, however, new information has value only to the extent that more scientific information reduces uncertainty in ways that are economically valuable. In the case of planning for and responding to natural hazards, information about weather and climate will be valuable to the extent that: (1) having more information provides a measur-

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[8] NOAA, Geostationary Operational Environmental Satellite System (GOES)
GOES-R Sounder and Imager Cost/Benefit Analysis (CBA). Prepared for the GOES Users Conference 1-3 October 2002, Boulder, CO; accessed at: http://www.osd.noaa.gov/goes_R/goesrconf.htm, October 2002; Del Jones, "Forecast: 1 Degree Is Worth $1B In Power Savings," *USA Today*, June 19, 2001, Money. Note, though that other factors including political and regulatory actions can overshadow any savings from forecasts. For example, the wild fluctuations in price and energy availability in California over the past several years resulting from a policy of deregulation would make an economic analysis of separating out the price and efficiency effects of better forecasts very difficult.

able or significant reduction in uncertainty; and (2) reducing uncertainty "matters" in the sense that having more, or more reliable information has the potential to affect choices made by individuals, businesses, and government. Similarly, increased scientific knowledge about weather and climate by itself does not facilitate pricing in insurance and/or hedge markets if this information cannot be translated into the probability distribution of future weather events and then efficiently distributed to users.

Additional Considerations

These considerations suggest that increases in *scientific* information about weather and climate do not automatically or immediately create information that is of *economic* value. A direct implication is that the mix of funded projects could change over time depending on how considerations of economic value are weighed along with the scientific merits of earth sensing activities.

The value of weather and climate information itself has been shown to be relatively small as a percentage of the economy.[9] However, when dealing with weather and climate where each year billions of dollars and many lives are lost as a result of severe weather events, even a small improvement in predictive capability can add up to major savings.[10]

The value of information has particularly interesting qualities. Before information is released to potential buyers (ex ante), the value to a potential user of the information is not known. Information has economic value only when it is actually used. The transmission of information gained from analysis of data from the environmental satellites to end-users is complex and much information is ignored, lost, or not used. Even if information is disseminated in a timely fashion, sometimes the interpretation may not be clear and potential benefits will disappear. Who will ultimately pay for the information, how much will they pay for it, and what is the actual value of the information are all difficult to evaluate until after the information is obtained and actually used.

The unique character of information complications the analysis; after the information is released (ex post), the economic value of that information may be close to zero since the information is often not "protected" and is easily disseminated to virtually anyone at a very low cost. Therefore, measuring only the purchase price or sale of the information may result in a large under-valuation of its true worth to the economy.

The workshop presentations and discussion illustrated the difficulty of evaluating the socio-economic value of weather and climate information. One participant[11] attributed large dollar benefits (on the order of $10 to $15 billion per year, worldwide) to cost savings from weather and climate predictions. Others discussed the public-good value of the information

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[9] A good review of some of the economic issues in measuring the value of weather information can be found in: Macauley, Molly K., "Some Dimensions of the Value of Weather Information: General Principles and a Taxonomy of Empirical Approaches." The article can be found at: http://sciencepolicy.Colorado.edu/socasp/weather1/macauley.html, accessed March 2002.

[10] For a review of the magnitude of losses from extreme weather, see Tom Ross and Neal Lott, op. cit.; "Extreme Weather Sourcebook 2001," http://sciencepolicy.Colorado.edu/sourcebook/data.html. Other compilations can be found in Munich Re, "Natural Disasters 2000, Annual Review," Munich, Germany (also available as a CD-ROM); Arguez, A, and Elsner, J., "Trends in U.S. Tropical Cyclone Mortality During the Past Century," Florida State University, Tallahassee, Florida, April 11, 2001.

[11] Dr. Ants Leetma, Presentation at the Space Policy Institute Workshop on the Economic Value of Improved Weather and Climate Information, March 18-19, 2002.

in emergency planning for floods and hurricanes, as well as its application for industry, particularly the energy and utility sectors.

Participants also mentioned difficulties of both miscommunication and timeliness in delivering weather information to the end user. For example, during the North Dakota floods of 1997, officials in Grand Forks, ND interpreted the National Weather Service prediction of the flood crest level as a maximum level rather than a probable one within a range of possible levels. This contributed to less than adequate responses from local officials and substantial damage from the flooding river.[12]

Valuing information from weather and climate satellites and valuing the incremental improvements in predictive capability in future satellite systems is not only a question of the value of the science and knowledge of the earth and its climatic and weather phenomenon, but it is also closely tied to the process of how the information is transmitted, incorporated into forecast models, developed into predictions, presented to emergency planners and government officials, and finally used by the public. Measuring the value of the information implies assigning monetary totals to both cost savings and to actual demonstrated economic sales and benefits. Many of these calculations are "what ifs" and involve indirect estimation rather than presentation as normal economic metrics such as the Gross Domestic Product, employment or sales data. Further, many of the benefits are qualitative, relating to the value of human life, the improvement of well-being, and the myriad subtle benefits that individuals and business may enjoy.

Finally, the fact that weather and climate information can provide economically valuable benefits should not be confused with arguments for or against privatizing the creation and provision of some or all of such information. A defining aspect of most weather and climate information is that it is a "collective consumption" or a public good. Private market incentives are often inadequate to provide a socially desirable level of funding for goods of this type. Nonetheless, the fact that such information yields scientific, social,[13] and economic benefits and assists in providing for national security offer a clear rationale for public investment to maintain and enhance the capability to make available such information.

Economists who have studied public financing and public investments often pose a series of questions that attempt to determine how people would react to different economic conditions by asking how they would choose to allocate their funds. When asking about future expenditures (as compared to examining how people spent money in the past), a number of problems arise, the most obvious of which is that respondents are not required actually to commit their own funds to their choices. Examples of such questions include:

- What would you spend for tomorrow's weather forecast?
- What would you spend for a year's worth of weather forecasts?
- What would you spend for a more reliable weather forecast?

Or questions aimed at evaluating trivial or subjective values:

- What is it worth to you to take an umbrella to work, if there is a prediction of rain?
- What is the difference in your answer if you are wearing "wash-and-wear" clothes vs. a suit that might be ruined, or need to be dry-cleaned?

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[12] Roger Pielke, Presentation at the Space Policy Institute Workshop on the Economic Value of Improved Weather and Climate Information, March 18-19, 2002.

[13] Social benefits include collective benefits such as national security, public health, and public safety.

Or,

- How much time did you spend watching the weather forecast on TV?
- How much is that time worth to you?

One can also examine past expenditures and evaluate how people and companies have reacted to prior choices and to changing prices (possibly adjusted for quality differences over time). Studies of past trends are very useful and often quite revealing. However, past trends provide little guidance for extrapolations into the longer-term future because future conditions and technologies may be very different than we have previously experienced. This is likely to be the situation in long-term weather forecasting, since history has shown no good precedent for generating accurate long-term forecasts.

Another line of research relates to the discussion above of weather and climate forecasting as a public good. If we recognize that the U.S. government is going to perform weather research (and operate weather data and forecasting centers) indefinitely into the future for military, strategic, and public safety reasons, and if we also recognize that most of the data will be disseminated to the public at little or no cost, then there is only the question left of how much *additional* money should the government spend on improving civilian forecasts. Additionally, the question of how much money should be devoted to civilian weather and climate instruments on research satellites also becomes an important issue.

One way of approaching that question, which again leads to hypothetical models rather than real world spending decisions is to evaluate the alternative. That is, if there were no civilian spending on weather, what would the private sector response be? Would there be companies selling weather information? What type of research would they be doing? How much would a company devote to additional research?[14] What would be the role of space technologies in such systems? Who would be their clients and how much are people really willing to pay for the information?

Since we cannot put these questions to actual tests, we have to resort to proxy data that focus on the amount of losses suffered as a result of severe weather (both short and long term), and to make assumptions about human behavior in light of this information. Such value estimates that look back cannot lead to accurate forward-thinking answers to the value question. But, the information can lead to order-of-magnitude *potential* savings from better weather prediction that is coupled either with actual human behavior responses and/or government incentive programs to encourage more "rational" human behavior in light of better forecasts. (e.g., tax and zoning changes to discourage land development in known flood plains with histories of severe human life and property loss.)

In order to gain an understanding of the potential socioeconomic benefits from Earth science research it is also important to follow the complex chain of development from the research stage through to the delivery of information to the ultimate end user, whether a government office or the general public. The following sections examine the potential use of NASA's research findings in the development of better weather and climate predictions and explore the process from research to information of practical use.

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[14] Studies of other industries, including the communications industry, have shown that private companies rarely devote significant funds to basic research. One reason for the government's investment in the NASA's Advanced Communication Technology Satellite (ACTS) program during the 1990s was the perceived loss in U.S. leadership (and consequent loss of economic competitiveness) in communications research resulting from the pull-back in government funds for communications research in the 1970s and 1980s.

CURRENT AND FORESEEABLE IMPROVEMENTS IN WEATHER AND CLIMATE PREDICTIONS

Measurements from several new NASA instruments are well poised to contribute to improvements in weather and climate prediction. NASA is interested not only in conducting research to increase the scientific understanding of weather and climate but also in improving the ability to predict future weather and climate behavior for direct, practical benefits. Hence, where possible, NASA also supports the incorporation of data from its research missions into weather and climate computational models in an attempt to learn how to improve their quality and accuracy. In cooperation with NOAA's research and applications efforts, these thrusts are designed to create and augment social and economic benefits for the taxpayer.

Over the years, weather and climate forecasts have improved both in accuracy and forecast time-span in part because of the integration of satellite observations into forecast models. For severe weather conditions, especially, the additional information that synoptic, global satellite data provide, if properly integrated into appropriate forecast models and effectively communicated to the public, can save lives, reduce costs, and improve the quality of life in affected areas. NASA's Tropical Rainfall Measuring Mission (TRMM) provides an instructive example of how the process of moving from research to operational information products such as forecasts can work.

Tropical Rainfall Measuring Mission (TRMM)

We chose to focus on TRMM as an example because it is a current mission that is not only providing scientific insights into the complex physical processes of tropical cyclones but also producing data that can be incorporated into forecast models. Scientists have shown that the rainfall and other data from TRMM can improve not only the estimates of precipitation produced by tropical cyclone conditions, but can also contribute to improved predictions of the paths of cyclones as they approach the coastlines. Such information is of particular importance to the Southeastern U.S. coast, which experiences devastating hurricanes nearly very year. Over the last decade, the east coast of the United States has suffered total losses of about $58 billion from hurricanes and tropical storms alone, most of which occurred in the Southeast.[15]

The following paragraphs summarize the capabilities of TRMM and illustrate how data from the sensors aboard this satellite can be used to enhance weather and climate prediction. TRMM, which was launched in 1997 in a cooperative program with the Japanese space agency, NASDA, carries five instruments, including: the Precipitation Radar (PR), the TRMM Microwave Imager (TMI), and the Visible and Infrared Scanner (VIS). Appendix B summarizes the characteristics of these sensors and the atmospheric parameters they were intended to measure. The satellite flies in an inclined orbit of 35º in order to collect precipitation and other data in the Tropics, areas that are generally poorly covered by *in situ* measurements.

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[15] Tom Ross and Neal Lott *A Climatology of Recent Extreme Weather and Climate Events*, National Climate Data Center Technical Report 2000-02. October 2000; updated with information from 2000 and 2001 [http://lwf.ncdc.noaa.gov/oa/reports/billion/new-paper2x.pdf], accessed July 2002. Hurricane Andrew, which struck Florida in 1992 caused an estimated $27 billion in damage and associated costs.

- ***Tropical Cyclone Monitoring.*** Tropical cyclone position and intensity as the severe storms develop and move toward landmasses are of great interest not only for operational weather forecasters and scientists but also for local authorities that must prepare themselves and the affected public for the potential onslaught of the storm. Typically, authorities err on the side of caution when issuing warnings and evacuation orders because under-warning risks serious economic damage and possible loss of life. If their advice proves incorrect during the storm, authorities risk severe criticism after the fact. However as noted above, over-warning also carries certain costs. Estimates of the cost of evacuation can reach as high as $1 million per mile of coastline.[16] Hence, improved accuracy in the forecasts of the path and intensity of tropical cyclones would potentially assist local authorities reduce evacuation and preparation costs. Hawkins, et al.,[17] have shown that data from the TRMM Microwave Imager (TMI), can improve the ability of scientists to understand the structure and of tropical cyclones and how they change with time. Passive microwave can see through non-raining clouds, permitting meteorologists to identify and follow cyclonic features such as rainbands, eyewalls, and eyes, which are critical for estimating the intensity of tropical cyclones. Because these images also allow forecasters to view the eye and eyewalls of the hurricane with greater accuracy, they contribute to improved tracking accuracy.

  Delivering data to the forecast models quickly and efficiently after sensor acquisition is an important component of forecasting the location and intensity of tropical cyclones. Hawkins, et al., have developed image products derived from TMI sensor data combined with data from the SSM/I sensors aboard the two Defense Meteorological Satellite Program (DMSP) polar-orbiting satellites. They are able to make them available to forecast modelers within 1 to 3 hours of the TRMM satellite passing over the tropical cyclone.

  Additionally, research reveals improved hurricane track forecasts in large-scale and mesoscale forecast models when TRMM rainfall data are assimilated into the model.[18] Also, the TRMM Microwave Imager can detect cold sea-surface temperatures (SST) that significantly affect the process of hurricane intensification. Typically, infrared SST retrieval from the AVHRR[19] sensor aboard NOAA's POES satellites is ineffective in the cloudy environment of hurricanes. Finally, the U.S civilian (National Hurricane Center) and military (Joint Typhoon Warning Center) centers now routinely employ TRMM data in operational forecasts and decision-making processes.

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[16] The value of $1 million per mile is often quoted, yet we have not found a definitive study that confirms or denies this value. A study of the evacuation costs of Hurricane Bonnie in the affected counties of North Carolina reached the conclusion that: "hurricane evacuation costs for ocean counties in North Carolina range from about $1 million to $50 million depending on storm intensity and emergency management policy. Considering that North Carolina has much more than 50 miles of coastline, "one million dollars per mile" is a gross overestimate of the opportunity costs of evacuation." John C. Whitehead, "One Million Dollars Per Mile? The Opportunity Costs of Hurricane Evacuation," http://www.csba.uncwil.edu/people/whiteheadj/research/Papers/Evacuation%20costs.pdf

[17] Hawkins, J. D., T. F. Lee, K. Richardson, C. Sampson, F. J. Turk, and J. E. Kent, "Real-Time Internet Distribution of Satellite Products for Tropical Cyclone Reconnaissance," *Bulletin of the American Meteorological Society*, Vol. 82, 4, 567-578, 2001. See: http://kauai.nrlmry.navy.mil/sat-bin/tc_home.

[18] Arthur Y. Hou1, Sara Q. Zhang, Jui-Lin Li, and Oreste Reale, Better Weather Prediction and Climate Diagnostics Using Rainfall Measurements From Space." Presented at the 83rd Annual Meeting of the American Meteorological Society, February 2003. Accessed at http://ams.confex.com/ams/annual2002/Observations/abstracts/27308.htm

[19] AVHRR: Advanced Very High Resolution Radiometer

- ***Improving Global Analysis and Short-Range Forecasts.*** The rate, distribution, and total amount of precipitation are crucial inputs to short-range forecast models. However, until the data from TRMM were available, operational forecasters and scientists had relatively limited knowledge of precipitation distribution and variability in the Tropics and over the oceans, where approximately 67% of global rainfall occurs. Precipitation directly affects cloud generation and large-scale atmospheric motions, indirectly influencing the distribution of moisture in Earth's atmosphere. Improvements in short-range forecasts thus depend on assimilating better precipitation into forecast models. Hou, et al.,[20] have shown that data from the TRMM TMI sensor, when combined with similar data from the SSM/I instruments aboard the DMSP satellites and inserted into forecast models, can improve the accuracy of their forecasts.

  Improved forecasts can provide coastal communities more accurate warning of the amount and intensity of rainfall they are likely to receive, allowing emergency managers to evaluate flood risks using hydrological models of the area. Rainfall data from imagery provided in real time would be extremely important for updating flood information as river levels rise (see flood prediction case study below).

These results not only provide crucial information for follow-on missions such as the Global Precipitation Measurement mission, but also suggest that data from research missions can be successfully incorporated into forecast models in advance of the development of operational sensors that might be developed as a result of such research. This is an important step in the transition from research to applications to useful information. Nevertheless, forecasters may be reluctant to incorporate new data sets fully into operational models until they are confident that they can count on routine delivery of the data.

Quikscat Scatterometer

Surface wind speed and direction near the ocean surface are also important inputs to weather forecast models. Such data are sparse in many parts of the world, especially over the oceans. In June 1999, NASA launched the Quikscat satellite into polar orbit, in order to acquire all-weather, high-resolution, global measurements of near-surface ocean winds.

The Seawinds scatterometer aboard Quikscat has proved valuable in tracking wind speed and direction over the oceans, providing data especially from regions where other measurements are few and far between, both in time and space.[21] These data, when assimilated into predictive models, have already contributed to improved predictions of the onset of severe weather. For example, Cobb, Brown, and Molleda[22] have shown that these data can be used

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[20] Arthur Y. Hou, Sara Q. Zhang, Arlindo M. da Silva, William S. Olson, Christian D. Kummerow, and Joanne Simpson, "Improving Global Analysis and Short-Range Forecast Using Rainfall and Moisture Observations Derived from TRMM and SSM/I Passive Microwave Sensors," *Bulletin of the American Meteorological Society*, Vol. 82, No. 4, pp. 659-679.

Shannon R. Davis, Mark A. Bourassa, Robert M. Atlas, J. Ardizzone, Eugenia Brin, Dennis Bungato, , and James J. O'Brien, "Wind and Sea Surface Pressure Fields from the , Presented at the Joint Poster Session between the 12th Conference on Satellite Meteorology and Oceanography and the 12th Conference on Interactions of the Sea and Atmosphere, Long Beach, CA February 2003 Accessed at: http://ams.confex.com/ams/.

[22] Hugh, D. Cobb, III, Daniel P. Brown, and Robert Molleda, "Use of Quikscat Imagery in the Diagnosis and Detection of Gulf of Tehuantepec Wind Events, 1999-2002. Presented at the Joint Poster Session between the

to predict the advent of storm force winds across the Isthmus of Tehuantepec in Mexico. Sharp, Bourassa, and O'Brien[23] have used Seawinds data to assist in the early detection of tropical cyclones in the Atlantic hurricane basin.

In January 2002, the United States and Europe incorporated Quikscat data on wind speed and direction into their operational global weather analysis and forecast systems.[24] In 2003, the use of data from Quikscat will be enhanced by the December 14, 2002 launch of an additional U.S. Seawinds instrument aboard the Japanese Adeos-2 spacecraft.[25] In addition to Seawinds, Adeos-2 carries the Advanced Microwave Scanning Radiometer (AMSR), the Global Imager (GLI), the Improved Limb Atmospheric Spectrometer-II (ILAS-II), both from Japan, and the European Polarization and Directionality of the Earth's Reflectances (Polder). Each of these instruments will contribute detailed knowledge of Earth's weather and climate. In addition to Seawinds data, measurements from several of these instruments may find their way into operational forecasts.

Global Precipitation Measurement (GPM)

Along with temperature and wind, precipitation is one of the most important weather prediction variables. GPM is a future NASA mission currently under formulation that will extend the geographic scope of precipitation measurements and improve their quality compared to its predecessor, TRMM. NASA scientists expect GPM data to contribute to improved accuracy of climate, weather, and precipitation forecasts by making accurate measurement of rain rates and latent heating of the atmosphere. Both are key inputs to forecast models. GPM will also provide more frequent and complete sampling of precipitation than now exists. The information regarding precipitation can be fed into hydrological models, making possible better flood prediction and assisting in the management of agricultural and other activities that depend upon the supply of fresh water.

GPM will employ a constellation of 8 to 10 satellites carrying active (dual frequency radar) and passive microwave instruments. With goals of improving climate, weather, and hydrologic prediction, GPM seeks to achieve near global coverage at short time scans (~order of 3 hours). The mission also involves a comprehensive ground calibration-validation program and data distribution system.

NPOESS Preparatory Mission (NPP)

NPP is under development by the NPOESS Integrated Program Office (IPO) as a precursor to the NPOESS satellites planned for launch later in the decade. The IPO plans to launch NPP in December 2005. The office, which draws personnel from NOAA, NASA, and the Department of Defense, expects the sensors to reduce technical and program risk for the operational NPOESS satellites. In addition, data from the satellite can be used to provide improvements in weather and climate forecast models. NPP instruments include: the Visible/Infrared Imager/Radiometer Suite (VIIRS), the Cross Track Infrared Sounder (CrIS) and

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12th Conference on Satellite Meteorology and Oceanography and the 12th Conference on Interactions of the Sea and Atmosphere, Long Beach, CA February 2003. Accessed at: http://ams.confex.com/ams/.

[23] Ryan. J. Sharp, Mark A. Bourassa, and James J. O'Brien, "Early Detection of Tropical Cyclones Using Seawinds-Derived Vorticity, *Bulletin of the American Meteorological Society*, Vol. 83, No. 6, pp. 879-889, June 2002.

[24] NASA Quikscat web site: http://www.winds.jpl.nasa.gov/missions/quikscat/quikindex.html.

[25] ADEOS II was launched aboard a Japanese HIIA.

the Advanced Technology Microwave Sounder (ATMS). Appendix C contains a brief description of these sensors.

In particular, NPP will provide the IPO with new data that it can use to prepare and validate algorithms and ground processing for the three instruments. Data products from these instruments will feed research on new forecast models and allow forecasters to provide feedback to the IPO concerning data algorithms. NASA will receive data from NPP to extend many of the observations begun by its EOS TERRA and Aqua satellites for: atmospheric temperature and humidity sounding, sea surface temperature, land and ocean biological productivity, and cloud and aerosol properties.

Data from this satellite will contribute to better forecasts of the paths and strengths of tropical cyclones. When combined with precipitation data from TRMM or later from GPM, these data will significantly increase our knowledge of these damaging storms, potentially saving millions of dollars for industries that are especially affected by them. For example, recent research by Dr. Tim Considine on the costs of evacuating energy production platforms in the Gulf of Mexico has suggested that achieving a 50% reduction in hurricane and tropical storm forecast error would save producers about $18 million annually. A perfect forecast could lead to savings between $225 million and $275 million, illustrating the non-linear nature of forecast value in this case. For energy producers in the Gulf, averting the risk of losing lives is generally more important than saving short-run operations costs. The costs of evacuation from a platform are much lower than the perceived costs of loss of life. If "losses are perceived to be very substantial, producers will always take preventive action regardless of evacuation costs."[26]

Geostationary Imaging Fourier Transform Spectrometer (GIFTS)

Operational satellites such as NOAA's GOES series provide a strong foundation for sensor improvements that would lead to better forecasting capabilities. GIFTS is a collaborative technology project of NASA, NOAA and the US Navy designed to obtain sounding data on tropospheric winds and temperature, water vapor, and composition at high spatial and spectral resolution. NASA will develop the instruments for demonstrating the measurement concept for sounding of the troposphere from geosynchronous orbit and validate the supporting technologies; the NAVY will provide GOES-like imaging data products to support fleet operations; and NOAA will demonstrate the operational utility of the data and infuse the resulting technology into NOAA operational instruments. The team will first place the GIFTS satellite above the continental United States to validate the observations in comparison with GOES West and East satellites. After a year it will be shifted to the Indian Ocean to support fleet operations, where high-quality weather data are currently sparse.

The GIFTS development team expects the satellite to contribute to major improvements in the spatial, spectral, and temporal resolution of observations, which will lead to major improvements in the timeliness and accuracy of short-term weather forecasts. If the experience with GIFTS proves successful, NOAA plans on inserting this technology into the GOES-R series of geostationary environmental satellites.[27] NOAA officials believe that the GIFTS' contribution to GOES-R will lead to additional economic benefits. A study carried

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[26] Timothy Considine, Christopher Jablonowski, and Barry Posner, "The Value of Hurricane Forecasts to Energy Producers in the Gulf of Mexico," Discussion Paper, Resources for the Future, November 2002. Accessed at http://www.rff.org.

[27] GOES-R is planned for launch in 2012. See http://www.osd.noaa.gov/goes_R/

out by Mitre in support of GOES-R development found significant marginal economic benefits as a result of the increased capabilities of GOES-R compared to the current series (Table 3).[28] Although benefits to the public sector are much harder to quantify, public sector weather and climate information consumers are expected to benefit substantially from improved GOES-R data.

Table 3. Estimated Marginal Benefits from Future GOES-R Satellite Data

Industry	Total Yearly Savings
Agriculture: • Orchard frost mitigation ($9 million) • Irrigation efficiency ($41 million)	$50 million
Utilities: • Electric power fuel cost reduction ($479 million) • Natural gas ($7-$28 million)	$486-$507 million
Commercial aviation: • Avoiding weather induced delays • Avoiding volcanic ash in-flight	$41 million
Commercial trucking:	$28-$56 million
Recreational boating:	$86-$130 million

TRANSFORMING INFORMATION FROM RESEARCH TO VALUABLE PRODUCTS

Prospective consumers of improved weather and climate predictions often fail to realize the potential value of scientific and technological improvements because the process of transferring basic scientific knowledge into practical applications contains many hurdles, both small and large.[29] These include mismatches between institutional practices and cultures, technical impediments, and the costs of assimilating new, more capable data sets into predictive models. Further, even when the various processes work smoothly, they are generally not well understood by all participants, which reduces the prospects for realizing expected benefits and of effective planning for process improvements.

U.S. science and technology policy and the resultant institutional structures tend to treat the transfer process as a linear one, where the results of scientific research flow through a series of steps from basic research to applied research, to technology development to an application generating socioeconomic benefits (Figure 1).

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[28] NOAA, Geostationary Operational Environmental Satellite System (GOES)
GOES-R Sounder and Imager Cost/Benefit Analysis (CBA). Prepared for the GOES Users Conference
1-3 October 2002, Boulder, CO; accessed at: http://www.osd.noaa.gov/goes_R/goesrconf.htm, October 2002.

[29] National Research Council, *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death*, (Washington, DC: National Academy Press, 2000).

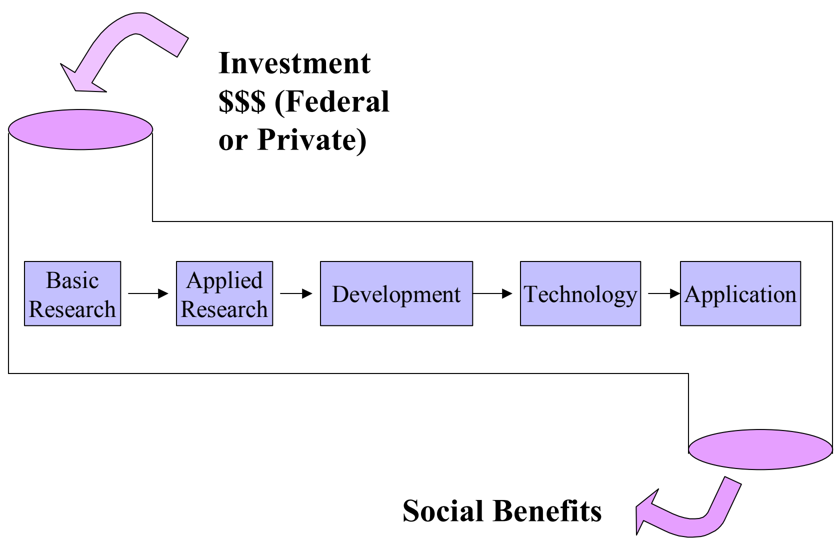

Figure 1. The Typical Image of the R&D Pipeline Model that Guides U.S. R&D Policy.[30]

In reality, the process is much more complex, with multiple flow impedances and feedback loops along the way (Figure 2). For example, one version of the weather forecasting process (Figure 3), illustrates numerous feedback loops and complex interactions. The *details* of this process are especially important, because small impedances in the process flow, when added up, can result in large barriers to implementation and great difficulty in providing information consumers with the type and quality of information they require.

[30] Source: Roger A. Pielke, Jr.

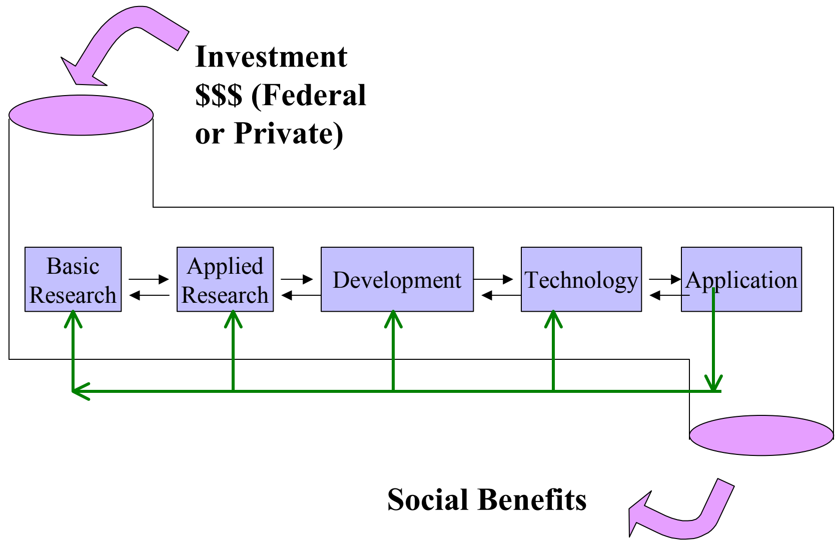

Figure 2. The Interactive R&D Pipeline

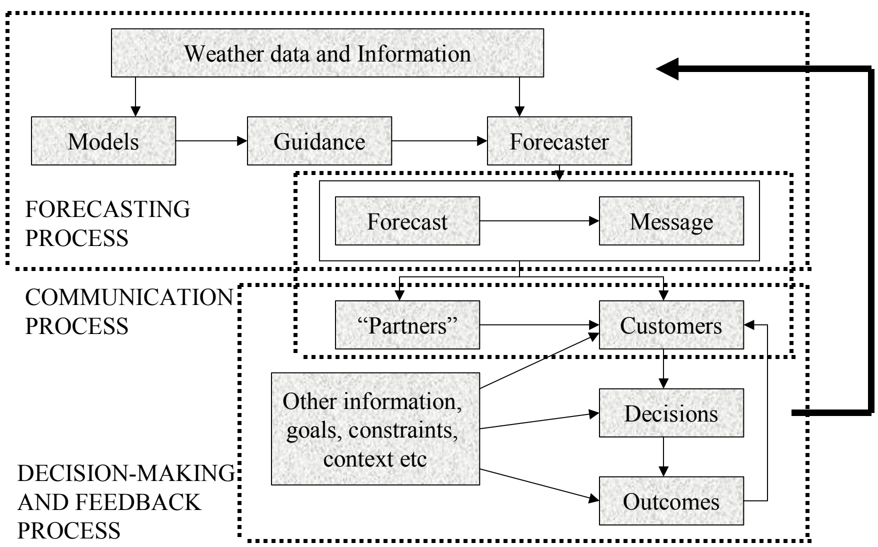

Figure 3. The Weather R&D Pipeline[31]

NASA therefore faces a number of challenges in assuring that its research programs result in economic benefits to the U.S. economy. Not only is the process of knowledge trans-

[31] Source: Roger A. Pielke, Jr.

fer complex, but also many decisions regarding the applications of information derived from NASA's technology and research results are out of NASA's direct control. They may reside either in other government agencies or in the private sector. In many ways, this is a classic case of understanding and improving the complex process of technology transfer.

This section illustrates the process of turning research results into useful information to support decision making for three subjects: hurricanes, flooding, and the effects of ENSO on agricultural production. In each case, the use of satellite data has increased the ability of governmental authorities and citizens to mitigate the potential negative economic effects of weather patterns. These broad-brush accounts are meant to illustrate both the promise inherent in using satellite data and the scope of the challenge of creating useful information out of the results of scientific research. Detailed examination of all the steps in the process is beyond the limited scope of this study.

Flood Management

Each year, floods resulting from heavy rainfall in the United States alone cause an average $4.8 billion in direct and indirect economic damage,[32] displace thousands of individuals from their homes and businesses, and cause numerous deaths. Better knowledge of the amount and spatial distribution of rainfall over an area, and detailed knowledge of the affected terrain would allow local and regional authorities to predict which areas are most at risk and to institute plans for mitigating the effects of flooding.

The prediction and management of impending flooding is a particularly salient case because it potentially involves satellite data from many different sources as well as data from aircraft and ground based sensors. Figure 4 illustrates a watershed management model developed by the Committee on Earth Observation Satellites (CEOS) Disaster Management Support Group flood team.[33] Tables 4 and 5 provide lists of inputs from satellite-based sensors to this model. Implicit in the model and not shown are: 1) the data from POES, GOES, and TRMM necessary to develop precipitation estimates and 2) the various feedback mechanisms in each step that substantiate and improve the information flow between steps. It is these feedback mechanisms that must be understood and strengthened if such a model is to be successful in use. Additional flow diagrams would be necessary to illustrate the steps in moving from research instruments such as TRMM or the future GPM to operational instruments capable of assuring long-term continuity of data delivery.

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[32] Average from 1980 – 2000 (2001 dollars). See Roger A. Pielke, Jr., Mary W. Downton, and J. Zoe Barnard Miller, Flood Damage in the United States, 1926-2000, accessed at http://www.flooddamagedata.org, Sept. 2002.

[33] T. J. Pultz and R.A. Scofield, "Applications of Remotely Sensed Data in Flood Prediction and Monitoring: Report of the CEOS Disaster Management Support Group Flood Team," presented at IGARSS 2002, Toronto, CA, June 2002.

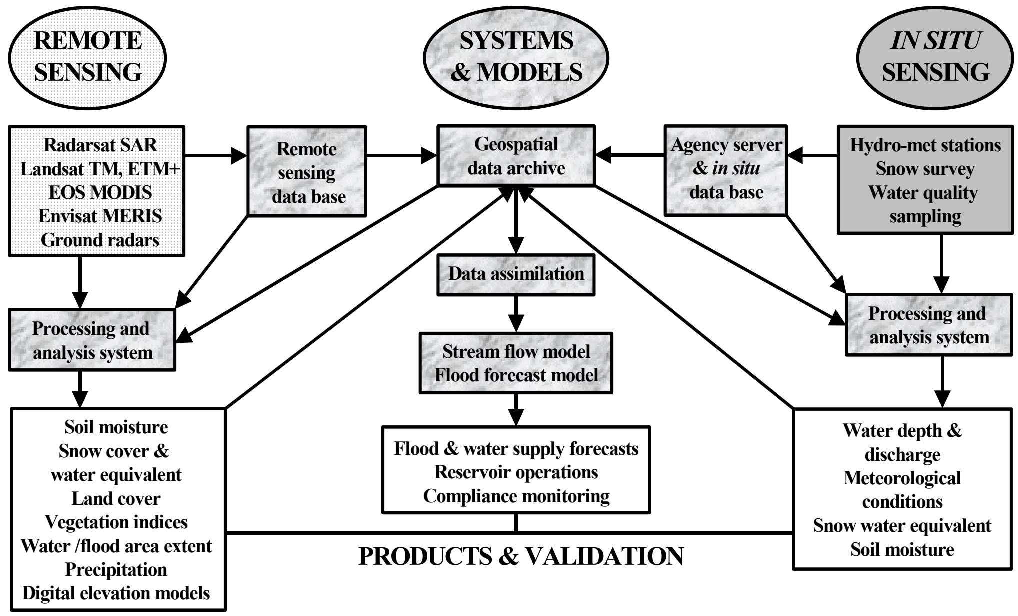

Figure 4. CEOS Flood Management Model

Table 4. Remote Sensing Inputs to Flood Prediction
• Prediction of floods through Numerical Weather prediction Models that produce Quantitative Precipitation Forecasts (QPF) • QPF can be inserted into hydrological models to predict river flows and crests • Precipitable water products for assessing the atmosphere with respect to the magnitude of the moisture and its transport • Soil Moisture Maps • Land cover Maps • Snow cover Maps • Digital Elevation Models • Flood Risk Maps SOURCE: Pultz, et al.

Table 5. Remote Sensing Inputs to Monitoring and Assessment

• Estimation of precipitation amounts through Quantitative Precipitation Estimation (QPE) Algorithms
• QPE can be inserted into hydrological models to predict river flows and crests
• NOWCASTS --- 3 hour outlooks of precipitation
• Ground or Space based weather radar
• Estimation of flood extent using SSM/I, NOAA, high-resolution imagery, SAR (RADARSAT, JERS, ERS), SPOT, LANDSAT.
• Damage Assessment
  - High resolution for local assessment
  - Low to moderate resolution for regional assessment
SOURCE: Pultz, et al.

This model, which, if successful in practice would save lives and reduce economic losses, has not yet been put into practice. Nevertheless, it illustrates the complexity of creating viable decision-making tools for complex Earth systems. Each required data set, whether derived from sensors based on satellites or other platforms, must undergo its own complex transfer from research to applications and must be tailored to a specific use in the system. Further, the development and implementation of such a decision support tool requires interacting and coordinating with a number of different state agencies. Finally, for the system to provide benefits, the ultimate users must understand not only what they could gain from using it, but also the limitations inherent in its use to monitor flood conditions. For example, what errors do predictions produced by the models carry? How should information users interpret the predictions and the range of errors? What feedback mechanisms are available for reducing or correcting errors?

Preparing For and Responding To Hurricanes

As noted earlier, satellite data from several instruments make a major contribution to the delivery of more accurate, timely hurricane forecasts (Table 6). Satellite data also have a crucial role to play in mitigating the damaging effects of hurricanes and in responding to and recovering from hurricane damage (Table 7). For example, digital elevation models, coupled with land cover information and estimates of storm force, allow modelers to estimate the force and extent of storm surge along the coast.[34] Remotely sensed satellite data, coupled with other geospatial data and tools and storm surge models, have recently demonstrated that New Orleans would suffer incalculable losses of life and property from a category 5 storm unless federal and state authorities are able to alter the local landscape to mitigate such damage.[35]

Table 6. Satellite Contributions to More Accurate, Timely Hurricane Forecasts

Satellite Instrument	Measurement	Utility
TRMM TMI and PR*	Precipitation rate and distribution	Improved rain estimates, flood warnings
Quikscat*	Surface winds speed and direction	Improved storm force estimates, track predictions
GOES	Precipitation rate and distribution	Storm size, movement, intensity
POES	Precipitation rate and distribution	Storm structure, motion, direction

*Research instrument

[34] LiDAR-derived digital elevation models (from aircraft instruments) of Broward County, Florida have allowed the county to avoid significant evacuation costs during severe hurricanes by reducing the required evacuation area. Ray A. Williamson, Henry R. Hertzfeld, Joseph Cordes, and John M. Logsdon, "The Socio-economic Benefits of Earth Science and Applications Research: Reducing the Risks and Costs of Natural Disasters in the USA," *Space Policy* 18: 57-65, 2002.

[35] Jon Nordheimer, "Nothing's Easy for New Orleans Flood Control," p. 1, *New York Times, Science Times* (Sec. F), April 30, 2002, Tuesday.

Table 7. Satellite Contributions to Mitigation, Response and Recovery of Hurricane Damage

Satellite Instrument	Measurement	Utility
Landsat Thematic Mapper, SPOT	Land cover, flooding extent	Flood modelling, recovery planning
Quickbird, Ikonos	Damage type, extent; detailed digital elevation model	Insurance estimates, detailed cleanup planning
Shuttle Radar Topographic Mapper	Digital elevation model	Storm, flood modeling
Radarsat	Flooding extent	

El Niño and the Southern Oscillation (ENSO)

The changes in temperature and precipitation caused by ENSO lead to significant losses *and* benefits for various regions. Among other things, this interannual climate swing is responsible for a significant level of uncertainty in the prediction of long-term weather patterns. Hence, U.S. and global climate research has focused considerable attention, not only on a deeper understanding of the biophysical mechanisms behind ENSO, but also on the ability to predict ENSO effects. Scientists have also studied the social and economic effects of ENSO around the world in considerable detail.

The climate research community has made significant progress in the past decade on understanding the physical relationships between the warming or cooling of the ocean along the western coast of South America and changes in weather patterns elsewhere in the world. This understanding, coupled with data from several satellites, has led to an improved ability to predict the return of El Niño, which can then be used to alert weather sensitive industries around the world that they may face increased risk of experiencing abnormal weather phenomena in their regions.[36]

Although economists have examined the costs and benefits of ENSO on the U.S. economy, they have not quantified the socioeconomic benefits of better forecasts. Nevertheless, it is clear that learning to predict accurately the onset of El Niño and its sister phenomenon La Niña, can have a major economic impact. Table 8 summarizes one analyst's estimates of the socioeconomic gains and losses from the El Niño of 1997-'98. Although the media and even formal reports on ENSO effects tend to focus on the occasional large losses caused by the phenomenon, as Table 8 indicates, the overall benefits of a given event can outweigh the losses. Similar charts for other regions might show a different picture, with greater losses than gains. Whether net gains or losses are at stake, however, better knowledge of the timing and strength of the ENSO cycle would assist governmental policymakers and private sector investors to capitalize on the benefits of this important interannual climate cycle and reduce the risk of losses.

[36] Richard A. Kerr, "Signs of Success in Forecasting El Niño," *Science*, 297: 497-98, 26 July 2002; Dake Chen, "Applying Satellite Remote Sensing to Pridicting 1999-2000 La Niña," *Remote Sensing of the Environment,* 77, pp. 275-278, 2001.

TABLE 8 - 1997-1998 ENSO COST-BENEFIT TALLY[37]

	SOURCE	ESTIMATED AMOUNT
LOSSES	• Property Losses	• $2.8 billion (insured losses were $1.7 billion)
TOTAL LOSSES • Human lives lost = 189 • Economic losses and costs = $4.2-$4.5 billion	• Federal government relief costs • State costs • Agricultural losses • Lost sales in housing and snow-related equipment • Losses in the tourist industry	• $410 million • $125 million • $650-700 million • $60-80 million • $180-200 million
SAVINGS/BENEFITS	• Reduced heating costs	• $6.7 billion
TOTAL GAINS • Loss of human life avoided = ~850 • Economic Gains = $19.6-$19.9 billion	• Increased sales of merchandise, homes, and other goods • Reduced costs for snow/ice removal from roads • Reduction in normal losses because of the lack of snowmelt flood and Atlantic hurricanes • Income from increased construction and related employment • Reduced costs to airline and trucking industry	• $5.6 billion • $350-400 million • $6.9 billion • $450-500 million • $160-175 million

Potential International Benefits of Earth Science Research

Although the United States will benefit significantly from improved weather and climate prediction, and the ability to follow the development of severe storms in real time, the rest of the world will receive even greater total economic benefit from such improvements. Table 9 summarizes the immediate economic damage and recorded deaths for Hurricane Mitch, which swept across Central America in November 1998. However, these figures do not reveal the subsequent long-term losses from damaged agricultural production, or the displacement of residents. This admittedly extreme example of a low-probability event[38] nevertheless illustrates the potential severity of damage in some developing countries. Table 10 summarizes losses sustained in Southeast Asia during the floods of 2000.

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[37] Changnon, Stanley A, *El Nino 1997-1998:The Climate Event of the Century*, Oxford University Press, 2000, pp 144, 149, 152.

[38] Category 5 Hurricane Mitch was the worst such storm to hit Central America since Hurricane Fifi struck Honduras in 1974.

Table 9. Estimated Deaths and Damage Costs from 1998 Hurricane Mitch

Country	Deaths	Damage Costs
Honduras	6500	$4 billion
Nicaragua	3800	$1 billion
El Salvador	239	Not available (NA)
Guatemala	256	NA
México	9	NA
Costa Rica Jamaica Panama U.S.	7 3 3 1	NA

Source: http://lwf.ncdc.noaa.gov/oa/climate/severeweather/extremes.html

Table 10. Southeast Asia Floods of 2000

Country	Human Impact	Aid (2000$)	Donors
Bangladesh	3 million affected, 23 confirmed deaths	1,044,120	USAID/OFDA, CARE, World Vision
Cambodia	2.2 million affected, 252 deaths	2,014,199	USAID/OFDA, USAID/FFP, ARC, IFRC, CARE, World Vision, Partners for Development, CONCERNS Worldwide, WFP
Laos	400,000 affected	25,000	US Embassy
Vietnam	5 million affected; 450 deaths	697,645	USAID/OFDA, DOD,

In both these cases, most of the loss of life and a significant percentage of the economic losses could likely have been avoided with better advanced planning and mitigation using geospatial information and weather predictions supported by satellite data products. For example, in the case of Hurricane Mitch, landslides and severe flooding caused much of the damage and loss of life. Many of these conditions can be mitigated using modern geospatial tools and modeling to assess the potential risk, prepare plans to reduce it, and implement these plans. However, few developing countries have the basic infrastructure and trained personnel to use such tools effectively. Further, they lack the resources to develop them and often lack the ability quickly to initiate appropriate action.

In the international community, the challenge will be to involve the international funding agencies in supporting the development of decision support tools appropriate for local use and to train a cadre of personnel to apply them. Such tools need to be focused on the needs of local communities and understood by local leaders. Many of the fixes, such as avoiding construction on steep, denuded slopes, or in flood plains are fairly obvious, but providing analytical methods to demonstrate the potential danger would assist local officials in correcting destructive land use practices. Correcting these practices will also require significant outside investment coupled with the political and financial ability of local governments to plan and implement significant changes in the long term.

RECOMMENDATIONS

As noted above, both workshop participants and other experts we queried concurred that the benefits from Earth science research, though extremely difficult to quantify, were likely to be high, especially in preparing for and responding to the effects of natural disasters. NASA's primary role in the process of gaining socioeconomic benefits for the nation is to pursue the basic science that underlies future benefits. Yet, without sustained and persistent NASA involvement in the task of turning research into useful information, the transfer of knowledge and technology is not likely to be successful. Workshop participants therefore noted that NASA has a major responsibility for taking the lead in assuring that promised economic benefits of Earth science research from space are actually achieved in practice.

Infusing the results of NASA's Earth science research into useful applications and decision support tools will require NASA to work closely with other Federal, state, and local agencies. It will also require NOAA, and other federal agencies making use of information products derived from NASA's Earth science research, to focus more of their effort on assuring that these products meet the needs of information consumers and that they are delivered in formats that fit the consumer's needs.

Several recommendations have emerged from our research:

1. **NASA should expend sustained resources on improving the flow of information from science to the end user in an application.** The economic value of new data and information is effectively zero until the information is used productively in an application that actually brings economic benefit to an end user. Hence, NASA should focus on developing an integrated perspective concerning improvements in prediction.

   Because the process of moving from research to applications is essentially an interactive process, it will be important for NASA scientists to look outward to other agencies and institutions for their expertise and wisdom in applying NASA's research. This will require NASA scientists to understand enough of the vocabulary and information needs of other groups in order to prepare their data products for employment in routine applications. Success in achieving expected benefits will ultimately depend on continued close collaboration and each agency's ability to follow through in its special role.

2. **NASA should conduct a detailed analysis of the research to applications process for several specific cases, in order to achieve the best return on investment in Earth science research.** Under business as usual, NASA generally hands off data and data products from its instruments to the operational users after the scientific objectives of the mission are met. Then it is up to the operational users to explore their use in predictive models. However, by understanding the details of the applications process more fully, NASA scientists could help design data products that are of greater utility to the modelers, the users of the models, and the customers of those users (e.g., see Figure 3). In other words, quantifiable socioeconomic benefits should an intended part of the mission, not merely a residual outcome.

What are the feedback loops in the process? How are improvements incorporated into the process? How can the process be improved? Whose responsibility are the different steps in the process? NASA could examine in detail a few high economic or social value applications for potential savings and increased output. In addition NASA and all of the other government agencies involved in the flow of information to the various government and private sector end-use customers of weather predictions should encourage continuous dialogue with those users to insure that the products are as nearly as possible optimizing the uses and consequent benefits.

3. **NASA could improve the long-term economic value of its Earth science investments by investing a small percentage of each mission's funds on identifying potential future user communities and potential barriers to information transfer.** Such an investment would make it possible for NASA to improve its ability to match the scientific outcomes of its research with potential applications. To reap these additional benefits from Earth science research, it will also be important for NASA to experiment with inserting new types of data into applied models during the research phase, such as has been done with the precipitation data from TRMM.

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APPENDIX A.
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The Economic Value of Improved Weather and Climate Information

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APPENDIX B: TROPICAL RAINFALL MEASURING MISSION (TRMM)

The TRMM satellite was launched from Japan on November 11, 1997. The mission is a collaborative endeavor between NASA and Japan's National Space Development Agency (NASDA). It is designed to study the effects of tropical rainfall and the subsequent heat release on atmospheric circulation, which effects both weather and climate. Tropical rainfall accounts for more than two thirds of the global precipitation and is the primary global distributor of heat through atmospheric circulation. By providing information regarding tropical rainfall and the latent heat associated with it, TRMM is expected to validate and improve existing weather and climate models. Three instruments on TRMM contribute to the measurement of precipitation rates and quantities: the Precipitation Radar, the TRMM Microwave Imager and the Visible and Infrared Scanner. In addition, the satellite carries two other instruments: the Lightning Imaging Sensor and the Clouds and Earth's Radiant Energy System Instrument.[39]

Precipitation Radar (PR): The PR has three-dimensional resolution and obtains information on precipitation type, distribution and intensity, height at which snow melts into rain and storm depth. The data collected by the PR is used to estimate the heat released into the atmosphere at different altitudes and thereby enhance the global atmospheric circulation model.[40]

TRMM Microwave Imager (TMI): The TMI produces accurate quantitative data regarding water vapor, cloud water and rainfall intensity over large areas by measuring the weak microwave energy emissions from the Earth and atmosphere.[41]

Visible and Infrared Scanner (VIRS): The VIRS detects radiation in five bands (ranging from visible to infrared), which is used to derive information regarding the brightness and temperature of clouds. This instrument also helps to link TRMM measurements to similar data obtained by the Polar Orbiting Environmental Satellites (POES) and the Geostationary Environmental Satellite (GEOS).[42]

Lightening Imaging Sensor (LIS): The LIS is a sensor that studies the distribution and variability of lightening over the tropical region. It gathers information pertaining to cloud features, storm dynamics and seasonal and annual variability in thunderstorms.[43]

Clouds and Earth's Radiant Energy System (CERES): The CERES is a broadband scanning radiometer that makes measurements pertaining to the amount of energy received by the earth's surface (including land, atmosphere, clouds, aerosols etc) and the amount radiated into space. Besides gathering data regarding the Earth's radiation budget, CERES will also collect detailed information about cloud properties.[44]

TRMM measurements are validated using the data gathered by ground-based validation radars located throughout the globe in Darwin Australia; Melbourne, Florida; Houston, Texas; Kwajalein Atoll, Republic of Marshall Islands, Tel Aviv, Israel; Sao Paolo, Brazil, Guam, Marianas Islands; Kaohsiung, Taiwan; and Om Koi, Thailand. TRMM data are transmitted from the satellite to Earth via the Tracking and Data Relay Satellite System (TDRSS). The TRMM Science Data and Information System (TSDIS) process

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[39] Goddard Space Flight Center, http://www.trmm.gsfc.nasa.gov, Accessed on October 9, 2001
[40] Goddard Space Flight Center, http://www.trmm.gsfc.nasa.gov/overview_dir/pr.html, Accessed on October 9, 2001
[41] Goddard Space Flight Center, http://www.trmm.gsfc.nasa.gov/overview_dir/tmi.html Accessed on October 9, 2001
[42] Goddard Space Flight Center, http://www.trmm.gsfc.nasa.gov/overview_dir/virs.html Accessed on October 9, 2001
[43] Goddard Space Flight Center, http://www.trmm.gsfc.nasa.gov/overview_dir/lis.html Accessed on October 9, 2001
[44] Goddard Space Flight Center, http://www.trmm.gsfc.nasa.gov/overview_dir/ceres.html Accessed on October 9, 2001

the raw data into standard data products, which are archived and distributed by Goddard Distributed Active Archive Center (DAAC).[45]

TRMM SCIENCE OBJECTIVES

- To obtain and study multi-year visible, infrared and microwave measurements of tropical and subtropical rainfall and estimate its associated latent heating
- To understand how interactions between the ocean, air and land masses produce change sin global rainfall and climate
- To improve modeling of tropical rainfall processes and their influence on global circulation in order to predict rainfall and its variability at various space and time scales
- To test, evaluate and improve satellite rainfall measurement techniques

Source: NASA, Goddard Space Flight Center

http://tsdis.gsfc.nasa.gov/tsdis/tsdis_redesign/TRMMBackground.html, Accessed on June 20, 2002

[45] Goddard DAAC, http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/hydrology/hd_trmm_intro.shtml, Accessed on June 20, 2002

Appendix C. GLOBAL PRECIPITATION MEASUREMENT (GPM)

GPM is scheduled for launch in 2007. TRMM measurements have been instrumental in reducing uncertainties pertaining to global tropical rainfall from 50% to 25%. GPM is expected to produce better estimates by extending TRMM's "observations to higher latitudes and yielding a more complete and accurate representation of global water cycle."[46] It will increase the spatial coverage and temporal resolution of precipitation observations. GPM is expected to bring about improvements in "water resource management, agriculture, policy and planning, transportation, forestry, natural hazards assessment, hydrology and oceanography, agriculture and weather forecasting."[47]

Why Measure Rainfall?

- Rain is a true global variable
- Rain is one of the three foremost weather prediction variables (along with temperature and wind)
- Rain causes floods
- Rain is a major climate change variable
- Rain through latent heating is a principle determinant of general circulation
- Rain is a key forcing variable for eco-hydrometeorological modeling
- Rain is one of three primary controls on air-sea moisture fluxes (along with change in temperature and surface wind)
- Rain is a by-product of microphysical processes – perhaps the least understood physics component of modern cloud-weather-climate prediction models
- Rain manifests itself within differing macrophysical cloud systems (connective, stratiform, frontal, orographic and/or warm) whose spatial-temporal distributions are poorly understood
- Rain affects almost everyone's life and work – GPM offers the possibility that everyone can obtain precipitation data using Internet-like access facilities

Source: http://gpm.gsfc.nasa.gov/documents/GPM_Industry_Briefing/smith_science.pdf, Accessed on June 22, 2002

[46] Goddard Space Flight Center, http://gpm.gsfc.nasa.gov/documents/GPM_Industry_Briefing/smith_science.pdf, Accessed on June 22, 2002

[47] Goddard Space Flight Center, http://gpm.gsfc.nasa.gov/, Accessed on June 20, 2002

Architecture:

- Primary spacecraft to measure precipitation structure and to provide a calibration standard for the constellation spacecraft
- International constellation of NASA and contributed spacecraft to provide frequent precipitation measurements on a global basis
- Calibration/Validation sites with a broad array of precipitation-measuring instruments
- Global Precipitation Data System to produce and distribute global rain maps, weather data, and climate research products

Primary Instruments:

- Primary Spacecraft:

  Dual-frequency Precipitation Radar

  Passive Microwave Radiometer
- Constellation Spacecraft:

  Passive Microwave Radiometer

Source: Goddard Space Flight Center, http://gpm.gsfc.nasa.gov/, Accessed on June 20, 2002

APPENDIX D. NPOESS PREPARATORY PROJECT (NPP)

The NPP is being developed by the Integrated Program Office (IPO), which draws personnel from NASA, NOAA and the Department of Defense, and is scheduled for launch in 2005. NPP is expected to cut future program costs and reduce transitional risk by providing the partner agencies with early access to operational sensors. This mission is intended to validate three crucial instruments intended for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) – the Visible/Infrared Imager/Radiometer Suite (VIIRS), the Cross Track Infrared Sounder (CrIS) and the Advanced Technology Microwave Sounder (ATMS). NPP will gather data regarding climate trends and global biological activity and provide a transition between elements of NASA's Earth Observing System (EOS) and IPO's NPOESS missions. The IPO expects that NPOESS satellites to yield substantial benefits to scientific, civilian and military users by making detailed observations of the Earth's lands, oceans, atmosphere, space environment and climate.

NPP Mission Objectives

- Provide NASA with continuation of global change observations after Earth Observing System (EOS) TERRA and Aqua:

  Atmospheric and sea surface temperatures, humidity sounding, land and ocean biological productivity, and cloud and aerosol properties

- Provide National Polar-orbiting Operational Environmental Satellite System (NPOESS) with risk reduction demonstration and validation for 3 of the 4 critical NPOESS sensors, algorithms, and processing:

  VIIRS, CrIS, ATMS

Source: NPP, http://jointmission.gsfc.nasa.gov/ Accessed on June 21, 2002

INSTRUMENT	DATA TYPE
Visible/Infrared Imager/Radiometer Suite (VIIRS)	Visible and infrared radiometric data of the Earth's atmosphere, ocean and land surfaces. Data types include atmospheric, clouds, Earth radiation budget, land/water and sea surface temperature, ocean color and low light imagery
Cross Track Infrared Sounder (CrIS)	Measures Earth's radiation to determine the vertical distribution of temperature, moisture and pressure in the atmosphere
Advanced Technology Microwave Sounder (ATMS)	Makes daily global observations of temperature and moisture profiles at high temporal resolution, in conjunction with CrIS

Source: http://www.ipo.noaa.gov/sensors.html, Accessed on August 22, 2001

APPENDIX E. GEOSTATIONARY IMAGING FOURIER TRANSFORM SPECTROMETER (GIFTS)

GIFTS, which is scheduled to be launched in November 2004, is a collaborative project of NASA, NOAA and the US Navy. It is a component of NASA's New Millennium Program, which seeks to provide impetus to promising but risky emergent technologies. After the instruments have undergone testing in space for a year, the technologies will be adopted by NOAA for its Advanced Baseline Sounder Program and finally transferred to the US Navy in 2006. GIFTS will carry state-of-the-art remote sensing equipment that will enable us to obtain high-accuracy data on winds and atmospheric temperature and composition. These measurements are expected to enhance weather predictions, air quality monitoring and aviation management.