NATIONAL WINDSTORM IMPACT REDUCTION PROGRAM

Biennial Report to Congress for Fiscal Years 2011 and 2012

Executive Office of the President

National Science and Technology Council

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Report prepared by

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EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

Dear Members of Congress,

I am pleased to transmit to you the report, *National Windstorm Impact Reduction Program, a Biennial Report to Congress for Fiscal Years 2011 and 2012*, produced by the National Science and Technology Council's (NSTC) Subcommittee on Disaster Reduction and its Windstorm Working Group.

Windstorms such as hurricanes, tornadoes, and severe and fast-moving thunderstorm complexes are among the most destructive and economically-damaging hazards that affect the United States on an annual basis. Each year, windstorms claim lives, cause injuries, and result in billions of dollars in property damage. In recent decades, rapid development and population growth in areas at high-risk of windstorm hazards have posed increased risks to the Nation.

In 2004, as part of a Government-wide effort to counteract that trend, Congress called for the establishment a National Windstorm Impact Reduction Program (NWIRP), a coordinated approach to achieve major reductions in windstorm-related losses of life and property. In 2006, the Windstorm Working Group delivered to Congress a *Windstorm Impact Reduction Implementation Plan*, which identified research activities needed to improve windstorm hazard mitigation and served as a guide for Federal agencies to coordinate new and existing research to fill knowledge gaps in understanding, predicting, and forecasting windstorms. Subsequently, NWIRP member-agencies contributed to the development of a series of 15 implementation plans, which articulated necessary steps for reducing windstorm impacts. This series included plans that prescribed specific actions for mitigating impacts of hurricane and tornado hazards, as well as the coastal inundation and flood hazards that hurricanes and other windstorms often produce.

This new report fulfills NSTC's congressionally mandated responsibility to provide biennial reports on the NWIRP. Overall, it finds that the Program has successfully facilitated improvements in forecast models, warning systems, evacuation planning, structural-design technology, and community preparedness. These improvements have reduced vulnerabilities to windstorms even as the quantity of people, buildings, and critical infrastructure exposed to windstorms across the country has grown dramatically.

In coordination with academia and the private sector, the NWIRP agencies look forward to identifying and prioritizing additional research and development needs and achieving even greater successes in windstorm-impact reduction.

Sincerely,

John P. Holdren

John P. Holdren
Director, Office of Science and Technology Policy
Assistant to the President for Science and Technology

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1. BACKGROUND

In 2004, Congress recognized that rapid development and population growth in high-risk areas during the preceding decades had greatly increased the Nation's overall vulnerability to windstorm hazards. To counteract that trend, Congress prescribed the establishment of a coordinated Federal-agency effort – the National Windstorm Impact Reduction Program (NWIRP) – to achieve major reductions in windstorm-related losses of life and property. The NWIRP has been successful in its mission of facilitating improvements in forecast models, warning systems, evacuation planning, structural-design technology, and community preparedness. These improvements have reduced vulnerabilities to windstorms—even as the quantity of people, buildings, and critical infrastructure exposed to windstorms across the country has grown dramatically in recent years.

Fiscal Years 2011 and 2012 brought windstorms of increased frequency and intensity. An historic number of powerful and destructive tornadoes struck the Southeastern and Midwestern regions of the United States, and elevated hurricane activity in the Atlantic basin during the same period resulted in devastating impacts from Hurricanes Irene, Isaac, and, more recently, Sandy. Windstorms that struck the United States in 2011 alone took nearly 700 lives and injured nearly 7,000 people,[1] causing an estimated $11 billion in total direct property losses in the process.[2] As these impacts demonstrate, the continued support and leadership of senior Federal policymakers in reducing windstorm impacts through enhanced knowledge and applied science and technology is critical to increasing disaster resilience throughout the Nation.

2. THE SCOPE OF THE PROBLEM

Windstorms such as hurricanes and tornadoes are among the most destructive and economically-damaging hazards that affect the United States on an annual basis. Each year, these storms claim lives, cause injuries, and result in billions of dollars in property damages. The outbreak of tornadoes that occurred during April 25 - 28, 2011 in Alabama, Mississippi, Tennessee, and Georgia, and on May 22, 2011 in Joplin, Missouri was the deadliest and most destructive group of tornadoes to affect the United States in more than 50 years, killing 479 people.[3] April 2011 is ranked as the country's most active tornado month on record, with 753 tornadoes—more than 200 tornadoes above the previous record for any month, set in May 2004.[4]

The fiscal period of this report also saw significant impacts from hurricanes and other tropical cyclones, with the 2011 and 2012 seasons marking two consecutive years during which several portions of the country sustained devastation from these storms. Windstorms struck many parts of the country, including Tropical Storms Beryl and Debby in Florida, Hurricanes Isaac in

[1] NOAA/NWS fatality and injury data (2011) for tornado, thunderstorm wind, hurricane/tropical storm, and high wind hazards, http://www.nws.noaa.gov/om/hazstats/sum11.pdf
[2] NOAA/NWS property loss data (2011) for tornado, thunderstorm wind, hurricane/tropical storm, and high wind hazards, http://www.nws.noaa.gov/om/hazstats/sum11.pdf
[3] NOAA/NWS, *2011 Tornado Information*, http://www.noaanews.noaa.gov/2011_tornado_information.html
[4] NOAA/NWS, *2011 Tornado Information*, http://www.noaanews.noaa.gov/2011_tornado_information.html

Louisiana, Irene in the Mid-Atlantic region, and Sandy in New York and New Jersey.[5] Most notably, Sandy in late October 2012 during Fiscal Year 2013 caused fatalities and injuries, widespread power outages, and tremendous destruction from coastal storm surge, heavy rainfall, inland flooding, and high wind. Preliminary loss estimates due to residential, commercial, and economic damage from Sandy could exceed over $50 billion[6], which would make it the second-costliest Atlantic hurricane behind only Hurricane Katrina in 2005.

Additional windstorms, such as straight-line derechos and other severe and fast-moving thunderstorm complexes, have also caused extensive damage throughout the United States during the fiscal period. On June 29 - 30, 2012, an intense derecho tracked across a large section of the Ohio Valley in the Midwestern U.S. and into the mid-Atlantic region resulting in 22 deaths, widespread infrastructure damage, and power outages across 11 states and the District of Columbia, affecting more than four million people.[7] The storm prompted the issuance of four separate severe thunderstorm watches by the NOAA Storm Prediction Center (SPC), and damage was widespread along the entire path of the derecho – especially in northern Indiana and the Fort Wayne, Indiana metro area; central and western Ohio; northeastern Kentucky; southwestern Pennsylvania; West Virginia; northern, central, and southwestern Virginia; Maryland; Washington, D.C.; Delaware; and southern New Jersey.

Today, windstorm impacts of increasing frequency and intensity pose a grave threat to the safety and security of our citizens and our communities. Improved prediction and forecasting of windstorms is essential, but additional observations, models, and tools are also needed to advance the understanding of how the built environment and structural design responds within windstorm events. Often overlooked, efficient warning systems and social analysis are critically needed to improve warning response, mitigate user complacency, better support effective decision making, and reduce the losses associated with devastating windstorms. To help meet these and related issues, the NWIRP agencies, academia, and the private sector will build on past activities to identify and prioritize specific measurement science research and development needs for windstorm impact reduction.

3. PROGRAM OBJECTIVES AND AGENCY ROLES

The NWIRP was established by Public Law 108-360, Title II, which is known as the National Windstorm Impact Reduction Act (NWIRA) of 2004. This legislation called for the Director of the Office of Science and Technology Policy (OSTP) to establish an interagency working group, and charged that working group with developing and transmitting to Congress:

1) an implementation plan for achieving the objectives of the program; and

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[5] NOAA/NWS, *Busy 2012 hurricane season continues decades-long high activity era in the Atlantic*, http://www.noaanews.noaa.gov/stories2012/20121129_hurricaneseasonwrapup.html

[6] Williams Walsh, M., Schwartz, N.D., *Estimate of Economic Losses Now Up to $50 Billion*, New York Times, http://www.nytimes.com/2012/11/02/business/estimate-of-economic-losses-now-up-to-50-billion.html?_r=0, November 2012

[7] Report from DOE Office of Electricity Delivery and Energy Reliability, Infrastructure Security and Energy Restoration Division: *A Review of Power Outages and Restoration Following the June 2012 Derecho*, http://energy.gov/sites/prod/files/Derecho%202012_%20Review_0.pdf, August 2012

2) a biennial report describing the status of the program and progress achieved.

Following passage of the NWIRA and within the structure of the National Science and Technology Council (NSTC), OSTP established an interagency working group of the Committee on Environment, Natural Resources, and Sustainability's Subcommittee on Disaster Reduction (SDR), in accordance with the law, consisting of the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the Federal Emergency Management Agency (FEMA), and, at the Director's discretion, the Federal Highway Administration (FHWA) to coordinate activities in furtherance of the program's objectives. Although the NWIRA officially expired in October 2007 and has yet to be reauthorized by Congress, these agencies continue to pursue measurable reductions in losses of life and property from windstorms per the original legislation.

As an initial step, the working group developed the *Windstorm Impact Reduction Implementation Plan*, which was sent to the Congress on April 5, 2006. The plan identified research activities needed to improve windstorm hazard mitigation and served as a guide for Federal agencies to coordinate new and existing research to fill knowledge gaps in understanding, predicting, and forecasting windstorms. Building on that plan in a subsequent and related effort, and as part of a broader undertaking by the NSTC and SDR to identify and prioritize the Federal investments in science and technology needed to reduce future disaster losses, the NWIRP agencies contributed expertise to the development of a series of 15 implementation plans, which, in addition to addressing other hazards, articulated necessary steps for reducing windstorm impacts. This series includes plans that prescribe specific actions for mitigating impacts of hurricane and tornado hazards, as well as the coastal inundation and flood hazards which hurricanes and other windstorms often produce. Published in 2008, these plans – the *Grand Challenges for Disaster Reduction Implementation Plans* for *Hurricane*, *Tornado*, *Coastal Inundation*, and *Flood* – are also available online at the SDR website at http://www.sdr.gov/.

This document is the biennial report for Fiscal Years 2011 and 2012 – the reports for Fiscal Years 2009 and 2010 and Fiscal Years 2007 and 2008 are included in this report's appendix. The present report provides examples of relevant Federal activities undertaken by the abovementioned agencies during the fiscal period. The examples herein reflect instances of collaboration and cooperation across levels of government, among Federal agencies, and with academia and the private sector.

The sections of this report are organized in thematic sections according to the goals of: improved understanding of windstorms; impact assessment and reduction; and outreach. Within these sections, the report summarizes activities undertaken by:

- NIST, in support of research and development to improve codes, standards, and practices for design and construction of buildings, structures, and lifelines.[8]

[8] The term 'lifelines' means public works and utilities, including transportation facilities and infrastructure, oil and gas pipelines, electrical power and communication facilities and infrastructure, and water supply and sewage treatment facilities.

- NSF, in support of research in engineering, atmospheric sciences, and social sciences to improve understanding of the behavior of windstorms and their impact on buildings, structures, lifelines, and society.
- NOAA, in support of atmospheric sciences research to improve the understanding of the behavior of windstorms and their impact on buildings, structures, and lifelines.
- FEMA, in support of the development of risk assessment tools and effective mitigation techniques, windstorm-related data collection and analysis, public outreach, information dissemination, and implementation of mitigation measures consistent with the agency's all-hazards approach.
- FHWA, in support of research to improve the understanding of windstorm impacts on bridges and other highway structures to advance corresponding design, engineering, and construction standards.

4. PROGRESS IN FISCAL YEARS 2011 AND 2012

4.1 UNDERSTANDING WINDSTORMS FOR IMPROVED PREDICTIONS, FORECASTS, AND WARNINGS

Federal efforts to understand, predict, and forecast windstorms span a broad array of activities, from basic research funded by the NSF and other agencies to severe weather warnings provided by NOAA. During Fiscal Years 2011 and 2012, NSF and NOAA supported research to advance the understanding of the physical processes that determine hurricane intensity, tornadogenesis, tornadic vortex structure, and other weather phenomena. NOAA activities included research to improve observations of physical phenomena; development of novel data assimilation and forecasting techniques; and applications of observations, models, and forecasts.

4.1.1 Hurricanes

Through advances in satellite-based observations, supercomputers, and modeling, tremendous strides over recent decades have reduced average hurricane forecast track errors significantly. They are now about half as large as what they were 15 years ago.[9] Much of this progress is the result of advances in numerical weather prediction: that is, the use of computer models to extrapolate future weather based on current conditions and knowledge of atmospheric dynamics. Further advances in hurricane modeling will require the development of models that can accurately depict large-scale atmospheric flows (which are primarily responsible for steering hurricanes), while at the same time representing the finer-scale details of their inner cores, which influence hurricane intensity.

Prediction of hurricane formation and intensification remains one of the most challenging aspects of atmospheric science. Efforts during the past decade have only yielded slight improvements in this area. Moreover, while statistical-dynamical models have provided the most accurate guidance for intensity prediction in recent years, experts at NOAA's National Hurricane Center (NHC) project that limitations inherent to these joint models will likely restrict the ability to

[9] NOAA/NHC, NHC Tropical Cyclone Forecast Verification, http://www.nhc.noaa.gov/verification/verify5.shtml

derive further skill improvements from them to a range of 10 to 20 percent. Improvement beyond this ceiling must come from other applications. Within this context, high-resolution atmospheric modeling systems based on dynamical and ensemble approaches offer the best hope for significantly improving intensity forecasts.[10] Future progress in hurricane forecasting will depend upon the success of programs such as NOAA's Hurricane Forecast Improvement Program (HFIP) and others highlighted in the following section.

NOAA: Hurricane Forecast Improvement Program. The HFIP provides the basis for NOAA and other agencies to coordinate and align Federal research with that of the larger scientific community. The specific goals of the HFIP are to reduce the average errors of hurricane track and intensity forecasts by 20 percent within five years and 50 percent in approximately 10 years while extending the forecast period out to seven days with accuracy equal to today's five-day forecast.[11] NOAA is making significant progress toward meeting these goals. In Fiscal years 2011 and 2012, HFIP provided funding to numerous efforts within NOAA, other Federal agencies, and universities to support the development, testing, and evaluation of enhanced numerical prediction systems. Successful demonstration of the systems illustrated that the five-year track forecast goals should be achieved through the use of recently developed data assimilation systems and existing operational global models when run as an ensemble at 30 km resolution. The initial operational version of this new data assimilation was implemented within the National Weather Service (NWS) in May 2012. Preliminary results showed that the intensity-forecasting goals can be achieved using inner core data from Doppler radar data transmitted to the ground in real-time from NOAA research aircraft, advanced data assimilation systems, and regional models run at high resolution (3 km). Other notable successes under the program include the rapid deployment of models from research application to operational application and the development and testing of HFIP's Real-time Experimental Forecast System, which uses NOAA Research and Development High Performance Computing with real-time support to the NHC during the hurricane season. This system allowed the demonstration of advances in model guidance for which additional operational computing is needed in order to implement.

NOAA: Joint Hurricane Testbed. During Fiscal Years 2011 and 2012, the U.S. Weather Research Program within the NOAA Office of Oceanic and Atmospheric Research (OAR) Office of Weather and Air Quality supported 11 projects conducted at the Joint Hurricane Testbed (JHT) in Miami, Florida, a NOAA testbed jointly managed by NHC and the NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML)[12]. These projects involved joint testing of new techniques, applications, and model enhancements to improve the analysis and prediction of tropical cyclones. The JHT is designed to transfer more rapidly and smoothly new technology, research results, and observational advances by partnering researchers from the academic community, federal agencies, and other groups with hurricane forecasters at the NHC throughout the entire project.

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[10] NOAA/NHC, http://www.nhc.noaa.gov/outreach/presentations/2011_IntensityForecastingImprovement_Pasch.pdf
[11] Gall, R., Franklin, J., Marks, F., Rappaport, E.N., and Toepfer, F., 2012: The Hurricane Forecast Improvement Project. Bulletin of the American Meteorological Society, in press. Early online release http://dx.doi.org/10.1175/BAMS-D-12-00071.1
[12] Rappaport, E., J-G Jiing, C.W. Landsea, S. T. Murillo, and J.L. Franklin, 2012: The Joint Hurricane Test Bed: It's First Decade of Tropical Cyclone Research Research-to-Operations Activities Reviewed. Bulletin of the American Meteorological Society, 93, pp. 371-380.

NOAA/NSF/NASA: NOAA Intensity Forecasting Experiment. NOAA's HRD is in the midst of a multi-year experiment to improve hurricane-intensity forecasting. Developed in partnership with other parts of NOAA, the Intensity Forecasting Experiment (IFEX) is: collecting observations that span the tropical cyclone (TC) life cycle in a variety of environments for improvements in the initialization and evaluation of the next-generation Hurricane Weather Research and Forecasting operational model; developing and refining measurement strategies and technologies that provide improved real-time monitoring of TC intensity, structure, and environment; and improving the understanding of physical processes important to intensity change for a TC at all stages of its life cycle. Measurable progress is occurring in TC intensity forecasts as a result of these efforts, though much work remains. When possible, IFEX partners with other agencies to accomplish a more complete sampling of TC structure and intensity. For example, during Fiscal Year 2010, IFEX partnered with NSF for the PRE-Depression Investigation of Cloud-Systems in the Tropics (PREDICT) and the National Aeronautics and Space Administration (NASA) on Genesis and Rapid Intensification Processes (GRIP) in a tri-agency collaborative and coordinated study of the formation of hurricanes in the Atlantic basin. In combination, these agencies deployed multiple aircraft over a 45-day period during the peak of the Atlantic hurricane season to gather robust and complementary data sets. One of the noteworthy aspects of this collaboration was the use of NASA's remotely piloted Global Hawk scientific research drone in a hurricane research capacity. It is particularly significant that the drone’s 24-hour flight time gave scientists the ability to directly observe Hurricane Karl as it changed over time in a way that conventional planes and satellites had not done before. In addition to demonstrating new skill in identifying those long-traveling Atlantic basin disturbances that ultimately deepen to form tropical depressions capable of fostering hurricane genesis, PREDICT and GRIP scientists have shed light on the processes tied to winds surging from the South American continent that ultimately played a key role in the genesis of Karl. These innovative interactions continued during Fiscal Years 2011 and 2012, with IFEX partnering with NASA during their Hurricane and Severe Storm Sentinel experiment to utilize two Global Hawk drones for hurricane observation.[13]

NOAA: *In situ* Measurements of Turbulence in Hurricanes – Extreme Turbulence Probe. For a number of years as part of NOAA’s ongoing effort to improve forecasting of rapid changes in hurricane intensity, the agency has been developing a pressure-sphere anemometer – known as the Extreme Turbulence Probe – for measuring turbulence and flux within hurricanes. Since 2009, NOAA’s Air Resources Laboratory has received funding through the HFIP to deploy these probes on offshore platforms to measure air-sea exchange in hurricane conditions. Funding for onshore deployment of the probes in Fiscal Years 2011 and 2012 allows for measurements when hurricanes make landfall. Data from the probes are being used to better understand wind loading on structures. The wind energy industry has also expressed interest in such measurements as a means to better understand the impacts of hurricanes on near-shore wind farms.

4.1.2 Tornadoes, Thunderstorms, and Other Severe Weather

[13] Murillo, S. Summary of NOAA’s 2011 Hurricane Field Program. Available at: http://www.nws.noaa.gov/om/.../NOAA-Hurr-Conf-IFEX2011-Murillo.ppt

Tornadoes and other severe weather such as thunderstorms also continue to claim lives and cause damage in the United States on an annual basis. Historic tornado events such as the tornado that ravaged Alabama in April 2011 and the largest tornado ever recorded which struck El Reno, Oklahoma in May 2013 during Fiscal Year 2013 cause havoc and terrorize communities. In June 2012, a derecho straight-line windstorm moved through the Ohio Valley and mid-Atlantic regions producing widespread, significant wind damage and the highest recorded June or July wind gusts at several official observing sites along its path, including: Fort Wayne, Indiana; Zanesville, Ohio; and Huntington, West Virginia.[14] The storm struck nearly every metropolitan area in a wide path that extended from Chicago, Illinois and Indianapolis, Indiana to Baltimore, Maryland and Washington, District of Columbia. More than four million people lost power and 22 were killed.[15]

Investments over the last two decades have led to advances in the understanding of tornadogenesis and improvements in windstorm prediction and have enabled NWS to double the average lead time for tornado warnings to 13 minutes[16]. Yet, even with the application of best-available science, the rate at which warnings result in false alarms remains high, at 70 percent[17]. To reduce this rate and further increase warning lead times for devastating windstorms such as tornadoes and the June 2012 derechos mentioned above, the Federal agencies conducted an array of focused efforts during the fiscal period. Examples of agency efforts related to tornadoes, thunderstorms, and other severe weather follow below.

NOAA: Warn-On-Forecast. NOAA's National Severe Storms Laboratory (NSSL) is working with the NWS to develop a new vision for the warning decision process, which continues to evolve as scientists and engineers work toward integrating the next generation radar (e.g., rapid scanning phased array radar and very rapid-scanning radar with data in < 1 minute) and storm-scale numerical models to create a storm-scale prediction capability for the NWS. The NSSL will continue to investigate various model parameterization schemes, along with techniques to improve model initialization through three- and four-dimensional data assimilation. Beginning in Fiscal Year 2010 and continuing through this reporting period, the NSSL received funding to support the Warn-on-Forecast (WoF) program. Within the next decade, the NSSL envisions operational units evaluating a Warn-on-Forecast methodology, allowing forecasters to use thunderstorm-resolving computer models to guide severe weather warnings for tornadoes, winds, hail, and flash floods in the same way they do today with the current Doppler radar systems. In conjunction with the WoF program, NSSL is also demonstrating the capabilities of the Multi-function Phased Array Radar (MPAR), a program funded through NOAA Office of Oceanic and Atmospheric Research to NSSL with large technical contributions from industry and academia. The MPAR project was established to demonstrate the potential to simultaneously perform aircraft tracking, wind profiling, and weather surveillance with a single, phased array

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[14] NOAA/SPC, *The Ohio Valley/Mid-Atlantic Derecho of June 2012*, http://www.spc.noaa.gov/misc/AbtDerechos/casepages/jun292012page.htm#

[15] NOAA/SPC, *The Ohio Valley/Mid-Atlantic Derecho of June 2012*, http://www.spc.noaa.gov/misc/AbtDerechos/casepages/jun292012page.htm#

[16] NOAA, *Tornadoes 101: Stay alert and stay alive*, http://www.noaa.gov/features/03_protecting/tornadoes101c.html

[17] From VORTEX2 website: http://www.vortex2.org/home/

weather radar.[18] NOAA's National Weather Radar Testbed is a phased array radar actively being tested and evaluated in Norman, Oklahoma. Evidence suggests that these enhancements to operational weather capabilities will lead to a more accurate warning system, increase lead time, and provide probabilistic information to the public to support risk-wise actions during severe weather events. The WoF program is being conducted in collaboration with the NOAA Earth Systems Research Laboratory Global Systems Division (ESRL/GSD), the NWS SPC, and the NWS Forecast Office in Norman, Oklahoma.

NOAA/NSF: Verification of the Origins of Rotation in Tornadoes Experiment 2. In Fiscal Years 2009 and 2010, the NSF and NOAA jointly supported the Verification of the Origins of Rotation in Tornadoes Experiment 2 (VORTEX2), which was the largest and most ambitious tornado field study conducted to date. This $14 million effort involved nearly 100 scientists and students from 16 American universities and academic organizations; forecasters from NOAA/NWS and the NWS SPC; and Environment Canada, the Australian Bureau of Meteorology, and the Finnish Meteorological Institute. The VORTEX2 teams sought to better understand how, when, and why tornadoes form. Specifically, they investigated the wind, temperature, and humidity conditions that result in the development of tornadoes within thunderstorms; the detailed structure of tornadic winds and their relationship to localized damage patterns; and the relationships between tornadoes, their parent thunderstorms, and the larger-scale environment. Further analysis in Fiscal Years 2011 and 2012 of these and other data from the two-year VORTEX2 experiment is advancing the understanding of tornado formation, improving prediction, and offering prospects for increased warning times. Ongoing analyses are pointing to a complex interplay of previously-recognized broad storm-scale rotation and far more subtle processes hinging on the detailed makeup and evaporative potential of precipitation particles within the rear-flank regions of supercell thunderstorms in triggering (or in some cases, apparently blocking) the spin-up of intense near-surface rotation on the tornado scale.

NSF: Center for Collaborative Adaptive Sensing of the Atmosphere. The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), an NSF-funded Engineering Research Center led by the University of Massachusetts, seeks to increase the warning times and forecast accuracy for tornadoes and other severe weather. During the fiscal period, a CASA data stream was integrated into NOAA’s Advanced Weather Interactive Processing System (AWIPS) with the assistance of researchers from the NSSL, allowing for the display of real-time data from the Integrated Project 1 Systems Test Bed (located in southwestern Oklahoma) to be accessed by NWS forecasters, warning coordination meteorologists, and other key personnel who assist in storm evaluation, local warning issuance, and siren activation. The CASA radar data were also accessed by emergency management personnel, both at operational centers and in the field via wireless communications technologies, to facilitate improved neighborhood-level response to severe weather events impacting the testbed region. During Fiscal Year 2012, arrangements were solidified in collaboration with the NOAA/NWS Office of Science and Technology, the Dallas-Fort Worth NWS Forecast Office, and North Central Texas Council of Governments and its member municipalities to relocate CASA testbed operations to the Dallas-Fort Worth, Texas metropolitan region, which will allow for a more intensive evaluation of system performance and emergency management user integration in a major urban area and transportation hub. An initial

[18] From MPAR website: http://www.nssl.noaa.gov/tools/radar/mpar/

four-radar network is set to begin full operation in 2013 and plans call for four additional sites to be added to extend coverage to the zone east of Dallas-Fort Worth, Texas soon thereafter.

NOAA: Hazardous Weather Testbed. During Fiscal Years 2011 and 2012, NOAA's NSSL, NWS SPC, and NWS Forecast Office in Norman, Oklahoma, continued joint testing of new techniques and applications for enhancing forecasts and warnings of hazardous weather, particularly thunderstorms and their attendant damaging winds, hail, and tornadoes. This project – the Hazardous Weather Testbed (HWT) – is designed to accelerate the transition of promising new meteorological insights and technologies into advances in forecasting and warning for hazardous mesoscale weather events throughout the United States. The testbed project includes the University of Oklahoma's Center for Analysis and Prediction of Storms and the NOAA/NASA Geostationary Operational Environmental Satellite – R Series (GOES-R) Proving Ground as core partners for numerical prediction and satellite observations, respectively. Several collaborative experiments like GOES-R are conducted within the HWT each year, often involving multiple external partners such as the National Center for Atmospheric Research, other universities, and various NOAA agencies.

NOAA: Severe Hazards Analysis and Verification Experiment. Within the fiscal period, NOAA's NSSL collected high-resolution severe weather reports as part of the Severe Hazards Analysis and Verification Experiment (SHAVE). The primary goal of the SHAVE program during this initial period has been to blend high-resolution radar data with geographic information system (GIS) data to obtain detailed verification of automated, radar-based hail algorithms as well as algorithms related to wind damage and flash flooding. SHAVE further expanded in Fiscal Years 2011 and 2012 to include lightning and severe winter weather. The algorithms are validated based on severe weather reports obtained through the NWS's verification process. The high spatial and temporal resolution of the GIS datasets collected by this project will facilitate the development of decision-making tools that improve forecasts and warnings of severe thunderstorms, tornadoes, and winter weather and pave the way for improvements to the historical severe storms database.

NOAA: Toward Seasonal Prediction and Long-term Severe Weather Variability in a Changing Climate. In Fiscal Year 2012, the NWS SPC partnered with the NWS Climate Prediction Center, academia, and the NOAA NSSL to work toward an improved understanding of the links between large-scale climate variability and windstorm and tornado activity. The NWS SPC maintains the long-term observational record of severe weather in the United States, and a result of initial interactions occurring in Fiscal Year 2012, a NOAA "State-of-the-Science Fact Sheet" titled *Tornado Activity and Climate Variability and Change* was created. This publication has been accepted pending revisions and will be highlighted by NOAA in Fiscal Year 2013. The SPC has also recently collaborated with scientists from the International Research Institute, at the Earth Observatory at Lamont-Doherty Laboratory, Columbia University to test the viability of using climate forecasting models in detecting seasonal severe-weather trends.[19] This ongoing research shows promise and may contribute to extending

[19] Representative publication: Tippett, M.K., Sobel, A.H., and Camargo, S.J., 2012: Association of U.S. tornado occurrence with monthly environmental parameters. *Geophys. Res. Lett.*, 39, L02801, doi:10.1029/2011GL050368

NOAA's forecasts for damaging windstorm and tornado episodes and to developing longer-lead risk assessments that vary as a function of climate change.

NSF: Development of SPA-10 Storm Penetrating Aircraft. Through cooperation with several branches of the Department of Defense in Fiscal Year 2012, NSF obtained access to a previously mothballed A-10 Thunderbolt II aircraft. This platform will be suitably modified (e.g., to include improved de-icing capabilities) and instrumented to obtain in-storm measurements in a variety of weather systems, including high-wind producing thunderstorms. Once readied for use, the platform will be housed and operated for NSF by the U.S. Navy's Center for Interdisciplinary Remotely-Piloted Aircraft Studies in Monterey, California. The storm-penetrating A-10 (SPA-10) replaces a smaller, single-engine propeller-driven T-28 aircraft that was previously supported by NSF but retired in 2005, and will bring greatly enhanced capabilities for direct meteorological sampling in a variety of hazardous weather environments. In particular, the A-10's high-altitude capabilities (an operational ceiling approaching 40,000 ft (~12 km) mean sea level) will allow researchers to directly observe various aspects of internal storm structure and associated dynamics as well as to evaluate model-based forecasts of these storms. The A-10's comparatively low stall speed is ideal for detailed sampling of in-storm cloud and precipitation microphysics involved in energy release and evaporative processes pivotal to generation of high thunderstorm winds ultimately reaching the surface. The SPA-10 is currently undergoing refurbishment and installation of specialized meteorological instrumentation and is expected to begin limited flight testing in the spring of 2015.

4.2 ASSESSING AND REDUCING WINDSTORM IMPACTS

Federal efforts to assess and reduce the impacts of windstorms cover a wide range of activities, including: studying the performance of buildings, structures, and infrastructure during and after windstorms; research, development, and technology transfer of windstorm modeling, simulation, risk assessment, and loss estimation techniques; development of cost effective windstorm-resistant materials and systems; and information dissemination and outreach to a wide range of stakeholders in the engineering and construction industries, government, and the general public (see Section 4.3 for additional information on outreach activities).

During Fiscal Years 2011 and 2012, NSF and NOAA supported research in areas of simulation of hurricane and tornado wind fields and the understanding of tornado, hurricane, and wind-driven rain effects on buildings. NIST activities included development of improved tools for estimating wind hazards and combined hurricane wind, storm surge, and wave hazards, and estimation of wind loads on structures. NIST and FEMA conducted post-windstorm studies, and results of such prior and current studies led to changes in building codes to improve windstorm resistance. NOAA and FEMA supported the continued development of hurricane loss estimation models. FHWA activities included real-time monitoring of weather conditions and bridge response to winds and physical and computational modeling of wind effects on highway structures. NSF also supported research related to resilience to natural hazards.

4.2.1 Buildings and Structures

NIST: Wind Engineering. NIST's wind engineering research is focused on developing the measurement science, tools, and methodologies necessary to substantially improve: (1) wind hazard estimation through better extreme wind databases and maps; (2) the estimation of wind loads on structures, through the development of database-assisted design techniques incorporating wind directionality effects and prediction of structural responses to these loads; and (3) science-based methodologies for aerodynamic simulation and measurements, for determination of wind loads on buildings and structures. Progress in wind-hazard estimation during Fiscal Years 2011 and 2012 saw the completion of the new United States extreme-wind database, including validation of historical data, standardization of wind data to uniform height (10 m) and terrain (flat, open), and separation of extreme-wind speed records by storm type (tropical, thunderstorm, other).[20] Also in Fiscal Years 2011 and 2012, NIST: (1) commenced the development of design wind speed maps based on the new extreme wind database, intended for submission to the American Society of Civil Engineers (ASCE) Standard on Minimum Design Loads for Buildings and Other Structures (ASCE 7); and (2) finished work on a multi-year effort to develop database-assisted design tools to improve the estimation of wind loads and structural responses, with software completed for wind design of high-rise reinforced concrete buildings.[21] The software is available online, along with the previously completed software tools for wind design of high-rise steel frame buildings and for low-rise buildings, at http://www.nist.gov/wind. Additionally, NIST initiated new research during Fiscal Years 2011 and 2012 to develop science-based methodologies for aerodynamic simulation and measurements, investigating a novel approach to atmospheric turbulence modeling that could potentially help simplify and improve standardization of both wind tunnel and computational wind engineering methods for determining wind loads.[22]

FEMA: Improving Wind-Resistant Provisions. During the fiscal period, FEMA continued to work with its partners to develop and incorporate high-wind-resistant provisions and requirements in the Nation's model building codes and standards. Working with other Federal agencies, state and local governments, building regulators, building industry groups, and other entities, FEMA advocated for specific changes to increase wind-resistant requirements of the following building and structural codes: International Building Code (IBC), International Residential Code (IRC), International Code Council Storm Shelter Standard (ICC-500) and High Wind Standard (ICC-600), and other industry regulations such as ASCE 7. As a result of these efforts, buildings are being built stronger, reducing the risks of death, injury, and property loss from high-wind storms.

NSF: Hurricane Wind and Wind-Driven Rain Impact on Buildings. Windstorms of hurricane-force cause a large amount of damage by high winds and wind-driven rain. Even when visible damage is not evident, the interior of houses and small commercial buildings can sustain large amounts of economic losses due to wind-driven rain. During the fiscal period, NSF awarded three grants – one each to the University of Florida, Louisiana State University, and Florida International University – to investigate the problem of wind and wind-driven rain

[20] Representative publication: Lombardo, F.T., *Improved extreme wind speed estimation for wind engineering applications*, Journal of Wind Engineering & Industrial Aerodynamics, Volumes 104–106, May–July 2012, pages 278-284

[21] Representative publication: Yeo, D. and Simiu, E., *High-Rise Reinforced Concrete Structures: Database-Assisted Design for Wind*, J. Struct. Eng., Vol. 137, No. 11, Nov. 2011, 1340-1340

[22] Representative publication: Yeo, D. and Chowdhury, A.G., *A Simplified Wind Flow Model for the Estimation of Aerodynamic Effects on Small Structures*, Journal of Engineering Mechanics-ASCE, in press

damage and to develop cost-effective mitigation measures. The three institutions have the goal of educating young professionals to be knowledgeable in building-design improvements that protect against high wind and wind-driven rain.

NSF: Tornado Impact on Residential Structures. In Fiscal Year 2011, the U.S. experienced many tornadoes that caused large amounts of destruction and numerous fatalities. An NSF grant was awarded to the University of Florida to document and assess the severity of damages caused in Tuscaloosa, Alabama and Joplin, Missouri. In addition, a Young Investigator Career grant was awarded for an extended period (generally five years) to pursue research beyond the current practice with the hopes of discovering innovative approaches to mitigate damage to residential and commercial buildings during tornadoes. Potential use of new material, connections, construction methods, and other possible avenues resulting from this research can lead to more cost-effective construction and reduce damages from tornadoes.[23]

NOAA: Reducing Wind-Induced Damages. During the fiscal period, and with funding from NOAA, Iowa State University collected wind data in the vicinity of tornadoes for verification and calibration of a wind simulation and testing simulator. Additional tasks undertaken by Iowa State include:

- Working to simulate hurricane winds around built structures;
- Modeling tornadic winds near a "rough" surface in a tornado simulator;
- Simulating straight-wind and tornado flow fields in and around different types and configurations of buildings and vegetative barriers;
- Assessing wind damage potential of buildings as a function of distribution of local wind speed and wind-borne debris impacts;
- Studying the optimum shelterbelt configuration to reduce hurricane wind hazard to cities along coastal areas; and
- Investigating a new aerodynamic shape of an extreme-wind-resistant residential building.[24]

NIST: Combined Hurricane Storm Surge, Wind, and Wave Modeling. NIST's research on storm surge is aimed at providing a science-based methodology for accurate characterization of the risks associated with combined hurricane hazards, including hurricane wind, storm surge, and waves. The methodology will provide: (1) estimation of design risk associated with combinations of hurricane wind speeds and storm surge heights, with appropriate accounting for site dependency (i.e., the effects of local topography and bathymetry on which storm surge at any specific location is highly dependent); and (2) consideration of the effects of waves, which add to total inundation. During Fiscal Years 2011 and 2012, NIST completed development of the

[23] Representative publication: Prevatt, D.O., Van de Lindt, J.W., Back, E., Graettinger, A.J., Pei, S., Coulbourne, W., Gupta, R., James, D., Agdas, D., *Making the Case for Improved Structural Design: The Tornado Outbreaks of 2011*, ASCE Journal of Leadership and Management in Engineering, Accepted (2012).
[24] Representative publication: Karstens, C.D. and Gallus, Jr., W.A. (2008), *Simulations of near-ground hurricane winds influenced by built structures, Extended Abstracts, 28th Conference on Hurricanes and Tropical Meteorology*, Orlando, Florida: Amer. Meteor. Soc.
Also: Sengupta, A., Haan, F.L., Sarkar, P.P., and Balaramudu, V. (2008), *Transient loads on buildings in microburst and tornado winds*, J. Wind Eng. Ind. Aerodyn, dio:10.1016/j.jweia.2008.02.050

methodology for accounting for the effects of waves on total storm surge inundation,[25] which was used for a pilot study on wave effects for the Tampa Bay, Florida area during the fiscal period.

FEMA: Mitigation Assessment Team Evaluations Following Major Hurricanes, Tornadoes and Windstorms. In Fiscal Year 2011, a FEMA Mitigation Assessment Team (MAT) responded to the April tornadoes in the southeastern United States and the May 22 tornado that struck Joplin, Missouri. FEMA deployed a MAT to investigate the damage and provide technical assistance to the affected communities through the Joint Field Offices established in response to these events. Examples of some of the products conceived as a result of recent studies include eight new Recovery Advisories (RA) from the tornado MATs for Alabama, Mississippi, Tennessee, Georgia, and the Joplin, Missouri tornado outbreaks:

- RA1 – Tornado Risks and Hazards in the Southeastern United States;
- RA2 – Safe Rooms: Selecting Design Criteria;
- RA3 – Residential Sheltering: In-Residence and Stand-Alone Safe Rooms;
- RA4 – Safe Rooms and Refuge Areas in the Home;
- RA5 – Critical Facilities Located in Tornado-Prone Regions: Recommendations for Facility Owners;
- RA6 – Critical Facilities Located in Tornado-Prone Regions: Recommendations for Architects and Engineers;
- RA7 – Rebuilding and Repairing Your Home after a Tornado; and
- RA8 – Reconstructing Non-Residential Buildings after a Tornado.

The FEMA MAT investigated the performance of residential buildings, commercial and industrial buildings, critical and essential facilities, and infrastructure as well as safe rooms, storm shelters, hardened areas, and tornado refuge areas. Additionally, the MAT rated building damage according to the Enhanced Fujita (EF) tornado scale to assess wind speeds exerted on affected buildings and developed conclusions and recommendations based on their assessments. The final MAT report (FEMA P-908: *Mitigation Assessment Team Report – Spring 2011 Tornadoes: April 25-28 and May 22; Building Performance Observations, Recommendations, and Technical Guidance*) was released in Fiscal Year 2012 and presents field observations and conclusions, which include:

- Propose changing IBC code to require all new elementary, middle, and high schools with 50 or more occupants and all new 911 call stations, emergency operation centers, and fire, rescue, ambulance, and police stations to have a FEMA P-361: *Design and Construction Guidance for Community Safe Rooms*-compliant safe room or an ICC-500-compliant storm shelter in areas where the shelter design wind speed for tornadoes is 250 mph;
- Adopt and enforce current model building codes;
- Increase emphasis on code compliance;

[25] Representative publication: Phan, L.T. and Simiu, E.; *Estimation of risk for design of structures exposed to combined effects of hurricane wind speed and storm surge hazards*, ICASP11, Applications of Statistics and Probability in Civil Engineering, Faber, Köhler, and Nishijima (eds), 2011 Taylor & Francis Group, London, ISBN 978-0-415-66986-3

- Maintain and rigorously enforce the adopted model building code since amendments or lax enforcement practices may weaken the continuous load path of the building; and
- Implement voluntary best practices to mitigate damage to one- and two family residential buildings.

For Fiscal Year 2013, FEMA is also performing a MAT study on the Hurricane Sandy disaster, due for public release in September 2013.

NIST: Study of the Dallas Cowboys Indoor Practice Facility Collapse. Following the collapse of the Dallas Cowboys indoor practice facility during a thunderstorm on May 2, 2009, NIST conducted a study in collaboration with NOAA's NSSL to determine how and why the facility collapsed. The facility was a fabric-covered, tubular, steel-frame structure, a design often used for sports facilities, industrial and agricultural facilities, casinos, military installations, and aircraft hangars. The final report,[26] which was completed in Fiscal Year 2010, included recommendations for improving the safety of these structures. During Fiscal Years 2011 and 2012, NIST worked with the ASCE to develop code change proposals. Two code changes, responsive to NIST's recommendation, were adopted by the ICC for the 2015 IBC.

NIST: Technical Investigation of the Joplin Tornado. Following the May 22, 2011 tornado that devastated the city of Joplin, Missouri, NIST sent four engineers to the area from May 24 through May 28 to conduct preliminary reconnaissance. Based on analysis of the data collected and other criteria required by law and regulation, the NIST Director established a team under the National Construction Safety Team (NCST) Act on June 29, 2011 to proceed with a more comprehensive study of the impacts of the disaster. The NCST study is ongoing during the fiscal period, and the team includes staff from NIST and NOAA. The primary objectives of the Joplin tornado study[27] are to:

- Determine the tornado hazard characteristics and associated wind fields in the context of historical data;
- Determine the pattern, location, and cause of fatalities and injuries and associated performance of emergency communications systems and public response;
- Determine the response of residential, commercial, and critical buildings, including the performance of designated safe areas;
- Determine the performance of lifelines as it relates to the continuity of operations of residential, commercial, and critical buildings; and
- Identify areas in current building, fire, and emergency communications codes, standards, and practices that warrant revision.

FHWA/NIST/NOAA/NSF: U.S.-Japan Panel on Wind and Seismic Effects. FHWA, NIST, NOAA, and the NSF all participate on the U.S.-Japan Panel on Wind and Seismic Effects. NIST

[26] Gross, J.L., Main, J.A., Phan, L.T., Sadek, F.H., Cauffman, S.A., and Jorgensen, D.P., *Final Report on the Collapse of the Dallas Cowboys Indoor Practice Facility, May 2, 2009.* NISTIR 7661, National Institute of Standards and Technology, Gaithersburg, Maryland, January 2010

[27] Levitan, M.L., Phan, L.T., Kuligowsli, E.D., Lombardo, F.T., and Jorgensen, D.P., *Investigation Plan, National Institute of Standards and Technology (NIST) Technical Investigation of the Joplin, Missouri, Tornado of May 22, 2011*, NIST Special Publication 1132, May 2012

also chairs and provides a technical secretariat for the panel. The panel serves as a mechanism for the exchange of technical data, information, and researchers, as well as the coordination of joint research on wind and seismic-related topics of mutual interest to the United States and Japan. NIST and FHWA staff participate on the panel and its wind engineering Task Committees addressing wind and storm surge hazards, specifically the Task Committee "D" (Wind Engineering), Task Committee "G" (Transportation), and Task Committee "H" (Storm Surge and Tsunami) groups. The Task Committee "D" group has held five international workshops and the Task Committee "G" group has held 28 such workshops. During Fiscal Year 2011, the U.S. hosted a side-panel meeting in San Francisco, California. Meetings and workshops were hosted by Japan in Tsukuba, Japan, including site visits to areas damaged by coastal inundation resulting from the tsunami following the March 2011 Tohoku Earthquake. The U.S. also hosted a bridge engineering workshop in Portland, Oregon during Fiscal Year 2012.

NIST: Hurricane-Borne Missiles. During the fiscal period, NIST conducted a study for the United States Nuclear Regulatory Commission (NRC) to develop the technical basis for a potential new regulatory guide that would provide licensees and applicants with guidance that the staff of the NRC considers acceptable for use in selecting the design-basis and hurricane-borne missile speeds for the design of nuclear power plants.[28]

NIST/NSF: R&D Roadmap for Windstorm and Coastal Inundation Impact Reduction. NIST and NSF jointly sponsored a two-day workshop in June 2012 to gather input from scientists, engineers, and other stakeholders in professional practice, industry, academia, and government to support the development of a measurement science R&D roadmap for windstorm and coastal inundation impact reduction. Federal Government participants included representatives from FEMA, FHWA, HUD, NOAA, OSTP, and USGS, in addition to NIST and NSF. The roadmap will be completed in Fiscal Year 2013.

4.2.2 Bridges and Highways

FHWA: Monitoring of Wind Conditions and Structural Performance. During the fiscal period, the FHWA Office of Infrastructure Research and Development (HRDI) monitored winds and structural performance at selected bridge sites to establish and characterize site-specific wind conditions and the responses of the bridges to varying wind conditions. The sites of two major long-span, cable-supported bridges were monitored during the reporting period – the Deer Isle-Sedgwick Bridge (Maine) and the Hale Boggs Bridge (Louisiana). Data was collected on a continuous basis; however, few major storm events were observed with the exception of Hurricane Isaac in August 2012. The data gathered during this monitoring period provided valuable information for the calibration of numerical tools and predictive methods; the improvement of physical modeling techniques in the laboratory; the evaluation and validation of new designs; and the development and assessment of mitigation measures.

FHWA: Full Scale Measurement of Structural Dynamic Properties. In an ongoing program to characterize the dynamic properties of bridge stay cables, which are critical to structural

[28] Simiu, E. and Potra, F., *Technical Basis for Regulatory Guidance on Design-Basis Hurricane-Borne Missile Speeds for Nuclear Power Plants*, NUREG/CR-7004, U.S. Nuclear Regulatory Commission, November 2011

performance and aerodynamic stability, the analysis of data from full-scale, forced vibration tests on selected major structures continued during Fiscal Years 2011 and 2012. Tests had been previously performed on the Zakim (Massachusetts), Emerson (Missouri), and Penobscot Narrows (Maine) bridges. Information collected during the tests has enabled further evaluation of design details and assessment of the effectiveness of various mitigation measures such as dampers, cross ties, and aerodynamic surface treatments. The information also serves as a benchmark that will be useful during later inspections to assess the bridge's structural condition and overall health.

FHWA: Physical Modeling of Wind Effects on Highway Structures. A project continued during the fiscal period under FHWA's Exploratory Advanced Research (EAR) program to develop a new system to perform volumetric particle image velocimetry. This will enable detailed flow visualizations during laboratory study of fluid-structure interactions. This new technology will be a valuable tool in performing aerodynamic studies of wind effects on highway structures as well as for hydraulic issues associated with scour and storm surge. Another project underway within the EAR program will develop a system using pressure-sensitive paint and surface-stress-sensitive film to measure wind forces on structural models in the laboratory. Two small-scale bridge models, fabricated and instrumented with pressure taps in the previous reporting period, were tested in the FHWA's small wind tunnel at the Turner-Fairbank Highway Research Center (TFHRC) to evaluate the performance of pressure-sensitive paint and surface-stress-sensitive film as sensing technologies in the laboratory setting. In collaboration with the National Research Council of Canada (NRCC) and in cooperation with the University of Stavenger in Norway, the University of Bristol in the United Kingdom, and the design consultancy firm RWDI, wind tunnel tests were performed at NRCC on a full-scale section model of a bridge stay cable. Tests were performed in simulated wind conditions over a broad range of wind speeds to evaluate the influence of wind speed, turbulence intensity, wind/cable orientation, cable roundness, and aerodynamic surface treatment on overall performance and aerodynamic stability.[29]

FHWA: Numerical Modeling of Wind Effects on Highway Structures. During the fiscal period, an interagency agreement has continued between the Department of Transportation (DOT) and the Department of Energy (DOE) for modeling the effects of natural hazards, such as windstorms, hydraulics, and flooding, on infrastructure. This agreement enables FHWA to utilize high-performance computing and support staff from the Argonne National Laboratory (ANL). Resources located at the Transportation Research and Analysis Computing Center (TRACC) are being used to model wind effects on highway users as well as highway structures. A detailed Computational Fluid Dynamics (CFD) model of the FHWA Aerodynamics Laboratory at TFHRC, including the large wind tunnel, was developed to evaluate performance of the facility and to enhance simulation capability. Special techniques have been developed by ANL staff to couple CFD software with computational structural mechanics software to enable study of wind and structure interaction problems. These emerging tools were used to develop initial models to study the interaction of wind with inclined bridge stay cables as well as wind (or truck-induced gust) interaction with large message sign structures. ANL staff has also refined skills with using

[29] Larose, G.L., D'Auteuil, A., *Wind Tunnel Investigations of an Inclined Stay Cable with a Helical Fillet,* LTR-AL-2011-0093, National Research Council Canada, Ottawa, Ontario, Canada, October 2011

moving mesh capabilities of CFD software so that objects, such as trucks, can be moved through still air or wind fields to study fluid/structure interaction. These CFD tools were used to study the impact of salt spray from trucks, moving either through still air or a wind field, on weathering steel girders of highway overpasses. They were also incorporated into the aforementioned study on message signs. In another area, finite element modeling, using the commercial program SAP 2000, was performed to study the efficacy of various approaches for mitigating wind-induced vibration of bridge stay cables. A comprehensive laboratory report was submitted for publication and should be available early in the next biennial reporting period.[30]

FHWA: Development of Design Guidelines. Research continued in Fiscal Years 2011 and 2012 on the issue of wind- and rain-induced vibration of bridge stay cables. The FHWA draft guidelines document on the aerodynamic design of bridge stay cables was further updated. Following review and approval, the document will provide guidance on the aerodynamic design of cables and cable networks on major new highway bridges and for the retrofit of existing structures to mitigate wind-induced vibration problems.

4.2.3 Power Grid, Aviation, and U.S. Space Centers

NOAA: High-Resolution Rapid Refresh Model. To improve guidance for air traffic managers and other windstorm prediction and forecasting applications, NOAA scientists at the ESRL/GSD developed and tested a High-Resolution Rapid Refresh (HRRR) weather forecast model. The HRRR is a 3 km research version of the coarser (12 km) resolution Rapid Refresh (RAP) Model, which replaced the Rapid Update Cycle model as the NOAA next-generation hourly-updated assimilation/modeling system operational at the NOAA National Center for Environmental Prediction in May 2012. The HRRR is an hourly-updated, radar-initialized, storm-resolving model currently covering the U.S. It is designed to provide air traffic managers with rapidly updated projections of developing severe weather and potential windstorms. During the fiscal period of 2011 and 2012, NOAA scientists made several breakthroughs, including the development of an effective technique for assimilating 3-D radar reflectivity data into the RAP Model.

NOAA: Hazardous Weather System for U.S. Space Centers. Operations at United States space centers are heavily dependent on severe weather conditions and windstorm forecasts. Safety regulations restrict work on tall gantries, shuttle transport, refueling, and other operations during high wind events. Winds may also impact safety following rocket blasts, fuel spills, and other accidents by carrying toxins from an accident zone farther afield. During the fiscal period, NOAA's ESRL/GSD developed and implemented a state-of-the-art analysis and forecasting system supporting the Eastern and Western Ranges as part of the Range Standardization and Automation (RSA) program. Due to advances by the RSA program in Fiscal Years 2011 and 2012, NOAA now can deliver 24-, 12-, and nine-hour forecasts of varying spatial resolutions to address space center needs.

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[30] Bosch, H., Park, S., and Shen, J. (Pending), *Mitigation of wind-induced vibration of stay cables: numerical simulations and evaluations*, FHWA Staff Report Number TBD, FHWA/TFHRC, McLean, VA, Date TBD

NOAA: Microburst Studies. The NSSL maintained an ongoing program with the Arizona-based Salt River Project (SRP), which provides electricity and water management to the Phoenix, Arizona metropolitan area, to study and document the impact of severe winds on electrical power infrastructure. During SRP field operations, radar is automatically monitored for thunderstorms reaching thresholds that could result in outflows producing strong surface winds and blowing dust. When thresholds are reached, operational personnel receive an alert to prepare for the impact of wind loading on SRP power poles and substations. In a prior fiscal period during summer 2008, 140 microburst windstorms were identified in Phoenix and the surrounding Sonoran Desert. The Sonoran microbursts were studied and examined for their frequency and characteristics, as observed from data collected from three Doppler radars and electrical power infrastructure damage reports. Stronger maximum differential wind velocities were observed more frequently in the Sonoran microbursts than in many previously documented microbursts. Further comparison analysis conducted in Fiscal Years 2011 and 2012 of the Doppler radar data to the wind damage reports found that the microburst winds caused more significant damage to electrical power infrastructure than gust-front winds.

NOAA/NSF: Reliability-Based Hurricane Risk Assessment for Offshore Wind Farms. Meeting the national goal of generating 20 percent of total energy needs from renewable source by 2030 will require placing wind farms offshore. These wind farms located on the Gulf and East coasts are vulnerable to hurricanes, and in order to make offshore wind farms viable economically, it is necessary to have knowledge of how hurricane hazards can impact the fragility of wind turbines. NOAA AOML and Florida State University scientists published a paper in Proceedings of the National Academy of Sciences outlining the need for stochastic, wind field-based hurricane risk analysis. An NSF grant was awarded during the fiscal period to Northeastern University in Boston, Massachusetts to pursue research in this area and develop cost-effective design of turbine structures that will be resilient to hurricanes and other high-wind storms.

NSF: Collection of Perishable Hurricane Isaac Data on Weather-Related Damage to Power Infrastructure. Hurricane Isaac was a slow-moving tropical cyclone that severely impacted the Gulf coastlines of Louisiana and Mississippi during Fiscal Year 2012. It was a Category 1 storm with wind speeds in the range of the structural wind load design; however, the primary damage from the storm was the loss of electrical power over a large area due to high wind and a relatively large storm surge, with the total number of people affected by the power outage exceeding one million. Due to these impacts, a Rapid Response Collaborative Research (RAPID) grant was given to Louisiana State University and the University of Washington to investigate and analyze the extensive power outages due to Isaac.

4.2.4 Community Services and Resilience

NSF: CAREER Grant on Integrated Modeling of Sustainability and Reliability for Interdependent Infrastructure Systems. An NSF CAREER grant-funded research project at Johns Hopkins University awarded during the fiscal period is developing an approach for assessing the economic, environmental, and social sustainability and reliability of interdependent power and water systems. This approach will support proactive management of public and private infrastructure, particularly in areas susceptible to hurricanes and other windstorm hazards. The research is developing indicators for measuring trends in the sustainability of power and water and new computational frameworks for modeling interdependent power and water systems. The impacts of natural hazards such as hurricanes and other windstorms will be combined with the effects of aging to develop a more holistic reliability modeling approach for infrastructure systems. The reliability and sustainability models are brought into the infrastructure management process to help support meaningful change in power and water systems in hazard-prone areas.

NSF: From Warnings to Evacuation in Hurricanes: A Holistic Investigation Using an Interdisciplinary Approach. In Fiscal Years 2011 and 2012, researchers at Purdue University and Florida International University are developing new methodologies for hurricane evacuation by integrating behavioral modeling of household decision making with stochastic transportation modeling. The research will integrate social science concepts, network science tools, stochastic optimization, and agent base modeling (ABM) with the aim of understanding evacuation decision making at the household level. The project will undertake a survey of 800 households that have experienced a hurricane evacuation and determine what factors are related to compliance with evacuation warnings. These data will then be put into ABM transportation models. The proposal has the potential to significantly impact evacuation planning for hurricanes. An analysis of factors associated with household compliance with evacuation orders should facilitate the construction and dissemination of warning messages.

NSF: Prioritizing and Selecting Bridge Management Actions for Heightened Truck Loads and Natural Hazards in Light of Funding Allocation Patterns. During the reporting period, a team of investigators at Rice University is undertaking research related to bridge management for both normal operations and resilience to hurricanes and other windstorm hazards. It is examining both normal, day-to-day maintenance of bridges and the toll taken by aging infrastructure on survivability of bridges during extreme events. The project is developing new prioritization approaches to rank critical bridges for upgrade accounting for their vulnerability, network-level topology, and freight flow traversal. Also, the project involves probabilistic risk assessment and selection of mitigation actions to achieve operational safety, hazard protection, and economic development, while reflecting aid allocation preferences and past project experience. It is likely to produce more cost-effective normal maintenance of bridge infrastructure as well as heightened resilience from extreme events.

NOAA: State of Florida Public Hurricane Loss Model. NOAA continued to work with the State of Florida during the fiscal period on the Public Hurricane Loss Model (FPHLM). The FPHLM is an open, transparent computer model that will be used by the Florida Office of Insurance Regulation to provide a baseline for evaluating rate change requests for windstorm insurance. The FPHLM is the first such model that enables all of the results and details from the modeling approach to be open to scrutiny. The model's engineering component estimates damage to residential structures within Florida zip codes and an actuarial component then estimates the insured loss. The average annual loss is then estimated statewide for every zip code in Florida. The FPHLM was approved by the Florida Commission on Hurricane Loss Projection Methodology in August 2010 and successfully passed the state certification process initiated in late 2012.

FEMA: Maintain HAZUS-MH Hurricane Loss Estimation Model. FEMA developed and maintained the Hazards – U.S., Multi-Hazard model (or HAZUS-MH), a nationally applicable standardized methodology that contains models for estimating potential losses from multiple hazards, including hurricane winds. HAZUS-MH uses GIS technology to estimate physical, economic, and social impacts of disasters and graphically illustrates the limits of identified high-risk locations due to a region's hazards. Users can then visualize the spatial relationships between populations and other more permanently fixed geographic assets or resources for the specific hazard being modeled, a crucial function in the pre-disaster planning process. During the reporting period for Fiscal Years 2011 and 2012, a storm surge component was added to the model as a collaborative effort with support from NOAA. In addition, a NOAA hurricane scientist and a NIST wind engineer serve on the Technical Advisory Committee (TAC) for the hurricane hazard modeling portion of HAZUS-MH. The TAC provides expert review and oversight for the science and engineering behind HAZUS-MH.

4.3 OUTREACH

Reducing susceptibility to and destruction from severe windstorms requires action beyond the purview of the Federal Government. Zoning laws, building codes, and jurisdictional resources central to promoting pre-disaster mitigation and fostering disaster-resilient communities are controlled by state and local authorities. Ultimately, state, county, and municipal officials must implement sound land-use practices, informed urban-planning techniques, prudent development and reconstruction decisions, and effective disaster-response and recovery strategies that underpin resilient communities. Windstorm disaster-risk reduction is equally critical at the individual- and family-level and must be facilitated throughout community social networks.

History shows that a lack of situational awareness and preparation amongst citizens are common threads among many major wind-related disasters. By knowing one's vulnerabilities and what actions should be taken to lessen them, members of the public can reduce the harmful effects of windstorms. Disaster preparedness significantly improves one's ability to respond to the consequences of a windstorm hazard event – this means having emergency plans in place concerning what to do and where to go if a windstorm warning is issued or a hazard is observed. This type of community resilience, especially in vulnerable social populations, can be enhanced through a variety of means, including outreach and awareness programs and partnerships among Federal and state agencies and the other members of the local community. Numerous informational and educational materials are distributed each year to promote the protection of individuals and property from high-wind events, including hurricanes, tornadoes and straight-line winds and from thunderstorms. Selected examples of such activities are highlighted below.

NOAA: Weather-Ready Nation Project. In the fiscal period of this report, the Weather-Ready Nation (WRN) project was initiated by NOAA. The purpose of the WRN initiative is, first and foremost, to save more lives and livelihoods. By increasing the Nation's weather-readiness, the country will be prepared to protect, mitigate, respond to, and recover from weather-related disasters such as severe windstorms. Society's ability to prepare for natural disasters requires a societal response equal to the risk, which is why NWS is leveraging its vast nationwide network of partners, and incorporating new ones who are beginning to share the vision of building a weather-ready nation.[31] Partners in this program include: other Federal agencies, emergency managers, researchers, the media, the insurance industry, non-profits, and the private sector. In Fiscal Year 2012, three new emergency response specialists at the Baltimore, Maryland and Washington, District of Columbia forecast office under this project will allow NWS to improve its service to the region in a number of ways. For example, the office will now be able to provide a highly-trained and certified meteorologist on the scene during major weather events to give on-demand briefings.[32] Other service enhancements include: cataloging local impacts from weather to give the public and local governments more information about what actions they need to take; providing better explanations about differences between the forecast and the range of possibilities to help decision-makers plan for any possible scenario; mapping flood threats to allow emergency managers keep the public out of areas that are expected to flood; improving the distribution of weather information by keeping up with new communication technologies and social media; and working to achieve local weather-readiness where everyone gets a clear, understandable message when weather hazards such as severe windstorms are imminent and knows what to do to protect themselves. NSF joined NOAA in sponsorship of two of workshops (the first held in December 2011 at the National Weather Center in Norman, Oklahoma and the second in April 2012 in Birmingham, Alabama in recognition of recent tornado disasters impacting the southeastern United States) that served to bring together a broad range of physical and social scientists, emergency managers, and practicing forecasters to better frame next-steps in this highly cross-disciplinary activity.

FEMA: Education, Outreach, and Information Dissemination. The FEMA website, http://www.fema.gov, serves as the Nation's portal to emergency and disaster information. Most FEMA publications related to wind hazards were placed on the web, including many older documents that needed to be digitized in order to do so. Along with this digitization effort, a majority of FEMA wind and other hazard publications, which were previously uploaded to the Google Books website and are still maintained there, have now also been uploaded to MADCAD website and are now available for download on the Google E-Reader and other electronic reading devices as well as through the MADCAD system. Dozens of presentations were given at conferences and other forums highlighting the importance of hurricane mitigation, and a number of outreach documents were produced, highlighting successful wind mitigation projects. FEMA partnerships were established with external organizations such as the Disney Corporation and the Federal Alliance for Safe Homes (FLASH), which has been operating an interactive exhibit titled "StormStruck: The Tale of Two Homes" at Epcot at the Walt Disney World Resort Innoventions Pavilion for the last several years with over 700,000 annual visitors. The FLASH attraction allows visitors to experience a severe weather incident, such as a hurricane, with the goal of teaching the guests about cutting-edge technology used to protect homes.

FEMA: Development of Technical Guidance Materials on State-of-the-Art Wind-Resistant Design and Construction Methods. Each year, many thousands of publications dealing with wind hazards are ordered and distributed by FEMA. For example, FEMA partnered with Texas Tech University and others to produce guides and provisions for safe room design and

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[31] NOAA/NWS, *Weather-Ready Nation FAQs*, http://www.nws.noaa.gov/com/weatherreadynation/faqs.html
[32] NOAA/NWS, *NOAA ramps up Weather-Ready Nation initiative in nation's capital*, http://www.noaanews.noaa.gov/stories2012/20120922_weatherready.html, September 2012

construction (FEMA P-320: *Taking Shelter From the Storm: Building a Safe Room For Your Home or Small Business* and FEMA P-361: *Design and Construction Guidance for Community Safe Rooms*). During the fiscal period, over 65,000 copies of FEMA P-320 and over 8,500 copies of FEMA P-361 were distributed to organizations across the U.S. Other recent examples include:

- Produced the *Wind Retrofit Guide for Residential Buildings* (FEMA P-804, December 2010): The purpose of the document is to provide guidance on retrofitting existing buildings for improved performance during high-wind events in all coastal regions. It is applicable to one- and two-family dwellings. Although this guidance is primarily intended to be applied in the hurricane prone regions of the United States, it may also be applied to other regions.
- Completed an appendix to the *Mitigation Assessment Team Report from the Spring 2011 Tornadoes* (FEMA P-908, May 2012): This appendix provides prescriptive guidance for enhanced construction techniques to improve performance of wood-frame residential structures when impacted by tornadoes rated EF-2 or less.
- Updated the *Home Builder's Guide to Coastal Construction, Technical Fact Sheet Series* (FEMA P-499, December 2010): A series of 37 fact sheets provide technical guidance and recommendations concerning the construction of coastal residential buildings. The fact sheets are aimed at improving the performance of buildings subject to flood and wind forces in coastal environments. Photographs and drawings illustrate the recommended design and construction practices for building components, including structural connections, the building envelope, and utilities.
- Updated the *Coastal Construction Manual Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas* (FEMA P-55 Volume I, August 2011): This is a two-volume publication that provides a comprehensive approach to planning, siting, designing, constructing, and maintaining homes in the coastal environment. Volume I provides information about hazard identification, siting decisions, regulatory requirements, economic implications, and risk management. The primary audience for Volume I is design professionals, officials, and those involved in the decision-making process. Volume II contains in-depth descriptions of design, construction, and maintenance practices that, when followed, will increase the durability of residential buildings in the harsh coastal environment and reduce economic losses associated with coastal natural disasters. The primary audience for Volume II is design professionals familiar with building codes and standards and has a basic understanding of engineering principles.

FHWA: Training and Technology Transfer. Technology transfer of high performance computational analysis techniques is an important part of ANL's work to support and advance wind-related engineering and research programs at TFHRC. The technology transfer is accomplished by publishing techniques developed and the work done in reports and papers, presentations at conferences, and training courses in CFD capabilities and techniques offered by TRACC. A second two-day, hands-on training course was developed and provided to students, professionals, and U.S. Government representatives in March 2011 at ANL. The course consisted of lectures, practical examples, and detailed hands-on tutorials to demonstrate cutting-edge capabilities and techniques using CFD. In addition, a third course with updated and expanded materials was developed and presented in March 2012.

FHWA: Seminar on Arch and Cable-Supported Signature Bridges. In Fiscal Year 2012, the National Highway Institute (NHI) launched a new training course on arch and cable-supported signature bridges with windstorm-related impacts in mind. The NHI's one-day Cable-Stayed Signature Bridge Seminar is intended to provide participants with an introduction to planning, design, and construction of long-span, cable-stayed bridges. The seminar provides an overview of the features of cable-stayed bridges; their construction and maintenance considerations; and analyses needed to design these highly redundant structures including special aerodynamic studies. Major topics covered in this seminar include: bridge configurations, construction methodology, component details, analysis, aerodynamics, design methodology, construction engineering, and maintenance and inspection.

5. THE NEED FOR CONTINUED INVESTMENT

The destructive impacts of recent extreme windstorms – including the outbreak of tornadoes in April 2011 in Alabama, Mississippi, Tennessee, and Georgia and in May 2011 in Joplin, Missouri, as well as Hurricane Sandy in October 2012, Isaac in August 2012, and Irene in August 2011 – underscore the need for continued investments to make the buildings, cities, towns, and communities in which we live, and the infrastructure upon which we depend, not only less vulnerable to the forces of nature, but also more resilient when disasters unfold. How these events affect us reflects not only the power of nature, but also the decisions we make in how we build and safeguard our communities. Although hurricanes and other windstorm-related drivers of coastal inundation, storm surge, and high wind are inevitable, disaster-resilient communities experience less damage and recover more quickly from hazard events.

Successfully reducing the impact of wind hazards requires that actions be taken, directly or indirectly, to lengthen warning lead-times while improving accuracy and precision and change or enhance existing building practices, infrastructure resilience, social behavior patterns, and evacuation processes. Recent improvements in warning systems, evacuation planning, and building technology have reduced the threat of windstorms to people even while the total number of people, buildings, and critical infrastructure exposed to windstorms has grown dramatically. Fundamental research on the meteorological aspects of wind hazards is continuing with support from the Federal agencies, and there are a number of areas where additional knowledge and action have reduced the impact of windstorms to lives and property. Notable successes have been demonstrated in the following areas:

- Advances in NOAA's satellite-based observations, supercomputers, and data assimilation and modeling have reduced average hurricane forecast track errors significantly, to about half as large as they were 15 years ago;
- Advances in the use of aircraft data have demonstrated the potential for significant improvements in hurricane intensity forecasts (20 to 40 percent), breaking a 30-year logjam in intensity forecast improvements;
- Improvements in the understanding of tornadogenesis as well as forecasting and prediction have enabled NWS to double the average lead time for tornado warnings over the past two decades to 13 minutes;

- Gains in structural engineering research and mitigation assessment have allowed FEMA to issue new guides and provisions for better and more efficient safe room design and construction against windstorms;
- Results of wind engineering research and post-storm studies by NIST have led to changes in the wind loading provisions of the ASCE 7 Standard and IBC that enhance life safety and property protection for windstorms;
- Improvements in tornado intensity estimation (developed jointly by NIST, NOAA, and Texas Tech University) have allowed the EF tornado scale to be introduced by the NWS in 2007 to reflect more accurate examinations of tornado damage surveys and to align wind speeds more closely and effectively with associated storm damage;
- Advances in cutting-edge research through NSF grants to academic institutions will improve understanding of wind, rain, and surge effects on buildings and has promoted the development of the next generation of professionals educated in the windstorm mitigation discipline; and
- Progress in research funded by NSF grants have strengthened windstorm disaster evacuation management practices in the U.S. through advancements in planning and preparedness efforts and a better understanding of how communities perform in hosting incoming evacuees.

Although the overall threat of injury or death posed by windstorms is being reduced, the total amount of damage and loss continues to rise and much more needs to be done. Further improvements in windstorm prediction capabilities are essential, and additional observations are also needed to advance understanding of how the built environment responds to windstorm events. Methods and tools for wind-hazard exposure predictions are required for structural design purposes and improved methodologies for site-specific wind models and more refined and locally-detailed wind speed/hazard maps remain a critical need. In addition, efficient warning systems and social analysis are critically needed to improve warning response, mitigate user complacency, better support effective decision making, and reduce the losses associated with devastating windstorms.

To help address these and related issues, the NWIRP agencies, academia, and the private sector will build on past activities to identify and prioritize specific measurement science research and development needs for windstorm impact reduction. Continued support and leadership of senior Federal policymakers and a national commitment to reducing hazard vulnerability through enhanced knowledge and applied science and technology should lead to enhanced disaster prevention and resilience throughout the Nation’s communities.

APPENDIX A: AGENCY ACTIVITIES IN FISCAL YEARS 2009 AND 2010

UNDERSTANDING WINDSTORMS FOR IMPROVED PREDICTIONS, FORECASTS, AND WARNINGS

Hurricanes

NOAA: Hurricane Forecast Improvement Program. The HFIP provides the basis for NOAA and other agencies to coordinate and align Federal research with that of the larger scientific community. The specific goals of the HFIP are to reduce the average errors of hurricane track and intensity forecasts by 20 percent within five years and 50 percent within 10 years while extending the forecast period out to seven days with accuracy equal to today's five-day forecast. In Fiscal Years 2009 and 2010, HFIP provided funding to numerous efforts within NOAA, other Federal agencies, and universities to support the development, testing, and evaluation of enhanced numerical prediction systems. System demonstrations showed that five-year track forecast goals can be achieved when recently developed data assimilation systems and existing operational global models are run as an ensemble at a specific resolution (20 km). Preliminary results also showed that intensity forecasting goals can be achieved using Doppler radar and other data from aircraft, advanced data assimilation systems, and regional models, when run as an ensemble at high resolution (3 km). Another notable success of the program included the rapid transitioning of models from the research phase to development and testing as part of HFIP's Real-time Experimental Forecast System.

NOAA: Hurricane Wind Analysis System. Developed by the Hurricane Research Division of NOAA's Atlantic Oceanographic and Meteorological Laboratory, H*Wind is an integrated tropical cyclone observing system in which wind measurements from a variety of observation systems are used to objectively analyze the distribution of wind speeds in a hurricane. The product is designed to improve understanding of the extent and strength of the wind field as well as the assessment of hurricane intensity. H*Wind "snapshot" products are provided both in image and gridded form for research purposes and are useful for storm surge and wave forecasting applications. Wind swath maps are also produced and are helpful for damage and loss assessment. Within the fiscal period, retrospective analyses of 2008 Hurricanes Ike and Gustav were supplied to the U.S. Army Corps of Engineers (USACE) to be used as input to wave and storm surge models to better understand damage to coastal structures.[33]

[33] Representative publications: Dietrich, J.C., J. J. Westerink, A. B. Kennedy, J. M. Smith, R. E. Jensen, M. Zijlema, L. H. Holthuijsen, C. Dawson, R. A. Leuttich Jr., M. D. Powell, V. J. Cardone, A. T. Cox, G. W. Stone, H. Pourtaheri, M. E. Hope, S. Tanaka, L. G. Westerink, H. J. Westerink, Z. Cobell (2011). Hurricane Gustav (2008) waves and storm surge: Hindcast, synoptic analysis, and validation in Southern Louisiana. *Mon. Wea. Rev.*, 137, in press.

Kennedy, A. B., U. Gravious, B. C. Zachary, J. J. Westerink, M. E. Hope, J. C. Dietrich, M. D. Powell, A. T. Cox, R. A. Luettich Jr., and R. G. Dean (2011). Origin of the Hurricane Ike forerunner surge. *Geophys. Res. Lett.*, 38, L08608.

NOAA/NSF/NASA: Tri-agency Study on Hurricane Formation and Intensification. NOAA's Hurricane Research Division implemented a multi-year experiment to improve hurricane intensity forecasting. The IFEX is collecting observations that will aid in the improvement of current operational models and the development of the next-generation Hurricane Weather Research and Forecasting operational model. During Fiscal Year 2010, the NOAA IFEX team partnered with NSF and NASA in a tri-agency study of the formation of hurricanes in the Atlantic basin. In combination, these agencies deployed multiple aircraft over a 45-day period during the peak of the Atlantic hurricane season to gather robust and complimentary data sets. Within this broader effort, the NSF's PREDICT field experiment specifically focused on multi-scale interactions in the tropical wave-like disturbances that influence cyclone formation. During the effort, NASA's GRIP experiment featured the debut of the agency's Global Hawk drone in a hurricane research capacity. The drone's 24-hour flight time gave scientists the ability to directly observe Hurricane Karl as it changed over time in a way that conventional planes and satellites had not done before. The time on station for conventional manned aircraft reconnaissance is typically about 6 hours, with a lapse of about 6 hours before the next aircraft may arrive when the storm is within reach of conventional aircraft. Unmanned aircraft have significantly more capacity for time on station – typically up to 24 hours for a single aircraft – allowing continuous surveillance of the storm to measure high frequency (1 hour or less) changes in storm structure not observable by other platforms.

NOAA: *In situ* Measurements of Turbulence in Hurricanes – Extreme Turbulence Probe. As part of NOAA's ongoing effort to improve forecasting of rapid changes in hurricane intensity, the agency has been developing a pressure-sphere anemometer – known as the Extreme Turbulence Probe – for measuring turbulence and flux within hurricanes. Since 2009, NOAA's Air Resources Laboratory has received funding through the HFIP to deploy these probes on offshore platforms to measure air-sea exchange in hurricane conditions. Funding for onshore deployment of the probes would allow for measurements when hurricanes make landfall. Data from the probes will be used to better understand wind loading on structures. The wind energy industry has also expressed interest in such measurements as a means to better understand the impacts of hurricanes on near-shore wind farms.

Tornadoes, Thunderstorms, and Other Severe Weather

NOAA: Warn-on-Forecast. NOAA's NSSL is working with NWS to develop a new vision for the warning decision process, which continues to evolve as scientists and engineers work toward integrating the next generation radar (e.g., rapid scanning phased array radar) and storm-scale numerical models to create a storm-scale prediction capability for the NWS. The NSSL will continue to investigate various model convective parameterization schemes, along with techniques to improve model initialization through four-dimensional data assimilation. Beginning in Fiscal Year 2010, the NSSL received funding to support the WoF program. Within the next decade, the NSSL envisions operational units using a Warn-on-Forecast methodology, allowing forecasters to use thunderstorm-resolving computer models for severe weather warnings for tornadoes, winds, hail, and flash floods in the same way they do today with the current Doppler radar systems. Evidence suggests that these enhancements to operational weather capabilities will lead to a more accurate warning system, increase lead time, and provide probabilistic information to the public to support risk-wise actions during severe weather events.

The WoF program is conducted in collaboration with the NOAA ESRL/GSD, the NWS SPC, and the NWS Forecast Office in Norman, Oklahoma.

NOAA/NSF: Verification of the Origins of Rotation in Tornadoes Experiment 2. In Fiscal Years 2009 and 2010, NSF and NOAA jointly supported VORTEX2, the largest and most ambitious tornado field study conducted to date, at the writing of this report. This $14 million effort involved nearly 100 scientists and students from 16 American universities and academic organizations; forecasters from NWS and its SPC; as well as Environment Canada, the Australian Bureau of Meteorology, and the Finnish Meteorological Institute. The VORTEX2 teams sought to better understand how, when, and why tornadoes form. Specifically, they investigated the physical properties governing the timing and location of tornadogenesis; tornado structure; low-level winds within tornadoes and their relationship to localized damage patterns; and the relationships between tornadoes, their parent thunderstorms, and the larger-scale environment. Efforts in and around central Oklahoma yielded a particularly rich and promising set of data harvested from Multifunction Phased Array Radar and *in situ* observing assets of the Center for Collaborative Adaptive Sensing of the Atmosphere. Further analysis of these and other data from the two-year VORTEX2 experiment should advance the understanding of tornado formation, improve prediction, and offer prospects for increased warning times.

NSF: Center for Collaborative Adaptive Sensing of the Atmosphere. CASA, an NSF-funded Engineering Research Center led by the University of Massachusetts, sought to increase the warning lead-times and forecast accuracy for tornadoes and other severe weather during the reporting period. In Fiscal Years 2009 and 2010, a CASA data stream was integrated into NOAA's AWIPS, allowing for the display of real-time data from the Integrated Project 1 Systems Test Bed (located in southwestern Oklahoma) to be accessed by NWS forecasters, warning coordination meteorologists and other key personnel who assist in storm evaluation, issuance of local warnings, and siren activation. The CASA radar data were also accessed by emergency-management personnel, both at operational centers and in the field via wireless communications technologies, to facilitate improved neighborhood-level response to severe weather events impacting the test-bed region. Work is underway for the Dallas-Fort Worth CASA radar network to be fully installed and operational starting in Fiscal Year 2014, which would allow for a more intensive evaluation of system performance and emergency management user integration in a major urban area.

NOAA: Hazardous Weather Testbed. NOAA's NSSL, NWS SPC, and NWS Forecast Office in Norman, Oklahoma continued joint testing of new techniques and applications for enhancing forecasts and warnings of hazardous weather, particularly thunderstorms and their attendant damaging winds. HWT is designed to accelerate the transition of promising new meteorological insights and technologies into advances in forecasting and warning for hazardous mesoscale weather events throughout the U.S. The testbed project has also been expanded to include high-resolution model runs conducted by the University of Oklahoma's Center for Analysis and Prediction of Storms and the National Center for Atmospheric Research.

NOAA: Severe Hazards Analysis and Verification Experiment. Within the fiscal period, NOAA's NSSL collected high-resolution severe weather reports as part of the SHAVE program. The primary goal of the SHAVE program is to blend high-resolution radar data with geographic information to obtain highly-detailed verification reports. These reports were initially undertaken to compile hail data for the verification of automated, radar-based hail algorithms. In Fiscal Years 2009 and 2010, the scope of the reports was expanded to include data from algorithms on wind damage and flash flooding. The algorithms are validated based on severe weather reports obtained through NWS's verification process, and data collected during the project should facilitate the development of decision-making tools for improving forecasts and warnings of severe thunderstorms and tornadoes. Additionally, this effort will better establish the timing, extent, and intensity of severe weather, paving the way for improvements to the historical severe storms database.

NOAA: Large-Scale Influences on Seasonal Severe Weather Behavior. NOAA has an ongoing mission to develop a severe weather database to empirically estimate wind hazards across the continental United States. During Fiscal Years 2009 and 2010, the NWS SPC developed hazard estimates as a function of the various Global Climate Cycles related to the occurrence of convective storms. This ongoing research will permit NOAA to provide risk assessments that vary as a function of climate indices.[34]

ASSESSING AND REDUCING WINDSTORM IMPACTS

Buildings and Structures

NIST: Wind Engineering. NIST's wind engineering research is focused on developing the measurements, tools, and methodologies necessary to substantially improve: (1) wind hazard estimation through better databases and maps; (2) the estimation of wind loads on structures, through the development of database-assisted design techniques incorporating wind directionality effects; and (3) the prediction of structural responses to these loads, leading to safer and more economical designs. Progress in wind-hazard estimation was made in Fiscal Years 2009 and 2010 through the development of improved methods for estimating directional wind speeds, which in turn can improve the engineering designs for buildings and structures.[35] A new and comprehensive analysis of historical records of wind events in the U.S. was undertaken to: (1) account for directional variation in the wind exposure of the anemometers and changes in exposure over time; and (2) identify extreme wind events in the record by type (hurricane, thunderstorm, or synoptic). Once completed, this analysis will provide the basis for a significantly improved set of wind-speed design maps for use in wind loading standards and codes. NIST's research in wind loading on structures during Fiscal Years 2009 and 2010 included: (1) the initial development of a novel wind tunnel testing methodology that incorporated recent findings regarding aerodynamic contributions of low-frequency turbulent fluctuations to total response to wind loads; (2) studies comparing database-assisted design methods with standard estimates from the ASCE 7 national wind loading standards; and (3) the investigation of numerical analysis methods (computational fluid dynamics approaches) for use

[34] Representative publication: Cook, A.R., & Schaefer, J.T. (2008). The Relation of El Niño Southern Oscillation (ENSO) to winter tornado activity. *Mon. Wea. Rev.*, 136, 3121-3137.

[35] Representative publication: Grigoriu, M.D. (2009). *Algorithms for Generating Large Sets of Synthetic Directional Wind Speed Data for Hurricane, Thunderstorm, and Synoptic Winds*. NIST Technical Note 1626.

in determining wind loads on buildings and structures.[36] During the fiscal period, NIST also developed powerful and comprehensive database-assisted design procedures that substantially improved modeling of wind effects and design algorithms for buildings subjected to wind loads.[37] The procedures incorporate some aspects of the wind hazard and wind loading research described previously, as well as:

- Effects of veering of wind on dynamic response of tall buildings;
- More accurate, transparent, and user-friendly approaches to calculating wind effects on tall buildings, made possible by novel capabilities to numerically solve simultaneous differential equations of dynamic motion, and which will replace obsolete spectral methods developed in the 1960's; and
- Multi-hazard approaches to assessing synergy of structural solutions in multi-hazard conditions and design criteria on wind and earthquake load combinations.

The described wind engineering data, analysis methods, tools, and reports are available on the NIST website at http://www.nist.gov/wind. NIST also invested significant effort to advance the latest design methods and standards.[38] NIST research influenced the development of the latest edition of the national wind loading standards ASCE 7 in the following areas:

- The application of database-assisted design in engineering practice;
- The relationship between the Saffir-Simpson Hurricane Intensity Scale and design wind speeds for buildings and other structures; and
- Accounting for wind directionality effects in structural design.

FEMA: Improving Wind-Resistant Provisions. During the fiscal period, FEMA worked with its partners to develop and incorporate high-wind-resistant provisions and requirements in the Nation's model building codes and standards. Working with other Federal agencies, state and local governments, building regulators, building industry groups, and other entities, FEMA advocated for specific changes to increase wind-resistant requirements of the IBC, ASCE 7, American Society for Testing and Materials standards, and other industry documents. As a result of these efforts, buildings are being built stronger, reducing the risks of death, injury, and property loss from high-wind storms. Furthermore, using the initial FEMA Safe Room

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[36] Representative publications: Coffman, B., Main, J., Duthinh, D., and Simiu, E. (2010). "Wind Effects on Low-Rise Metal Buildings: Database-Assisted Design vs. ASCE 7-05 Standard Estimates." *J. Struct. Eng.*, June 2010, 744-748.

Simiu, E. (2009), *Toward a Standard on the Wind Tunnel Method.* NIST Technical Note 1655.

Yeo, D. (2010). *Numerical simulation of along-wind loading on small structures using a simplified wind flow model.* NIST Technical Note 1683.

[37] Representative publications: Spence, S.M.J. (2009). *High-Rise Database-Assisted Design 1.1(HR_DAD_1.1): Concepts, Software, and Examples*, Building Science Series 181.

Yeo, D. (2010). *Database-Assisted Design of high-rise reinforced concrete structures for wind: Concepts, software, and application.* NIST Technical Note 1665.

Yeo, D., and Simiu, E. (2010). *Effects of veering wind and structure orientation on a high-rise structure*. NIST Technical Note 1672.

Duthinh, D., and Simiu, E. (2010). Safety of Structures in Strong Winds and Earthquakes: Multihazard Considerations. *J. Struct. Eng*., March 2010, 136, 330-333.

Potra, F. and Simiu, E. (2009). Optimization and Multi-Hazard Design. *J. Eng. Mech.*, Dec. 2009, 1472-1475.

[38] Representative publication: Simiu E., "Wind Loading Codification in the Americas: Fundamentals for a Renewal," Keynote lecture, Proc., 11th Americas Conference on Wind Engineering, June 2009.

publications as a pre-standard, design and construction professionals, led by the ICC and NSSA, joined forces to produce the first ICC/NSSA Standard for the Design and Construction of Storm Shelters (ICC-500), which was adopted in 2009 as a referenced standard to the IBC.

FEMA: Mitigation Assessment Team Evaluations Following Major Hurricanes, Tornadoes and Windstorms. In Fiscal Year 2010, a FEMA MAT responded to the April 23-24 tornado outbreak in Mississippi. As part of that effort, FEMA also deployed a Pre-Mitigation Assessment Team to survey the general structural damage and the performance of the residential and community safe rooms located along the path of the Tallulah-Yazoo City-Durant tornado. Tornado classification, building damage, building performance, and safe room information was collected through investigative site visits and surveys by the PMAT. These investigations allowed the team to capture important observations, lessons learned, and recommendations regarding the performance of:

- FEMA-funded residential safe rooms, which were impacted by tornadic winds and debris, and that had been constructed in accordance with guidance provided by the FEMA P-320 report *Taking Shelter from the Storm: Building a Safe Room for your Home or Small Business*;
- FEMA-funded community safe rooms, which were impacted by tornadic winds and debris, and that had been constructed in accordance with provisions contained in the FEMA P-361 report *Design and Construction Guidance for Community Safe Rooms*; and
- Community safe room operations plans.

In Fiscal Year 2009, FEMA completed a report based on the field investigation findings of a MAT it had previously deployed in response to the damage caused by Hurricane Ike in 2008 to Galveston, Texas, and the nearby Bolivar Peninsula. The team was sent to evaluate and assess damage from that storm and provide observations on the performance of structures impacted by flood and wind forces. The team was also asked to develop recommendations for improved disaster-resistant construction based on best-available practices and science. The resulting report laid out a number of important recommendations, including the need to sufficiently elevate coastal structures to withstand the effects of hurricane storm surge and the importance of adopting and enforcing disaster-resistant building codes, including wind provisions.

NIST: Study of the Dallas Cowboys Indoor Practice Facility Collapse. Following the collapse of the Dallas Cowboys indoor practice facility during a thunderstorm on May 2, 2009, NIST conducted a study to determine how and why the facility collapsed and identify areas of improvement to current building codes and standards. The facility was a fabric-covered, tubular, steel-frame structure, a design often used for sports, industrial, and agricultural facilities, as well as casinos, military installations, and aircraft hangars. NIST worked with NOAA's NSSL to estimate the wind conditions at the time of the collapse, and conducted a field investigation and analytical study to evaluate and understand the wind loads and structural response. The final report[39] includes recommendations for improving the safety of these structures.

[39] Gross, J.L., Main, J.A., Phan, L.T., Sadek, F.H., Cauffman, S.A., and Jorgensen, D.P., *Final Report on the Collapse of the Dallas Cowboys Indoor Practice Facility, May 2, 2009.* NISTIR 7661, National Institute of Standards and Technology, Gaithersburg, Maryland, January 2010.

NSF: Multi-Scale Computational Evaluation of Wind Load on Buildings. The NSF supported research at Florida International University to develop and validate new, multi-scale modeling approaches appropriate for evaluating wind loads for both low- and high-rise buildings. The models will be validated through small-scale experiments in a wind tunnel and full-scale experiments in the university's Wall of Wind facility. The project is expected to provide accurate methods for evaluating wind loads on buildings for high-wind-speed events (such as category 4 and 5 hurricanes). The results of the project will be used to improve building codes to advance safer, economical housing design, and for work with the insurance industry and government to develop mitigation implementation strategies and improved loss estimation models.

NSF: Full-Scale and Modeled Hurricane Wind Loads on Residential Structures. Scale model tests in boundary layer wind tunnels have been the primary tool for the development of the design wind loads prescribed in codes. However, questions have been raised concerning the ability of wind-tunnel methods to replicate the hurricane wind environment and to determine peak loads on low-rise structures in hurricanes. An NSF grant awarded to the University of Florida during the fiscal period will fund research to: (1) quantify the precision and accuracy of wind-tunnel modeling of extreme wind loads on low-rise structures; and (2) develop more accurate representations of the turbulence within hurricane wind fields. Both efforts will utilize an existing hurricane wind velocity and pressure-load database collected in-field during eleven hurricane seasons. Results of the research are expected to provide a basis for changes to enhance current experimental wind-load evaluation methods and prescriptive wind-load practice.

NOAA: Reducing Wind-Induced Damages. In Fiscal Years 2009 and 2010, with funding from NOAA, Iowa State University collected wind data in the vicinity of tornadoes for verification and calibration of a wind simulation and testing simulator. Additional tasks undertaken by Iowa State include:

- Working to simulate hurricane winds around built structures;
- Modeling tornadic winds near a "rough" surface in a tornado simulator;
- Simulating straight-wind and tornado flow fields in and around different types and configurations of buildings and vegetative barriers;
- Assessing wind damage potential of buildings as a function of distribution of local wind speed and wind-borne debris impacts;
- Studying the optimum shelterbelt configuration to reduce hurricane wind hazard to cities along coastal areas; and
- Investigating a new aerodynamic shape of an extreme-wind-resistant residential building.[40]

NIST: Combined Hurricane Storm Surge, Wind, and Wave Modeling. NIST's research on storm surge is aimed at providing a science-based methodology for accurate characterization of

[40] Representative publication: Karstens, C.D. & Gallus, Jr., W.A. (2008). Simulations of near-ground hurricane winds influenced by built structures. *Extended Abstracts, 28th Conference on Hurricanes and Tropical Meteorology*, Orlando, Florida: Amer. Meteor. Soc. Also: Sengupta, A., Haan, F.L., Sarkar, P.P., & Balaramudu, V. (2008). Transient loads on buildings in microburst and tornado winds. *J. Wind Eng. Ind. Aerodyn.*, dio:10.1016/j.jweia.2008.02.050.

the risks associated with combined hurricane hazards, including hurricane wind, storm surge, and waves. The methodology will be used for developing risk-consistent structural design criteria for structures in coastal regions which are affected by the combined effects of hurricane hazards. NIST's approach in this project is integrative and interdisciplinary, incorporating state-of-the-art knowledge in hurricane science (wind speed modeling), hydrology (storm surge modeling), and probabilistically-based structural engineering. The developed methodology allows: (1) estimation of design risk associated with combinations of hurricane wind speeds and storm surge heights, with appropriate accounting for site dependency (i.e., the effects of local topography and bathymetry on which storm surge at any specific location is highly dependent); and (2) consideration of the effects of waves, which add to total inundation. During Fiscal Years 2009 and 2010, working in collaboration with NOAA's NWS, Office of Oceanic and Atmospheric Research (OAR), and NHC, as well as the University of Florida, NIST:

- Implemented the methodology developed in the pilot effort carried out in Fiscal Years 2007 and 2008 (NIST TN 1482, *Methodology for Development of Design Criteria for Joint Hurricane Wind Speed and Storm Surge Events: Proof of Concept* (2007)) to test its application in four large basins in the State of Florida, encompassing the Tampa Bay, Fort Myers, Biscayne Bay, and Florida Keys areas;
- Developed a graphical user interface tool, known as Sea, Lake, and Overland Surges from Hurricanes (SLOSH) MapXtract, to address the data processing challenges associated with large amounts of data generated by the methodology and to make the NIST methodology practical by providing users with a map-based tool for selecting the site of interest with knowledge of local topography; and
- Developed a pilot methodology to account for waves in storm surge simulations using NOAA's SLOSH program by coupling the Simulating Waves Nearshore wave model with the SLOSH model.[41]

NOAA Alternative Metrics of Tropical Cyclone Impact Project. The Saffir-Simpson Hurricane Scale, which categorizes tropical cyclones according to maximum sustained surface wind speed, fails to consider the size of the area impacted by the winds, which influences storm surge and wave height. The Hurricane Research Division of NOAA's Atlantic Oceanographic and Meteorological Laboratory, in partnership with external researchers and the IBHS, previously developed a measurement tool known as IKE to better capture the wind-related forces associated with severe storms. The IKE, which is computed from H*Wind gridded surface wind fields, represents a framework that captures the physical process of ocean surface stress that forces waves and surge, while also taking into account structural wind loading and the spatial coverage of wind.

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[41] Representative Publications: Phan, L.T., and Simiu, E., "*A Methodology for Developing Risk-Consistent Design Criteria For Coastal Structures Exposed To Hurricane Wind Speed And Storm Surge Hazards*," Proceedings, Hurricane Hugo 20th Anniversary Symposium on Building Safer Communities – Improving Disaster Resilience, ATC-77, pp 3-1 to 3-19, Charleston, South Carolina, October 2009.

Phan, L.T.; Slinn, D.N., Kline, S.W., *Introduction of Wave Set-up Effects and Mass Flux to the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Model,* NISTIR 7689, National Institute of Standards and Technology, Gaithersburg, Maryland, May 2010.

An IKE calculator was tested during the 2009 and 2010 hurricane seasons and will be implemented for real-time use in 2011. The calculator allows users to enter wind radii from official hurricane advisories in order to estimate IKE-based measures of a storm's destructive wind and surge potential. The scale proved useful for depicting the destructive potential of Hurricane Igor as it approached Canada in 2010; Igor possessed one of the largest wind fields yet documented in the Atlantic hurricane basin, at the time of this writing.

FHWA/NIST/NOAA/NSF: U.S.-Japan Panel on Wind and Seismic Effects. FHWA, NIST, NOAA, and the NSF all participate on the U.S.-Japan Panel on Wind and Seismic Effects. NIST also chairs and provides a technical secretariat for the panel. The panel serves as a mechanism for the exchange of technical data, information, and researchers, as well as the coordination of joint research on wind and seismic-related topics of mutual interest to the U.S. and Japan. FHWA staff participate on the panel and its wind engineering task committees (TC), specifically the TC-D Wind Engineering and TC-G Transportation groups. The TC-D group has held five international workshops, and the TC-G group has held 26 such workshops. During Fiscal Year 2010, the U.S. hosted the fifth U.S.-Japan Workshop on Wind Engineering in Chicago, Illinois. The meeting focused on assessing the results of recently completed collaborative research[42] on tornado loads on low-rise buildings, stay cable vibrations, long-span-bridge flutter, as well as identifying new collaborative projects.

Bridges and Highways

NSF: Reliability-Based Analysis and Design Loads For Slender Long-Span Bridges. More than 800 slender long-span bridges contained in the national bridge inventory are classified as fracture-critical, which means they do not contain redundant supporting elements and would be in danger of collapse if the bridge's key supports fail. With NSF funding, researchers at Colorado State University undertook studies of the dynamic interaction of slender long-span bridge structures under combined wind and traffic loads. These combined loads can cause fatigue-fracture accumulation, deterioration, and, at times, related safety issues for these bridge systems. The project focused on understanding the dynamic behavior of bridge structures and the development of an integrated, dynamic model to assess the lifetime performance of slender long-span bridges under combined wind and traffic loads. This research will help engineers to: (1) reliably predict load response, performance, and remaining life of slender long-span bridge systems; (2) identify potential sources and risk of damage; and (3) design retrofit measures to improve performance and prolong the lives of these structures.

FHWA: Monitoring of Wind Conditions and Structural Performance. During the fiscal period, the FHWA HRDI monitored winds and structural performance at selected bridge sites to establish and characterize site-specific wind conditions and the responses of the bridges to varying wind conditions. The sites of three major long-span, cable-supported bridges were monitored during the reporting period – Deer Isle, Hale Boggs, and the C&D Canal. Data were collected on a continuous basis; however, no major storm events were observed. The data

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[42] Representative publication: W. P. Fritz, B. Bienkiewicz, B. Cui, O. Flamand, T. C. E. Ho, H. Kikitsu, C. W. Letchford, and E. Simiu, "International Comparison of Wind Tunnel Estimates of Wind Effects on Low-Rise Buildings: Test-Related Uncertainties," *J. Struct. Eng.*,134, 1887–1890, 2008.

gathered during this monitoring period provided valuable information for the calibration of numerical tools and predictive methods; the improvement of physical modeling techniques in the laboratory; the evaluation and validation of new designs; and the development and assessment of mitigation measures.

FHWA: Full Scale Measurement of Structural Dynamic Properties. In an ongoing program to characterize the dynamic properties of bridge stay cables, which are critical to structural performance and aerodynamic stability, the analysis of data from full-scale, forced vibration tests on selected major structures continued during Fiscal Years 2009 and 2010. Tests were performed on the Zakim, Emerson, and Penobscot Narrows bridges. The results of cable tests performed on the Penobscot Narrows Bridge, both prior to the opening of the bridge in 2006 and one year later, following installation of dampers on the cables, were reported at the 2009 Americas Conference on Wind Engineering.[43] Information collected during the tests enabled further evaluation of design details and an assessment of the effectiveness of various mitigation measures such as dampers, cross ties, and aerodynamic surface treatments. The information also serves as a benchmark that will be useful during later inspections to assess the bridge's structural condition and overall health.

FHWA: Physical Modeling of Wind Effects on Highway Structures. A project continued during the fiscal period under FHWA's EAR program to develop a new system to perform volumetric particle image velocimetry. This will enable detailed flow visualizations during a laboratory study of fluid-structure interactions. This new technology will be a valuable tool in performing aerodynamic studies of wind effects on highway structures as well as for hydraulic issues associated with scour and storm surge. Another project underway within the EAR program will develop a system using pressure-sensitive paint and surface-stress-sensitive film to measure wind forces on structural models in the laboratory. Two small-scale bridge models were fabricated and instrumented with pressure taps for testing in the FHWA's small wind tunnel. Also within the fiscal period, automation of both wind tunnels in the Aerodynamics Laboratory at the FHWA's TFHRC was completed.

FHWA: Numerical Modeling of Wind Effects on Highway Structures. An interagency agreement was established between DOT and DOE for modeling the effects of natural hazards, such as windstorms, hydraulics, and flooding, on infrastructure. This agreement will enable FHWA to utilize high-performance computing and support staff from the Argonne National Laboratory. Resources located at the Transportation Research and Analysis Computing Center will be used to model wind effects on highway users as well as highway structures. Enhancement of the UABRIM (University of Arkansas BRIdge Moving) computational fluid dynamics model continued through the implementation of unstructured and adaptive grids for use in simulating the interaction between wind and structures such as large bridges.[44, 45] This computer simulation

[43] Bosch, H.R., and Pagenkopf, J.R., "Dynamic Properties of Stay Cables on the Penobscot Narrows Bridge," *Proceedings*, 11th Americas Conference on Wind Engineering, San Juan, Puerto Rico, June 2009.

[44] Selvam, R.P., Bosch, H.R., Joshi, R. (2010). Comparison of 2D and 3D CFD modeling of bridge aerodynamics. *Proceedings*. 5th International Symposium on Computational Wind Engineering, Chapel Hill, NC, May.

[45] Patro, S. K., Selvam, R. P., & Bosch, H. R. (2010). Bridge flutter modeling using h-adaptive FEM. *Journal of Wind and Engineering*, Vol. 7, No. 2, pp. 39-48.

tool will be used to evaluate wind flow around and interaction with major highway bridges. It also will identify undesirable tendencies for vortex-induced response, or "flutter" instability. Finite element modeling, using the commercial program SAP 2000, was performed to study the efficacy of various approaches for mitigating wind-induced vibration of bridge stay cables. A comprehensive laboratory report was drafted for internal review and should be published early in the next biennial reporting period.[46]

FHWA: Development of Design Guidelines. Research continued on the issue of wind- and wind/rain-induced vibration of bridge stay cables. A second iteration of a draft guidelines document on the aerodynamic design of bridge stay cables was further updated. Following review, the document will provide guidance on the aerodynamic design of cables and cable networks on major new highway bridges and for retrofit of existing structures to mitigate wind-induced vibration problems.

FHWA: Monitoring Weather and Alleviating Impact on Highway Operations. Below is a short list of major activities and accomplishments associated with monitoring weather and alleviating the weather-related impacts to highway operations. Publications associated with these efforts are located at: http://www.ops.fhwa.dot.gov/weather/resources/publications.htm.

- Developed the Clarus System, a database management system that acquires, checks quality and disseminates road weather observations from 1,700 sensor stations (comprised of more than 34,000 sensors, including wind sensors);
- Developed the Maintenance Decision Support System, a computer-based decision support tool that enables state and local agencies to combat snow and ice more efficiently (and takes wind into account, especially with respect to blowing snow);
- Developed the first generation of a Vehicle Data Translator, a mobile sensing program that translates data coming from vehicles into valid road weather observations;
- Developed a planning tool to aid transportation agencies with the integration of weather information into the Traffic Management Center;
- Developed multiple training programs for a variety of audiences to better educate both the transportation and meteorological communities about the challenges of adverse weather on the surface transportation system; and
- Developed performance measures to assess the deployments of weather-responsive transportation management solutions, and collected data to assess these measures.

Power Grid, Aviation, and U.S. Space Centers

NOAA: High-Resolution Rapid Refresh Model. To improve guidance for air traffic managers, NOAA scientists at the ESRL/GSD developed and tested the HRRR weather forecast model. A component of the broader Rapid Update Cycle model, the HRRR is the only hourly-updated, radar-initialized, three-kilometer, storm-resolving model currently running in the U.S. It is designed to provide air traffic managers with rapidly updated projections of developing severe weather, and will also support NWS's future WoF capability. During Fiscal Years 2009 and 2010, NOAA scientists made several breakthroughs, including the development of an effective

[46] Bosch, H., Park, S., & Shen, J. (Pending). Mitigation of wind-induced vibration of stay cables: numerical simulations and evaluations. *FHWA Staff Report*, Report No. TBD, TFHRC, McLean, VA, Date TBD.

technique for assimilating 3-D radar reflectivity data into the existing 13-km Rapid Update Cycle and an upcoming 13-km RAP model.

NOAA: Hazardous Weather System for U.S. Space Centers. Operations at U.S. space centers are heavily dependent on weather conditions and forecasts. Safety regulations restrict work on tall gantries, shuttle transport, refueling, and other operations during high-wind events. Winds may also impact safety following rocket blasts, fuel spills, and other accidents by carrying toxins from an accident zone farther afield. During the fiscal period, NOAA's ESRL/GSD developed and implemented a state-of-the-art analysis and forecasting system supporting the Eastern and Western Ranges as part of the RSA program. Due to advances by the program, NOAA now can deliver 24-, 12-, and nine-hour forecasts of varying spatial resolutions to address space center needs.

NOAA: Microburst Studies. NOAA's NSSL maintained an ongoing program with the Arizona-based SRP, which provides electricity to the Phoenix metropolitan area, to study and document the impact of severe winds on electrical power infrastructure. During the summer of 2008, 140 microburst windstorms were identified in Phoenix and the surrounding Sonoran Desert. The Sonoran microbursts were studied and examined for their frequency and characteristics, as observed from data collected from three Doppler radars and electrical power infrastructure damage reports. Stronger maximum differential wind velocities were observed more frequently in the Sonoran microbursts than in many previously documented microbursts. This is important because higher wind differentials can cause significantly more damage to electrical infrastructure. The observed greater frequency of higher wind differentials in the Sonoran microbursts than previously seen in other studies can imply that the vulnerability of the electrical infrastructure to microbursts in general has been significantly underestimated. Also, a comparison of the Doppler radar data to the wind damage reports found that the microburst winds caused more significant damage to electrical power infrastructure than gust-front winds.

Community Services and Resilience

NSF: Development of a Quantitative Model for Measuring Regional Economic Resilience to Hurricanes. The NSF supported research at Texas Tech University to develop a quantitative model for measuring regional economic resilience to hurricane hazards. Developing an accurate picture of a region's resilience requires measurements at multiple timescales of relevant indicators, including infrastructure reconstruction, mitigation activities, public disaster expenditures, local employment, housing permits, retail sales, and personal income. By integrating atmospheric properties of storms, physical attributes of a region's built environment, and economic characteristics, the proposed model should be capable of forecasting the rate of recovery in a local economy at multiple timescales. Such forecasts – based on quantifiable and verifiable data – would support informed public policies and economic investment for vulnerability reduction and post-disaster recovery in hurricane-prone regions.

NSF: Managing Evacuee Ingress: Network Interactions and Community Hosting Performance. With funding from the NSF, a research team at the University of Colorado-Denver examined recent, major hurricane evacuations in Florida, Alabama, Texas, and Louisiana, and from its study developed an analytic framework to explain evacuation management performance. Prior research on disaster evacuations has focused on how and why large numbers of people move out of disaster areas. In contrast, this project addresses how well communities can absorb and manage the needs of evacuees moving into their area. The study, which stands to improve disaster evacuation management practices in the United States, looks at how governmental agencies interact during evacuations with voluntary organizations, faith-based groups, and private-sector service providers like nursing homes. The potential impacts of the study include:

- Improved planning and preparedness efforts through better understanding how communities perform in hosting incoming evacuees;
- Improved planning and preparedness for helping those most vulnerable to the negative effects of an evacuation (e.g. elderly, disabled persons, lower income families); and
- Enhanced graduate student and professional training in this area.

The project also advances research frontiers by:

- For the first time, providing systematic empirical evidence that accounts for how networks of governmental and nongovernmental organizations respond separately and in coordination on the issue of managing the needs of evacuees entering a hosting area;
- Identifying and providing a framework for performance measures at a community level for how well the needs of evacuees are met when they move into a new area; and
- Producing evidence that demonstrate which factors are most important for successfully managing the needs of evacuee ingress.

NSF: Extreme Weather Events and Emergency Medical Services. Emergency medical dispatching protocols are typically designed for delivering services under normal weather conditions. In general, little guidance exists for how dispatching protocols may need to change under extreme weather conditions. With NSF funding, Virginia Commonwealth University developed new models and algorithms for improving the design and operation of emergency medical services (EMS) systems in response to medical emergencies that arise during extreme weather events. The research effort specifically focused on how EMS systems and protocols can be optimized for dispatching medical units to geographically dispersed patients during extreme weather events, as well as normal conditions. This effort is expected to provide a basis for more effective policies and protocols for allocating scarce EMS resources during both sets of conditions.

NOAA: State of Florida Public Hurricane Loss Model. NOAA continued to work with the FPHLM during the 2009-2010 fiscal period. The FPHLM is an open, transparent computer model that will be used by the Florida Office of Insurance Regulation to provide a baseline for evaluating rate change requests for windstorm insurance. The FPHLM is the first such model that enables all of the results and details from the modeling approach to be open to scrutiny. (As of the end of the fiscal period, all other models used for ratemaking in Florida have been proprietary.) The model's engineering component estimates damage to residential structures within Florida zip codes, and an actuarial component then estimates the insured loss. The average annual loss is then estimated statewide for every zip code in Florida. The FPHLM was approved by the Florida Commission on Hurricane Loss Projection Methodology in June of 2009 and is now available for insurance ratemaking purposes in Florida.

FEMA: Maintain HAZUS Hurricane Loss Estimation Model. FEMA developed and maintained HAZUS-MH, a nationally applicable standardized methodology that contains models for estimating potential losses from multiple hazards, including hurricane winds. HAZUS-MH uses GIS technology to estimate physical, economic, and social impacts of disasters and graphically illustrates the limits of identified high-risk locations due to a region's hazards. Users can then visualize the spatial relationships between populations and other more permanently fixed geographic assets or resources for the specific hazard being modeled, a crucial function in the pre-disaster planning process.

OUTREACH

FEMA: Education, Outreach, and Information Dissemination. The FEMA website, www.fema.gov, serves as the Nation's portal to emergency and disaster information. Most FEMA publications related to wind hazards were placed on the web, including many older documents that needed to be digitized in order to do so. Along with this digitization effort, a majority of FEMA wind and other hazard publications were uploaded to the Google Books website and are now available for download on the Google E-Reader and other electronic reading devices. Dozens of presentations were given at conferences and other forums highlighting the importance of hurricane mitigation, and a number of outreach documents were produced, highlighting successful wind mitigation projects. FEMA partnerships were established with external organizations such as the Disney Corporation and FLASH, which opened a new interactive exhibit titled "StormStruck: A Tale of Two Homes" at Epcot's Innoventions pavilion. The attraction allows visitors to experience a severe weather incident, such as a hurricane, with the goal of teaching the guests about cutting-edge technology used to protect homes. Also, since the devastation of Hurricane Katrina in 2005, FEMA's Mitigation Directorate continued to help the residents of the Gulf Coast rebuild by providing support and resources. Researchers continue to analyze the data collected in the aftermath of the hurricane and apply the lessons learned in educating designers, decision-makers, and the public in order to positively influence ongoing recovery and rebuilding efforts.

FEMA: Development of Technical Guidance Materials on State-of-the-Art Wind-Resistant Design and Construction Methods. Each year many thousands of publications dealing with wind hazards are ordered and distributed by FEMA. For example, FEMA partnered with Texas Tech University and others to produce guides and provisions for safe room design and construction (FEMA P-320: *Taking Shelter from the Storm: Building a Safe Room For Your Home or Small Business* and FEMA P-361: *Design and Construction Guidance for Community Safe Rooms*). During the fiscal period, more than 11,000 copies of FEMA P-320 and over 3,000 copies of FEMA P-361 were distributed to organizations across the U.S. In Fiscal Year 2009, FEMA also revised a report outlining and identifying safe areas in buildings for protection during tornadoes (FEMA P-431 *Tornado Protection: Selecting Refuge Areas in Buildings*).

APPENDIX B: AGENCY ACTIVITIES IN FISCAL YEARS 2007 AND 2008

UNDERSTANDING WINDSTORMS FOR IMPROVED PREDICTIONS, FORECASTS, AND WARNINGS

Hurricanes

NIST: Storm Surge. NIST research on storm surge aims to provide a methodology for accurately characterizing the risk associated with combined hazards posed by extreme hurricane wind and storm surge. The methodology will be used for developing design criteria for structures in coastal regions. The methodology takes into consideration the effects of local topography and bathymetry on which storm surge at any specific location is highly dependent, as well as the effects of waves, which add to total inundation. NIST is collaborating with NOAA's NWS, OAR, and NHC, as well as the University of Florida to develop this methodology.

NOAA: Shared Mobile Radars. Through a cooperative effort between the University of Oklahoma and NOAA, Shared Mobile Atmospheric Research and Teaching Radars (SMART-R) were deployed during hurricane landfalls to collect and deliver wind data directly to forecast offices in real time. During Fiscal Years 2007 and 2008, one SMART-R was outfitted with dual polarization capability to better distinguish between hydrometeor types, estimate precipitation amount, and distinguish rain and hail from debris during tornadoes and other high wind events. NOAA's NSSL also developed a new X-Band mobile Doppler radar for use in both research and operational aircraft to improve surface wind and vertical wind profiling over water during hurricanes. These radars are also used in NOAA's operational hurricane model and for real-time hurricane intensity analysis.

NOAA: *In situ* Measurements of Turbulence in Hurricanes – Extreme Turbulence Probe. For a number of years, NOAA has been developing an Extreme Turbulence probe, a pressure-sphere anemometer for measuring turbulence and fluxes in hurricanes. During Fiscal Years 2007 and 2008, NOAA wrote and published a paper that described planned future upgrades to the probes.[47]

NOAA: Hurricane Wind Analysis System. H*Wind, developed by the Hurricane Research Division of NOAA's Atlantic Oceanographic and Meteorological Laboratory, is a diagnostic tool that determines the extent of a tropical cyclone wind field. H*Wind is an integrated tropical cyclone observing system in which wind measurements from a variety of observation platforms can be used to develop an objective analysis of the distribution of wind speeds in a hurricane. The product is designed to improve the understanding of the extent and strength of the wind field and to improve the assessment of hurricane intensity. H*Wind "snapshot" products are provided in image and gridded form for research purposes and are useful for storm surge and wave

[47] Representative publication: Eckman, R.M., Dobosy, R. J., Auble, D.L., Strong, T. W., & Crawford, T.L. (2007). A pressure-sphere anemometer for measuring turbulence and fluxes in hurricanes. *J. Atmos.Ocean. Technol.*, 24, 994-1007.

forecasting applications. Wind swath maps are also produced and are helpful for damage and loss assessment. In Fiscal Year 2007, 74 H*Wind analyses were produced, and an unprecedented 276 analyses were produced in Fiscal Year 2008.

NOAA: Alternative Metrics of Tropical Cyclone Impact: Integrated Kinetic Energy and Surge/Wave Destructive Potential. The Hurricane Research Division of NOAA's Atlantic Oceanographic and Meteorological Laboratory, in partnership with external researchers and the IBHS, developed a new measure known as IKE to better capture the wind-related forces associated with a given storm. The IKE, which is computed from H*Wind gridded surface wind fields, represents a framework that captures the physical process of ocean surface stress forcing waves and surge while also taking into account structural wind loading and the spatial coverage of the wind. Starting in the 2007 hurricane season, the H*Wind analyses included information on IKE and surge/wave destructive potential.[48]

NOAA: State of Florida Public Hurricane Loss Model. NOAA continued to work with the FPHLM during the 2007-2008 reporting period. The FPHLM is an open, transparent computer model that will be used by the Florida Office of Insurance Regulation to provide a baseline for evaluating rate change requests for windstorm insurance. The FPHLM is the first model that enables all of the results and details from the modeling approach to be open to scrutiny. To date, all other models used for ratemaking in Florida have been proprietary.

NOAA: Improving Hurricane Risk Communication. In partnership with the NSF, NOAA co-sponsored an extramural research competition titled, "Communicating Hurricane Information." Grants awarded through this competition sought to improve the understanding of the social science elements of individual and community response to hurricane forecasts and warnings. Results from this research will: 1) aid NOAA and other Federal agencies in improving the design and delivery of hurricane and other severe storm-related products and services; and 2) assist in prioritizing future physical and social science research at NOAA.

Tornadoes, Thunderstorms, and Other Severe Weather

NOAA: Hazardous Weather Testbed. NOAA's NSSL and the NWS SPC work with numerical modeling centers throughout the agency to conduct collaborative experimental forecasting activities using the HWT. In Fiscal Years 2007 and 2008, the HWT was used to explore applications of very large domain (three-fourths of the continental U.S.), high-resolution (~4 kilometer grid length) Weather Research and Forecasting models and a 10-member Storm Scale Ensemble Forecast system for operational severe weather forecasting. Specialized fields, such as simulated radar reflectivity and lowest model-level wind speed, were developed to assess their potential to improve forecast guidance on damaging wind gusts generated during thunderstorms. Several high-resolution WRF models are run year-round to support operational severe weather

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[48] Representative publication: Powell, M.D. & Reinhold, T.A. (2007). Tropical cyclone destructive potential by integrated kinetic energy. *Bull. Amer. Meteo. Soc.,* 88, 513-526. Also: *State of Florida Public Hurricane Loss Model* (Project Lead: NOAA Atlantic Oceanographic and Meteorological Laboratory)

forecasters. One such high-resolution model forecast correctly predicted a swath of damaging winds across parts of northern Oklahoma and southern Kansas in June 2008.[49]

NOAA: Rapid Update Cycle. During Fiscal Year 2007, NOAA scientists at the ESRL/GSD improved the forecasting capabilities of the Rapid Update Cycle model. This hourly assimilation and atmospheric prediction model is used by the SPC for near-real-time analysis and predictions of severe storm conditions over the continental U.S., Alaska, Canada, Mexico, and the northern Caribbean. The model assimilates information from a variety of sources, including surface observations, aircraft sensors, and radar and satellite data. The assimilation of radar reflectivity data in Fiscal Year 2007 provided significant improvements for the prediction of severe weather. Further enhancements to the model in Fiscal Year 2008 led to improved assimilation of cloud and visibility information, forecasts of wind gusts, and forecasts of precipitation type.[50]

NOAA: High-Resolution Rapid Refresh. To improve severe weather guidance and air traffic management, NOAA scientists at the ESRL/GSD worked during Fiscal Year 2008 to develop and test the HRRR model. The HRRR model, which is nested within the Rapid Update Cycle model, is the only hourly updated, radar-initialized, 3-kilometer, storm-resolving model currently running in the U.S. It is designed to provide rapidly updated model guidance on convective storms for air traffic management, severe weather forecasting, and the NWS's future WoF capability.

NOAA: Large-Scale Influences on Seasonal Severe Weather Behavior. NOAA has an ongoing mission to develop a severe weather database to empirically estimate wind hazards across the continental U.S. During Fiscal Years 2007 and 2008, the NWS SPC continued to develop hazard estimates as a function of the various Global Climate Cycles. This ongoing research may permit NOAA to provide risk assessments that vary as a function of climate indices.[51]

NOAA: Reducing Wind-Induced Damages. With funding from NOAA, Iowa State University collected wind data in the vicinity of tornadoes for verification and calibration of a wind simulation and testing tornado simulator. Additional tasks undertaken by Iowa State in Fiscal Years 2007 and 2008 included:

- Initial work to simulate hurricane winds around built structures;
- Modeling tornadic winds near a "rough" surface in a tornado simulator;

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[49] Representative publications: Coniglio, M.C., Kain, J.S., Weiss, S.J., Bright, D.R., Levit, J.J., Carbin, G.W., Thomas, K.W., Kong, F., Xue, M., Weisman, M.L., & Pyle, M.E. (2008). Evaluation of WRF model output for severe-weather forecasting from the 2008 NOAA Hazardous Weather Testbed Spring Experiment. *Preprints, 24th Conference on Severe Local Storms, Amer. Meteor. Soc.*, Savannah, GA. CD-ROM 12.4. Also: Weisman, M.L., Davis, C., Wang, W., Manning, K.W., & Klemp, J.B. (2008). Experiences with 0–36-h explicit convective forecasts with the WRF-ARW model. *Wea. Forecasting*, 23, 407–437.

[50] Representative publications: Smith, T.L., Benjamin, S.G., Gutman, S.I., & Sahm, S. (2007). Short-range forecast impact from assimilation of GPS-IPW observations into the Rapid Update Cycle. *Monthly Weather Review*, 135, 2914-2930. Also: Lu, C., Yuan, H., Schwartz, B.E., & Benjamin, S.G. (2007). Short-range numerical weather prediction using time-lagged ensembles. *Weather and Forecasting*, 22, 580-595.

[51] Representative publications: Cook, A.R., & Schaefer, J.T. (2008). The Relation of El Niño Southern Oscillation (ENSO) to winter tornado activity. *Monthly Weather Review*, 136, 3121-3137.

- Simulating straight-wind and tornado flow fields in and around different types and configurations of buildings and vegetative barriers;
- Assessing wind damage potential of buildings as a function of distribution of local wind speed and wind-borne debris impacts;
- Studying the optimum shelterbelt configuration to reduce hurricane wind hazard to cities along coastal areas; and
- Investigating a new aerodynamic shape of an extreme-wind resistant residential building.[52]

NSF: Verification of the Origins of Rotation in Tornadoes Experiment 2. VORTEX2 is an NSF and NOAA effort being planned to investigate tornadogenesis, tornado structure, and the relationships between tornados and their parent thunderstorms in the larger-scale environment. The experiment will involve a large, multi-investigator field campaign and a number of mobile radars, atmospheric sounding systems, and ground based sensors during the spring of Fiscal Years 2009 and 2010.

NSF: Windstorm Damage Assessments. During the fiscal period, the NSF funded teams to assess structural damage in areas impacted by windstorms. These studies were valuable for identifying specific anecdotal damage examples as well as issues that require further study. The NSF also funded research to develop models for measuring storm surge and wave actions generated by severe storms and hurricanes. Other research focused on detailed wind tunnel studies of structures under a variety of wind environments to determine the adequacy of current design and modeling approaches. Social science research at NSF supported quick-response research efforts to assess community damages, infrastructure disruption, and individual, organizational, and community social, political and economic impacts. The goal of the research was to develop damage assessment tools for use by emergency response officials. The NSF also awarded funding to Texas Tech University for research on the utilization of remote hyperspectral imaging technology for rapid assessment of damage caused by hurricane winds. The research is expected to produce much more efficient damage assessments than manual investigations, which can be time consuming, subjective, and expensive. The new methods under development through this research are also expected to provide useful data for risk assessments by insurers and for response and recovery planning by public agencies.

NSF: The Center for Collaborative Adaptive Sensing of the Atmosphere. CASA, an NSF-funded Engineering Research Center led by the University of Massachusetts, sought to dramatically increase the warning time and forecast accuracy for tornadoes and other wind-related severe weather hazards. CASA's research introduced a new dimension to weather forecasting and warning, yielding novel capabilities, including the detection of tornado precursors that were not fully resolved by the operational Doppler radar network.

[52] Representative publications: Karstens, C.D. & Gallus, Jr., W.A. (2008). Simulations of near-ground hurricane winds influenced by built structures. *Extended Abstracts, 28th Conference on Hurricanes and Tropical Meteorology*, Orlando, Florida: Amer. Meteor. Soc. Also: Sengupta, A., Haan, F.L., Sarkar, P.P., & Balaramudu, V. (2008). Transient loads on buildings in microburst and tornado winds. *J. Wind Eng. Ind. Aerodyn.*, dio:10.1016/j.jweia.2008.02.050.

NSF: Social Science Interdisciplinary Research. The NSF has a long history of supporting social science research on risk communication; warning systems and processes; evacuation planning and effectiveness; and individual, organizational, and community protective actions undertaken prior to a severe weather impact. For example, the NSF has supported research on factors facilitating societal adoption of structural and non-structural mitigation measures for over two decades. Research funded by the NSF has also focused on elements of community preparedness and capabilities, such as improving understanding of windstorm hazards; developing tools to measure social vulnerability and damage assessment; and developing tools to measure household, business and community recovery from wind disasters. The Human and Social Dynamics Priority Area at NSF funded significant interdisciplinary evacuation research related to wind hazards in Fiscal Years 2007 and 2008. Examples include:

- "Collaborative Proposal: DRU: Incorporating Household Decision Making and Dynamic Transportation Modeling in Hurricane Evacuation: An Integrated Social Science-Engineering Approach."
- "Collaborative Proposal: From Warnings to Dynamic Hurricane Evacuation Modeling: an Integrated Social Science-Engineering Perspective."

In Fiscal Year 2008, the Infrastructure Management and Extreme Events Program in the Engineering Directorate, and the Decision, Risk and Management Sciences Program in the Social, Behavioral, and Economic Sciences Directorate (with support from NOAA) ran a special competition entitled "Communicating Hurricane Information." Sample awards from this competition include:

- "Collaborative Research: Understanding Dynamic Responses to Hurricane Warnings – Implications for Communication and Research."
- "Collaborative Research: Examining the Hurricane Warning System: Content, Channels, and Comprehension."
- "Communicating Forecast Information to Optimize Evacuation Behavior."

ASSESSING AND REDUCING WINDSTORM IMPACTS

Buildings and Structures

NIST: Wind Engineering. In Fiscal Years 2007 and 2008, NIST's wind engineering research was focused on developing the measurement science tools and methodologies necessary to substantially improve: 1) wind hazard prediction through better databases and maps; 2) the estimation of wind loads on structures through the development of database-assisted design techniques that incorporate wind directionality effect (which was determined by the World Trade Center investigation to be a source of major errors in current practices); and 3) the prediction of the structural responses to these loads, leading to safer and more economical designs with reduced embodied energy. In addition to performing research, NIST has voting memberships in the ASCE 7 Subcommittee on Wind Loads and the ASCE 7 Main Committee, and is represented on the ASCE 7 Loads Committee (ASCE 7 is the standard for minimum design loads for buildings and other structures and is the basis for provisions in model building codes used throughout the U.S.). During Fiscal Years 2007 and 2008, NIST developed powerful and comprehensive database-assisted design procedures that substantially improve modeling of wind effects on both low- and high-rise structures. The procedures incorporate:

- Novel synchronous pressure measurement technologies capable of capturing the imperfect spatial coherence of pressures on the building facades;
- Modern computational capabilities such as wavelet-based data compression techniques that enable the use of large datasets by design practitioners;
- Findings based on NIST-led investigations that established the need to improve the physical and probabilistic modeling of design criteria, including a world-wide inter-laboratory comparison of wind effects estimates;
- Multi-hazard approaches to developing mixed probability distributions (frequency and maximum wind speeds) of hurricanes, large-scale extra-tropical storms, thunderstorm winds, and to wind and seismic effects;
- Innovative methods for establishing previously unknown strength reserves of deformed structures under wind loads;
- More accurate, transparent, and user-friendly approaches for calculating wind effects on tall buildings, which was made possible by the capability to solve simultaneously differential equations of dynamic motion, replacing obsolete and impractical spectral methods developed in the 1960's;
- Novel probabilistic approaches to establishing design values consistent with acceptable reliability levels; and
- Relations between the Saffir-Simpson hurricane classification and specified wind speeds required in the design process.

The procedures and data developed by NIST were posted on the NIST website at http://www.nist.gov/wind. Procedures developed by NIST in Fiscal Years 2007 and 2008 led to the changes in the ASCE 7 standards, which were approved by the ASCE 7 Wind Loads Subcommittee to address:

- The application in engineering practice of database-assisted design;
- The relationship between the Saffir-Simpson Hurricane Intensity Scale and the design wind speeds for buildings and other structures; and
- Accounting for wind directionality effects in structural design.

Further, NIST provided comments aimed at substantively improving the draft ASCE standard for wind tunnel testing and, through publications and mechanisms afforded by NIST participation in professional entities, actively promoted the adoption of the requisite improvements in the draft standards.

NSF: Structural Engineering Research and Development. The development of improved modeling of wind effects on structures was a primary outcome of NSF-funded structural engineering research in Fiscal Years 2007 and 2008. Design standards, such as ASCE 7, have benefited greatly from Federally-funded research into wind and its effects on structures. The current version of these consensus standards is more comprehensive than previous versions due to these contributions. Training the next generation of wind engineers was another important objective of the NSF in Fiscal Years 2007 and 2008. As the modern generation of wind engineers retires over the next decade, there will be an urgent need to ensure continuity of knowledge and expertise through continued training of young engineers. Within this context, the NSF's support for universities engaged in wind engineering research is a key component to building and supporting the next generation of engineers in this valuable discipline. The NSF funded research at the University of Florida to define the distribution of hurricane-induced wind loads on low-rise structures. The project will use wind tunnel and experimental data from tests on a 1/3-scale model of a wood-frame residential structure. The research is expected to improve the performance-based design methods for low-rise, wood-frame buildings by identifying ways to distribute and reduce wind load on the structures.

FHWA/NIST/NOAA/NSF: U.S.-Japan Panel on Wind and Seismic Effects. FHWA, NIST, NOAA, and the NSF all participated on the U.S.-Japan Panel on Wind and Seismic Effects in Fiscal Years 2007 and 2008. NIST chaired and provided a technical secretariat for the panel, which serves as a mechanism for the exchange of technical data, information, and researchers, as well as the coordination of joint research on wind and seismic-related topics of mutual interest to the U.S. and Japan. FHWA co-sponsors the panel, and FHWA staff members actively participated on its wind engineering task committees (TC), especially TC-D Wind Engineering and TC-G Transportation in Fiscal Years 2007 and 2008. USACE also participated in the panel during the reporting period.

Bridges and Highways

NSF: Assessing Bridge Performance Against Extreme Wind. The NSF awarded funding to Oregon State University for research on the effects of hurricane-induced waves on low-lying highway bridges in coastal areas. The research will focus on the hydraulic-structure interaction during hurricane-induced wave loads to better define the wave loads on bridge structures. The results of this research are expected to provide new insights into the failure mechanisms of highway bridges subjected to hurricane wave loads, as exemplified by the bridge failures along the U.S. Gulf Coast Region during Hurricanes Ivan in 2004 and Katrina in 2005. The better understanding of wave characteristics and bridge response expected from this research should provide tools for engineers to evaluate the risk of failure for existing bridges and to design new and retrofit existing bridges to withstand these loads. Researchers at Texas Tech University received funding from the NSF to develop advanced methods for performance assessment and reliability-based risk consistent designs of long-span bridges subjected to damaging winds. The research aims to define improved wind force models, which would reduce the complexity of the current linear force model and efficiently describe nonlinear, unsteady force characteristics. The project will utilize wind tunnel testing data, full-scale monitoring of bridge responses to strong winds, and field data provided by international collaborators. The project deliverables include a new wind load effects model, an approach for modeling of parameter uncertainties, a methodology for assessing uncertainty of bridge response, and analysis tools for the design of wind-excited bridges.

FHWA: Monitoring of Wind Conditions and Structural Performance. The FHWA HRDI continued to monitor winds and structural performance at select bridge sites to establish and characterize site-specific wind conditions and the responses of the bridges to wind hazards. The sites of three major long-span, cable-supported bridges were monitored during Fiscal Years 2007 and 2008. Data was collected on a continuous basis and included information obtained during severe storms such as Hurricanes Gustav, Ike, and Kyle. The data gathered during this period provided valuable information for the calibration of numerical tools and predictive methods, the improvement of physical modeling techniques in the laboratory, the evaluation and validation of new designs, and the development and assessment of mitigation measures.

FHWA: Full-Scale Measurement of Structural Dynamic Properties. In an ongoing program to characterize the dynamic properties of bridge stay cables that are critical to structural performance and aerodynamic stability, full-scale forced vibration tests on selected major structures continued during the period. Cable tests were performed on the new Penobscot Narrows Bridge prior to opening of the bridge in 2006 and following installation of dampers on the cables in 2007.[53] Information collected during the tests enabled an evaluation of design details and an assessment of the effectiveness of various mitigation measures such as dampers, cross ties, and aerodynamic surface treatments. The information also is a benchmark that will be useful during later inspections to assess structural condition or health.

FHWA: Physical Modeling of Wind Effects on Highway Structures. During the fiscal period, analysis of wind force measurements on a series of generic bridge deck sections in the FHWA wind tunnel was completed.[54] Other efforts included an initiative by FHWA's EAR program to develop a new system to perform volumetric particle image velocimetry. This will enable detailed flow visualization during a laboratory study of fluid-structure interaction. This new technology will be a valuable tool in performing aerodynamic studies of wind effects on highway structures as well as hydraulic issues associated with scour and storm surge. An additional project set to begin under the EAR program will develop a system using pressure-sensitive paint and surface-stress-sensitive film to measure wind forces on structural models in the laboratory. Also, automation of both wind tunnels in the Aerodynamics Laboratory at TFHRC is nearly complete.

FHWA: Numerical Modeling of Wind Effects on Highway Structures. Enhancement of the UABRIM (University of Arkansas BRIdge Moving) computational fluid dynamics model continued in Fiscal Years 2007 and 2008 with the implementation of unstructured and adaptive grids to simulate the interaction between wind and large bridges[55]. This computer simulation tool can be used to evaluate wind flow around, and interaction with, major highway bridges. It also can identify undesirable tendencies for vortex-induced response, or "flutter" instability. Finite element modeling using the commercial structural design program SAP 2000 was performed to study the efficacy of various approaches for mitigating wind-induced vibration of bridge stay cables.[56] FHWA's Non-Destructive Evaluation Center at TFHRC continued research to develop Chaos Theory Analysis of Bridge Response (CTBR) software for bridge structural health monitoring.[57] As part of this work, the fractal interpolation algorithm was incorporated into the

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[53] Bosch, H.R., Pagenkopf, J.R., and Park, S., "Measurement of Dynamic Properties of Bridge Stay Cables," *Proceedings*, 7th International Symposium on Cable Dynamics, Vienna, Austria, December 2007.

[54] Bosch, H. R., & Dhall, T. (2008). Aerodynamic investigation of generic bridge deck section models. *Proceedings*, 6th International Colloquium on Bluff Body Aerodynamics and Applications, Milan, Italy, July.

[55] Patro, S. K., Selvam, R. P., & Bosch, H. R. (2008). Bridge aerodynamics using h-Adaptive FEM and moving grids. *Proceedings*, 1st AAWE Workshop on Wind Engineering, Vail, Colorado, August.

[56] Bosch, H., Park, S., & Shen, J. (2007). Mitigation of stay cable vibrations using crossties and dampers. *Proceedings*, 12th International Conference on Wind Engineering, Cairns, Australia, July.

[57] Livingston, R.A., & Jin, S. (2007). Application of chaos theory to evaluate possible instability conditions in cable-stayed bridges. *Proceedings*, 18th Engineering Mechanics Division Conference of American Society of Civil Engineering (EMD 2007), June, Blacksburg, Virginia.

CTBR software to improve the Probability Density Function computation from bridge chaotic response data. The work included enhancements to the analysis, graphics and input/output functions of the CTBR software. Development of a user's guide and analysis of data sets from bridge health monitoring systems will be part of the continuing work. The Non-Destructive Evaluation Center also purchased a *Thinkmate* parallel computer that has access to ANL's TRACC high performance computing facilities for performing large-scale simulations of structural dynamics problems through finite element modeling. This new resource will enable detailed simulation and study of the effects of wind loads, wind/rain interaction, earthquakes, and traffic loads on major highway structures.

FHWA: Development of Design Guidelines. Research continued in Fiscal Years 2007 and 2008 on the issue of wind- and wind/rain-induced vibration of bridge stay cables. Version 2 of a draft guidelines document has been developed for the aerodynamic design of bridge stay cables. This document was under review at the end of Fiscal Year 2008 and will provide guidance on the aerodynamic design of cables and cable networks for major new highway bridges as well as for retrofit of existing structures to mitigate wind-induced vibration problems.

Power Grid, Aviation, and U.S. Space Centers

NOAA: Hazardous Weather System for U.S. Space Centers. Operations at U.S. space centers are heavily dependent on atmospheric conditions and weather forecasts. During Fiscal Years 2007 and 2008, NOAA's ESRL/GSD continued to develop and implement a state-of-the-art analysis and forecasting system supporting the Eastern and Western Ranges as part of the RSA Project.

Community Services and Resilience

FEMA: Mitigation Assessment Team Evaluations Following Major Hurricanes, Tornadoes and Windstorms. In Fiscal Year 2007, a FEMA MAT effort was undertaken to respond to a tornado that struck the town of Greensburg, Kansas and destroyed or severely damaged 90 percent of the community's buildings. Among the observations and recommendations that came out of the investigation was the need for sufficient numbers of individual and community safe rooms to protect the lives of the citizens from future tornado impacts. FEMA also responded to Hurricane Ike by deploying a MAT team to study of effects of this devastating hurricane on Galveston, Texas, including the area known as the Bolivar Peninsula, which was particularly hard hit. The team was sent to evaluate and assess damage from that storm and provide observations on the performance of structures impacted by flood and wind forces. The team will develop recommendations for improved disaster resistant construction based on best-available practices and science. The report from that field investigation was under development as Fiscal Year 2008 ended but will contain a number of important recommendations, including the need to sufficiently elevate coastal structures to withstand the effects of hurricane storm surge and the importance of adopting and enforcing disaster-resistant building codes and wind provisions. FEMA's Mitigation Directorate continued to help the residents of the Gulf Coast rebuild from the 2005 hurricane season by providing support and resources during Fiscal Years 2007 and 2008. As part of this effort, FEMA continued to educate designers, decision-makers, and the public to positively influence ongoing recovery and rebuilding efforts. FEMA also provided ongoing support for those impacted by Hurricane Katrina through technical guidance, support for housing pilot programs, and mitigation assistance grants totaling more than $1 billion.

OUTREACH

FEMA: Education, Outreach, and Information Dissemination. Each year thousands of publications dealing with hazards are ordered and distributed free of charge by FEMA. Over 750,000 copies of *Taking Shelter from the Storm* (FEMA 320) have been distributed and over 30,000 copies of a FEMA guidance document on state-of-the-art building practices in the Gulf Coast Region have been sent out since Hurricane Katrina. Also, a multi-year initiative to develop a consensus standard for tornado and hurricane safe rooms for residences, businesses, and communities was completed in Fiscal Year 2008 and adopted by the ICC. The FEMA website serves as the Nation's portal to emergency and disaster information. Most FEMA publications related to wind hazards have now been placed on the web, including digitized versions of older documents that were previously unavailable electronically.

APPENDIX C: KEY ABBREVIATIONS

AOML	Atlantic Oceanographic and Meteorological Laboratory
AWIPS	Advanced Weather Interactive Processing System
ABM	Agent Base Modeling
ANL	Argonne National Laboratory
ASCE	American Society of Civil Engineers
CASA	Center for Collaborative Adaptive Sensing of the Atmosphere
CFD	Computational Fluid Dynamics
CTBR	Chaos Theory Analysis of Bridge Response
DOE	Department of Energy
DOT	Department of Transportation
EAR	Exploratory Advanced Research
EF	Enhanced Fujita
EMS	Emergency Medical Services
ESRL/GSD	Earth Systems Research Laboratory Global Systems Division
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FLASH	Federal Alliance for Safe Homes
FPHLM	Florida Public Hurricane Loss Model
GIS	Geographic Information System
GOES-R	Geostationary Operational Environmental Satellite – R Series
GPS	Global Positioning System
GRIP	Genesis and Rapid Intensification Processes
HAZUS-MH	Hazards U.S. Multi-Hazard
HFIP	Hurricane Forecast Improvement Project
HRD	Hurricane Research Division
HRDI	[FHWA] Office of Infrastructure Research and Development
HRRR	High-Resolution Rapid Refresh
HWT	Hazardous Weather Testbed
H*Wind	Hurricane Winds Analysis System
IBC	International Building Code
IBHS	Institute for Business and Home Safety
ICC	International Code Council
IRC	International Residential Code
IFEX	Intensity Forecasting Experiment
IKE	Integrated Kinetic Energy
IWG	Interagency Working Group
JHT	Joint Hurricane Testbed
MAT	Mitigation Assessment Team
MPAR	Multi-Function Phased Array Radar
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCST	National Construction Safety Team
NDE	Non-Destructive Evaluation
NHC	National Hurricane Center
NHI	National Highway Institute
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
NRCC	National Research Council of Canada
NSF	National Science Foundation
NSSA	National Storm Shelter Association
NSSL	National Severe Storms Laboratory

NSTC	National Science and Technology Council
NWIRA	National Windstorm Impact Reduction Act
NWIRP	National Windstorm Impact Reduction Program
NWS	National Weather Service
OAR	Oceanic and Atmospheric Research
OSTP	White House Office of Science and Technology Policy
PREDICT	PRE-Depression Investigation of Cloud-Systems in the Tropics
RAP	Rapid Refresh
RHPS	Roadway Wind/Solar Hybrid Power Generation and Distribution System
RSA	Range Standardization and Automation
SDR	Subcommittee on Disaster Reduction
SHAVE	Severe Hazard Algorithm Verification Experiment
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SPA-10	Storm-Penetrating A-10
SPC	Storm Prediction Center
SRP	Salt River Project
TAC	Technical Advisory Committee
TC	Tropical Cyclone
TFHRC	Turner Fairbank Highway Research Center
TRACC	Transportation Research and Analysis Computing Center
TRB	Transportation Research Board
USACE	United States Army Corps of Engineers
VORTEX2	Verification of the Origins of Rotation in Tornadoes Experiment 2
WoF	Warn-on-Forecast
WRN	Weather-Ready Nation