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Hurricane Warning:
The Critical Need for a National Hurricane Research Initiative

DRAFT FOR PUBLIC COMMENT

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[*]Pending Presidential appointment.

Hurricane Warning: The Critical Need for a National Hurricane Research Initiative

Executive Summary

The United States possesses the most capable research enterprise, the largest economy, and the most sophisticated societal infrastructure in the world, yet it remains notably vulnerable to catastrophic damage and loss of life from natural hazards. Among weather hazards, hurricanes[1] account for over half of the total damage inflicted.[2] Hurricane-induced economic losses have increased steadily in the U.S. during the past 50 years, with estimated *annual* total losses (in constant 2006 dollars) averaging $1.3 billion from 1949-1989, $10.1 billion from 1990-1995, and $35.8 billion per year during the last 5 years. The 2005 season was exceptionally destructive, with Hurricane Katrina pushing annual damage loss over the $100 billion[3] mark for the first time since records began. Added to this financial cost is the intolerable and unnecessary loss of life associated with hurricanes – 196 individuals perished from 1986-1995 and approximately 1,450 were lost in the past 2 years alone.[4] Of course, hurricane impacts are not confined to the U.S.; weather-related disasters worldwide have outnumbered their less predictable geophysical counterparts (e.g., earthquakes, tsunamis, volcanoes) nine to one during the past decade.[5]

To place the Nation's vulnerability in perspective, 50 percent of the U.S. population lives within 50 miles of a coastline. [6] The physical infrastructure in coastal regions has grown dramatically over the past few decades and in the late 1990's was worth about $3 trillion in the Gulf and Atlantic regions alone.[7] Trillions of dollars in new seaboard infrastructure investment are expected over the next several decades.[8] As our economy grows and the value of built-infrastructure continues to increase, the economic and societal impacts of hurricanes also can be expected to escalate.[9] Although not all coastal regions are directly vulnerable to hurricanes, impacts from those regions which are affected can have national consequences, for example, via increased fuel prices. Additionally, even though decaying tropical storms are an important source of fresh water for inland regions, associated flooding – occurring hundreds of miles from the coast and days after storm landfall – can be astonishingly destructive. Historically, flooding has claimed more lives in the U.S. than any other weather phenomenon[10] and destructive tornadoes frequently accompany hurricanes.

Despite their destructive power and certainty of future occurrence, we know relatively little about the most important aspects of hurricanes including their internal dynamics and interactions with the larger-scale atmosphere and ocean; methods for quantifying and conveying uncertainty and mitigating hurricane impacts; associated short and long term consequences on the natural and built environment; and the manner in which society responds before, during, and after landfall. Billions of tax dollars have been provided for rescue, recovery, and rebuilding *after* hurricanes strike. Also important is national investment in the creation of new knowledge, and more effective application of existing knowledge to reduce these enormous public outlays, loss of life, and the associated societal disruption caused by hurricanes.

Recent hurricanes – catastrophic but not unprecedented – have focused public attention on the imperative to enhance our understanding of tropical weather systems and their multi-faceted impacts, ranging from geophysical and engineering elements to human and economic dimensions. They also have heightened our awareness of the need to use new knowledge to prepare more effectively for, and respond more efficiently to hurricanes that are an inevitable part of our future. Recognizing the many vital challenges associated with hurricanes, the National Science Board (the Board) has engaged the Nation's experts in science and engineering from government, academia, and industry in an intensive study to identify priorities in fundamental research, and complementary applied or mission-directed research, which can improve our Nation's ability to become more resilient to hurricane impacts.

The Board presents herein an agenda for action – a **National Hurricane Research Initiative (NHRI)** – that will provide urgently needed hurricane science and engineering research and education that engages relevant agencies across the Federal government, involves industry, academia, and other levels of government, establishes highly focused priorities, strengthens disciplinary research, creates multidisciplinary frameworks for studying the hurricane in an integrative fashion, and stimulates the efficient transfer of research outcomes to operational practice. An *additional* annual national investment of approximately $300 million is required to implement this critical agenda. Owing to the clear and increasing threat posed by hurricanes and their unique challenges relative to other natural hazards, the Board strongly recommends that the NHRI be established as a focused activity with well defined metrics for success, effective assessment mechanisms and a clearly articulated pathway from research to operations.

The present Federal investment in hurricane science and engineering research relative to the tremendous damage and suffering caused by hurricanes is insufficient and time is not on our side. The hurricane warning for our Nation has been issued and we must act vigorously and without delay.

Introduction

The United States possesses the most capable research enterprise, the largest economy, and the most sophisticated societal infrastructure in the world, yet it remains notably vulnerable to catastrophic damage and loss of life from natural hazards. Among weather hazards, hurricanes[11] account for over half the total damage inflicted.[12] In economic terms, hurricane-related losses in the U.S. during the last 2 years are estimated to be $168 billion,[13] and estimated annual losses, in constant 2006 dollars, averaged $1.3 billion from 1949-1989, $10.1 billion from 1990-1995 and $35.8 billion per year over the last 5 years (Appendix A). Added to this financial cost is the intolerable and unnecessary loss of life associated with hurricanes – 196 individuals perished from 1986-1995 and approximately 1,450 were lost in the past 2 years.[14]

These figures, and more importantly their change with time, are not surprising given that 50 percent of the U.S. population lives within 50 miles of a coastline,[15] with significant portions of this population directly vulnerable. The physical infrastructure in coastal regions has grown dramatically over the past few decades and in the late 1990's was worth about $3 trillion in the Gulf and Atlantic regions.[16] Trillions of dollars in new seaboard infrastructure investment are expected over the next several decades.[17] As our economy grows and the value of built-infrastructure continues to increase, the economic and societal impacts of hurricanes also can be expected to escalate.[18]

Hurricane and tropical storm impacts are confined not only to coastal communities, however; although decaying tropical storms are an important source of inland fresh water, inland flooding from decaying tropical storms – occurring hundreds of miles from the coast and days after storm landfall – is astonishingly destructive. Historically, flooding has claimed more lives in the U.S. than any other weather phenomenon[19] and destructive tornadoes frequently accompany hurricanes. Neither are hurricane impacts confined to the U.S.; weather-related disasters worldwide have outnumbered their less predictable geophysical counterparts (e.g., earthquakes, tsunamis, volcanoes) nine to one during the past decade.[20]

Despite their destructive power and certainty of future occurrence, we know relatively little about the most important aspects of hurricanes including their internal dynamics and interactions with the larger-scale atmosphere and ocean; methods for quantifying and conveying uncertainty and mitigating hurricane impacts; associated short and long term consequences on the natural and built environment; and the manner in which society responds before, during, and after landfall. Billions of tax dollars have been provided for rescue, recovery, and rebuilding *after* hurricanes strike. Also important is national investment in the creation of new knowledge and more effective application of existing knowledge to reduce these enormous public outlays, loss of life, and the associated societal disruption caused by hurricanes.

Future land-falling hurricanes of tremendous destructive potential are inevitable and the Nation's vulnerability continues to increase.[21] We urgently need a determined effort to maximize our understanding of hurricanes and ensure the effective application of science and engineering outcomes for the protection of life and property. The appropriate starting point is a careful examination of the Nation's current investment relative to national need, and our analysis revealed two troubling findings. First, considerable uncertainty exists regarding the amount of Federal dollars directed toward hurricane science and engineering research, thus suggesting a lack of focus and coordination, especially when compared, for example, to the well organized and funded National Earthquake Hazard Research Program. Second, even the most optimistic view suggests an average annual total Federal investment in hurricane science and engineering research that is inadequate for meeting the many challenges posed by hurricanes. (Appendices A and B).

NSF funding for hurricane-related research has varied little from year to year during the past several years, except for a significant increase in FY 2006 due largely to the funding of over 100 Katrina-related projects under the Small Grants for Exploratory Research program. The focal point for the National Oceanic and Atmospheric Administration (NOAA) hurricane research is the Hurricane Research Division (HRD) of the Atlantic Oceanographic and Meteorological Laboratory. Additional research is performed at the NOAA National Hurricane Center, Geophysical Fluid Dynamics Laboratory, and Environmental Modeling Center. Total annual funding for HRD has never exceeded $5.1 million[22], and despite the increase in our Nation's vulnerability, HRD staff levels declined by 30 percent (from 30 to 21 full time equivalent positions) during the past ten 10 years. The National Aeronautics and Space Administration (NASA), Office of Naval Research, and several other agencies also perform research on hurricanes, with NASA operating numerous spaceborne and airborne platforms. It has been reported to Congress[23] that the majority of research funding related to hurricanes has been focused on short-term forecasting efforts, with less than 2 percent targeted to research on the prevention of loss through improved engineering and design of structures. Analyses of the top 40 most costly insurance losses worldwide for 1970-2005 indicates that $147 billion in worldwide insured losses were associated with hurricanes compared to $25 billion for earthquakes (in constant 2006 dollars).[24] Actual hurricane economic losses are typically estimated to be twice the insured loss. Over the last 5 years, actual economic losses from U.S. hurricanes alone are estimated[25] to be $179 billion (in constant 2006 dollars).

Hurricane-related research has been conducted, for the most part, as a relatively modest, loosely coordinated enterprise. Topics addressed by this research range from basic research in hurricane dynamics and atmospheric and hydrologic numerical prediction to human behavior and economic impacts. Although the quality of current hurricane research efforts[26] is generally quite high and in some cases strategically performed,[27] much of it is accomplished within the boundaries of traditional disciplines and thus the potential benefits arising from synergistic integration of research across disciplines seldom occurs. A recent RAND study[28] underscores this fact, noting in the context of natural hazards that "…policy makers face less a geophysical problem than an inherently *societal* [italics in original] problem with a geophysical underpinning. Any strategy to attack this problem thus requires not geophysical research but the all-encompassing strategies that would be used to confront any other large-scale societal problem." Hurricanes, and their typhoon cousins, slice across political boundaries, social strata, ideologies and scientific disciplines. Consequently, an integrative approach to hurricane science and engineering research is needed to fully address the many compelling problems that transcend conventional thinking and organizational infrastructures. Further, the transfer of research outcomes to operational practice, which presently is hampered by insufficient funding, facilities and coordination, must be an important part of the overall goal.

With trillions of dollars in coastal infrastructure already in place and trillions more on the horizon, and with an enormous population base in harm's way, our Nation would be wise to reduce the risk to this investment and population by dedicating significant additional funding towards expanding the current hurricane science and engineering research enterprise and engaging other important disciplines in a nationally coordinated manner. Although funding for hurricane impact relief is provided almost annually through emergency supplemental appropriations – which are not constrained by normal Federal budget ceilings – Federal appropriations of the scale needed to address the challenges of hurricane related research will require extraordinary political willpower. Hurricane research focused on long-term loss reduction strategies and advanced technologies will improve the resilience of communities and infrastructure as well as save numerous lives. Such an investment in research should explicitly include the development of strategies and technologies to strengthen the built environment to better withstand hurricanes, transfer research outcomes into operational practice in government and industry, and build awareness within the population to promote "risk-wise" behavior.

The Board, with its independent advisory role to the President and Congress and policy-making responsibility for the National Science Foundation (NSF), is uniquely positioned to frame the hurricane science and engineering research challenge and recommend a national imperative to address it.[29] This report has been produced within the Board's statutory responsibility to recommend and encourage the pursuit of national policies for the promotion of research and education in science and engineering.[30] Accordingly, the *Board did not directly consider operational decision-making and organized civil response, or human health issues that are better addressed by other bodies*. However, the Board does recognize the important role of these elements in developing relevant procedures, equipment, and processes for effective hurricane response and mitigation and anticipates that the benefits of the research proposed will be realized through practical implementation – the pathways for which must be addressed as part of the activities proposed herein.

After reviewing the state of hurricane science and engineering research and its alignment with national needs, the Board has concluded that the U.S. must engage in a nationally coordinated, multi-agency and multi-disciplinary research initiative to greatly expand our understanding of hurricanes and identify more effective strategies for dealing with them. The Board's analysis and recommendations were informed by three data-gathering workshops (for a summary of the workshops, see www.nsf.gov/nsb/committees/hurricane/index.htm) where researchers, policy makers, and agency officials discussed ongoing projects, challenges, and suggestions for change. In addition, Board Members and staff met with officials in Executive offices and Federal research-focused agencies to share information and coordinating activities wherever possible. All hurricane-related science and engineering disciplines must be strengthened and brought together to address fundamental questions regarding hurricanes as natural disasters, and work to translate this new knowledge into operational practice to improve the Nation's ability to predict, prepare for, and react to hurricanes.

Research Imperatives

The Board hosted three workshops to identify knowledge gaps and issues in the structure and operation of the Nation's hurricane research enterprise and to identify priorities for future investment. The first workshop focused on research activities of Federal agencies while the latter two involved the same topic for academia and industry, respectively. The workshops covered a broad spectrum of hurricane science and engineering ranging from meteorology and hydrology to social science, engineering and economics. In addition, the Board was informed by numerous reports, archive publications and informal conversations. A summary of workshop discussions and related background information may be found at www.nsf.gov/nsb/committees/hurricane/index.htm.

From a careful analysis of this material and extensive discussions, several common themes emerged that are deemed to be of greatest urgency for the Nation. We summarize and prioritize them below as the Board's recommended topics for *strategic investment of new dollars* in science and engineering research and education that could substantially reduce hurricane impacts in the near-term and lessen our Nation's vulnerability in the long-term. Building upon previous work by the National Science and Technology Council's Interagency Working Group on Windstorm Impact Reduction, we have organized our recommendations into three overarching investment categories: *Understanding and Prediction; Impacts and Interactions; Preparedness and Building Resiliency*.

Investment Category #1: Understanding and Prediction

- ***High Priority:*** *Predicting hurricane intensification and size, and reducing the uncertainty associated with where and when hurricanes will make landfall.* The 72-hour track forecast of hurricanes increased by nearly a factor of four during the past 40 years, and by 50 percent during the past 15 years,[31] owing to dramatic improvements in computing capabilities, numerical models, and an increasing number of and improved ability to assimilate observations. However, the prediction of hurricane intensity and size remains a challenge, and a recent report[32] from the NOAA Science Advisory Board's Hurricane Intensity Research Working Group addressed this issue in detail. In order to better predict both the location and intensity of tropical cyclones at landfall, research is needed to better understand rapid intensity change, relationships among storm structure, motion and intensity, the internal dynamics of hurricanes and the manner in which hurricanes interact with their environment. Particularly important is the development and application of fine-scale models and techniques for more effectively assimilating the numerous observations already being made. Within this context, quantifying and conveying uncertainty regarding hurricane predictions is essential, requiring research in ensemble forecasting, the blending of model output with observations using advanced statistical approaches, and decision science.

- ***High Priority:*** *Understanding air-sea interactions.* Traditional theories of air-sea interaction are not applicable to the strong wind and high wave conditions associated with hurricanes, where the air-sea interface beneath hurricanes vanishes and is replaced by an emulsion – the properties of which are poorly understood and not effectively accounted for in computational models. Theoretical, observational (especially with remotely piloted vehicles) and modeling research is needed to address this problem.

- ***High Priority:*** *Predicting storm surge, rainfall, and inland flooding from hurricanes and tropical storms.* Hurricanes frequently produce significant and beneficial rainfall many days following landfall, but inland flooding often is severe. Research is needed to understand and use both observed and modeled rainfall in comprehensive distributed hydrologic models in order to map stream flow, storm surge risk, and other factors using both deterministic and probabilistic approaches to adequately quantify uncertainty. The impacts of flooding on community water supplies, ecosystems and the built infrastructure must be better understood to promote and enforce more effective building practices.

- ***Medium Priority:*** *Understanding the relationship between hurricanes and climate.* The physics of hurricanes have been an important area of research, highlighting the significant role hurricanes play in the transfer of energy and water within the atmosphere and between the atmosphere and ocean. However, hurricanes currently are not resolvable in most climate models, and observational data that can link hurricane behavior to regional and global climate characteristics are limited and imperfect. Thus, research is needed to understand the complex relationships between hurricanes and climate as well as the most effective ways of using observational information. Specific emphasis should be given to increasing the presently limited skill of seasonal predictability, determining natural decadal and multi-decadal signals, understanding the role of anthropogenic impacts on hurricane size, frequency, intensity, precipitation and track, and exploring how future climate scenarios might impact tropical cyclone frequency, intensity and location. Very high resolution Earth System Models capable of resolving hurricanes will be needed to address these relationships and quantify uncertainty in a statistically reliable manner.

- ***Medium Priority:*** *Improved observations.* Observations are one of the most important factors in both improving our understanding of hurricanes and predicting them operationally. In many cases, a single observation system can satisfy both requirements and thus the research and operations communities must work closely together to leverage shared assets. Although considerable need exists for observations collected across a spectrum of platforms, we emphasize here the importance of ground-based and airborne *in situ* observations, for which hurricanes represent an extremely hostile environment. The current fleet of piloted operations and research aircraft, especially of the turboprop class, is aging and needs to be upgraded or replaced. New observing technologies such as airborne and surface mobile radars and lidars, global positioning system water vapor sensing arrays, unmanned aerial vehicles and distributed arrays of ground-based and airborne wireless sensors must be developed. Existing assets, such as the Long-Term Ecological Research sites, and those now being planned, such as the National Ecological Observatory Network, should be part of the overall portfolio and closely coordinated with other systems. All such observing systems must be able to function in the most severe hurricane conditions and in the case of piloted systems, minimize the exposure of pilots, crews, and technicians to hazardous conditions.

- ***Medium Priority:*** *Fundamental hurricane predictability*. The practical numerical prediction of day-to-day, large-scale weather preceded by several decades a general theory of atmospheric predictability. However, that theory, developed in the late 1960s and continuing to be refined, has been important in advancing data assimilation and forecasting techniques, particularly the introduction of stochastic approaches involving ensembles. In order to assess whether numerical forecasts of hurricanes are approaching any sort of fundamental capability limit, research should be conducted in hurricane predictability and efforts made to verify the resulting theories via observations and numerical experimentation.

- ***Medium Priority:*** *Hurricane modification.* The potential for modifying hurricanes to reduce their intensity or alter their movement through human intervention has long been pondered. Despite advances in computational modeling approaches for assessing atmospheric sensitivity to imposed perturbations and recent demonstrations of such capabilities,[33] practicable techniques for modifying hurricanes will require considerably more accurate weather and climate forecasts, greater insight regarding the potential effects of hurricane modification on ecosystems, precipitation, fresh water supply and climate, and a careful analysis of legal[34] and ethical issues.

Investment Category #2: Impacts and Interactions

- ***High Priority:*** *Interaction of hurricanes with engineered structures.* The characteristics of land or water beneath hurricanes dramatically affects their behavior via wind stress, turbulence, and heat and moisture flux changes induced at the atmosphere-land interface. Likewise, engineered structures are vulnerable to damage from wind, precipitation and storm surge though the combined impacts are not well understood. Research therefore is needed to better understand fluid-structure interactions at fine spatial scales, with the coupling of atmospheric and land-surface/built infrastructure models essential for guiding the creation of improved building designs and construction codes in particularly vulnerable locations. Developing a better understanding of how the land-atmosphere interface impacts hurricane morphology also is needed. Risk prediction models, many of which are highly parameterized and overly simplified, should be retooled to accommodate the detailed characterization of four-dimensional atmospheric structure that will be possible with tomorrow's advanced forecast models.

- ***High Priority:*** *Economic and social impact of hurricanes and mitigation measures.* The impacts of hurricanes are not limited to the regions in or near landfall, nor are they limited to the days or even weeks following the storm. Following particularly destructive storms, or in the even that the frequency and intensity of hurricanes increases, a significant fraction of the human population may permanently relocate to less vulnerable regions. Research on the patterns and underlying processes driving such relocations should be conducted. Additionally, research is needed to better understand the socio-economic costs of hurricanes and the distribution of costs and impacts across a range of stakeholders and time and space scales, including the effect on post-hurricane demographics, industrial production, the supply chain, and migration and economic recovery.

- ***High Priority:*** *Technologies for disaster response and recovery.* Recent hurricanes have demonstrated a significant requirement for technologies to enhance response and recovery operations after hurricanes come ashore. For example, further development of communication technologies such as self-powered and self-organizing *ad hoc* networks could lead to systems that can be easily deployed and seamlessly integrated with surviving communications infrastructure, thus enabling communication services for government agencies and non-government organizations assisting in response and recovery efforts. Rapidly deployable technologies and systems to assess damage to the environment and built infrastructure immediately following landfall should be developed and fielded. Equally important is the need to address cyber-security in such environments and the ability to provide priority-based access to network resources. In addition, basic and applied information technology research is needed to enable the response community to accurately assess the impact of a hurricane within the first 24 hours. The inability to rapidly and adequately determine the extent of damage, and to communicate that knowledge, causes delays and non-optimal allocation of rescue and recovery resources, exacerbating loss of life, suffering, and property damage. Post disaster recovery also has a long-term component. Understanding the needs and investment strategies for rebuilding often has not been well coordinated or informed by the need to improve long-term resiliency of the built environment. Research on public and private investment decision-making and ways to improve the long-term recovery and rebuilding process should be considered.

- ***Medium Priority:*** *Interactions of hurricanes with natural ecosystems.* Hurricanes have enormous impacts on terrestrial and marine ecosystems, and a better understanding is needed regarding their response and adaptation to hurricanes on both short and long time scales. These scale-dependent responses are a critical component of the overall robustness (resistance to changes in structure and processes) and resilience (ability to return to a pre-disturbance state) as well as the long-term evolution of ecosystems. Development of a predictive capability for ecosystem processes and structure in the face of individual hurricane events, as well as in response to changes in long-term patterns of hurricanes, is essential for both maintaining ecosystem health and mitigating economic loss to important coastal industries.

Investment Category #3: Preparedness and Building Resiliency

- ***High Priority:*** *Assessing and improving the resilience of the built environment.* Resiliency of physical and social infrastructure is enormously important for successful disaster response and recovery operations. The establishment and sustainability of lifelines to victims remains one of the greatest challenges following the failure of transportation, power, and communication infrastructures, and research is needed to provide such lifelines as well as design infrastructures that gracefully degrade, rather than fail indiscriminately, during extreme conditions. A requirement exists for a national engineering assessment of coastal infrastructure – including levees, seawalls, drainage systems, bridges, water/sewage, power, and communications – to ascertain their level of vulnerability to hurricanes. Studies are needed to identify and prioritize the most cost-effective improvements and develop a national loss reduction strategy that addresses inevitable degradation of built infrastructure. Careful attention also should be paid in infrastructure research to existing building codes and the extent to which recent damage has been a result of non-compliance.

- ***High Priority:*** *Human behavior and risk planning*. Communities often are overwhelmed with sometimes conflicting information regarding risk planning and procedures for action. Research is needed to identify methods and tools for increasing the likelihood that people, businesses, and communities fully understand and appropriately consider risks when planning homes, facilities and communities, and likewise which they understand and trust information conveyed during an event and are prepared to act upon it. Additionally, training and outreach activities, involving policy and decision makers, are needed to ensure that research efforts are appropriately applied, thus meeting the societal demand for protection of life and property and responsible management of resources.

- ***High Priority:*** *Evacuation planning.* Evacuation planning is a highly complex challenge that involves human behavior, fixed and mobile infrastructure, and the assembly, delivery, and understanding of critical information. Models should be developed and refined to address the spatial and temporal aspects of evacuations including the time required to prepare, receive and understand warnings, mobilize, and move to an evacuation destination, and an understanding of how individual behavior is affected by others in communities broadly defined. Research is needed to better characterize the reactions of both the general public and government officials to hurricane-related information and the manner in which such information is most effectively processed and shared. Improved means of communicating potential hurricane impacts should be developed to most effectively capitalize upon recent advances such as the Tropical Cyclone Probabilistic Surface Wind Speed Graphic and Text products. Further, improved understanding is needed to determine which circumstances require “evacuation in place” rather than traditional displacement evacuation of large urban areas.

- ***Medium Priority:*** *Computational capability*. Raw computing power continues to advance at a dramatic rate while the ability to use computers effectively is proceeding much more slowly, thereby widening the divide between what’s possible and what’s achievable. Research is needed to effectively utilize the next generation of petascale computers (those which have the capability to perform a thousand trillion calculations per second) in the development and application of models and in their transition to operations. Additionally, efforts must be directed toward understanding the efficient utility of multiple coupled and linked models requiring sharing and inter-operability of databases, computing environments, networks, visualization tools, and analysis systems beyond what is currently available for transitioning hurricane research community assets to operational practice. Access to robust computational facilities beyond those currently accessible by the civilian research community is essential for the hurricane research and operations enterprise, including data acquisition, assimilation, and modeling capability during hurricane events. Particular emphasis should be given to ensemble forecasting and techniques for quantifying uncertainty.

- ***Medium Priority:*** *Training and education programs related to hurricane impacts.* The application to hurricane impacts of engineering principles presently is not included in engineering curricula, textbooks, or professional certification for engineers. Additionally, few faculty are involved in hurricane engineering research and practice. Education and training regarding the interaction of structures with wind and water will help scientists and engineers of the future accommodate hurricane risks in coastal zones, help enhance the Nation's resilience and ensure an educated workforce for studying hurricanes in an integrated fashion. Further, owing to their broad impacts, hurricanes are a somewhat unique phenomena for stimulating interest in all areas of science and engineering both by the general public and those entering the educational system.

Recommendations

The Board's recommendations are grouped into three categories: (1) overriding keystone recommendation which sets the stage for more specific recommendations; (2) general implementing recommendations directed both within and across research communities, governmental agencies, and international partners; and (3) guidance to NSF, for which the Board sets policy and provides oversight.

Keystone Recommendation

> ***The United States should marshal its substantial science and engineering research enterprise to undertake a focused, sustained and multi-agency initiative — a National Hurricane Research Initiative (NHRI) — to improve our understanding of and ability to predict, mitigate, and respond to the impacts of hurricanes on the population, the built-infrastructure and the natural environment.***

NHRI should emphasize the conduct of potentially transformative and highly integrative research, the engagement of partners including international experts, private industry and state and local governments, and the enhancement of education tightly integrated across relevant areas of science and engineering. Effective mechanisms for the rapid transfer of knowledge into the practices of preparation, response, and recovery should be implemented as a fundamental component of this effort.

General Implementing Recommendations

1. Create a **National Hurricane Research Initiative** (NHRI) to unify and strengthen the presently inadequate, loosely organized and under-funded hurricane research portfolio. The successful and well-funded National Earthquake Hazard Reduction Program, which was developed as a coordinated and focused response to destructive earthquakes,[35] could serve as a model for designing and implementing NHRI. The main characteristics of NHRI are summarized below to guide an implementation effort where further detail will be added.

    a. <u>*Broad Base for Design and Implementation*</u>: Specific implementation details for NHRI might best be defined via a coordinated inter-agency framework that, whenever appropriate utilizes existing administrative organizations such as the White House Office of Science and Technology Policy's National Science and Technology Council. However, owing to the clear and increasing threat posed by hurricanes and the unique challenges relative to other natural hazards, we strongly recommend that NHRI be established as a focused activity with clearly defined metrics for success, an associated assessment component, and a well defined pathway from research to operations including close coordination with programs such as the Global Earth Observing System of Systems, Climate Change Science Program, and the National Windstorm Impact Reduction program. NHRI is ideally positioned to draw upon and leverage the expertise and capabilities of all relevant public agencies and private organizations. This includes *but is not limited to* NSF, NOAA, NASA, National Institute of Standards and Technology, Department of Homeland Security, Department of Energy, Office of the Federal Coordinator for Meteorology, Office of Naval Research, Department of Defense, Federal

Emergency Management Agency, Department of Housing and Urban Development, Defense Advanced Research Projects Agency, U.S. Army Corps of Engineers, United States Geological Survey, and Environmental Protection Agency, as well as the American Red Cross, Salvation Army, Institute for Business and Home Safety, and United Way. A NHRI Federal Advisory Committee could be established to help steer the program and bring to it the expertise and experience of non-Federal researchers, educators, state and local governments, and industry.

b. *Leadership*: A variety of leadership models and frameworks are possible for NHRI. An obvious one involves the NSF, with its mandate for supporting fundamental research and science education across all disciplines; NOAA, with its mission for basic and applied research, observing and monitoring the Earth system, and predicting weather, water and climate, serving as co-leaders; and NASA, with its research programs on natural hazards and its mission to help understand and protect the planet, serving as co-leaders. Other possibilities should be considered but in all cases careful thought should be given to inclusiveness and maximizing overall efficiency, accountability and engagement of appropriate communities, as noted below.

c. *Maintaining Dialog with the Broad Community*: The positive dialog among traditionally disparate disciplines evidenced in the three Board workshops clearly points to both the need and strong desire for researchers to collaboratively address shared goals much more effectively than is presently the case. Thus, a series of national and international forums could be organized to assemble diverse disciplines and create a collaborative hurricane science and engineering research and education *community*. This community would, for example, be a valuable resource for informing NHRI implementation strategies.

2. Establish a **National Infrastructure Data Base (NIDB)** for characterizing the physical, social and natural infrastructure in order to provide a baseline for developing standards, measuring modification and loss, and establishing public policy. The lack of such a comprehensive data base has significantly hampered the research community's ability to quantify hurricane impacts, separate those impacts from other effects both natural and anthropogenic, make effective recommendations for improved building codes and urban planning practices, and develop effective procedures for responding to infrastructure disruption based upon local characteristics rather than a non-optimal one-size-fits-all approach. The proposed NIDB need not and mostly likely could not be a single physical data system but rather an aggregation of existing and planned systems that interoperate, provide uniform security and information standards, and support a broad array of data search, acquisition and mining capabilities. Current research in federated data repositories, meta-data standards, and other information technology infrastructures are ideally suited for meeting this challenging goal.

3. Establish a **National Hurricane Research Test Bed (NHRTB)** to conduct integrative research and facilitate the transfer of research knowledge to operational applications and decision makers. Although a Joint Hurricane Test Bed is in place under the auspices of the U.S. Weather Research Program (USWRP) and has made considerable progress toward improving operational forecasts, it is appropriately but narrowly focused on atmospheric science. In sharp contrast, the proposed NHRTB will involve linking relevant theoretical, physical and computational models from atmospheric, oceanic, economic, sociological, engineered infrastructure, and ecologic

fields, conducting experimental research to understand the complexities of hurricanes, and obtaining measurable results in a comprehensive framework suitable for testing *end-to-end integrative systems*. Test Bed results can be applied experimentally to real situations and provide simulations of important transfer linkages to operational entities and decision makers. The NHRTB could be a single facility or a physically distributed environment; regardless of its structure, the NHRTB should be operated an interdisciplinary working laboratory where much of the basic research from NHRI can be experimentally substantiated using suitable quantitative metrics, and where a culture of interaction and collaboration can further be promoted.

Guidance to NSF

The Board is statutorily charged with setting policy for and providing strategic guidance to the NSF. The Board discharges that responsibility in a variety of ways, one of which involves making specific recommendations in response to Board studies and needs articulated by the community. With that preface the Board offers the following guidance to the NSF for contributing to the strategic hurricanes research and education themes described earlier. No priority is specified as these components are tied directly to the prioritized research imperatives described earlier.

1. Consider serving as the co-lead agency, with NOAA, NASA, or other organizations, for further developing and implementing the National Hurricane Research Initiative.

2. Evaluate *mechanisms* for supporting integrative and potentially transformative research in hurricane science and engineering at a variety of organizational levels (from individual investigators to centers) in a manner that ensures active engagement by relevant research directorates. Multidisciplinary proposals, of the sort needed for effective hurricane research, are challenging to prepare and review. The NSF could aid this process by developing and widely disseminating a set of best practices for proposers, reviewers, and program managers.

3. Consider implementing a special program of "Hurricane Science and Engineering (HSE) awards-in-waiting" that are pre-reviewed and approved for activation and funding immediately prior to, during, or immediately following the occurrence of a hurricane or related natural disaster. Such awards ideally would facilitate entry by principal investigators into affected areas quickly, which can be challenging in light of rescue/recovery efforts but often is critical to achieving research goals. Further, the awards could be updated periodically, in the event that they are not used, to ensure their continued presence at the frontier of science and engineering. The Small Grants for Exploratory Research (SGER) program may be suited to this task with appropriate modification to achieve the special goals noted here.

4. Working with the operational community, and in coordination with the Nation's organization that operate computers dedicated to responding to urgent circumstances, the NSF should assess the efficacy of making its supercomputing center resources available on short notice for running operational hurricane and other models in times of national need. In the evolving age of grid computing and interoperability, sophisticated prediction models and

analysis/decision support tools, particularly those that are coupled or linked, could be maintained in "stand by" mode at the NSF-sponsored supercomputing centers during the hurricane season and thus be available for quick activation as formally operational systems should the need arise.

5. Explore funding for pilot university curricula in hurricane science and engineering that encompass all relevant science and engineering disciplines. Much of the education associated with the research imperatives described previously occurs within traditional "stove pipe" disciplines (e.g., engineering, atmospheric science, ecology, economics, and social science) that have infrequent interaction. Yet, some of the most compelling and societally relevant questions about hurricanes occur not within but at the intersection of these disciplines, and consequently new integrative approaches are needed to adequately educate the next generation of scientists and engineers for addressing them. Recent hurricanes have stimulated action along these lines (e.g., Louisiana State University's Hurricane Engineering Curriculum) and resources are needed to expand this notion across all areas of hurricane science and engineering. NSF should explore existing programs (e.g. Integrative Graduate Education and Research Traineeship or IGERT; Research Experiences for Undergraduates) as possible mechanisms for addressing this recommendation.

Budget Recommendations

Successful implementation of NHRI will require substantial inter-agency coordination and leadership, effective integration of activities across many traditionally distinct disciplines and organizational boundaries, a reorganization of existing investments, new modalities of support, and considerable new funding – some of which must be sustained in order to fully realize systemic improvements. Based on input received by the Board from various sources (www.nsf.gov/nsb/committees/hurricane/index.htm) and examination of available information on current federal investment in hurricane research, the Board recommends that approximately $300 million in new funding will be needed for NHRI. Reliable mechanisms must be applied to monitor hurricane research investments and associated returns, and a majority of the funds should be directed to support integrative and potentially transformative research in hurricane science and engineering and its movement into operational practice in both the government and private sectors. Appendix C summarizes the proposed new investments in broad categories, each of which is discussed in greater detail.

National Infrastructure Data Base. NSF, NOAA, NASA, and many other agencies have invested substantial resources during the past decade toward developing policies, infrastructure and software for the stewardship and provisioning of data, particularly via federated databases[36]. NIDB thus is in a position to leverage this investment yet faces new challenges owing to the highly variable characteristics and sources of data it is intended to house. NIDB is not envisioned as a single physical facility but rather a virtual cyber environment that draws upon numerous existing capabilities and facilities, and establishes new ones as appropriate, to provide an interoperable environment and the necessary meta data and other resources needed by its multidisciplinary user base.

Some of the leveraging opportunities open to NIDB include the NASA Earth Observing System Data and Information System and Earth Science Enterprise, the Socioeconomic Data and Applications Center, the Physical Reference Data archive at the National Institute for Standards and Technology, and the Canopy Database Project, to name just a few. The recommended new funding of $20 million should be used to identify (and in some cases create), collect, bring into appropriate formats, catalog and make accessible the many data sets required to establish baselines for developing standards, measuring modification and loss, supporting education and basic research across the spectrum of hurricane science and engineering, and establishing public policy. A portion of the new funding also should be directed toward standardized portal interfaces for users, implementing meta data and ontology systems, and providing tools for mining across heterogeneous data sets. The recommended funding level is half the yearly budget of NSF's recently completed 5-year Information Technology Research program, which supported hundreds of projects across a spectrum of sizes which can serve as enabling mechanisms for NIDB.

National Hurricane Research Test Bed (NHRTB). NHRTB is envisioned to be a collaborative environment for conducting integrative research, testing new ideas in an *end-to-end fashion* under the rigors of operational constraints (real and simulated), and facilitating the transfer of research knowledge to operational practice. Unlike the existing Joint Hurricane Test Bed, which under the auspices of USWRP has made considerable progress toward improving operational hurricane forecasts with an appropriately narrow focus on atmospheric science, NHRTB is envisioned to be much broader in scope, encompassing the physical, social, behavioral, economic, ecologic, and related sciences as well as engineering. Integration mechanisms exist within certain disciplinary areas, such as the Earth System Modeling Framework, and these might be extensible to social science as well as engineering models. Engagement of the operational and decision-making communities in developing research directions and activities, and the transition of research outcomes to operations and applications, are vitally important areas that should be supported. Likewise, NHRTB will provide unique opportunities for formal as well as informal education, outreach and workforce development, including but not limited to the support of graduate and undergraduate student research, a venue for classroom activities and resources developed as part of NHRI, public education programs, and outreach to communities to improve awareness and warning processes.

NHRTB will require considerable infrastructure to accommodate the numerous models and associated data streams utilized across the hurricane science and engineering enterprise, and adequate funding should be directed toward the complex task of integrating disparate software elements from these models and coupling them as appropriate. It is especially important to recognize that end-to-end systems testing, which is the foundation of NHRTB, cannot reasonably be accommodated by existing computing environments at NSF or elsewhere. Such environments either are highly subscribed and constrained because of mission-oriented operational use or must meet the needs of thousands of users in traditional batch modalities that offer limited flexibility for being dedicated to specific problems, real time testing and on-demand utilization.

We Recommend an initial investment of $20 million for hardware, to be renewed approximately every 4 years, and an annual investment of $3 million for personnel. This funding will provide dedicated resources for experimenting with coupled and linked models, exploring new modalities of computing (e.g., on-demand and dynamically adaptive, which are difficult to accommodate within current centers), and developing and testing decision support systems. To contextualize the recommended funding for NHRTB cyberinfrastructure, NSF presently expends approximately $30 million per year on the TeraGrid and its recent track-2 cyberinfrastructure solicitation allocated $30 million for hardware over four years. Staff costs typically range from 50 to100 percent of the total hardware investment over the useful lifetime of the equipment.

NHRI Research Program. The centerpiece of NHRI is a **portfolio of basic and applied research programs** funded across Federal agencies. A recent study[37] of US funding for weather- related hazard research concluded that “most of the effort is focused on short-term prediction efforts, which have limited loss reduction potential within the full range of losses from natural hazards, and; research focused on long-term loss reduction strategies could improve the resilience of communities and infrastructure, protecting lives and property in a far more substantial way.” The Board’s proposed new NHRI investment would increase the most optimistic estimate of current levels of Federal HSE research expenditures by 50 percent. It also would provide *strategic investment* in those areas of greatest need and potential return. The recommended division of support is shown in Appendix D. The largest three proposed investments -- in hurricane behavior, engineering and the built environment, and power/communication/access systems research -- reflect the infrastructure-intense aspects of these topics, particularly with regard to both physical and computational models. Support for the biological, ecological and social sciences components are of lesser size but equivalent importance if NHRI is to be a truly integrative program.

To place the basic and applied research funding recommendation in context, NSF investments in hurricane-related research, exclusive of broader elements such as cyberinfrastructure, averaged around $5 million per year from FY 2001 through FY 2004 and were approximately $9 million and $13 million in FY 2005 and FY 2006, respectively. Priority areas at NSF, which typically extend over 5 years and represent strategic investments based upon national priorities articulated by the Office of Science and Technology Policy or the NSF, operate with yearly budgets of approximately $20 to $40 million. Thus, the recommended levels of investment for hurricane research within NHRI are nominal considering that the funding will be directed toward multiple agencies and heavily leveraged against existing activities.

A compelling additional need are **pre-approved NSF grants** that can be activated immediately prior to or upon the occurrence of a hurricane. SGER awards associated with recent hurricanes suggest that the recommended funding level is appropriate, particularly because the grants will need to be updated if they are not activated in a given year. Support also is needed to develop new curricula geared toward integrative hurricane science and engineering research, perhaps via existing mechanisms such as IGERT, and to leverage the capabilities of national supercomputing centers, particularly those at NSF, for running operational models in a “quick start” fashion when conditions warrant. Research in this capability has obvious value in homeland security and other areas where the disruption of mission-critical facilities is possible and cannot be anticipated.

Conclusion

The Board has engaged the Nation's experts in science and engineering throughout government, academia and industry in an intensive study of how fundamental research, and complementary applied or mission-directed fundamental research, can improve the ability of our Nation to become more resilient to hurricane impacts. The outcome of that effort, described in this report, is an action agenda – a National Hurricane Research Initiative (NHRI) – for urgently needed hurricane science and engineering research and education that engages relevant agencies across the Federal government, is built upon highly focused priorities, will strengthen disciplinary research and create multidisciplinary frameworks for studying the hurricane in an integrative fashion, and provide mechanisms for the efficient transfer of research outcomes to operational practice. An *additional* annual national investment of approximately $300 million is required to implement this critical agenda. The return on this investment will be enormous, both economically and for personal well-being. The imperative to act has never been clearer, nor have the science, technology, and intellectual capacity needed to address the challenge been more capable of rising to the occasion.

The Board recognizes the extraordinary challenges facing the Nation as it fights the war on terrorism, secures the homeland, seeks to double the funding for research in key agencies, and strengthens education to improve the Nation's competitiveness. It also sees an opportunity to build within many of these important activities a focus on hurricane science and engineering that holds real promise for near-term benefits in protecting lives and property and reducing economic impact through more accurate forecasts and effective response measures, and longer-term benefits that will increase the Nation's resilience to hurricanes through improved building standards and a greater understanding of risk by the public. Among the many questions needing to be addressed today by an increasingly small non-defense discretionary budget, perhaps an important one to ponder is: Can we as a Nation continue to remain vulnerable to hurricanes that are an inevitable part of our future, that have the demonstrated capacity to inflict catastrophic damage to our economy, and that kill hundreds of our citizens?

The devastation resulting from hurricanes is significant and widespread – more so than any other natural disaster. Our Nation – in a coordinated manner from individual towns to states and in collaboration with the international community – must respond vigorously and with undeterred resolve to mitigate the astounding loss of life and property associated with hurricanes. The research community is poised as never before to make major advances in hurricane science and engineering and to translate new knowledge into operational practice in ways that yield tangible benefits to society for decades to come. The proposed National Hurricane Research Initiative will build on a foundation of previous investments and unprecedented intellectual and technological capacity to address one of society's greatest challenges. The hurricane warning has been issued — now we must act to safeguard our Nation.

Appendix A

Calendar year financial losses due to hurricanes and earthquakes in the U.S. Losses are presented in constant 2006-dollar increments of $1,000. Figures for calendar year 2006 are not yet available. Endnotes provide more detailed explanation on data sources and calculation methods.

U.S. Catastrophe Losses (2001-2006)
(Thousands, constant 2006 dollars)

	Hurricane		Earthquake	
Calendar Year	**Hurricane Insured Losses[38]**	**Estimated Hurricane Actual Losses[39]**	**Earthquake Insured Losses[40]**	**Estimated Actual Earthquake Losses[41]**
2001	2,989,938	5,979,876	348,731	14,300,000
2002	714,768	1,429,536	*	*
2003	1,953,555	3,907,110	*	*
2004	24,549,743	49,099,486	*	*
2005	59,348,196	118,696,392	*	*
2006[42]	N/A	N/A	N/A	N/A
Annual Average[43]	**17,911,240**	**35,822,480**	**93,746**	**N/A**

Appendix B

Federal fiscal year budget investments for science and engineering research related to hurricanes and earthquakes by various Federal agencies.* Budget investments are presented in constant 2006-dollar increments of $1,000. Endnotes provide more detailed explanation on data sources and calculation methods.

U.S. Hurricane and Earthquake Research Funding (2001-2006)
(Thousands, 2006 constant dollars)

	Hurricane							Earthquake	
	NSF	**US Navy**[44]			**NIST**	**NOAA**	**USG**	**NSF**	**USG**
Fiscal Year	Total[45]	ONR Funding[46]	CBLAST Funding[47]	NRL Funding[48]	Total	Total[49]	Estimated Total[50]	Total[51]	Total[52]
2001	4,952	N/A	1,715	1,715	2,567	N/A	228,676	67,830	N/A[53]
2002	5,498	1,801	1,688	N/A	4,711	N/A	225,124	64,918	N/A
2003	4,900	N/A	1,651	N/A	2,969	6,120	220,119	51,594	N/A
2004	4,527	N/A	1,608	N/A	2,402	6,873	214,408	46,239	N/A
2005	9,266	N/A	1,555	N/A	698	8,226	207,383	56,361[54]	127,057[55]
2006	13,490	850	1,000	400	737	8,557	200,000	53,770[56]	118,681[57]
Annual Average[58]	**7,106**	**1,326**	**1,536**	**1,058**	**2,347**	**7,444**	**215,952**	**56,785**	**122,869**

*NSF	National Science Foundation
ONR	Office of Naval Research
CBLAST	Coupled Boundary Layers Air-Sea Transfer Defense Research Initiative
NRL	Naval Research Laboratory
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
USG	U.S. Government- wide

Appendix C

Proposed new investments in essential areas of science and engineering research for the National Hurricane Research Initiative. The areas of investment are presented in rank order by level of recommended new annual funding and do not necessarily indicate priority.

Area of Investment	Recommended New Annual Funding ($millions per year)
NHRI Research Programs (See Appendix D)	200
National Hurricane Research Test Bed	68
Facilities and Cyberinfrastructure	
Hardware Cost Every 4 Years ($20)	
Yearly Recurring Personnel and Support ($3)	
Software Integration and Coupling ($10)	
Community Engagement and Transition to Operations ($5)	
Education, Outreach and Workforce Development ($10)	
Fixed and Mobile Data Collection Platforms and Data Provisioning Systems ($20)	
National Infrastructure Data Base	20
NSF Grant Awards-in-Waiting	5
Curricula Development	5
Hot-Start Prediction Capability at National Centers	5
Total	**$303 million**

Appendix D

Proposed strategic investment in the National Hurricane Research Initiative portfolio of fundamental and mission-oriented basic research programs across Federal agencies. Research programs are presented in rank order by level of recommended new annual funding and this ordering does not necessarily indicate priority.

NHRI Research Programs	Recommended New Annual Funding ($millions per year)
Power, Communication and Remote Access Systems Research and development of new technologies that are able to operate effectively in the challenging conditions found during and after hurricane landfall.	60
Structure and Behavior of Hurricanes Observation, theory, and simulation modeling directed toward characterizing and predicting the four-dimensional structure of hurricanes, understanding the relationships between hurricanes and climate, and intentional hurricane modification.	40
Engineering and the Built-Environment Research directed toward making the built environment more resilient to damage and more amenable to rapid recovery.	40
Risk Assessment, Communication and Response Understanding the risk associated with hurricanes, both prior to and following their occurrence, and its effective communication to the public.	20
Biological and Ecosystem Dynamics The theory, observation and modeling of biological and ecological systems on short and long time scales and the manner in which they both affect and are affected by hurricanes.	20
Economic and Societal Impacts The economic and societal impacts of hurricanes at multiple time and space scales in regional, national and international frameworks.	20
Total	**$200 million**

Endnotes

[1] Quoting from the American Meteorological Society's Statement on Hurricane Research and Forecasting, "Hurricanes (in the North Atlantic and eastern North Pacific; "typhoons" in the western North Pacific; "cyclones" in the Indian Ocean and throughout the Southern Hemisphere) belong to a class of phenomena referred to generically as tropical cyclones. The term hurricane is applied whenever the surface (33 ft or equivalently 10 m) winds reach a one-minute sustained speed of 64 kt (74 mph or 33 m s^{-1})."

[2] Lott, N. and T. Ross, 2006: Tracking and evaluating U.S. billion dollar weather disasters, 1980-2005. Forum on Environmental Risk and Impacts on Society: Successes and Challenges, American Meteorological Society. Available from http://ams.confex.com/ams/pdfpapers/100686.pdf

[3] National Oceanic and Atmospheric Administration, Office of Climate, Water and Weather Services. Available at http://www.nws.noaa.gov/om/hazstats.shtml

[4] Pielke, R.A Jr., *Trends in Hurricane Impacts in the United States*. Available from http://sciencepolicy.colorado.edu. Also see e.g., House Report 109-364 (December 22, 2005) and Government Accountability Office report GAO-06-518, Disaster Relief: Reimbursement to American Red Cross for Hurricanes Charley, Frances, Ivan, and Jeanne, p. 1 (May 30, 2006).

[5] International Federation of the Red Cross and Red Crescent Societies, 2004: *World Disasters Report*.

[6] National Academy of Sciences, *Meeting Research and Education Needs in Coastal Engineering*, p. 11, National Academy Press (1999).

[7] National Academy of Sciences, *Meeting Research and Education Needs in Coastal Engineering*, p. 11, National Academy Press (1999).

[8] James Connaughten, White House Council on Environment Quality, IN: National Journal, May 27, 2006.

[9] After adjusting for inflation, hurricanes impacting the United States were responsible for an annual average economic losses of $1.6 billion for the period 1950-1989, and $6.2 billion over 1989-1995 – reflecting the growth of built infrastructure in the coastal zone. Pielke, R.A Jr., *Trends in Hurricane Impacts in the United States*, Crop Insurance Today, August 1997, p 8. Available from http://sciencepolicy.colorado.edu.

[10] Rappaport, E. N., 2000: "Loss of life in the United States associated with recent tropical cyclones." *Bull. Amer. Meteor. Soc.*, 81, 2065–2074.

[11] Quoting from the American Meteorological Society's Statement on Hurricane Research and Forecasting, "Hurricanes (in the North Atlantic and eastern North Pacific; "typhoons" in the western North Pacific; "cyclones" in the Indian Ocean and throughout the Southern Hemisphere) belong to a class of phenomena referred to generically as tropical cyclones. The term hurricane is applied whenever the surface (33 ft or equivalently 10 m) winds reach a one-minute sustained speed of 64 kt (74 mph or 33 m s^{-1})."

[12] Lott, N. and T. Ross, 2006: Tracking and evaluating U.S. billion dollar weather disasters, 1980-2005. Forum on Environmental Risk and Impacts on Society: Successes and Challenges, American Meteorological Society. Available from http://ams.confex.com/ams/pdfpapers/100686.pdf

[13] ISO Services Properties, Inc., PCS Estimates of Insured Property Loss. Calendar year data from PCS insured loss database for U.S. property losses. Only includes events with at least $25 million insured losses. Includes insured losses for tropical storms.

[14] Pielke, R.A Jr., *Trends in Hurricane Impacts in the United States*. Available from http://sciencepolicy.colorado.edu. Also see e.g., House Report 109-364 (December 22, 2005) and Government Accountability Office report GAO-06-518, Disaster Relief: Reimbursement to American Red Cross for Hurricanes Charley, Frances, Ivan, and Jeanne, p. 1 (May 30, 2006).

[15] National Academy of Sciences, *Meeting Research and Education Needs in Coastal Engineering*, p. 11, National Academy Press (1999).

[16] National Academy of Sciences, *Meeting Research and Education Needs in Coastal Engineering*, p. 11, National Academy Press (1999).

[17] James Connaughten, White House Council on Environment Quality, IN: National Journal, May 27, 2006.

[18] After adjusting for inflation, hurricanes impacting the United States were responsible for an annual average economic losses of $1.6 billion for the period 1950-1989, and $6.2 billion over 1989-1995 – reflecting the growth of built infrastructure in the coastal zone. Pielke, R.A Jr., *Trends in Hurricane Impacts in the United States*, Crop Insurance Today, August 1997, p 8. Available from http://sciencepolicy.colorado.edu.

[19] Rappaport, E. N., 2000: "Loss of life in the United States associated with recent tropical cyclones." *Bull. Amer. Meteor. Soc.*, 81, 2065–2074.

[20] International Federation of the Red Cross and Red Crescent Societies, 2004: *World Disasters Report*.

[21] After adjusting for inflation, hurricanes impacting the United States were responsible for an annual average economic losses of $1.6 billion for the period 1950-1989, and $6.2 billion over 1989-1995 – reflecting the growth of built infrastructure in the coastal zone. Pielke, R.A., Jr., *Trends in Hurricane Impacts in the United States*, Crop Insurance Today, August 1997, p 8. Available from http://sciencepolicy.colorado.edu.

[22] NOAA Budget Office

[23] Charles Meade, RAND Corp., February 9, 2004 testimony to the House Committee on Science.

[24] Swiss Reinsurance Company, Sigma Insurance Research, Natural catastrophes and man-made disasters 2005, No. 2/2006, p. 35, (2006).

[25] ISO Services Properties, Inc., PCS Estimates of Insured Property Loss. Calendar year data from PCS insured loss database for U.S. property losses. Only includes events with at least $25 million insured losses. Includes insured losses for tropical storms.

[26] Space does not allow for a comprehensive summary of all agency activities in hurricane science and engineering and thus the absence of acknowledgement here does not indicate a lack of recognition on the part of the National Science Board. Agency presentations from the first workshop can be found on the web at http://www.nsf.gov/nsb/committees/hurricane/index.htm.

[27] US Weather Research Program: National Need, Vision & Interagency Plan FY 2000-2006. Available at http://box.mmm.ucar.edu/uswrp/program_overview/USWRP_Program_Plan_4.2.pdf; and via many activities within NASA including the multi-year Convection And Moisture EXperiment (CAMEX).

[28] Meade, C. and M. Abbot, 2003: Assessing Federal Research and Development for Hazard Loss Reduction. RAND Science and Technology Policy Institute report for White House Office of Science and Technology Policy.

[29] In addition to serving as the oversight and policy setting body for the National Science Foundation, the National Science Board also serves as an independent body of advisors to the President and Congress on national policy issues related to science and engineering research and education, as the Board, the President or the Congress determines is needed.

[30] The Board is authorized [42 U.S.C. § 1862 (d)] to recommend and encourage the pursuit of national policies for the promotion of research and education in science and engineering.

[31] Franklin, J., 2006: National Hurricane Center Forecast Verification. http://www.nhc.noaa.gov/verification

[32] NOAA Science Advisory Board Hurricane Intensity Working Group Report - http://www.sab.noaa.gov/Reports/HIRWG_prelim_report_0506.pdf; NOAA Science Advisory Board Hurricane Intensity Working Group Minority Report - http://www.sab.noaa.gov/Reports/HIRWG_Minority_Report_0806.pdf

[33] "Controlling Hurricanes" by Ross N. Hoffman, *Scientific American*, October 2004, Volume 291, Issue 4, p. 68.

[34] For example, the United States is signatory to the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques. [E.g., 15 U.S.C. §330 et. seq., Public Law 92-205, 85 Stat. 736. See also United Nations, Treaty Series, vol. 1108, p. 151 and depositary notification C.N.263.1978). The Convention entered into force for the United States on January 17, 1980.]

[35] The National Earthquake Hazards Reduction Program (NEHRP) can serve as a model for a hurricane research initiative. NEHRP seeks to mitigate earthquake losses in the U.S. through both basic and directed research and implementation activities in the fields of earthquake science and engineering. It is authorized and funded by Congress and is managed as a collaborative effort among the Federal Emergency Management Agency (FEMA), the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the United States Geological Survey (USGS). These NEHRP agencies work jointly and in cooperation with other Federal and state agencies; local governments; private companies; academic institutions; and regional, voluntary, and professional organizations to improve the Nation's understanding of earthquake hazards and to develop methods to reduce their effects. Underpinning earthquake risk reduction is research that develops new knowledge about, and understanding of, 1) the earthquake hazard, 2) the response of the natural and built environment to that hazard, and 3) techniques to mitigate the hazard. The foremost challenge facing NEHRP is encouraging the use of knowledge to foster risk reduction among local and state agencies and private entities

[36] *inter alia:* National Science Board report - *Long-Lived Digital Data Collections: Enabling Research and Education in the 21st Century* (http://www.nsf.gov/pubs/2005/nsb0540/start.htm); NRC BASC study – *Archiving and Accessing Environmental and Geospatial Data at NOAA* (http://fermat.nap.edu/catalog/11659.html)

[37] Meade, C. and M. Abbot, 2003: Assessing Federal Research and Development for Hazard Loss Reduction. RAND Science and Technology Policy Institute for the White House Office of Science and Technology Policy.

[38] Calendar year data from PCS Catastrophe Database for U.S. property losses. Only includes events with at least $25 million insured losses. Includes insured losses for tropical storms.

[39] Calendar year estimate based on the general assumption that total damage from hurricanes is typically twice the insured losses. See e.g., James L. Franklin, Richard Pasch, Lixion A. Avila, John L. Beven II, Miles B. Lawrence, Stacy R. Stewart, and Eric S. Blake, Annual Summary: Atlantic Hurricane Season of 2004, Monthly Weather Review, March 2006, p. 981. (The authors note "the uncertainty in estimating meteorological parameters for tropical cyclones pales in comparison to the uncertainty in determining the cost of damage caused by these cyclones when they make landfall."

[40] Calendar year data from PCS Catastrophe Database for U.S. property losses. Only includes events with at least $25 million insured losses. Industry experts estimate 14percent of California homes are covered by earthquake insurance; uninsured losses are not included in this data. There were no U.S. earthquakes in 2002-2005 that satisfied the $25 million threshold.

[41] No databases tabulate uninsured losses from earthquakes. An estimate for the total losses from the 2001 Seattle earthquake is available at: Analysis: Seattle Quake Most Likely to Shake Small Insurers, BestWire, A.M. Best Company, Inc., March 07, 2001 (Available from Lexis/Nexis).

[42] Data not available for CY 2006.

[43] Average annual hurricane losses calculated from data presented for 2001-2005. Average annual earthquake loss calculated only for insured losses with assumption that $24 million in insured losses occurred in each year for 2002-2005 (see endnote xxxv). Insufficient data available to calculate average annual total estimated losses from earthquakes (see endnote xxxv and xxxvi).

[44] Office of Naval Research, Marine Meteorology.

[45] Data provided by NSF Office of the Director for 231 research awards related to typhoons, cyclones, and tropical storms/depressions, hurricane development, and assessing the impacts of hurricanes. Awards that deal with broader issues, such as cyberinfrastructure for weather forecasting, are excluded.

[46] Fiscal year extramural hurricane research funding from the Office of Naval Research (not including CBLAST). Data for fiscal years 2001, 2003-2005 was unavailable.

[47] Fiscal year extramural hurricane research funding of the Coupled Boundary Layers Air-Sea Transfer Defense Research Initiative (CBLAST-DRI), which focuses on processes that occur in the oceanic and atmospheric wave boundary layers, which are regions influenced by ocean surface waves, an Office of Naval Research (ONR) program that combines observational and modeling components in its investigations. The hurricane component of CBLAST includes an initial 5-year program to measure, analyze, and understand the critical air-sea coupling at hurricane winds and a 2-yr follow-on effort to extract and apply findings to increased understanding and development of advanced parameterizations.
[48] Fiscal year intramural hurricane research funding at the Naval Research Lab; does not include funding from the Office of Naval Research already included in the ONR budget. Data for fiscal years 2002-2005 was unavailable.
[49] NOAA Budget Office
[50] Office of the Federal Coordinator for Meteorology - data assumes approximately one-third of the estimated $3 billion annually being spent on meteorology operations and supporting research is associated with the tropics (and potentially tropical cyclone or tropical cyclone-related), for funding per year of and estimated $1 billion related to tropical cyclone activity. This includes the costs associated with satellites and other observation platforms and the infrastructure (e.g., computers, people, and facilities). The data also assume 20percent of this as related to tropical cyclone research and development, which equates to $200 million per year (this includes future satellite sensors development, data assimilation, ocean sensing and other costs).
[51] Data provided by NSF Office of the Director - NSF support for earthquake-related research activities and operations costs at major test facilities.
[52] National Earthquake Hazards Reduction Program (NEHRP). Data is only available for FY 2005 and 2006 pursuant to new Congressional reporting requirements specified in the NEHRP Reauthorization Act of 2004, PL 108-360. Presented data only applies to research, which occurs through NIST, NSF, and USGS. FEMA’s role in NEHRP is operational and is not included in this figure.
[53] Data is not available prior to FY 2005, when bookkeeping procedures were implemented to accommodate new Congressional reporting requirements were implemented.
[54] Actual, as reported to Congress
[55] Actual, as reported to Congress
[56] Enacted, as reported to Congress
[57] Enacted, as reported to Congress
[58] Average annual hurricane and earthquake research investment calculated from data presented for 2001-2006. Years in which data was not available (N/A) are not included in calculation.

Selected Acronyms

HRD	Hurricane Research Division (NOAA)
HSE	Hurricane Science and Engineering
IGERT	Integrative Graduate Education and Research Traineeship
LTER	Long-Term Ecological Research
NASA	National Aeronautics and Space Administration
NHRI	National Hurricane Research Initiative
NHRTB	National Hurricane Research Test Bed
NIDB	National Infrastructure Data Base
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
SGER	Small Grants for Exploratory Research
USWRP	U.S. Weather Research Program