National Windstorm Impact Reduction Program

Biennial Report to Congress for Fiscal Years 2013 and 2014

PRODUCT OF THE
Committee on Environment, Natural Resources, and Sustainability
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

August 2015

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Report prepared by
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
COMMITTEE ON ENVIRONMENT, NATURAL RESOURCES, AND SUSTAINABILITY (CENRS)
SUBCOMMITTEE ON DISASTER REDUCTION (SDR)

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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*: *Biennial Report to Congress for Fiscal Years 2013 and 2014*, produced by the National Science and Technology Council's (NSTC) Subcommittee on Disaster Reduction (SDR) 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 increased the Nation's vulnerability. 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 SDR Windstorm Working Group delivered to Congress an initial *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 and forecasting windstorms. Subsequently, the NWIRP developed biennial reports for Fiscal Years 2007-2008, 2009-2010, and 2011-2012 detailing examples of relevant Federal activities for reducing windstorm impacts undertaken by the NWIRP member agencies during the given reporting periods.

This new report for 2013-2014 continues to fulfill the NSTC's congressionally mandated responsibility to provide biennial reports on the NWIRP. Overall, it finds that the Program has successfully facilitated improvements in windstorm 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 in the built environment 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 reducing windstorm impacts.
Sincerely,

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

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1. BACKGROUND

Recognizing 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, in 2004 Congress prescribed the establishment of a coordinated Federal-agency effort– known as the National Windstorm Impact Reduction Program (NWIRP) – to accomplish significant reductions in windstorm-related losses of life and property. To this end, the NWIRP has focused on facilitating improvements in forecast models, warning systems, evacuation planning, structural design, and community preparedness to meet this goal. This report for Fiscal Years 2013-2014 (October 2012-September 2014) continues to fulfill the legislatively mandated responsibility to provide biennial reports to Congress on the NWIRP.

Windstorms pose a grave threat to the safety and security of our citizens and our communities. Improved forecasting of windstorms is essential, but additional observations, models, and tools are also needed to advance the understanding of how the built environment responds to windstorm events and to enable the cost-effective design, construction, and retrofit of windstorm-resistant buildings and infrastructure. Efficient warning systems and social analysis are also 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 continue to build on past activities, including those identified in this report, to identify and prioritize specific measurement-science research and development needs for windstorm impact reduction.

2. WINDSTORMS IN FISCAL YEARS 2013 AND 2014

Windstorms such as hurricanes, tornadoes, and severe thunderstorms are among the most destructive and economically-damaging hazards that affect the United States on an annual basis. Each year, such storms claim lives, cause injuries, and result in billions of dollars in damages to property. Fiscal Years 2013 and 2014 brought windstorms of a historic nature. The most impactful windstorm of the fiscal period of fiscal years 2013-2014 was Hurricane/Post-Tropical Cyclone Sandy, which damaged or destroyed upwards of 700,000 homes in the Northeast after it made landfall in the Northeastern United States in late October 2012. Storm surge created some of the most crippling, cascading impacts in the New York-New Jersey region, including flooding in New York City's subway tunnels, water covering runways at La Guardia and Kennedy airports, and damage to the New Jersey Transit System. Hurricane/Post-Tropical Cyclone Sandy was the worst disaster for mass public transit systems (e.g., bus, commuter rail, subway) in U.S. history. On October 30, 2012, the morning after the storm made landfall, more than half of the Nation's daily transit riders were without service.[1]

Sandy made landfall along the southern New Jersey shore near Brigantine, New Jersey, on October 29, 2012, causing historic devastation and substantial loss of life. In the United States, the storm was associated with 72 direct deaths in eight states: 48 in New York, 12 in New Jersey, 5 in Connecticut, 2 each in Virginia and Pennsylvania, and 1 each in New Hampshire, West Virginia,

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[1] HUD, Management's Discussion and Analysis Hurricane Sandy, https://portal.hud.gov/hudportal/documents/huddoc?id=afrfy13_sandy.pdf.

and Maryland. These deaths make Sandy the deadliest hurricane to hit the U.S. mainland since Hurricane Katrina in 2005, as well as the deadliest hurricane/post-tropical cyclone to hit the U.S. East Coast since Hurricane Agnes in 1972.[2] At the height of the event on October 29-30, 2012, approximately 8.5 million people were without power. Based on National Weather Service (NWS) forecasts and population statistics as the storm approached, it is estimated that approximately 58.7 million people were impacted by wind gusts of at least 58 miles per hour and 19.2 million people were impacted by wind gusts greater than 74 miles per hour[3] – an area so large that tropical-storm force winds extended about 1,000 miles in diameter.

In addition to Sandy, a series of powerful and destructive tornadoes of unprecedented size and intensity struck in and around the Newcastle, Moore, and El Reno, Oklahoma, areas in May 2013, causing many devastating impacts in the central part of the state. Windstorms that struck the United States in calendar year 2013 took 92 lives and injured almost 900 people,[4] causing an estimated $4.5 billion in total direct property losses in the process.[5] The deadly Enhanced Fujita scale 5 (EF-5) tornado that struck the cities of Newcastle and Moore, Oklahoma, on May 20, 2013, had a path length of 17 miles, was 1.3 miles wide, and had peak winds estimated at 210 miles per hour.[6] The tornado killed 24 people, injured at least 230, and destroyed over 1,050 homes – despite the city having a 36-minute warning lead-time as the storm was approaching.[7] The EF-3 tornado that ravaged rural areas surrounding El Reno, Oklahoma, on May 31, 2013, had a path length of 16.2 miles and was 2.6 miles wide, which was the largest tornado width ever recorded.[8] There were seven fatalities associated with this tornado.

Additional windstorms and related severe and fast-moving thunderstorm complexes caused extensive damage in other parts of the United States as well during the fiscal period. A massive storm system spawned a tornado outbreak between April 27-30, 2014, across several Central and Southern U.S. states, impacting thousands of residents in Alabama, Arkansas, Kansas, Mississippi, Oklahoma, and Tennessee. The small towns of Mayflower and Vilonia, Arkansas, in Faulkner County were hit particularly hard by an EF-4 tornado on the evening of April 27, 2014,[9] which resulted in 12 fatalities. According to the NWS, in Faulkner County the tornado destroyed 261 houses and 121 mobile homes, caused major damage to 77 houses, 29 mobile homes, and 5

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[2] NOAA/NWS Service Assessment, *Hurricane/Post-Tropical Cyclone Sandy, October 22-29, 2012*, http://www.nws.noaa.gov/os/assessments/pdfs/Sandy13.pdf.

[3] *Ibid.*

[4] NOAA/NWS fatality and injury data (2013) for tornado, thunderstorm wind, hurricane/tropical storm, and high wind hazards, http://www.nws.noaa.gov/om/hazstats/sum13.pdf.[5] NOAA/NWS property loss data (2013) for tornado, thunderstorm wind, hurricane/tropical storm, and high wind hazards, http://www.nws.noaa.gov/om/hazstats/sum13.pdf

[5] NOAA/NWS property loss data (2013) for tornado, thunderstorm wind, hurricane/tropical storm, and high wind hazards, http://www.nws.noaa.gov/om/hazstats/sum13.pdf

[6] NWS Weather Forecast Office, Norman, OK, The Tornado Outbreak of May 20, 2013, http://www.srh.noaa.gov/oun/?n=events-20130520.

[7] NOAA/NWS Service Assessment, *May 2013 Oklahoma Tornadoes and Flash Flooding*, http://www.nws.noaa.gov/os/assessments/pdfs/13oklahoma_tornadoes.pdf.

[8] NWS Weather Forecast Office, Norman, OK, May 31-June 1, 2013 Tornado and Flash Flood Event, http://www.srh.noaa.gov/oun/?n=events-20130531-elreno.

[9] NWS Weather Forecast Office, Little Rock, AR, Tornadoes on April 27, 2014 (Ground Photos), http://www.srh.noaa.gov/lzk/?n=svr0414cpics.htm.

apartments, and caused minor damage to 96 houses, 14 mobile homes, and 4 apartments.[10] Overall, during calendar years 2013 and 2014, there were 907 and 888 tornadoes, respectively, that occurred in the United States, 28 of which were killer tornadoes responsible for 102 combined tornado deaths over the two-year span.[11]

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

Following passage of the NWIRA, OSTP established, within the structure of the National Science and Technology Council (NSTC), an interagency Windstorm Working Group of the Committee on Environment, Natural Resources, and Sustainability Subcommittee on Disaster Reduction (SDR), 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 authorization for appropriations 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 the Federal agencies to coordinate new and existing research to fill 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 science and technology actions that inform and support 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*[12] – are available online at the SDR website at http://www.sdr.gov/.

[10] NOAA National Climatic Data Center, Storm Events Database, http://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=504760.

[11] NOAA/NWS Storm Prediction Center, Monthly and Annual U.S. Tornado Summaries, http://www.spc.noaa.gov/climo/online/monthly/newm.html.

[12] http://www.sdr.gov/

This document is the biennial report for Fiscal Years 2013 and 2014. The report provides examples of relevant Federal activities undertaken by the abovementioned agencies during the fiscal period (from October 2012 through September 2014). 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.
- NSF, in support of research in engineering, the atmospheric sciences, and social sciences to improve the 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. PROGRAM ACTIVITIES IN FISCAL YEARS 2013 and 2014

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 NSF and other agencies to severe weather warnings provided by NOAA. During Fiscal Years 2013 and 2014, 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 of what they were 15 years ago.[13] 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

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

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 their intensities.

Prediction of hurricane formation and intensification remains one of the most challenging aspects of atmospheric science, and 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 the National Hurricane Center (NHC) project that limitations inherent to these joint models will likely restrict their ability to 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.[14] 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. NOAA is making significant progress toward meeting these goals. In Fiscal years 2013 and 2014, HFIP continued to provide funding to numerous efforts within NOAA, other Federal agencies, and universities to support the development, testing, and evaluation of enhanced numerical prediction systems, better use of existing observation, evaluation of new potential observations, and support for improved forecasting techniques. 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, improved higher resolution models, and existing operational global models when run as an ensemble at 30 km resolution. Although there appears to have been significant progress in intensity prediction using high-resolution regional models, the past two seasons have provided relatively few challenging forecast scenarios. In addition, inner-core Doppler data are not consistently leading to forecast improvements, which likely reflect a continuing need to advance data assimilation systems and additional thermodynamic measurements in and around the hurricane core. However, hurricane model improvements have continued with the expectation that the five-year goal will be met in time for the calendar year 2015 hurricane season. 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.

NOAA: Joint Hurricane Testbed. During Fiscal Years 2013 and 2014, the U.S. Weather Research Program within the NOAA Office of Oceanic and Atmospheric Research (OAR) Office

[14] NOAA National Hurricane Center, presentation by Richard J. Pasch, *Hurricane Intensity Forecast Improvement: Is It Possible?,* April 21, 2011, http://www.nhc.noaa.gov/outreach/presentations/2011_IntensityForecastingImprovement_Pasch.pdf.

of Weather and Air Quality initiated the support of seven new projects conducted at the Joint Hurricane Testbed (JHT) in Miami, Florida – a NOAA testbed jointly managed by the NHC and the NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML). 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. These new projects represent a wide range of partners from academia (University of Miami, Florida International University, University of North Carolina, Florida State University, and University of Rhode Island) and U.S. government laboratories (NOAA's Geophysical Fluid Dynamics Laboratory, NOAA's Cooperative Institute for Research in the Atmosphere, and NOAA's Cooperative Institute for Meteorological Satellite Studies). During Fiscal Year 2014, earlier projects that had been recently completed were considered for operational implementation at either the NHC or the Environmental Modeling Center. Of these, six were accepted for implementation. Of particular note was the Tropical Cyclone Genesis Index, which will provide for the first time quantitative probabilistic guidance to assist NHC's Tropical Weather Outlook product.

NOAA/NASA: NOAA Intensity Forecasting Experiment. NOAA's Hurricane Research Division 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 Federal agencies to accomplish a more complete sampling of TC structure and intensity. For example, during Fiscal Year 2014, IFEX partnered with the National Aeronautics and Space Administration (NASA) on the Hurricane and Severe Storm Sentinel (HS3) Project and the Office of Naval Research (ONR) Tropical Cyclone Intensification and Structure (TCI-14) Project in a multi-agency collaborative and coordinated study of changes in hurricane intensity and structure 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 unmanned aircraft system 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 Edouard as it changed over time in a way that conventional planes and satellites had not done before. In addition to demonstrating new skill in sampling the wind and thermodynamic structure of tropical cyclones, scientists have shed light on the processes tied to the rapid intensity and structure changes of Hurricane Edouard. These innovative interactions continued during Fiscal Years 2013 and 2014, with IFEX partnering with NASA and ONR in the NOAA Sensing Hazards with Operational Unmanned Technology (SHOUT) experiment to utilize a Global Hawk and the NASA WB-57 High Altitude Research Program for hurricane observation.

NSF: Hurricane Predictions and Predictability. NSF continues to invest in studies related to the basic science behind tropical cyclones and hurricanes. These studies range from the small-scale analysis of how sea spray and cloud particles affect the development and intensity of storms to the questions of the genesis of cyclones and how large-scale environmental factors affect their intensity and movement. Hurricane Sandy is a prime example of the tragic toll that hurricanes can take on lives and property. In Fiscal Year 2013, NSF-funded researchers at Pennsylvania State University began analysis of the evolution of Hurricane Sandy through its lifecycle and landfall. A particular focus of the research is on ensemble modeling, where the same model is run with slightly different conditions to determine how robust a solution is.

4.1.2 Tornadoes, Thunderstorms, and Other Severe Weather

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 widest tornado ever recorded, which struck El Reno, Oklahoma, in May 2013 – cause havoc and terrorize communities. 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.[15] Yet even with the application of best-available science, the rate at which warnings result in false alarms remains high, at 70 percent[16]. To reduce this rate and further increase warning lead times for devastating windstorms such as tornadoes, 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 less than one minute) and storm-scale numerical models to create a storm-scale prediction capability for the NWS. The NSSL continues to investigate various model parameterization schemes, along with techniques to improve model initialization through three- and four-dimensional data assimilation. In Fiscal Years 2013 and 2014, the NSSL continued to receive funding to support the Warn-on-Forecast (WoF) project. Within the next decade, the NSSL envisions operational units evaluating a WoF 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 project, NSSL is also demonstrating the capabilities of the Multifunction Phased Array Radar (MPAR), a program funded through NOAA’s Office of Oceanic and Atmospheric Research 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 weather radar. NOAA's National Weather Radar Testbed centers on a phased array radar actively being tested and evaluated in Norman, Oklahoma. Evidence suggests

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

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

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 System Research Laboratory Global Systems Division (ESRL/GSD), the NWS Storm Prediction Center (SPC), and the NWS Forecast Office in Norman, Oklahoma (OUN).

NOAA/NSF: Verification of the Origins of Rotation in Tornadoes Experiment 2. In Fiscal Years 2009 and 2010, NSF and NOAA jointly supported the field phase of 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, as well as forecasters from the NWS (including the SPC), 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. Continuing analysis of the VORTEX2 dataset in 2013 and 2014 is advancing the understanding of tornado formation, improving prediction, and offering prospects for increased warning lead-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.

NOAA: Hazardous Weather Testbed. During Fiscal Years 2013 and 2014, NOAA's NSSL, SPC, and OUN 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 work has been conducted in the NOAA Hazardous Weather Testbed (HWT), which 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 NOAA/NASA Geostationary Operational Environmental Satellite – R Series (GOES-R) Proving Ground also conducts experiments within the HWT and the University of Oklahoma's Center for Analysis and Prediction of Storms to provide key contributions each spring during peak severe weather season. Several collaborative experiments are conducted in the HWT each year, typically involving multiple external collaborators such as the National Center for Atmospheric Research, other universities, various NOAA agencies, private industry, and leading research scientists and forecasters from around the world.

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 improve understanding of the links between large-scale climate variability and windstorm and tornado activity. The SPC maintains the long-term observational record of severe weather in the United States and a result of initial interactions, NOAA published a "State-of-the-Science Fact Sheet" in Fiscal Year 2013 titled *Tornado Activity* *and Climate Variability and Change*. While climate change can be expected to increase temperature and humidity in the lower atmosphere, it may also decrease wind shear. Since both factors are required to form tornadoes, NOAA research is focused on the prediction of these local factors as well as quantification of the role of more-remote climate signals.

NSF/NOAA: Predictability of Severe Convective Storms. In Fiscal Year 2013, NSF and NOAA researchers conducted the Mesoscale Predictability Experiment (MPEX). The goal of the experiment was to determine whether additional observations of weather conditions upstream of the U.S. Great Plains could improve predictions of severe convective storms, including tornadoes and straight-line wind producing events. The NSF/NCAR GV research aircraft deployed hundreds of instruments known as dropsondes in order to retrieve profiles of wind, moisture, and temperature of the atmosphere below the flight level of the aircraft. Weather balloons were also launched from the ground to supplement the aircraft observations. Analysis of the data is ongoing, and should allow researchers to determine whether it is observations or numerical models that are the limiting factor for prediction of these severe storms.

NSF: Tornado Theory and Observations. NSF continues to fund research in the fiscal period making use of the extraordinary efforts of the VORTEX2 field campaign that was originally conducted in Fiscal Years 2009 and 2010. In addition, new lines of research regarding the basic theory of tornadoes and ways to better observe them are now being conducted. In one case, a group of researchers at the University of Oklahoma are studying how tornado debris appears to weather radars. The recent upgrade to the Nation's WSR-88D radar system to retrieve polarimetric variables has allowed scientists to better determine the sizes and shapes of objects that the radars are detecting. Researchers are now investigating how items commonly lofted by tornadic winds, such as branches, pieces of wood, and small plastic and metal objects, are observed by weather radar. By better understanding what the radar is observing, weather forecasters and emergency managers can more promptly respond to recent tornado damage and provide better warnings to those along a tornado's path.

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 2013 and 2014, 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 estimation of wind loads on structures. NIST and FEMA conducted post-windstorm studies, and the 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 during Fiscal Years 2013 and 2014 included: continued development of new design wind speed maps intended for use in the American Society of Civil Engineers (ASCE) Standard on Minimum Design Loads for Buildings and Other Structures (ASCE 7); conversion of an existing smooth flow wind tunnel test section to a boundary layer test section; and initiation of computational fluid dynamics research to study computationally efficient means for simulation of atmospheric turbulence needed for accurate simulations of wind loads on buildings,[17, 18] to be supported by experiments conducted in the new boundary layer wind tunnel test section.

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 Residential 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.

As a result of the 2011 spring tornadoes Mitigation Assessment Team (MAT) research, FEMA proposed two code changes, which were approved for publication in the 2015 IBC. The code changes call for mandatory storm shelters in high-wind regions for schools and first-responder facilities as follows:

- In areas where the shelter design wind speed for tornadoes is 250 mph, all new kindergarten through 12th grade schools with 50 or more occupants in total per school shall have an ICC 500-compliant storm shelter.
- In areas where the shelter design wind speed for tornadoes is 250 mph, all new 911 call stations, emergency operation centers, and fire, rescue, ambulance and police stations shall have an ICC 500-compliant storm shelter.

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[17] NIST Advances in Computer-Aided and Computational Methods in Wind Engineering, by D. Yeo, F. Lombardo, D. Banerjee, E. Letvin, F. Potra, E. Simiu, and M. Levitan, *Proceedings of the ATC/SEI Advances in Hurricane Engineering Conference*, October 2012.

[18] Practical CFD Simulations of Wind Tunnel Tests, by D. Banerjee, S. Hemley, R. McDermott, D. Yeo, F. Lombardo, and M. Levitan. *Proceedings of the 12th Americas Conference on Wind Engineering*, June 2013.

FEMA: Mitigation Assessment Team Evaluations Following Major Hurricanes, Tornadoes and Windstorms. In Fiscal Year 2013, FEMA MATs responded to both Hurricane Isaac in Louisiana and Hurricane Sandy in New Jersey and New York. 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 two Recovery Advisories (RA) for Hurricane Isaac; and seven RAs and 3 fact sheets from the Hurricane Sandy MAT:

- RA 1 – Improving Connections in Elevated Coastal Residential Buildings
- RA 2 – Reducing Flood Effects in Critical Facilities
- RA 3 – Restoring Mechanical, Electrical, and Plumbing Systems In Non-Substantially Damaged Residential Buildings
- RA 4 – Reducing Interruptions to Mid- and High-Rise Buildings During Floods
- RA 5 – Designing for Flood Levels Above the Base Flood Elevation (BFE) After Hurricane Sandy
- RA 6 – Protecting Building Fuel Systems from Flood Damage
- RA 7 – Reducing Flood Risk and Flood Insurance Premiums for Existing Residential Buildings in Zone A
- Fact Sheet 1 – Cleaning Flooded Buildings
- Fact Sheet 2 – Foundation Requirements and recommendations for Elevated Homes
- Fact Sheet 3 – Building Science Support and Code Changes Aiding Sandy Recovery

The Hurricane Isaac MAT was charged with evaluating hurricane damage with focus on performance of post-Hurricane Katrina construction and reconstruction efforts. This included critical facilities affected by the storm, evaluating the performance of electrical distribution and communication facilities, and investigating claims of wind damage in newer buildings. The MAT's observations, conclusions, and recommendations are presented in FEMA P-938, *Mitigation Assessment Team Report – Hurricane Isaac in Louisiana: Building Performance Observations, Recommendations, and Technical Guidance*.[19]

The Hurricane Sandy MAT investigated the performance of building codes and standards; flood protective measures; residential construction; critical facilities and key assets; and mechanical, electrical, and plumbing systems. The final MAT report (FEMA P-942: *Mitigation Assessment Team Report – Hurricane Sandy in New Jersey and New York; Building Performance Observations, Recommendations, and Technical Guidance*[20]) was released in Fiscal Year 2014 and presents the conclusions and recommendations derived from the field observations with regards to key engineering concepts, codes and standards, mitigation measures and considerations that can be used in the planning and recovery process to help minimize future damage to structures and their related utility systems.

[19] *Hurricane Isaac in Louisiana: Building Performance Observations, Recommendations, and Technical Guidance*, Mitigation Assessment Team Report (P-938), Federal Emergency Management Agency, March 2013. Available at http://www.fema.gov/media-library-data/20130726-1908-25045-0581/fema_p_938_isaac_mat.pdf.

[20] *Hurricane Sandy in New Jersey and New York: Building Performance Observations, Recommendations, and Technical Guidance*, Mitigation Assessment Team Report (P-942), Federal Emergency Management Agency, November 2013. Available at http://www.fema.gov/media-library-data/1386850803857-025eb299df32c6782fdcbb6f69b35b13/Combined_Sandy_MAT_Report_508post.pdf.

In Fiscal Year 2014, FEMA also released a Formal Observation Report, FEMA P-1020[21], presenting the observations, conclusions, and recommendations in response to field investigations conducted after the EF-5 tornado that impacted the towns of Newcastle and Moore, Oklahoma, on May 20, 2013. The post-storm investigation team focused its efforts on safe rooms and storm shelters in the path of the tornado in order to analyze their performance, functionality, and use.

NIST/NOAA: Preliminary Reconnaissance of the Newcastle-Moore Tornado. At the time of the Newcastle-Moore tornado, NIST was nearing completion of its technical investigation of the 2011 Joplin tornado. The objectives of the Newcastle-Moore Tornado Preliminary Reconnaissance, conducted in collaboration with NOAA, were therefore limited to identifying information that might be relevant to aspects of the Joplin tornado investigation, including collection of data and information on: 1) the performance of the emergency communications systems immediately prior to and during the tornado; and 2) the response of critical and educational facilities to the tornado, including emergency operations, the physical performance of the buildings and designated safe areas, and life safety outcomes. One of the key observations described in the preliminary reconnaissance report[22] was that designated safe areas at one of the impacted elementary schools did not provide life safety protection. Seven schoolchildren died and several others were injured when part of the building's designated safe area, in which they were taking shelter, collapsed.

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 24-28 to conduct preliminary reconnaissance. This was the deadliest single tornado since official record keeping began in 1950, causing 161 fatalities. Based on analysis of the data collected and other criteria required by law and regulation, the Director of NIST established a team (including staff from NIST and NOAA) under the National Construction Safety Team (NCST) Act on June 29, 2011, to proceed with a more comprehensive study of the disaster. The final report of the technical investigation,[23] completed in Fiscal Year 2014, includes 47 findings that support 16 recommendations in the following broad areas: improving understanding of tornado hazard characteristics and associated wind fields; improving performance of buildings, shelters, designated safe areas, and lifelines; and improving performance of emergency communications systems and public response. Specifically, the NIST report includes calls for: 1) developing national performance-based standards for tornado-resistant design of buildings and infrastructure, as well as design methods to achieve those standards; 2) developing improved standards, codes and guidelines for siting, design, installation, and operation of tornado shelters, and installation of

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[21] *Tornado: Moore, Oklahoma, May 20, 2013: Safe Room Performance, Observations, and Conclusions*, Formal Observation Report (P-1020), Federal Emergency Management Agency, August 2014. Available at http://www.fema.gov/media-library-data/1418307179636-a018b8744801f8a770e6ea5c65eb5a4d/FEMA_P-1020_Moore_Tornado_Report_508.pdf.

[22] *Preliminary Reconnaissance of the May 20, 2013, Newcastle-Moore Tornado in Oklahoma*. By E. Kuligowski, L. Phan, M. Levitan, and D. Jorgensen. National Institute of Standards and Technology Special Publication 1164, December, 2013. Available at http://www.nist.gov/manuscript-publication-search.cfm?pub_id=914721.

[23] *Final Report - National Institute of Standards and Technology (NIST) Technical Investigation of the May 22, 2011, Tornado in Joplin Missouri*. By E. Kuligowski, F. Lombardo, L. Phan, M. Levitan, and D. Jorgensen. NCSTAR 3, March 2014. Available at http://www.nist.gov/manuscript-publication-search.cfm?pub_id=915628.

many more shelters in tornado-prone areas; and 3) creating national codes and standards for clear, consistent and accurate emergency communications and then ensure that emergency managers, the NWS, and the news media in local communities have a joint plan for delivering those messages quickly and persuasively during tornadoes.

NIST: Implementation of Recommendations from the Joplin Tornado Investigation. Following completion of its technical investigation of the Joplin Tornado, NIST initiated a new project to begin implementing the 16 recommendations identified in the final report.[24] Progress during Fiscal Year 2014 included approval of a proposal submitted to the ASCE to develop a new standard on methods of wind speed estimation in tornadoes. The scope of the new standard will include updating and improving the EF scale for rating tornadoes, development of standardized methods for radar data analysis, forensic engineering, and other wind speed estimation techniques, and minimum data archival requirements to support wind speed estimates. The new ASCE committee charged with developing this standard is co-chaired by a meteorologist from NOAA/NWS and a wind/structural engineer from NIST. A multi-year effort to develop new tornado hazard maps, for use in performance-based design of buildings and structures to resist tornadoes, was also initiated in Fiscal Year 2014.

FEMA/FHWA/NIST/NSF: U.S.-Japan Panel on Wind and Seismic Effects. FEMA, FHWA, NIST, and NSF all participate on the U.S.-Japan Cooperative Program in Natural Resources 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. Task Committees addressing wind and storm surge hazards include Task Committee "D" (Wind Engineering), Task Committee "G" (Transportation), and Task Committee "H" (Storm Surge and Tsunami). The Task Committee "D" group has held five international workshops and the Task Committee "G" group has held 30 such workshops. During Fiscal Year 2013, the U.S. side hosted a panel meeting at NIST in Gaithersburg, Maryland. The U.S. side also hosted a bridge engineering workshop in Portland, Oregon, and attended a bridge engineering workshop in Tsukuba Science City, Japan, during Fiscal Year 2013.[25]

NIST/NSF: R&D Roadmap for Windstorm and Coastal Inundation Impact Reduction. NIST completed and published an R&D roadmap for windstorm and coastal inundation impact reduction[26] during the current reporting period. The roadmap includes a vision for windstorm and coastal inundation resilient communities, identifies grand challenges, and provides descriptions of 30 priority R&D topics in areas of hazard characterization, loads and effects, resistance to loads, and performance-based design for wind, storm surge, and tsunami hazards. Input for the roadmap was acquired through a pair of workshops (held in Reston, Virginia, in Fiscal Year 2012, and Miami, Florida, in Fiscal Year 2013), the first of which was jointly sponsored by NSF. Over 100 industry leading practitioners, academics, and representatives from key government agencies

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[24] *Ibid.*

[25] *Proceedings of the 29th U.S. – Japan Bridge Engineering Workshop,* Public Works Research Institute, Tsukuba Science City, Japan, November, 2013. Available at http://www.pwri.go.jp/eng/ujnr/ujnr.htm.

[26] *Measurement Science R&D Roadmap for Windstorm and Coastal Inundation Impact Reduction* (NIST GCR 14-973-13), National Institute of Standards and Technology, 2014. Available at http://www.nist.gov/manuscript-publication-search.cfm?pub_id=915541.

participated in the two workshops. Federal government participants included representatives from the U.S. Department of Housing and Urban Development and the U.S. Geological Survey, in addition to FEMA, FHWA, NIST, NOAA, NSF, and OSTP.

NSF: RAPID Awards: Collection of Perishable Data. NSF has a standing program to provide funding to university faculty members to collect perishable data from the field after a significant windstorm event. During Fiscal Years 2013 and 2014, the institutions that were granted funds for collecting data after Hurricane Sandy completed their work. The data include level and impact of storm surge on residential structures and bridges in the New Jersey and New York coastal areas, power outages in New York City and surrounding areas, and impact of wind in inland areas. The institutions that participated in the research included: New York University, CUNY City College, Princeton University, Drexel University, Stevens Institute of Technology, Louisiana State University, University of Washington, and the University of Notre Dame. The collected data are housed on the web sites of the institutions and are available to principal investigators and the public. A similar effort of collecting data after Typhoon Haiyan that devastated islands of the Philippines was pursued by the University of North Carolina-Charlotte. In addition, faculty and students from University of Oklahoma, Mississippi State University, and University of Alabama documented perishable data and modes of collapse of buildings following the tornadoes that impacted the Newcastle, Moore, and El Reno, Oklahoma, areas in May 2013. This collection of field data after the tornado has led to significant changes in the building codes of the city of Moore, Oklahoma. Faculty and students from Lyndon State College were able to perform detailed ground and aerial surveys of the damage track caused by the Newcastle-Moore and El Reno tornadoes.

NSF: Planning Grant for Industry/University Cooperative Research Center (I/UCRC) for Windstorm Hazard Mitigation. NSF has provided a collaborative grant to Texas Tech University, Louisiana State University, and the University of Alabama to formulate a partnership center for research and development on windstorm hazard mitigation between the academic institutions and industry. The grant is for planning purposes and allows the group to meet and delineate the type of research that the industry would like the researchers to pursue. The goal is to produce synergy between academic researchers and industry personnel to use basic research and facilities to develop meaningful results that the industry can use. The plan of the center is to continue beyond funding from the NSF.

NSF: Awards for Response of Tall Buildings in High Winds. As buildings are planned and designed to be greater and greater in height, NSF is funding awards to assess the response of these tall structures in high winds and to create improved aerodynamic shapes to reduce drifts. Very tall buildings in the range of 100 stories or more can sway in high winds, and this swaying can be felt by people – making them uncomfortable. The optimum aerodynamic shape of a building can reduce swaying and the drift of the building; in addition, aerodynamic shapes can reduce wind-induced loadings and make very tall buildings more resilient to winds and potentially more economical. Awards were given in the fiscal period to Northeastern University and the University of Notre Dame to study emerging problems related to tall buildings.

NSF: Hurricane Wind and Surge Effects on Buildings and Bridges. NSF has provided grants to the University of Notre Dame and the City University of New York – City College to pursue fundamental research in understanding the impact of hurricanes on shoreline buildings and bridges.

These impacts are due to high winds as well as storm surge. In the research projects, loads are modeled in computer simulation to understand their impact on the coastal buildings and bridges. Responses of buildings to storm surge and waves are modeled using a structural mechanics approach, and responses will be compared with the damage data collected after Hurricane Sandy. The computer simulation model will be refined to duplicate the field data to the extent possible, and in addition, the computer simulation of storm surge will predict scour that the surge can cause around bridge piers. Another grant provided by NSF is developing rapid deployment of self-contained instrumentation that can measure loads on bridges during a hurricane. The Florida Department of Transportation is working closely with University of Florida faculty and students to facilitate rapid deployment of the instruments. This early-career grant will establish storm surge and wave impact on bridge structures in hurricanes using wireless smart sensors assisted by advanced cyberinfrastructure. The results of these studies have potential of improving coastal buildings and bridges to resist hurricane forces in the future.

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 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 were collected on a continuous basis; however, few major storm events were observed. The data gathered during this monitoring period are being used 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 2013 and 2014. Tests had been previously performed on the Zakim (Massachusetts), Emerson (Missouri), and Penobscot Narrows (Maine) bridges. During this reporting period, a technical report[27] on the Penobscot study and a technical paper[28] on the Emerson study were published. The report documents the behavior of large, ungrouted bridge cables and illustrates the effectiveness of viscous dampers as a mitigation measure. The paper summarizes the behavior of grouted and ungrouted cables as well as the effectiveness of cross ties as a mitigation measure. 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.

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[27] Dynamic Properties of Stay Cables on the Penobscot Narrows Bridge, by H.R. Bosch and J.R. Pagenkopf, Report No. FHWA-HRT-14-067, Federal Highway Administration, McLean, VA, September 2014. Available at http://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/14067/index.cfm.

[28] Dynamic Properties of Stay Cables on the Bill Emerson Bridge, by H.R. Bosch and J.R. Pagenkopf, *Proceedings of the 12th Americas Conference on Wind Engineering*, Seattle, Washington, June 2013.

FHWA: Physical Modeling of Wind Effects on Highway Structures. 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 in Canada, wind tunnel tests were performed (during the previous reporting period) 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 and cable orientation, cable roundness, and aerodynamic surface treatment on overall performance and aerodynamic stability. During Fiscal Years 2013 and 2014, a comprehensive technical report[29] and four technical papers[30, 31, 32, 33] were published. As noted in the report, the imperfect shape of High Density Polyethylene Pipe (HDPE) used on bridge stay cables can play an important role in the aerodynamic stability and performance of cables. Additional tests have been planned in the next reporting period to further investigate this area of wind and cable interaction. The design of these tests requires information regarding the roundness of typical HDPE used in bridge construction. To obtain this information, detailed field measurements must be undertaken at select bridge sites and an automated robotic device has been designed and fabricated for this purpose. Large Variable Message Signs can and have exhibited sensitivity to the effects of wind and truck gust loadings resulting in performance problems and structural failures. To investigate this, wind tunnel testing in the FHWA Aerodynamics Laboratory and computational modeling in the Argonne National Laboratory are ongoing. During this reporting period, wind force measurements on a 1:10 scale model of a representative message sign panel were completed for a wide range of vertical wind angles. Traffic signal standards and high light towers have also exhibited sensitivity to the effects of wind and structural failures have been observed. Research on this subject has been conducted under the National Cooperative Highway Research Program (NCHRP), and American Association of State Highway and Transportation Officials (AASHTO) standard specifications for these structures have been significantly updated. To evaluate and further build upon these improvements in design, wind tunnel testing in the FHWA Aerodynamics Laboratory is ongoing. During this reporting period, wind force measurements on multi-sided, tapered cylinders have resumed and tests were completed on 18 sectional models with representative geometries.

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[29] *Wind Tunnel Investigations of an Inclined Stay Cable with a Helical Fillet*, by G.L. Larose and A. D'Auteuil, Report No. FHWA-HRT-14-070, Federal Highway Administration, McLean, VA, September 2014. Available at http://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/14070/index.cfm.

[30] Wind-Induced Vibrations of Dry Inclined Stay Cables in the Critical Reynolds Number Range, by J.B. Jakobsen, G.L. Larose, A. D'Auteuil, J.H.G. Macdonald, and H.R. Bosch, *Proceedings of the 6th Symposium on Strait Crossings*, Bergen, Norway, June 2013.

[31] Wind-Tunnel Investigations of an Inclined Stay Cable with a Helical Fillet, by G.L. Larose, A. D'Auteuil, H.R. Bosch, J.B. Jakobsen, and J.H.G. Macdonald, *Proceedings of the 6th European-African Conference on Wind Engineering*, Cambridge, UK, July 2013.

[32] Sectional Load Characteristics of a Dry Inclined Helical Filleted Cable, by H. Christiansen, J.B. Jakobsen, J.H.G. Macdonald, G.L. Larose, and H.R. Bosch, *Proceedings of the 13th Conference of the Italian Association for Wind Engineering*, Genova, Italy, June 2014.

[33] Comparison of the Aerodynamics of a Bridge Cable with Helical Fillets in Smooth and Turbulent Flow, by H. Christiansen, J.B. Jakobsen, G.L. Larose, J.H.G. Macdonald, A. D'Auteuil, and H.R. Bosch, *Proceedings of the Symposium on the Dynamics and Aerodynamics of Cables*, Copenhagen, Denmark, September 2014.

FHWA: Numerical Modeling of Wind Effects on Highway Structures. During the reporting period, an existing interagency agreement has continued between the U.S. Department of Transportation and the U.S. Department of Energy for modeling the effects of natural hazards, such as windstorms, hydraulics, and flooding, on infrastructure. In addition, a second agreement was initiated to continue this collaboration and broaden the scope of research. These agreements have enabled 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. To evaluate performance of our facility and to enhance simulation capability, a detailed Computational Fluid Dynamics (CFD) model of the FHWA Aerodynamics Laboratory at the Turner Fairbank Highway Research Center (TFHRC) – including the large wind tunnel – was completed and a technical report[34] has been published. Research has continued in this area to further refine and streamline the model with the objective of developing an effective computational framework, or "virtual wind tunnel," that will complement physical testing facilities. Special techniques have been developed by ANL staff to couple CFD software with Computational Structural Mechanics (CSM) software to enable study of wind and structure interaction problems. These emerging tools have been used to develop and refine 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 and signal structures. FHWA and ANL staff have also refined skills with using "moving mesh" capabilities of CFD software so that objects, such as trucks, can be moved through still air or wind fields to study fluid and structure interaction. This complex meshing has been used to develop a computational model for studying the wind "shielding" effects of large bridge towers on trucks crossing elevated bridge structures. These CFD tools, as well as multi-physics modeling capabilities, 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. The first phase of this work established a modelling philosophy, which was found to include many assumptions regarding the initial size and velocity of spray droplets coming from tires. These results have been documented in an interim report,[35] and to validate the aforementioned assumptions, field measurements were conducted and completed. During the previous fiscal period of 2011 and 2012, finite element modeling was performed using the commercial program SAP2000 to study the efficacy of various approaches for mitigating wind-induced vibration of bridge stay cables. In the current reporting period, this study has been completed and a comprehensive laboratory report[36] has been published.

FHWA: Development of Design Guidelines and Specifications. Research continued in Fiscal Years 2013 and 2014 on the issue of wind- and rain-induced vibration of bridge stay cables. The

[34] *Wind Tunnel Model of the Turner-Fairbank Highway Research Center Aerodynamics Laboratory*, by S.A. Lottes and C. Bojanowski, Report No. ANL/ESD/13-3, Argonne National Laboratory, Argonne, IL, June 2013. Available at http://www.osti.gov/scitech/biblio/1111295.

[35] *Computer Modeling and Analysis of Truck Generated Salt-Spray Transport Near Bridges*, by S.A. Lottes and C. Bojanowski, Report No. ANL/ESD/13-1, Argonne National Laboratory, Argonne, IL, July 2013. Available at http://www.osti.gov/scitech/biblio/1087817.

[36] *Mitigation of Wind-Induced Vibration of Stay Cables: Numerical Simulations and Evaluations*, by S. Park and H.R. Bosch, Report No. FHWA-HRT-14-049, Federal Highway Administration, McLean, VA, August 2014. Available at http://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/14049/index.cfm.

FHWA draft guidelines document on the aerodynamic design of bridge stay cables was further updated, which 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. Results of research on bridge cables have been made available to the Post-Tensioning Institute's DC-45 Cable-Stayed Bridge Committee for consideration during periodic updates of their guide specification on cables. During this reporting period, FHWA also worked closely with the Transportation Research Board on the project NCHRP 20-07/Task 325 for updating AASHTO LRFD wind load provisions. The final study report and recommendations were submitted to the AASHTO SCOBS, Technical Committee on Load Distribution (T-5), for consideration in making changes to the code provisions on wind load.

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

NOAA: High-Resolution Rapid Refresh Model (HRRR) and the Rapid Refresh Model (RAP). There is a longstanding need for a higher-resolution weather models to increase accuracy of local forecasts for emergency managers, air traffic managers, renewable energy producers, wildfire managers, and others. To fulfil this need, scientists at the NOAA ESRL/GSD developed a radar-initialized, storm-resolving, high-resolution, hourly-updating assimilation and modeling system known as the High Resolution Rapid Refresh (HRRR) model to advance the prediction of weather changes in the environment. The HRRR provides hourly weather updates at 3 km resolution (i.e., a 3.5 square-mile area), which increases the protection of lives and property, helps to improve the efficiency and effectiveness of wind and solar energy of the U.S. energy sector, and provides air traffic managers with rapidly updated projections of developing severe weather. During Fiscal Year 2014, NOAA ESRL/GSD and NOAA National Centers for Environmental Prediction scientists worked together to transition the HRRR model into NWS operations, providing forecast products to users beginning on September 30, 2014. Version 2 of the HRRR is scheduled for release in late Fiscal Year 2015. The Rapid Refresh Model (RAP) is a coarser version of the HRRR assimilation and modeling system, providing forecasts for the North American domain and updated hourly. The RAP provides the boundary conditions used to execute the HRRR model. The initial version of the RAP was delivered to NWS operations in Fiscal Year 2014. A new version of the RAP, planned for delivery to NWS operations at the end of Fiscal Year 2015, will include a larger domain and forecast out to nearly 30 hours.

NOAA: Hazardous Weather System for U.S. Space Centers. Operations at U.S 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. The NOAA ESRL/GSD developed and implemented a state-of-the-art analysis and forecasting system as part of the Range Standardization and Automation program. A new version of the model was delivered to the Range in Fiscal Year 2014. The latest upgrade of the system – a triple-nested, three-dimensional analysis with a medium-range forecast – is currently undergoing on-site testing at Vandenberg Air Force Base in California.

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 are working with the Department of Energy (DOE) on evaluating the impact of hurricane winds on the turbine design and performance. DOE is providing support to collect and analyze vertical wind profiles from dropsondes within tropical cyclones affecting wind farm lease locations.

4.2.4 Community Services and Resilience

NOAA: State of Florida Public Hurricane Loss Model. NOAA continued to work with the state of Florida during the fiscal period on the Florida Public Hurricane Loss Model (FPHLM). The FPHLM is an open, transparent computer model that is 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 originally approved by the Florida Commission on Hurricane Loss Projection Methodology in August 2010 and successfully passed the state certification process initiated in late 2012. NOAA researchers at AOML and the Cooperative Institute for Marine and Atmospheric Studies partnered with the Florida International University researchers in the fiscal period to update and maintain the wind model within the FPHLM.

FEMA: Maintain Hazus-MH Hurricane Loss Estimation Model. FEMA developed and maintained the Hazards – U.S., Multi-Hazard model (Hazus-MH), a nationally applicable standardized methodology that contains models for estimating potential losses from multiple hazards, including hurricane winds. Hazus-MH uses geographic information system (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 2013 and 2014, the Hazus program was undergoing transition activities within the FEMA Risk MAP Program with little major activity concerning Hazus functionality. Hurricane-related activity during this time period included the release of Hazus 2.1 Patch 2 in February 2014, which updated Hazus compatibility with the HURREVAC model. The patch allows Hazus users to resume real-time downloads of HURREVAC products for integration with the Hazus hurricane model and better estimate potential structural damage and economic losses for a hurricane approaching the U.S.

NSF: Improving Economic Resilience on the U.S. Gulf Coast Communities to Coastal Hazards. This project funded through NSF in the fiscal period studies why communities with similar socio-economic compositions and facing identical disasters have different vulnerabilities and recovery rates. The goal is to explore the relationship of economic vulnerability, resilience, and recovery in three coastal counties in Mississippi. The research will identify variables that contribute to the recovery of these communities after disasters. It will directly benefit Gulf Coast communities in their efforts to increase resilience to tropical cyclones. Among the many benefits of the project are: increasing local participation in decision making regarding tropical cycles;

aiding local policymakers in the design and deployment of effective mitigation and economic development policies; and constructing a web-based Spatial Decision Support System.

NSF: Quantifying Disaster Resilience of Critical Infrastructure-based Societal Systems with Emergent Behavior and Dynamic Interdependencies. This NSF-funded project during the reporting period is creating a way to measure the resilience of critical infrastructure-based societal systems (CISSs) that are necessary for community functioning. A CISS is comprised of interdependent buildings that together serve a community function and are dependent on networks of critical lifelines. Examples include such infrastructure dependent systems as school districts, university campuses, central business districts, and health care systems, which is the focus of this research. The analysis requires dynamic fault-tree and modeling of complex, adaptive systems with time-varying states and changes. Results of this research can be used to improve, build, and maintain communities that are more likely to withstand disruption or disaster. The research will also inform practicing health care managers and emergency planners.

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 the 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 levels 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, the public can reduce the 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 from thunderstorms. Selected examples of such activities are highlighted below.

NOAA: Weather-Ready Nation. In the fiscal period of this report, the Weather-Ready Nation (WRN) initiative continued to make progress. The purpose of WRN 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 the 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. Partners in this program include: other Federal agencies, emergency managers, researchers, the media, the insurance industry, non-profits, and the private sector. Building a weather-ready nation starts with these internal actions but requires the action of a vast nationwide network of partners, including: other U.S. government agencies and emergency managers, researchers, the media, insurance industry, non-profits, the private sector, the weather enterprise, and more. Through a series of symposiums, the national dialog engages these partners in assessing why the Nation is experiencing such extreme impacts. Other service enhancements provided by WRN 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.

FEMA: Education, Outreach, and Information Dissemination. The FEMA website, http://www.fema.gov serves as the Nation's portal to emergency and disaster information. FEMA publications related to wind and coastal surge hazards are available for free on the web on FEMA's media library, the Google Books website, and MADCAD. Dozens of presentations were given at conferences and other forums highlighting the importance of both hurricane mitigation and safe rooms. FEMA has partnered with communities and community organizations to teach design professionals and local officials the concepts of hurricane mitigation and safe room design. FEMA has maintained its partnership with external organizations such as the Disney Corporation and the Federal Alliance for Safe Homes (FLASH), which have been operating an interactive exhibit titled "Storm Struck: 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 sponsored and provided technical direction for the National Building Museum's "Designing for Disaster" Exhibit, which opened May 11, 2014. Visitors to the exhibit explore new approaches in design and engineering to protect life and property against a range of natural hazards, including hurricanes and tornadoes. The exhibit includes a partially deconstructed safe room following the design plans in FEMA P-320. FEMA also sponsored curriculum kits that teach students in grades 7-9 about planning and designing in preparation for natural disasters.

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's safe room guidance publications are among the most widely downloaded and distributed documents by FEMA's library and publications warehouse (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, almost 12,000 copies of FEMA P-320 and over 3,400 copies of FEMA P-361 were distributed to organizations across the U.S. Other recent examples include:

- As part of the MAT Program, published the following reports and recovery advisories:

- FEMA P-938, *Mitigation Assessment Team Report – Hurricane Isaac in Louisiana: Building Performance Observations, Recommendations, and Technical Guidance* (March 2013)
  - Hurricane Isaac RA 1 – Minimizing Wind and Water Intrusion by Covering the Underside of Elevated Buildings
  - Hurricane Isaac RA 2 – Minimizing Flood Damage to Electrical Service Components
  - FEMA P-942: *Mitigation Assessment Team Report – Hurricane Sandy in New Jersey and New York; Building Performance Observations, Recommendations, and Technical Guidance* (November 2014)
  - Hurricane Sandy RA 1 – Improving Connections in Elevated Coastal Residential Buildings
  - Hurricane Sandy RA 2 – Reducing Flood Effects in Critical Facilities
  - Hurricane Sandy RA 3 – Restoring Mechanical, Electrical, and Plumbing Systems In Non-Substantially Damaged Residential Buildings
  - Hurricane Sandy RA 4 – Reducing Interruptions to Mid- and High-Rise Buildings During Floods
  - Hurricane Sandy RA 5 – Designing for Flood Levels Above the BFE After Hurricane Sandy
  - Hurricane Sandy RA 6 – Protecting Building Fuel Systems from Flood Damage
  - Hurricane Sandy RA 7 – Reducing Flood Risk and Flood Insurance Premiums for Existing Residential Buildings in Zone A
  - Hurricane Sandy Fact Sheet 1 – Cleaning Flooded Buildings
  - Hurricane Sandy Fact Sheet 2 – Foundation Requirements and recommendations for Elevated Homes
  - Hurricane Sandy Fact Sheet 3 – Building Science Support and Code Changes Aiding Sandy Recovery
- Developed in-person and online distance learning courses for FEMA's Emergency Management Institute, including an update to the four-day in-person course titled EMI E-312, Fundamentals of Building Science, which reviews information pertaining to impacts of wind, flood, earthquake, and wildland-urban interface fire on the constructed environment, and explains key performance and construction issues related to floods, wind, wildfires, and earthquakes.
- Updated FEMA P-784, Substantial Damage Estimator (SDE) Version 2.1, after piloting Version 2.0 in Louisiana following Hurricane Isaac. SDE is a tool developed to assist state and local officials in determining substantial damage for residential and non-residential structures in accordance with a local floodplain management ordinance meeting the requirements of the National Flood Insurance Program. The tool can be used to assess flood, wind, wildfire, seismic, and other forms of damage.
- Developed a new fact sheet titled "Residential Tornado Safe Room Doors" (September 2014) that provides technical information on the selection and installation of safe room doors.
- Developed a new publication, FEMA P-1019, *Emergency Power Systems for Critical Facilities: A Best Practices Approach to Improving Reliability* (September 2014). This publication discusses the effects of natural hazards on electrical transmission and distribution infrastructure and on building systems. It discusses how to determine what

facilities are critical, what equipment within a critical facility is needed to allow the facility to function and provide services, and how to provide emergency power to a critical facility.
- During the fiscal reporting period, FEMA has been updating FEMA P-320 and FEMA P-361, due out in December 2014 and March 2015, respectively, in the next fiscal period.

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 fourth two-day, hands-on training course was developed and provided to students, professionals, and U.S. Government representatives in March 2013 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 fifth course with updated and expanded materials was developed and presented in March 2014.

FHWA: Aerodynamics Webinar Series. In November 2013, the FHWA launched a new webinar series on the aerodynamics of highway structures. The objectives of this new series are to introduce our stakeholders to the aerodynamics of highway structures, provide a review of highway aerodynamic issues, highlight updates and advancements of highway wind design specifications and guidelines, demonstrate advancements in aerodynamic analysis of highway structures, and provide an introduction to available mitigation methods. During Fiscal Years 2013 and 2014, a total of five one-hour-long sessions were developed and delivered by experts in the field, including FHWA staff, and at least four more sessions have been planned. The titles of the completed sessions are as follows: *FHWA Aerodynamics Program—from galloping to cruising*; *Introduction to wind hazards in highway engineering*; *Wind loads and aerodynamic design of bridges*; *Wind induced vibration of bridge cables*; and *Experimental methods for wind design*.

5. CONCLUSION

The destructive impacts of recent extreme windstorms – such as the historic Hurricane/Post-Tropical Cyclone Sandy in October 2012 and the violent tornadoes impacting Newcastle, Moore, and El Reno, Oklahoma, in May 2013 and Mayflower and Vilonia, Arkansas, in April 2014 – 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.

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 of what 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;
- FEMA publications presenting design and construction guidance for safe rooms have been available since 1998. Since that time, over one million copies have been distributed and thousands of safe rooms have been built, and a growing number of these safe rooms have already saved lives in actual events. There has not been a single reported failure of a safe room constructed to FEMA criteria;
- Gains in structural engineering research and mitigation assessment have allowed FEMA to update its published guidance for better and more efficient safe room design and construction against windstorms, much of which has also been incorporated into the ICC 500 Standard for the Design and Construction of Storm Shelters;
- FEMA successfully proposed two building code changes for the 2015 IBC, which require ICC 500-compliant storm shelters in new schools and first-responder facilities in the areas of the Nation with the highest tornado risk;
- 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 International Building Code 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 Enhanced Fujita (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;
- The results of research funded by NSF grants have strengthened windstorm disaster evacuation management practices in the United States through advancements in planning and preparedness efforts and a better understanding of how communities perform in hosting incoming evacuees; and
- Results of wind engineering research by FHWA have contributed to a better understanding of bridge cable aerodynamics and effectiveness of associated wind mitigation techniques, improved techniques for physical and computational modeling of wind hazards to transportation structures, as well as updates of design guides and specifications.

There are opportunities for further improvements in windstorm prediction capabilities and for additional observations to advance understanding of how the built environment responds to windstorm events. In addition, efficient warning systems and social analysis can 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 continue to build on past activities, including those identified in this report, to identify and prioritize specific measurement science research and development needs for windstorm impact reduction.

APPENDIX A: KEY ABBREVIATIONS

ANL	Argonne National Laboratory
AOML	Atlantic Oceanographic and Meteorological Laboratory
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
BFE	Base Flood Elevation
CFD	Computational Fluid Dynamics
CISS	Critical Infrastructure-based Societal Systems
CSM	Computational Structural Mechanics
DOE	Department of Education
EF	Enhanced Fujita
ESRL/GSD	Earth System 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
GOES-R	Geostationary Operational Environmental Satellite – R Series
HDPE	High Density Polyethylene Pipe
HFIP	Hurricane Forecast Improvement Program
HRRR	High Resolution Rapid Refresh
HWT	Hazardous Weather Testbed
IBC	International Building Code
IFEX	Intensity Forecasting Experiment
IRC	International Residential Code
JHT	Joint Hurricane Testbed
MAT	Mitigation Assessment Team
MPAR	Multifunction Phased Array Radar
NASA	National Aeronautics and Space Administration
NCHRP	National Cooperative Highway Research Program
NCST	National Construction Safety Team
NHC	National Hurricane Center
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRCC	National Research Council of Canada
NSF	National Science Foundation
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
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
OUN	National Weather Service Forecast Office in Norman, Oklahoma
RAP	Rapid Refresh Model
SDE	Substantial Damage Estimator

SDR	Subcommittee on Disaster Reduction
SPC	Storm Prediction Center
TC	Tropical Cyclone
TFHRC	Turner Fairbank Highway Research Center
TRACC	Transportation Research and Analysis Computing Center
VORTEX2	Verification of the Origins of Rotation in Tornadoes Experiment 2
WoF	Warn-on-Forecast
WRN	Weather-Ready Nation