NATIONAL WINDSTORM IMPACT REDUCTION PROGRAM

BIENNIAL PROGRESS REPORT TO CONGRESS FOR FISCAL YEARS 2015 AND 2016

This progress report for the National Windstorm Impact Reduction Program (NWIRP) is submitted to Congress by the Interagency Coordinating Committee of NWIRP, as required by the National Windstorm Impact Reduction Act of 2004 (Public Law 108-360, Title II), as amended by the National Windstorm Impact Reduction Act Reauthorization of 2015 (Public Law 114-52).

Interagency Coordinating Committee

Dr. Walter G. Copan - *Chair*
Under Secretary of Commerce for Standards and Technology and Director
National Institute of Standards and Technology
U.S. Department of Commerce

Dr. John Cortinas
Director
Office of Weather and Air Quality
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

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Engineering Directorate
National Science Foundation

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Deputy U.S. Chief Technology Officer
Executive Office of the President

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Director
Office of Management and Budget
Executive Office of the President

Mr. John Murphy
Chief Operating Officer
National Weather Service
National Oceanic and Atmospheric Administration
U.S. Department of Commerce

Mr. David Maurstaud
Deputy Associate Administrator for Federal Insurance and Mitigation
Federal Emergency Management Agency
U.S. Department of Homeland Security

NWIRP Windstorm Working Group

Staff

Marc Levitan
Acting Director
National Windstorm Impact Reduction Program
National Institute of Standards and Technology

Stephen Potts
Program and Management Analyst
National Windstorm Impact Reduction Program
National Institute of Standards and Technology

Members

Jason Averill	National Institute of Standards and Technology
Dana Bres	Department of Housing and Urban Development
Harold Bosch	Federal Highway Administration
DaNa Carlis	National Oceanic and Atmospheric Administration
Sharon Jasim-Hanif	Department of Energy
Edward Laatsch	Federal Emergency Management Agency
Chungu Lu	National Science Foundation
Ted Mansell	National Oceanic and Atmospheric Administration
Jacqueline Meszaros	Office of Science and Technology Policy
Shirley Murillo	National Oceanic and Atmospheric Administration
Robert O'Connor	National Science Foundation
Joy Pauschke	National Science Foundation
Long Phan	National Institute of Standards and Technology
Lori Schultz	National Aeronautics and Space Administration
Michael Uhart	National Aeronautics and Space Administration
Ty Wamsley	U.S. Army Corps of Engineers
Jonathan Westcott	Federal Emergency Management Agency

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1. Background

Severe windstorms cause significant losses of life, injuries, destruction of property, and economic and social disruption in all states and regions. In recognition of this loss and dispruption, combined with ever increasing vulnerability due to rapid development and population growth in high risk areas, Congress established a coordinated federal-agency effort in 2004 – known as the National Windstorm Impact Reduction Program – to accomplish significant reductions in windstorm-related losses of life and property. Improved windstorm impact reduction measures requires a multidisciplinary approach based on atmospheric-related research to better understand the behavior and impact of windstorms on the built environment, engineering research on improving new structures and retrofitting existing ones to better withstand windstorms, and social sciences research to understand economic and social factors influencing windstorm risk reduction measures. This approach has the potential to reduce these losses through: improved data collection and analysis and impact prediction methodologies; cost-effective and affordable design and construction methods and practices; effective mitigation programs at the local, state, and national level; and public education and outreach.

1.1. Program Legislation and History

The **National Windstorm Impact Reduction Program (NWIRP or Program)** was established by Congress through the National Windstorm Impact Reduction Act (NWIRA) in 2004 to achieve "major measurable reductions in the losses of life and property from windstorms through a coordinated federal effort, in cooperation with other levels of government, academia, and the private sector, aimed at improving the understanding of windstorms and their impacts and developing and encouraging implementation of cost-effective mitigation measures to reduce those impacts."[1]

The Program consists of three components:

- Understanding of Windstorms;
- Assessing Windstorm Impact; and
- Reducing Windstorm Impact.

The Program agencies are the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the National Institute of Standards and Technology (NIST), and the Federal Emergency Management Agency (FEMA), each having defined responsibilities in research, development and/or implementation. Program leadership was provided by the Office of Science and Technology Policy (OSTP).

Following passage of the NWIRA in 2004, OSTP established, within the structure of the National Science and Technology Council (NSTC), an interagency Windstorm Working Group (WWG) of the Committee on Environment, Natural Resources, and Sustainability Subcommittee on Disaster Reduction (SDR). The WWG consists of the NSF, NOAA, NIST, and FEMA, and at the Director's discretion, the Federal Highway Administration (FHWA), and the group serves to coordinate activities in furtherance of the Program's objectives.

[1] Public Law 108-360 Title II - Windstorm Impact Reduction Act. https://www.congress.gov/108/plaws/publ360/PLAW-108publ360.htm

As an initial step, in 2006, the working group developed the Windstorm Impact Reduction Implementation Plan,[2] which identified research activities needed to improve windstorm hazard mitigation. The plan 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. These plans, published in 2008, include the Grand Challenges for Disaster Reduction Implementation Plans[3] for Hurricane, Tornado, Coastal Inundation, and Flood.

NWIRP activities from Fiscal Years 2005 through 2014 have been documented in a series of biennial reports to Congress.[4,5,6] NWIRP research, development, and implementation actions in a number of areas have reduced the impact of windstorms to lives and property. Highlights of these successes are also included in the biennial reports.

The Program was reauthorized at the end of Fiscal Year (FY) 2015.[7] The FY 2015 reauthorization moved the lead agency function to NIST and provided updated responsibilities for the four Program Agencies (see Appendix B). It additionally called for creation of an Interagency Coordinating Committee, comprised of the Directors (or their designees) of the four Program agencies, OSTP, and the Office of Management and Budget (OMB), with the Director of NIST as the Chair. The Interagency Coordinating Committee is responsible for planning and coordinating the Program, including development of a strategic plan. The Interagency Coordinating Committee also has reporting requirements, including submission of annual coordinated budgets for the Program, and reporting NWIRP progress to Congress.

1.2. Structure of the Progress Report

Section 1: An overview of the Program legislation and a brief history of NWIRP.

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[2] *Windstorm Impact Reduction Implementation Plan*, National Science and Technology Council, 2006. http://www.sdr.gov/docs/Windstorm%20Impact%20Reduction%20Implementation%20Plan%20FINAL.pdf

[3] *Grand Challenges for Disaster Reduction and Hazard-specific Implementation Plans*. National Science and Technology Council, 2008. http://www.sdr.gov/grandchallenges.html

[4] *National Windstorm Impact Reduction Program Biennial Report to Congress for Fiscal Years 2013 and 2014*. National Science and Technology Council. https://www.nist.gov/sites/default/files/documents/el/nwirp/NWIRP-FY2013-2014-Biennial-Report-to-Congress-2.pdf

[5] *National Windstorm Impact Reduction Program Biennial Report to Congress for Fiscal Years 2011 and 2012*. National Science and Technology Council. https://www.nist.gov/sites/default/files/documents/el/nwirp/NWIRP-FY2011-2012-Biennial-Report-to-Congress.pdf. (Note – activities for Fiscal Years 2007-2010 are included in appendices).

[6] *Windstorm Impact Reduction Program, Biennial Progress Report for Fiscal Years 2005-2006*. National Science and Technology Council. https://www.nist.gov/sites/default/files/documents/el/nwirp/NWIRP-FY2005-2006-Biennial-Report-to-Congress.pdf

[7] Public Law 114-52: National Windstorm Impact Reduction Act Reauthorization of 2015. https://www.congress.gov/114/plaws/publ52/PLAW-114publ52.pdf

Section 2: Provides a short description of windstorms occurring during calendar years 2015 and 2016[8] and their impacts on the loss of life and property.

Section 3: Describes program leadership and coordination, including development of the NWIRP Strategic Plan.

Section 4: Summaries of the major research, development, and implementation activities conducted by the program agencies, including collaborative activities with academia and the private sector. These activities are mapped to the Strategic Priorities and Objectives of the NWIRP Strategic Plan. Consistent with previous NWIRP reports to Congress, the descriptions focus on activities that have taken place during the past biennial period, in this case FYs 2015 and 2016 (also referred to in this document as the "reporting period"). Longer term projects also include brief descriptions of prior years' activities to provide context.

Section 5: Summarizes the outcomes achieved for each of three Strategic Goals, as well as a description of the path forward.

2. Windstorms and Their Impacts in 2015 and 2016

Each year, severe windstorms (such as hurricanes and tornadoes) and severe thunderstorms are among the most destructive and economically-damaging hazards that affect the United States, claiming many lives, causing even more injuries, and resulting in billions of dollars in damages to property. The years 2015 and 2016 were no exception.

There were 1,257 tornadoes in 2015, according to the Storm Prediction Center.[9] Tornadoes claimed 36 lives and caused 924 injuries.[10] The locations of these tornadoes are mapped in Figure 1. Thunderstorms and other high wind events claimed 65 lives and caused 221 injuries.[11] The 2015 season for hurricane activity in the Atlantic basin included 11 tropical storms, four of which became hurricanes, and two reached major hurricane strength (Category 3 or higher).[12] Most of the season's hurricanes remained well east of the United States east coast, although Tropical Storm Ana made landfall in South Carolina — the earliest U.S. hurricane making landfall on record — and Tropical Storm Bill made landfall along the central Texas coast. In total, windstorms that struck the United States in calendar year 2015 claimed 117 lives and injured 1,215 people.[13]

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[8] The summary of storm activities is provided for calendar years 2015 and 2016, rather than Fiscal Years referred to elsewhere in this report, consistent with how storm and loss data are typically available.

[9] *NOAA Annual Trends in Local Storm Reports-Tornadoes*: http://www.spc.noaa.gov/wcm/2015/torngraph-big.png

[10] Summary of Natural Hazard Statistics for 2015 in the United States http://www.nws.noaa.gov/om/hazstats/sum15.pdf

[11] Data Source: NOAA National Weather Service (NWS) Summary of Natural Hazard Statistics for 2015 in the United States. http://www.nws.noaa.gov/om/hazstats/sum15.pdf

[12] *National Hurricane Center Annual Summary – 2015 Atlantic Hurricane Season.* http://www.nhc.noaa.gov/data/tcr/summary_atlc_2015.pdf

[13] Data Source: NOAA National Weather Service (NWS) Summary of Natural Hazard Statistics for 2015 in the United States. http://www.nws.noaa.gov/om/hazstats/sum15.pdf

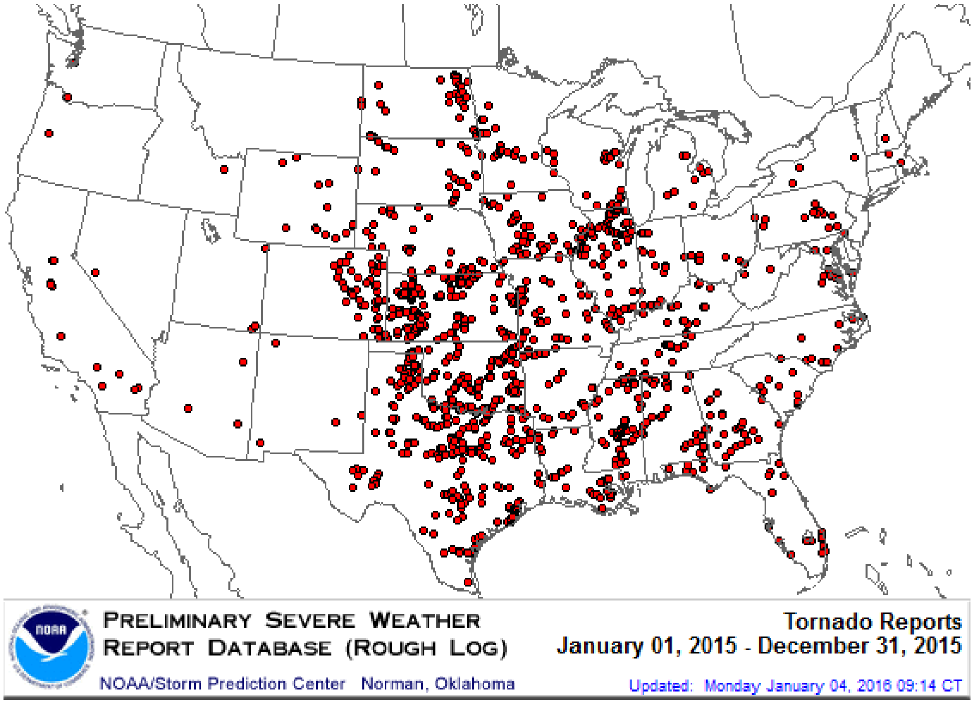

Figure 1. Tornadoes Occurring in 2015. Source: National Centers for Environmental Information, https://www.ncdc.noaa.gov/sotc/tornadoes/201513**.**

In 2016, there were 1,059 tornadoes and 13,578 reported wind events.[14] Figure 2 shows the locations where wind damage was reported as a result of severe weather. For the 2016 hurricane season, 15 named storms formed, seven of which became hurricanes, and three became major hurricanes. The number of named storms and hurricanes in 2016 was above the long-term averages of 12 and six per year, respectively. U.S. landfalling tropical cyclones included Tropical Storms Bonnie, Colin and Julia, and Hurricanes Hermine and Matthew. In total, windstorms that struck the United States in calendar year 2016 claimed 76 lives and injured 558 people.[15]

[14] NOAA Storm Prediction Center Annual Severe Weather Report Summary. http://www.spc.noaa.gov/climo/online/monthly/2016_annual_summary.html#

[15] Data Source: NOAA National Weather Service (NWS) Summary of Natural Hazard Statistics for 2016 in the United States. http://www.nws.noaa.gov/om/hazstats/sum16.pdf

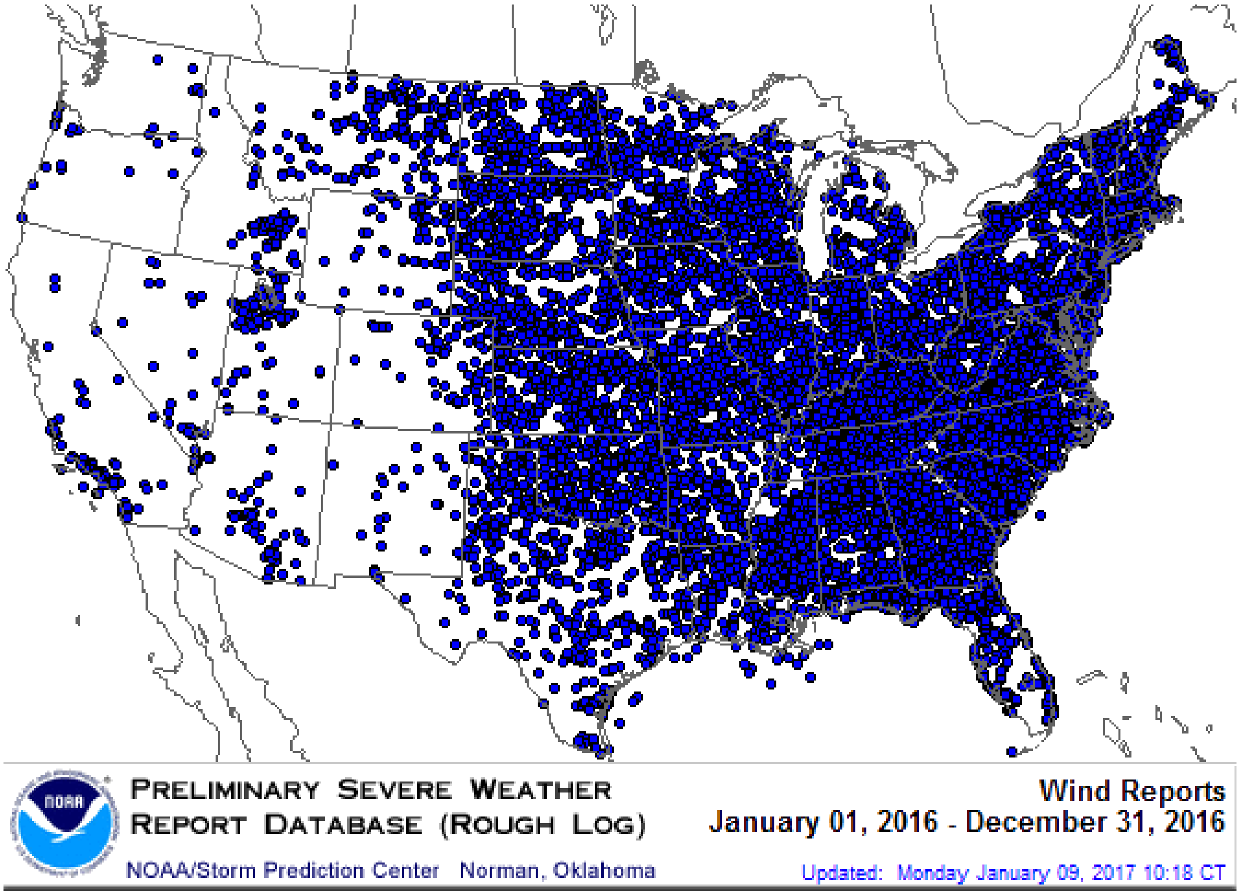

Figure 2. Wind Damage Reports Occurring in 2016.[11] Excludes damage from tropical cyclones.

One of the worst tornado events during this reporting period was the multi-state tornado outbreak which began on December 23, 2015. Tornadoes were reported to the National Weather Service (NWS) on each day from December 21 to December 27. The seven-day streak now represents the most consecutive tornado days on record in the month of December.[16] On December 24, seven tornadoes were reported to the NWS, along with nine reports of high winds.[17] On December 25, another seven tornado reports (with injuries) were filed across Alabama, Mississippi and Tennessee.[18] Then on December 26, the deadliest outbreak of the month ripped through northeast Texas in the dark. The event spawned nine tornadoes, including one with an intensity rating on the Enhanced Fujita Scale of 4 (i.e., EF-4) – with estimated winds of up to 180 miles per hour and a continuous damage path of 13 miles across two counties. Eleven

[16] Washington Post "This month is now the deadliest December for tornadoes in over 60 years". https://www.washingtonpost.com/news/capital-weather-gang/wp/2015/12/28/decembers-deadly-tornado-outbreaks-end-what-was-almost-the-safest-year-on-record/?utm_term=.c626bf4479a7

[17] Storm Prediction Center (SPC) – SPC Storm Reports for 12/24/15. http://www.spc.noaa.gov/exper/archive/event.php?date=20151224

[18] Ibid.

people lost their lives in tornadoes that night. In all, more than 40 people died in severe weather between December 23-26, 2015.[19]

Hurricane Matthew was the most impactful tropical cyclone that occurred in 2015 or 2016. The storm brought devastating flooding, strong winds, and moderate storm surge to the coast of North Carolina during the afternoon and evening of October 8 through the early afternoon hours of October 9. Cape Hatteras suffered a record six-foot storm surge.[20] River flood levels not seen since Hurricane Floyd in 1999 caused millions of dollars of damage and multiple deaths across the eastern third of the state. North Carolina's Governor at the time, Pat McCrory, said that more than 2,300 people were rescued in more than 600 rescue operations, eighty of which were air rescues.[21] Hurricane Matthew was responsible for 585 direct deaths, including 34 in the United States and its territories. The hurricane also resulted in an additional 18 indirect deaths in the United States as well as estimated $10 billion damage, mainly in the area from Florida to Virginia. Hurricane Matthew was the 10th most destructive hurricane to affect the United States.[22]

In addition to thousands of smaller windstorms, over the course of the two-year period from 2015 through 2016, there were 13 severe storm events and one tropical cyclone event (Hurricane Matthew) with losses exceeding $1 billion (CPI-adjusted) each across the United States. Figure 3 shows the states impacted by these billion-plus dollar disasters.

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[19] Washington Post: "This month is now the deadliest December for tornadoes in over 60 years". https://www.washingtonpost.com/news/capital-weather-gang/wp/2015/12/28/decembers-deadly-tornado-outbreaks-end-what-was-almost-the-safest-year-on-record/?utm_term=.c626bf4479a7

[20] NWS -Hurricane Matthew Summary. http://www.weather.gov/mhx/MatthewSummary

[21] The Weather Channel - Hurricane Matthew Leaves 43 Dead in the U.S.; Flooding Crisis Continues in North Carolina. https://weather.com/news/news/hurricane-matthew-southeast-updates

[22] NOAA National Hurricane Center Tropical Cyclone Report - Hurricane Matthew, April 2017. http://www.nhc.noaa.gov/data/tcr/AL142016_Matthew.pdf

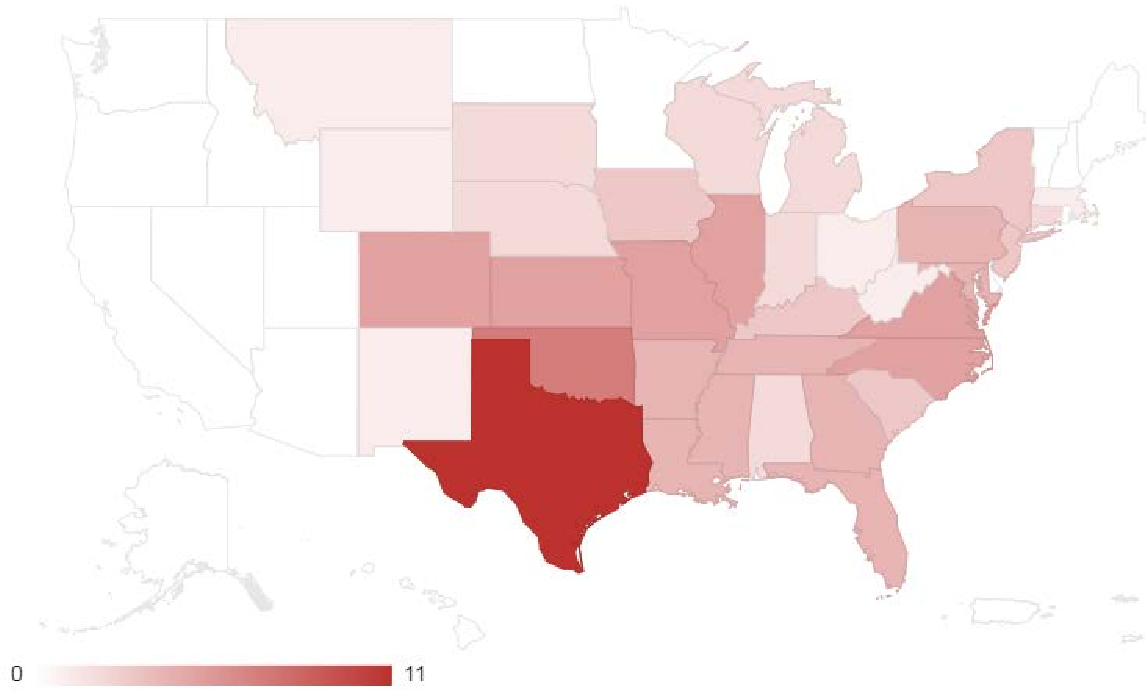

Figure 3. Billion-Dollar Severe Storm and Tropical Cyclone Disasters in 2015-2016, by State (CPI adjusted). Note: the map reflects a summation of billion-dollar events for each state affected (i.e., it does not mean that each state shown suffered at least $1 billion in losses for each event). Source: NOAA.[23]

3. Program Leadership, Management and Coordination

A change in Program leadership occurred since the last NWIRP biennial reporting period. Pursuant to Public Law 108-360, OSTP led NWIRP through FY 2015. Following passage of the National Windstorm Impact Reduction Act Reauthorization of 2015 (Public Law 114-52) on September 30, 2015, NIST began to lead NWIRP.

3.1. Windstorm Working Group

OSTP's WWG was most recently chartered in May 2015 as a Working Group of NSTC's Committee on Environment, Natural Resources, and Sustainability - Subcommittee on Disaster Reduction.[24] Its purpose was to "advance knowledge and policies that reduce the loss of life and property from windstorms." The WWG was co-chaired by NSF and NOAA. Other members included FEMA, FHWA, and NIST. During FY 2015, the WWG assisted OSTP in the development of the NWIRP Biennial Report to Congress for

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[23] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2017). https://www.ncdc.noaa.gov/billions/

[24] Charter of the Windstorm Working Group, Subcommittee on Disaster Reduction, Committee on Environment, Natural Resources, and Sustainability, National Science and Technology Council. http://www.sdr.gov/docs/SDR%20Windstorm%20Working%20Group%20-%20Charter%20FINAL%20Website%20Version.pdf

FYs 2013 and 2014.[25] The WWG also held a meeting in July 2015 titled, *"Computational Fluid Dynamics (CFD): Applications for Wind Engineering and Windstorm Impact Reduction."* The meeting included presentations by NSF, NOAA, NIST, FEMA, and the United States Navy, followed by discussion of federal research and development (R&D) needs and priorities in CFD.

With the change in leadership to NIST, the OSTP WWG was decommissioned,[26] and formal coordination activities between the program agencies are now handled by the new Interagency Coordinating Committee (see Section 3.2). To provide additional coordination at the working level, NIST formed a new WWG in FY 2016. In addition to the program agencies of NSF, NOAA, NIST, and FEMA, other federal agencies may participate. Current WWG membership also includes the Department of Energy (DoE), the Federal Highway Administration (FHWA), the Department of Housing and Urban Development (HUD), the National Aeronautics and Space Administration (NASA), the U.S. Army Corps of Engineers (USACE), and a liaison member from OSTP . The WWG has been active planning the future of the program and documenting its activities to date, including work on the NWIRP Strategic Plan and this Biennial Progress Report.

3.2. Interagency Coordinating Committee

The NWIRP Interagency Coordinating Committee oversees the planning and coordination of the Program. The Interagency Coordinating Committee consists of the heads or designees of FEMA, NOAA, NSF, OSTP, and the Office of Management and Budget (OMB), and is chaired by the Director of NIST or the Director's designee. The Interagency Coordinating Committee is charged with developing a Strategic Plan for NWIRP, reporting to Congress on NWIRP progress, and submitting annual coordinated budgets for the Program to Congress.

The NWIRP Interagency Coordinating Committee met on December 15, 2016, to review and discuss the following items: the draft NWIRP Strategic Plan prior to its release for public comment; NWIRP progress, including development of this report; and the NWIRP Coordinated Budget.

3.2.1. Strategic Plan

The NWIRP Strategic Plan (or Plan) was developed by the Program agencies and the WWG following review and assessment of national research needs and planning documents, and with stakeholder input from the NWIRP Strategic Planning Stakeholder Workshop. This Workshop, held at NSF on June 17, 2016, was attended by over 80 participants from the public and private sectors. Participants engaged in 11 breakout sessions and provided ideas to help shape the plan. To obtain feedback on the plan from a wider cross-section of the windstorm impact reduction community, a draft for public comment was released for a 60-day comment period on March 14, 2017. [27]

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[25] *National Windstorm Impact Reduction Program Biennial Report to Congress for Fiscal Years 2013 and 2014*, National Science and Technology Council. https://www.nist.gov/sites/default/files/documents/el/nwirp/NWIRP-FY2013-2014-Biennial-Report-to-Congress-2.pdf

[26] The SDR WWG ceased meeting following the NWIRP Reauthorization, and terminated per its charter on March 31, 2017.

[27] *Strategic Plan for the National Windstorm Impact Reduction Program: Draft for Public Comment.* March 2017. https://www.nist.gov/sites/default/files/documents/2017/03/13/strategic_plan_for_national_windstorm_impact_reduction_program_-_draft_f.pdf.

The plan establishes three overarching, long-term Strategic Goals, with 14 associated objectives, broadly outlining the range of activities needed to achieve major reductions in the losses of life and property from windstorms. Implementation strategies and anticipated outcomes are provided for each goal. Together, the linked goals and objectives provide a solid foundation for windstorm impact reduction, spanning the range of necessary actions from basic research through implementation.

Goal A. Improve the Understanding of Windstorm Processes and Hazards

Objective 1: Advance understanding of windstorms and associated hazards

Objective 2: Develop tools to improve windstorm data collection and analysis

Objective 3: Understand long term trends in windstorm frequency, intensity, and location

Objective 4: Develop tools to improve windstorm hazard assessment

Goal B. Improve the Understanding of Windstorm Impacts on Communities

Objective 5: Advance understanding of windstorm effects on the built environment

Objective 6: Develop computational tools for use in wind and flood modeling on buildings and infrastructure

Objective 7: Improve understanding of economic and social factors influencing windstorm risk reduction measures

Objective 8: Develop tools to improve post-storm impact data collection, analysis, and archival

Objective 9: Develop advanced risk assessment and loss estimation tools

Goal C. Improve the Windstorm Resilience of Communities Nationwide

Objective 10: Develop tools to improve the performance of buildings and other structures in windstorms

Objective 11: Support the development of windstorm-resilient standards and building codes

Objective 12: Promote the implementation of windstorm-resilient measures

Objective 13: Improve windstorm forecast accuracy and warning time

Objective 14: Improve storm readiness, emergency communications and response

The plan also identifies seven priority focus areas for new and enhanced efforts. These Strategic Priorities (SP), listed below, build upon and support elements of all 14 objectives. Strategic Priorities provide focused areas of foundational research critical to supporting future advances, as well as crosscutting themes and key opportunities for more rapid windstorm impact reduction.

SP-1: Develop Baseline Estimates of Loss of Life and Property due to Windstorms
SP-2: Obtain Measurements of Surface Winds and Storm Surge Current and Waves in Severe Storms
SP-3: Develop Publicly Available Databases of Windstorm Hazards and Impacts
SP-4: Develop Performance-Based Design for Windstorm Hazards

SP-5: Enhance Outreach and Partnerships to Improve Windstorm Preparedness and Hazard Mitigation
SP-6: Enhance and Promote Effective Storm Sheltering Strategies
SP-7: Develop the Nation's Human Resource Base in Windstorm Hazard Mitigation Fields

The plan includes a mapping of each program agency's statutory responsibilities (42 U.S.C. § 15703(b)) to the Strategic Plan's Goals, Objectives, and Strategic Priorities, reproduced in this report as Appendix B.

The goals, objectives, Strategic Priorities, and implementation strategies of the plan will serve as guidelines for NWIRP efforts, but NWIRP will remain adaptable to contingencies and opportunities as they arise. Progress on implementation of the plan and the rate of program accomplishment will depend on, among other things, the resources that are available to program agencies.

3.2.2. Coordinated Budget

The NWIRP Coordinated Budget summarizes the planned activities by each of the four program agencies and provides recently enacted funding levels and budget requests for the upcoming fiscal year. A copy of the FY 2016 Coordinated Budget submitted to Congress is provided in Appendix C.

3.3. National Advisory Committee on Windstorm Impact Reduction

The National Windstorm Impact Reduction Act Reauthorization of 2015 (Public Law 114-52) calls for the creation of a National Advisory Committee on Windstorm Impact Reduction (NACWIR or Committee). NACWIR is charged with offering assessments and recommendations on:

- trends and developments in the natural, engineering, and social sciences and practices of windstorm impact mitigation;
- the priorities of the National Windstorm Impact Reduction Program's Strategic Plan;
- the coordination of the program;
- the effectiveness of the program in meeting its purposes; and
- any revisions to the program which may be necessary.

The charter[28] for NACWIR was approved by the Department of Commerce in June 2016. Nominations were solicited via Federal Register Notice[29] in July 2016, which was publicized by NIST and distributed via email to windstorm impact reduction stakeholders, with vetting of nominees beginning shortly thereafter. Additional information about the Committee is available on the NACWIR website at https://www.nist.gov/el/mssd/nwirp/national-advisory-committee-windstorm-impact-reduction.

[28] NACWIR Charter. https://www.nist.gov/sites/default/files/documents/el/nwirp/Windstorm-Advisory-Committee-Charter.pdf
[29] NACWIR Federal Register Notice. https://www.federalregister.gov/documents/2016/07/12/2016-16373/request-for-nominations-of-members-to-serve-on-the-national-advisory-committee-on-windstorm-impact.

3.4. NIST Lead Agency Activities

NIST has a dual role in NWIRP; it is one of the four designated program agencies and also serves as the lead agency. Statutory responsibilities for all program agencies are listed in Appendix B; Table B.2 additionally identifies NIST lead agency responsibilities.

As the lead agency, NIST has the primary responsibility for planning and coordinating the program and ensuring that the program includes the necessary components to promote implementation of windstorm risk reduction measures. The strategic planning effort described in Section 3.2.1 identified these necessary components. NIST is also responsible for requesting assistance of federal agencies (other than the program agencies) to assist in carrying out the program. Section 3.1 describes the transition of the WWG from OSTP to NIST leadership. As a part of the transition, NIST invited other federal agencies to participate; several have joined the WWG. Fourteen federal agencies participated in the stakeholder workshop supporting the development of the NWIRP Strategic Plan, including all the agencies in the WWG, as well as the Department of Homeland Security (DHS), the General Services Administration (GSA), the Nuclear Regulatory Commission (NRC), the United States Geological Survey (USGS), and the Department of Veteran's Affairs (VA). Most of these agencies also participated in September 2015 workshops on tornado hazard mapping. These workshops were designed to inform stakeholders on NIST's multiyear effort to develop next generation tornado maps for engineering design and risk assessment, as well as to gather information on federal tornado impact reduction R&D needs (see Objective 4 in Section 4.2). NIST has continued direct engagement with the Nuclear Regulatory Commission, as potentially one of the primary users of new tornado hazard maps.

Three additional statutory lead agency responsibilities are to: support the development of performance-based engineering; coordinate federal post-windstorm investigations; and issue recommendations to inform development of model codes. NIST activities supporting these responsibilities are described in the following sections.

3.4.1. Support for Performance-Based Engineering

Performance-based engineering uses specific performance metrics to drive the assessment, design, and construction of engineered facilities and differs from more traditional, prescriptive procedures. Lead agency responsibilities in the National Windstorm Impact Reduction Act Reauthorization of 2015 (Public Law 114-52) include supporting "the development of performance-based engineering tools, and work with appropriate groups to promote the commercial application of such tools, including through wind-related model building codes, voluntary standards, and construction best practices." Strategic Priority 4 (SP-4) engages the Program agencies in performing basic and applied research that supports performance-based engineering development. SP-4 also encourages the knowledge-transfer activities needed to support implementation in national standards, model building codes, and professional practice. Activities in support of performance-based engineering are described in further detail under SP-4 in Section 4.1.

3.4.2. Coordination of Federal Post-Windstorm Investigations

NIST's statutory responsibilities as lead agency include coordination of "all federal post-windstorm investigations to the extent practicable." NIST has a long history of coordination and collaboration with other federal agencies on post-windstorm investigations and studies, including working with NOAA and FEMA on the tornado Super Outbreak in 2011, Hurricane Sandy in 2012, and the tornadoes in Joplin, Missouri in 2011 and Moore, Oklahoma, in 2013. In 2016, NIST-supported researchers studying tornado damage engaged with NWS meteorologists in the field following several tornadoes. This engagement allowed researchers to better understand the intricacies of NWS assessment procedures to best interpret the information in the NOAA tornado database.

NIST will continue to assess the scope of federal post windstorm activities during the FY 2017-2018 period, and it will use this information to complete a formal coordination plan by the end of FY 2019. This effort incorporates identification of existing federal coordination activities for windstorm investigations (including hazard and impact data collection) and currently unmet coordination needs, to identify opportunities for providing added value, as well as avoiding duplication of effort. The plan will leverage coordination functions that are already in place. For example, the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) already provides coordination for wind and storm surge hazard data collection for landfalling tropical cyclones. This coordination is accomplished through implementation of Annex 2 of the National Plan for Disaster Impact Assessments (NPDIA).[30] There is not a specific plan for other windstorm types.

NIST currently co-chairs the OFCM working group (Working Group for Disaster Impact Assessments and Plans (WG/DIAP[31])), which provides oversight and management of the NPDIA and coordination of event-driven wind and water data collection and documentation activities. NIST will be leading the effort to create a new Annex 3: Tornado/Windstorm Data and will support data collection for other types of storms beyond hurricanes. As part of this effort, NIST will cooperate with OFCM through the WG/DIAP to coordinate acquisition, dissemination, and exchange of windstorm data.

3.4.3. Recommendations for Model Codes

NIST and FEMA have program agency responsibilities in the broad area of supporting improvements to national standards and model building codes. In addition, NIST lead agency responsibilities include issuing recommendations to assist in informing the development of model codes, and informing Congress on the use of such recommendations. Work to improve national standards and model building codes to reduce the impacts of windstorms is integrated into several of the NWIRP Strategic Priorities and Objectives, as described in Section 4 (particularly in SP-4, SP-6, and Objectives 4, 5, and 11).

Recent program successes in making changes to national standards and model building codes are summarized in Section 5.2. Many of these improvements result from investigative findings from NIST and FEMA studies of recent storms, such as those mentioned in Section 3.4.2 and others described in previous NWIRP Biennial Reports. Code and standard improvements have also resulted from implementation of research findings (e.g., see Objective 4 in Section 4.2).

[30] *National Plan for Disaster Impact Assessments: Weather and Water Data*. OFCM, March 2017. http://www.ofcm.gov/publications/diap/newp33.htm.

[31] Working Group for Disaster Impact Assessments and Plans, OFCM. http://www.ofcm.gov/groups/DIAP/diap3.htm

4. Progress in Fiscal Years 2015 and 2016

Progress made during FYs 2015 and 2016 on windstorm impact reduction is summarized in this section. Activities are presented in terms of the seven Strategic Priorities and the broader Goals and Objectives described in the *NWIRP Strategic Plan: Draft for Public Comment*.[32]

4.1. Strategic Priorities

SP-1: Develop Baseline Estimates of Loss of Life and Property due to Windstorms

NIST: Planning began in FY 2016 for a new effort, beginning in FY 2017, to identify causes and trends in windstorm damage and fatalities. This work will aid in identification and prioritization of NWIRP R&D, tech transfer, and outreach activities, as well as the establishment of methods and data for tracking future losses of life and property.

SP-2: Obtain Measurements of Surface Winds and Storm Surge Current and Waves in Severe Storms

NSF: In-situ and Radar Observations at Low levels for Tornadic Winds. NSF funded studies to understand tornado formations using x-band polarimetric mobile radars. One of the studies is the "Tornadic Winds: In-situ and Radar observations at Low levels (TWIRL)" field campaign. TWIRL scientists, using Doppler on Wheels (DOW) radars (a component of NSF's Lower Atmosphere Observing Facilities portfolio, owned and operated by the Center for Severe Weather Research in Boulder, Colorado), are developing 3-D maps of the strongest tornado winds near the ground. These scientists are studying how these winds cause damage to buildings, power lines, trees and other structures. One of the DOW radars revealed winds of more than 224 mph and a dangerous multiple-vortex tornado structure. The TWIRL team also deployed weather "pods" out ahead of the path of developing tornadoes to measure winds near ground level; one of the pods measured winds over 100 mph before being destroyed by debris.

NOAA/NSF: Verification of the Origins of Rotation in Tornadoes Experiment. In FYs 2009 and 2010, NSF and NOAA's National Severe Storm Laboratory (NSSL) 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, organizations and federal agencies, as well as forecasters from the NWS, including the Storm Prediction Center (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

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[32] *Strategic Plan for the National Windstorm Impact Reduction Program: Draft for Public Comment.* March 2017. https://www.nist.gov/sites/default/files/documents/2017/03/13/strategic_plan_for_national_windstorm_impact_reduction_program_-_draft_f.pdf

the larger-scale environment. Continuing analysis of the VORTEX2 dataset advanced the understanding of tornado formation, improving prediction, and offering prospects for increased warning lead-times.

Following on from these VORTEX projects, the VORTEX-Southeast (VORTEX-SE) is a research program initiated in FY 2016 to understand how environmental factors characteristic of the southeastern United States affect the formation, intensity, structure, and path of tornadoes in this region (http://www.nssl.noaa.gov/projects/vortexse/). This is the first VORTEX experiment to have a focus on all the processes ranging from the conditions and storms that produce the tornadoes and the way NWS forecasters anticipate, detect, and warn for tornadoes, to the way the end users receive and respond to that information. As such, it integrates meteorology, NWS operations, and a broad range of social sciences, and supports a number of NWIRP Strategic Priorities and Objectives in addition to SP-2. VORTEX-SE projects include one related to forecasting the occurrence of tornadoes in landfalling tropical cyclones (Objective 13) and another characterizing the interconnected nature of debris and damage propagation within communities (Objective 5).

SP-3: Develop Publicly Available Databases of Windstorm Hazards and Impacts

NSF: National Center for Atmospheric Research (NCAR). Based on merit review and programmatic relevance, NSF funds projects aimed at increasing understanding of weather-related high impact events. NSF's federally funded research and development center, NCAR has played a crucial role in collaboration with the United States research community, especially academic researchers in large-scale field campaigns to gather critical observations. NCAR's role is several fold. First, it helps deploy research facilities, such as aircraft, radar, and LiDar, into the field. Second, it serves as a central repository for all collected data for the research community to use. Third, it provides large-scale, high performance computers and develop community models to assist the United States atmospheric research community. NCAR-supported projects include, for example, VORTEX-SE and its predecessors, and Plains Elevated Convection at Night (PECAN) (see SP-2 and Objective 1, respectively).

NIST: **Center for Risk-Based Community Resilience Planning**. The NIST-funded Center for Risk-Based Community Resilience Planning (http://resilience.colostate.edu), a collaboration of 10 universities led by Colorado State University, will be conducting extensive field studies to collect data on resilience and recovery from disasters for validation of community disaster resilience models. During FY 2016, the Center collected data in Joplin, Missouri, on the continuing impacts of and recovery from the May 22, 2011, Joplin tornado.

NSF: Rapid Response Research Facility. The scientific goal of the NSF-supported five-year Natural Hazards Engineering Research Infrastructure (NHERI) post-disaster, rapid response research (RAPID) facility, initially funded in September 2016, is to support natural hazard researchers to conduct next generation RAPID research through reliable acquisition and community sharing of high-quality, post-disaster data sets. These data sets will enable characterization of civil infrastructure performance under natural hazard loads, evaluation of the effectiveness of current and previous design methodologies, calibration of computational models used to predict civil infrastructure component and system response to natural hazards, and the development of solutions for resilient communities. As a community resource, the facility will:

(1) support acquisition of an unprecedented amount of perishable, post-disaster, high-quality, open data by the natural hazards community;
(2) provide learning and training opportunities in post-disaster reconnaissance;
(3) promote public engagement with science and technology through a citizen science data collection initiative; and
(4) develop new and strengthen existing international research partnerships by establishing collaborations with foreign organizations during global deployments.

The RAPID facility will also develop tools to support data collection and analysis (see Objective 8). The NSF-funded NHERI Cyberinfrastructure facility (see Objective 5) will archive the collected data.

SP-4: Develop Performance-Based Design for Windstorm Hazards

NSF: Design Frameworks for Structural Wind Performance. Reducing the impact on structures from wind hazards is a critical consideration in the design of buildings. NSF is funding awards that create design frameworks for satisfying performance requirements that go beyond prescriptive building code provisions. Principles of performance-based design have been adopted in earthquake engineering, and NSF-funded projects are extending these performance-based design principles to wind engineering.

An NSF award to Iowa State University is supporting performance-based design for structures equipped with high performance control systems for mitigation of wind hazards. The goal of the project is to improve structural performance by integrating control systems at the design stage, with particular attention to structures subjected to a variety of wind hazards, including thunderstorms, hurricanes, gust-fronts, and tornadoes. In a collaboration between the University of Notre Dame and the University of Michigan, researchers are developing a holistic performance-based design framework for a wide class of low- to mid-rise buildings sensitive to wind. Key to this framework is integration of water ingress, debris impact, impact on building envelope and other non-structural damage due to pressure and drift.

NIST: Performance-based Design for Wind. Implementing recommendations from the 2014 report on its technical investigation of the May 2011 Joplin Tornado, [33] NIST is developing a performance-based design for tornadoes, including new tornado hazard maps (see Objective 4). Both NIST and FEMA are also working with the American Society of Civil Engineers (ASCE) Ad Hoc Committee on Performance-based Design for Wind Hazards. This effort is focused on developing the overall framework and pre-standard provisions for performance-based design for all windstorms, including tornadoes. This effort includes adaptation of some elements of performance-based design for earthquakes, developed over the last decade through efforts of the National Earthquake Hazards Reduction Program.

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[33] *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. http://www.nist.gov/manuscript-publication-search.cfm?pub_id=915628

SP-5: Enhance Outreach and Partnerships to Improve Windstorm Preparedness and Hazard Mitigation

NOAA: Weather-Ready Nation. During FYs 2015 and 2016, 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 that share the NWS's 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 WRN starts with these internal actions but requires the action of a vast nationwide network of partners. In this reporting period, examples of new initiatives provided by WRN include: a project for simplifying the way hazards are communicated (hazards simplification); a NOAA water model for better predictions of streamflow at neighborhood scales of resolution for protecting life and property from localized flooding; a safety application from Raytheon Corp and NOAA designed to teach students and adults to prepare for, survive, and recover from weather and water emergencies; and an updated method for communicating risk published in the Bulletin of the American Meteorological Society (BAMS) published a study in its September 2016 edition titled, "Effectively Communicating Risk and Uncertainty to the Public." Additional information about WRN, publications, initiatives, and news and events can be found at: http://www.nws.noaa.gov/com/weatherreadynation.

FLASH/NOAA: #HurricaneStrong. Launched during the 2016 hurricane season, *#HurricaneStrong* is a national resilience initiative led by the Federal Alliance for Safe Homes (FLASH)® to save lives and homes through collaboration with leading organizations in the disaster safety community. The collaboration with NOAA and the National Hurricane Center offers empowering hurricane safety and mitigation information through business summits, digital channels, events, home improvement store workshops, media outreach, school lesson plans, and a social media campaign featuring a *#HurricaneStrong* "pose". In 2016, *#HurricaneStrong* garnered success with White House recognition, national television programming, public service announcements, more than 200 traditional news stories, 695 Home Depot workshops, 15,000 Tweets, 4,400 contributors on Twitter, and an audience reach exceeding 24 million. For more information, visit www.hurricanestrong.org.

IBHS: FORTIFIED Home™ Program. The Insurance Institute for Business & Home Safety's (IBHS) FORTIFIED Home™ program is a uniform, voluntary, superior set of standards to help improve a home's resilience by adding system-specific upgrades to minimum code requirements. Over this reporting time period, the program continued to gain momentum. The science-based, third-party validated FORTIFIED Home™ program comprises three progressive designation levels (Bronze, Silver and Gold) that address critical building systems, such as the roof, openings and attached structures, and the critical continuous load path. For hurricanes, these are the same standards outlined in FEMA P-804, the Wind Retrofit Guide for Residential Buildings.[34] IBHS launched the new FORTIFIED Home™–High Wind and Hail standards during the 2016 National Tornado Summit alongside several partners and supporters. Meanwhile, the FORTIFIED Home™–Hurricane program continued its significant growth in the Southeast with major companies such as DR Horton (America's largest homebuilder) building more than 1,000 FORTIFIED homes in coastal Alabama. Habitat for Humanity (HFH) adopted FORTIFIED standards in a new "Habitat STRONG" program, which includes training, information and resources for affiliates using IBHS standards – approximately 70 HFH affiliates were participating in the program by December 2016.

A critical development related to FORTIFIED occurred in 2016, when independent research identified the financial value of FORTIFIED standards. The study found that switching from a conventional construction standard to a FORTIFIED designation increases the value of a home by nearly seven percent.[35]

Both state and federal agencies have endorsed FORTIFIED Home™, and/or integrated FORTIFIED standards into their own programs and initiatives. For example, to address increasing risks of property damage due to natural disasters, which may adversely affect the mortgage market, the U.S. Department of Housing and Urban Development (HUD), U.S. Department of Agriculture and the U.S. Department of Veterans Affairs informed their lenders, borrowers, and stakeholders about the importance of using robust standards designed to strengthen homes. Together, these agencies back $400 billion in mortgages, which represents approximately 20 percent of the single-family mortgage market. IBHS' FORTIFIED™ programs were singled out in HUD's announcement about the new initiative as: "…robust resilient wind standard[s] validated by third parties. Recent academic research shows that the Fortified Home designation increases home resale values by seven percent."[36]

SP-6: Enhance and Promote Effective Storm Sheltering Strategies

NIST/FEMA: Storm Shelter Standard. NIST and FEMA made significant contributions to the Second edition of the International Code Council (ICC) 500 Standard for the Design and Construction of Storm Shelters, which was published in December 2014. Highlights include a new 10,000 year mean recurrence interval wind speed map for design of hurricane shelters developed by NIST. FEMA led many changes based on observations of shelter and safe room performance following severe storms, and to harmonize requirements for shelters and safe rooms. NIST and FEMA also worked together with the ICC to write the first ever commentary for the ICC 500 Standard, which was completed and published in 2016.

FEMA: Development of Technical Guidance Materials on Safe Rooms and 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

[34] *Wind Retrofit Guide for Residential Buildings*, FEMA P-804, December 2010. https://www.fema.gov/media-library/assets/documents/21082
[35] *Estimating the Effect of FORTIFIED Home Construction on Home Resale Value*. Alabama Center for Insurance Information and Research. https://culverhouse.ua.edu/uploads/ckeditor/attachments/31/FORTIFIEDReport_V2__2_.pdf, p.5.
[36] Federal Housing Administration, HUD. https://portal.hud.gov/hudportal/documents/huddoc?id=FTDOOct16.pdf, p. 2.

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: *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms*). During FYs 2015 and 2016, FEMA continued developing and publishing technical guidance materials related to state-of-the art wind-resistant design and construction methods and making these materials available to those who need them. Examples include:

- Published the fourth edition of FEMA P-320 *Taking Shelter From the Storm: Building a Safe Room For Your Home or Small Business.* https://www.fema.gov/fema-p-320-taking-shelter-storm-building-safe-room-your-home-or-small-business
  - Developed updated training curriculum to support updated FEMA P-320
- Published the third edition of FEMA P-361 *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms.* https://www.fema.gov/media-library/assets/documents/3140
  - Developed updated training curriculum to support updated FEMA P-361
- Developed numerous fact sheets supporting wind-resistant design and construction, including:
  - Flood Hazard Elevation and Siting Criteria for Residential Safe Rooms
  - Flood Hazard Elevation and Siting Criteria for Community Safe Rooms
  - Foundation and Anchoring Criteria for Safe Rooms
  - Community Safe Room Fact Sheet
  - Residential Safe Room Fact Sheet

NIST: Building Safety Assessment for New Mass Evacuation and Sheltering Standard. A new standard being developed by the National Fire Protection Association (NFPA), the NFPA 1616 Standard on Mass Evacuation, Sheltering, and Re-entry Programs will provide criteria for the process of planning and implementing mass evacuation and sheltering programs for all hazards, including hurricanes, tornadoes, and other windstorms. NIST developed all the requirements and supporting annex materials for consideration and assessment of building safety in the selection of facilities for use as shelters and best available refuge areas.

SP-7: Develop the Nation's Human Resource Base in Windstorm Hazard Mitigation Fields

NSF: Research Awards. NSF awards supporting NWIRP typically provide research funding for academic faculty, as well as graduate and undergraduate students. These awards are an invaluable learning experience for graduate and undergraduate students. Some NSF awards support post-doctoral early career researchers as well.

NSF: Research Experiences for Undergraduates (REU): The REU program supports active research participation by undergraduate students in any of the areas of research funded by the NSF. REU projects involve students in meaningful ways in ongoing research programs (REU supplements) or in research projects specifically designed for the REU program (REU sites).

Many NSF-funded projects supporting NWIRP have REU supplements. One REU site is located at the National Weather Center (NWC) on the campus of the University of Oklahoma. This is a 10-week summer research program and brings students together with faculty to conduct research on topics such as: severe weather, tornadoes, societal impacts of weather, numerical weather prediction models, atmospheric radiation, climatological studies, dryline studies, and more. The research is conducted through workshops, field trips and direct interaction with researchers working at the leading edge of science in severe weather and the impacts of wind. This REU site successfully attracts a diverse group of students to participate in the program and to increase their interest in conducting research in the field of severe weather and wind impacts.

NOAA: Storm Surge Education and Awareness. Storm surge is one of the most destructive threats to life and property in the path of a hurricane. Public awareness and outreach are vital to building a resilient community. NOAA's NWS along with the National Hurricane Center (NHC) developed new tools to improve communication and public understanding of storm surge. In FY 2015, NHC developed a series of YouTube videos that explain storm surge.[37] As part of hurricane awareness week, NHC posted a blog on storm surge. NHC also provide storm surge outreach material on its website. The web videos and outreach material are also available in Spanish. NHC also partnered with FEMA to teach emergency managers about the hazards of storm surge.

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™ service, and MADCAD.com. FEMA gave dozens of presentations 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 Walt Disney Company and the Federal Alliance for Safe Homes, Inc. (FLASH®), which have been operating an interactive exhibit titled "Storm Struck: The Tale of Two Homes" at the Innoventions Pavilion, Epcot® Theme Park, Walt Disney World® Resort, 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 was on display through September 13, 2015. 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 *Taking Shelter From the Storm: Building a Safe Room For Your Home or Small Business*. FEMA also sponsored curriculum kits that teach students in grades 7-9 about planning and designing in preparation for natural disasters.

In addition, FEMA participated in a Tornado Safe Room Showcase at the 2015 International Builders' Show and 2015 World of Concrete. This showcase promoted the use of safe rooms to approximately 100,000 attendees from the homebuilding and construction industry. An estimated 10,000 visitors stopped by to see the safe rooms first hand and took with them copies of the recently updated FEMA P-320 *Taking Shelter from the Storm: Building a Safe Room for Your Home or Small Business*.

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[37] For example, *Storm Surge Fast Draw*, NOAA/NWS National Hurricane Center. https://www.youtube.com/watch?v=bBa9bVYKLP0

FLASH/FEMA/NVOAD: Volunteer Construction Guides. In partnership with FEMA Building Science Branch and the National Voluntary Organizations Active in Disasters (NVOAD), the FLASH® developed high wind, flood, and wildfire guides and accompanying volunteer cards to assist volunteers that are doing rebuilding or retrofitting work. Assets are currently used by local volunteer organizations that rebuild or renovate hundreds of properties in at-risk communities. For more information, visit www.flash.org/volunteers.

FHWA: Training and Technology Transfer. Technology transfer of high performance computational analysis techniques is an important part of Argonne National Laboratory's (ANL) work to support and advance wind-related engineering and research programs at the Turner Fairbank Highway Research Center (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 the Transportation Research and Analysis Computing Center (TRACC).

4.2. Objectives

GOAL A. IMPROVE THE UNDERSTANDING OF WINDSTORM PROCESSES AND HAZARDS

Objective 1: Advance understanding of windstorms and associated hazards

NSF: Hurricane Predictability and Predictions. 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 the effects of sea spray and cloud particles to questions regarding the genesis of cyclones and how large-scale environmental factors affect their intensity and movement. In FYs 2015 and 2016, NSF funded studies on how wind shear affects intensity change in tropical cyclones, how radiation affects the early stages of a tropical cyclone, and how spiral rainbands affect tropical cyclone structure and intensity.

NSF: Understanding of Severe Thunderstorms at Night. In FYs 2015 and 2016, NSF funded a number of American institutions to conduct basic research on understanding of generation and development of tornadoes and severe storms that threaten human life and property. In particular, NSF funded a large field campaign: PECAN, which included over 20 university researchers and the involvement of other federal agencies such as NOAA, NASA, and DoE (https://www.eol.ucar.edu/field_projects/pecan). The field campaign focused on nocturnal severe storms initiated in the central plains of the United States, which are potentially dangerous to the general public.

NSF/NOAA: Predictability of Severe Convective Storms. The Mesoscale Predictability Experiment is (MPEX) is an ongoing research program which seeks to determine whether additional observations of weather conditions upstream form a target area could improve predictions of severe weather. In FY 2016, collected upsonde data on more cases in the southern plains. Results from recent (FY 2016) data assimilation experiments suggest that ingestion of data obtained from targeted weather balloons a few hours prior to thunderstorm development can significantly improve forecasts of severe thunderstorms made from high-resolution computer models.

NIST: Tornado Climatology. One of the major challenges in tornado climatology is understanding and accounting for limitations and biases in the national tornado databases, which date back to 1950. Changes over time in weather observing technology, communications technology, information technology, tornado science, NWS tornado rating and reporting practices, and many other factors serve to complicate the analysis of the 66 years of available tornado climate data. NIST began a study of the United States tornado climatology in FY 2015, with the goals of documenting, quantifying, and developing procedures to account for these limitations and biases, which are needed to produce accurate tornado hazard maps (Objective 4) and tornado loss estimation tools (Objective 9). Keys to this effort are better assessments of the population bias over time, and better correlation of the observed damage to wind speed relationship that provides the basis for tornado ratings in the Fujita (F) and Enhanced Fujita (EF) scales.

Objective 2: Develop tools to improve windstorm data collection and analysis

NOAA: New Observing Technologies. NOAA is testing new observing technologies as a part of the Intensity Forecasting Experiment (IFEX – see Objective 13). These technologies include use of NASA's remotely piloted high altitude Global Hawk scientific research unmanned aircraft system in a hurricane research capacity; the low altitude unmanned Coyote system for measuring winds, temperature, and moisture in the hurricane boundary layer where manned aircraft cannot safely reach; and the Doppler wind lidar, which provides the capability to sample winds in precipitation-free regions that radars cannot measure.

NOAA: Multifunction Phased Array Radar (MPAR). The National Severe Storms Laboratory (NSSL) is demonstrating the capabilities of the MPAR, a program funded through a partnership between NOAA's Office of Oceanic and Atmospheric Research (OAR) and the Federal Aviation Administration (FAA) with significant technical contributions from industry and academia. The MPAR project will demonstrate the potential to simultaneously perform aircraft tracking, wind profiling, and weather surveillance with a single, phased array weather radar. The capability to perform simultaneous weather and aircraft surveillance functions, with a multi-agency radar, is expected to provide significant cost savings through the reduction of the number of radars through consolidation, and joint research and development, engineering, and maintenance operations. Research conducted at NSSL is showing rapid-scan phased array technology to be beneficial in improving the detection and warning of severe storm phenomena and to improving numerical weather prediction in support of severe storm forecasting.

During FYs 2015 and 2016, engineering activities have primarily centered on the design and development of two demonstration radars, the Ten Panel Demonstrator (TPD) and the Advanced Technology Demonstrator (ATD). The purpose of these systems is to gain knowledge and reduce the technical risks associated with the engineering and application of phased array technology to meet the proposed multifunction goals. The TPD is a small-scale dual polarization phased array radar that was developed and delivered to NSSL for the purpose of mitigating engineering risks. Lessons learned from this engineering demonstrator have led to design changes for the ATD development. The ATD is a larger demonstration radar that will be capable of assessing the ability of phased array technology to address the operational meteorological requirements of the NWS as well as the multifunction requirements of all the agencies. Design and development of the ATD are underway with development, delivery and assessment occurring in the FYs 2017 and 2018 timeframe.

NOAA/NIST/ASCE: Tornado Wind Speed Estimation. Although the EF Scale adopted by the NWS in 2007 represented a major improvement over the previously used F Scale, it still has significant shortcomings. Most notably, the wind speed estimates from observed damage are based on expert elicitation, i.e., judgement. Users of the EF Scale and other stakeholders, including NWS, NIST, and FEMA, have identified many needed changes, including expansion of the number of damage indicators and, to the extent possible, incorporation of a more scientific basis for new and existing damage indicators. In FY 2015, NWS and NIST staff worked with the American Society of Civil Engineers to establish and co-chair a standards development committee on tornado wind speed estimation. This committee is charged with developing improvements to the EF Scale and other damage-based, post-storm techniques, including forensic engineering, analysis of airborne and space-based remotely sensed imagery, and treefall pattern analysis. The scope of the standard also includes methods of tornado wind speed estimation from data collected during the storm, including radar and in-situ measurements, as well as photogrammetric analysis. The Committee includes representatives from academia and the private sector, multiple units within NOAA and NIST, and other federal agencies, including FEMA, DoE, NRC, and NASA.

Objective 3: Understand long term trends in windstorm frequency, intensity, and location

NOAA: Toward Seasonal Prediction and Long-term Severe Weather Variability. In FY 2015, the NWS Storm Prediction Center (SPC) continued work started in 2012 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. While climate predictions expect increased temperature and humidity in the lower atmosphere, there may also be decreased wind shear. Since both factors are required to form tornadoes, NOAA research in FY 2015 continued to focus on the prediction of these local factors as well as quantification of the role of more-remote climate signals.

Objective 4: Develop tools to improve windstorm hazard assessment

NIST: Wind Speed Maps (nontornadic). In FY 2016, NIST completed the development of new design wind speed maps intended for adoption in current American building codes and standards (see also Objective 11). The project incorporated several technical advances over previous generations of maps.[38] In addition to using more years of data from more weather stations around the United States, NIST made adjustments to account for terrain conditions at anemometer locations, classified peak gusts at each station by storm type (thunderstorm, non-thunderstorm, and tropical), and used a peaks-over-threshold technique for estimation of wind speeds at the different return periods, instead of simply using annual extreme values. The new maps more accurately reflect the regional differences in extreme windstorm climatology.

[38] *Maps of Non-hurricane Non-tornadic Wind Speeds With Specified Mean Recurrence Intervals for the Contiguous United States Using a Two-Dimensional Poisson Process Extreme Value Model and Local Regression*, by Pintar, A.; Simiu, E.; Lombardo, F. and Levitan, M., NIST SP 500-301. National Institute of Standards and Technology, Gaithersburg, MD, 2015. http://dx.doi.org/10.6028/NIST.SP.500-301

NIST: Tornado Hazard Maps. In FY 2015, NIST initiated a multiyear effort to develop a new generation of tornado hazard maps, intended for use in tornado-resistant design of new buildings and structures (and supporting creation of performance-based design methodology for tornadoes – see SP-5), as well as risk assessment for existing facilities. NIST presented an overview of the tornado hazard mapping process and preliminary results to a broad group of windstorm impact reduction stakeholders at a workshop in September 2015. NIST also held a second workshop to brief federal agencies on this effort and learn more about their needs in tornado mapping and tornado hazard reduction, with 14 agencies participating.

GOAL B. IMPROVE THE UNDERSTANDING OF WINDSTORM IMPACTS ON COMMUNITIES

Objective 5: Advance understanding of windstorm effects on the built environment

NSF: Natural Hazards Engineering Research Infrastructure (NHERI). The NSF-supported NHERI consists of 11 awards made during the current reporting period: one award for the Network Coordination Office (NCO), one award for Cyberinfrastructure (CI), one award for the Computational Modeling and Simulation Center (SimCenter – see Objective 6), and eight awards for earthquake and wind engineering experimental facilities (including one award for a post-disaster RAPID facility – see Strategic Priority 3). The scientific purpose for NHERI is to:

- Understand, model, and predict the lifecycle performance of civil infrastructure, from component to holistic system levels, under different natural hazard events;
- Reduce the reliance on physical testing for modeling the performance of civil infrastructure under natural hazard events through advanced computational modeling and simulation capabilities;
- Build the basic science knowledge and computational modeling and simulation capabilities to evaluate multi-hazard resilient and sustainable civil infrastructure and communities;
- Translate research into innovative mitigation strategies and technologies to reduce the impact of natural hazards on existing and new sustainable civil infrastructure and communities; and
- Integrate research, education, and outreach to train a broad and inclusive science, technology, engineering, and mathematics workforce to conduct and translate research into an innovation ecosystem for multi-hazard resilient and sustainable civil infrastructure and communities.

Serving the wind engineering and coastal engineering research communities, the 12-fan Wall of Wind facility at Florida International University provides a testing ground for simulated hurricane wind speeds up to 157 mph which is the minimum wind speed for a Category 5 hurricane. Oregon State University houses a NHERI experimental facility consisting of a large wave flume and a directional wave basin for fundamental research to understand and reduce risks to civil infrastructure from windstorm surge, hurricanes, and other coastal windstorms. The NHERI experimental facility at University of Florida supports research for mitigating the impacts of extreme wind and rain events on civil infrastructure. The facility provides users with a suite of wind engineering experimental resources, including an atmospheric boundary layer wind tunnel which can replicate damaging effects from tornadoes, thunderstorms, and hurricanes.

The NSF-supported NHERI cyberinfrastructure award hosts online research and education tools for the natural hazards community at http://www.DesignSafe-ci.org. Publicly available tools will include the Data Depot for archiving earthquake and wind engineering experimental data generated at the NHERI experimental facilities, computational modeling and simulation tools, and a post-disaster, RAPID Reconnaissance Integration Portal for archiving perishable geotechnical, structural, coastal, and social science data obtained during field work by researchers following an earthquake or windstorm event in the United States or abroad.

NSF: RAPID Awards - Collection of Perishable Following Windstorms. The NSF has a standing funding mechanism, the RAPID mechanism, to provide funding to university faculty members to collect perishable data from the field after a significant windstorm or other hazard event. During FYs 2015 and 2016, the institutions that NSF funded for collecting data after Typhoon Haiyan completed their work. The data include hazard and damage levels of residential structures, transportation infrastructure, and government buildings, as well as environmental impacts on coastal aquifers, coral reef fishes and sediment patterns, among others. The institutions that participated in the research included: University of North Carolina-Charlotte, Rutgers University, University of Notre Dame, University of Southern Mississippi, University of Texas-Austin, and University of Washington. The institutions house the collected data on their web sites which are available to principal investigators and the public. In FY 2016, faculty and students at West Texas A&M University, Texas Tech University, and University of Nebraska-Lincoln began collecting perishable data and damage scene images following tornadoes that impacted areas near Pampa, Texas in November 2015. The data is expected to serve as a basis for collaborative, multi-disciplinary research extending knowledge of tornado wind structure, validity of the EF scale, damage scene preservation, structural performance, and advancement in the understanding of debris fields and debris field patterns.

FEMA: Mitigation Assessment Team Evaluations Following Major Hurricanes, Tornadoes and Windstorms. FEMA conducts building performance studies after unique or nationally significant disasters to better understand how natural events affect the built environment. A Mitigation Assessment Team (MAT) is deployed only when FEMA finds damage and believes the findings and recommendations derived from field observations and analysis will provide design and construction guidance that will improve the disaster resilience of the built environment in the affected state or region and will be of national significance to other disaster-prone regions. The MAT studies the adequacy of current building codes, local construction requirements, building practices, and building materials in light of the damage observed after a disaster. Lessons learned from the MAT's observations are communicated through a comprehensive MAT Report, Recovery Advisories, and Fact Sheets made available to communities to aid their rebuilding effort and enhance the disaster resistance of building improvements and new construction. In FYs 2015 and 2016, FEMA did not deploy any MATs for major windstorms but follow-on work related to previous MATs is ongoing.

NSF: Infrastructure Resilience. The electric power infrastructure in the United States, especially in coastal areas, faces substantial risk from wind hazards. Researchers at Iowa State University are building wind load models that can predict the dynamic response of bundled cables subjected to moderate and high wind speeds. The goal of this research is to improve the resilience of cables used in cable-supported structures and power transmission lines to hurricanes and other windstorms. Another project at Northeastern University is advancing our understanding of hazards impact on offshore wind energy technologies. By integrating models of wind and wave hazards with system-level performance models, findings from this research may contribute to more cost-effective renewable energy.

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, FHWA continued forced vibration tests on selected major structures during FYs 2015 and 2016. Tests had been previously performed on the Zakim (Massachusetts), Emerson (Missouri), and Penobscot Narrows (Maine) bridges. During this reporting period, a technical report on the Emerson study was finalized and submitted for publication.[39] The report documents the behavior of large, ungrouted bridge cables and illustrates 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. During this reporting period, measurements on the cables of five bridges (four in service and one under construction) were completed. Information from these measurements is being used to establish the degree of variance in pipe roundness as produced by vendors, as delivered to the bridge site, and as the result of environmental effects while in service. In addition, it is being used for the design of realistic physical experiments underway in the wind tunnel laboratory (see below).

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, FHWA performed wind tunnel tests at NRCC on small-scale section models representative of "out-of-round" bridge stay cables. Tests were performed in simulated wind conditions over a broad range of wind speeds to evaluate the influence cable roundness on overall performance and aerodynamic stability. A comprehensive technical report[40] was prepared for publication, one technical paper[41] was published, and five technical papers were submitted for journal publication. As noted in the report, the imperfect shape of High Density Polyethelene (HDPE) used on bridge stay cables can play an important role in the aerodynamic stability and performance of cables.

Objective 6: Develop computational tools for use in wind and flood modeling on buildings and infrastructure

NSF: NHERI Computational Modeling and Simulation Center. The goal of the NSF-supported five-year NHERI Computational Modeling and Simulation Center (SimCenter), awarded in FY 2016, is to provide the natural hazards engineering research and education community with access to next generation computational modeling and simulation software tools, user support, and educational

[39] *Dynamic Properties of Stay Cables on the Bill Emerson Bridge*, by H.R. Bosch and J.R. Pagenkopf, Report No. FHWA-HRT-xx-xxx, Federal Highway Administration, McLean, VA, Pending Publication.

[40] *Wind Tunnel Investigations of the aerodynamics of bridge stay cable cross-sectional shapes*, by Heidi Christiansen and Guy L. Larose, Report No. FHWA-HRT-xx-xxx, Federal Highway Administration, McLean, VA, Pending Publication.

[41] *Comparison of the Aerodynamics of Bridge Cables with a Smooth Surface and Helical Fillets in Turbulent Flow*, by H. Christiansen, G.L. Larose, J.B. Jakobsen, J.H.G. Macdonald, and H.R. Bosch, *Proceedings of the 14th International Conference on Wind Engineering*, Porto Alegre, Brazil, June 2015.

materials. Such research and education is needed to advance the nation's capability to simulate the impact of natural hazards on structures, lifelines, and communities, and to make informed decisions about the need for and effectiveness of potential mitigation strategies. These tools will be publicly available on the NHERI CI's DesignSafe-ci.org Discovery Workspace. The SimCenter will provide computational modeling and simulation tools using a new open source simulation framework that addresses various natural hazards, including windstorms and storm surge.

NIST: Science-Based Methodologies for Aerodynamic Simulation to Determine Wind Loads on Buildings and Structures. NIST is helping to develop practical CFD methods for the numerical determination of time and space dependent aerodynamic forces on structures induced by strong winds. Such methods have the potential to produce more accurate, site-specific wind loads, resulting in safer and more economical structures. During the reporting period, NIST performed a review of recent meteorological studies on turbulent atmospheric flows and their numerical modeling and on the structural engineering consequences of those studies.[42] NIST developed a physics-based methodology for simulating turbulent atmospheric flows for structural engineering applications,[43] and established its effectiveness through comparisons with turbulent flows defined in standards and achieved in wind tunnel simulations.[44] To begin development of methods for reliable prediction of pressures on bluff bodies, NIST employed state-of-the-art turbulence models to simulate flow past a square cylinder under smooth flow[45] and evaluated the sensitivity of the aerodynamic pressures to simulation parameters using experimental design techniques.[46] The wind tunnel tests were performed to support the validation of pressures in the CFD simulations.

FHWA: Numerical Modeling of Wind Effects on Highway Structures. During the reporting period, an existing interagency agreement continued to be in effect between the U.S. Department of Transportation and the DoE for modeling the effects of natural hazards, such as windstorms, hydraulics, and flooding, on infrastructure. This agreement enabled FHWA to utilize high-performance computing and support staff from the Argonne National Laboratory (ANL). Resources located at the TRACC were used to model wind effects on highway users as well as highway structures. To evaluate performance of the facility and to enhance simulation capability, a detailed CFD model of the FHWA Aerodynamics Laboratory at the TFHRC – including the large wind tunnel – was completed and a technical report published in a previous reporting period. Research has continued in this area to further refine and streamline the model with the objective of developing an

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42 Planetary Boundary-Layer Modelling and Tall Building Design, by Simiu, E., Shi, L., and Yeo, D., *Boundary-Layer Meteorology*, 159(1), 173-181, 2016.

43 *OpenFOAM large-eddy simulations of atmospheric boundary layer turbulence for wind engineering applications,* by Shi, L., and Yeo, D., NIST Technical Note 1944, National Institute of Standards and Technology, Gaithersburg, MD. 2016. http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1944.pdf

44 Large-Eddy Simulation of Atmospheric Boundary Layer Winds for Structural Engineering Applications, by Yeo, D. and Shi, L., *Engineering Mechanics Institute Conference 2016 (EMI 2016) & Probabilistic Mechanics & Reliability Conference 2016 (PMC 2016)*, Nashville, Tennessee, May 22-25, 2016

45 RANS and Hybrid LES/RANS Simulations of Flow over a Square Cylinder, by Ke, J and Yeo, D., *Eighth International Colloquium on Bluff Body Aerodynamics and Applications (BBAA VIII)*, Northeastern University, Boston, Massachusetts, Jun. 7-11, 2016.

46 A Practical Verification and Validation approach for Computational Wind Engineering Simulations Using an Experimental Design Technique, by Mac Réamoinn, R. and Yeo, D., *Eighth International Colloquium on Bluff Body Aerodynamics and Applications (BBAA VIII),* Northeastern University, Boston, Massachusetts, Jun. 7-11, 2016.

effective computational framework, or "virtual wind tunnel," that will complement physical testing facilities. A technical paper[47] was published during the performance period. This improved model is being tested and validated using results of physical tests in the laboratory. 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 were 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[48] 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.[49] 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 during the previous performance period. Work has also been underway to develop software tools using Large Eddy Simulation (LES) techniques to evaluate the performance of long span bridges in the wind and during windstorms.[50,51]

NIST: Tools for Analysis of Measured Wind Pressure Data. NIST is developing next-generation methods and tools to better characterize wind loads on buildings and structures. Progress during the current reporting period included improvements in analysis methods for wind pressures on building components and cladding. Area-averaging of wind pressures measured at discrete pressure taps on scaled wind tunnel models can now be performed efficiently for regular and irregular tap distributions, using methods[52] incorporating Delaunay triangulation and Voronoi diagrams. An improved procedure and software for estimating peaks of stationary wind pressure time series over

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[47] Modeling of Wind Flow in a Real-size Wind Tunnel at FHWA Turner-Fairbank Aerodynamics Laboratory, by C. Bojanowski, S. Lottes, M. Sitek, N. Zhang, and H. Bosch, *Proceedings of the 4th American Association for Wind Engineering Workshop,* Miami, Florida, August 2016.

[48] Vibration of Highway Variable Message Signs Caused by Wind and Truck-Induced Gusts, by Harold Bosch, Cezary Bojanowski, Steven Lottes, and Jerry Shen, *Proceedings of the 8th Colloquium on Bluff Body Aerodynamics and Applications,* Boston, Massachusetts, June 2016.

[49] Computational Fluid Dynamics Simulation and Parametric Study of Wake Effect of Bridge Tower on a Truck, by Nasi Zhang, Harold Bosch, and Jerry Shen, *Proceedings of the 8th Colloquium on Bluff Body Aerodynamics and Applications,* Boston, Massachusetts, June 2016.

[50] Effect of Initial Conditions and Grid Refinements on Bridge Flutter Calculations Using CFD and HPC, by R. Panneer Selvam and Harold Bosch, *Proceedings of the 8th Colloquium on Bluff Body Aerodynamics and Applications,* Boston, Massachusetts, June 2016.

[51] Aero Elastic Analysis of Bridge Deck Sections by FDM Using LES: Improving the Performance through Implementation of Parallel Computing, by B. Kemayou, N. Ahmed, R. Panneer Selvam, and H.R. Bosch, *Proceedings of the XIX National Congress of Civil Engineering 2015,* Huaraz, Peru, November 2015.

[52] *Methodology to Analyze Wind Pressure Data on Components and Cladding of Low-Rise Buildings,* by Dat Duthinh, Joseph A. Main, and Brian M. Phillips. NIST Technical Note 190, 2015. http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1903.pdf

time intervals longer than the scaled-up duration of wind tunnel tests was developed using the peaks-over-threshold method, including determination of the optimal threshold level and quantification of uncertainties inherent in the estimates.

Objective 7: Improve understanding of economic and social factors influencing windstorm risk reduction measures

NSF: Support for Windstorm Impact Reduction – Economic and Social Factors: In FYs 2015 and 2016, NSF made numerous awards that will produce significant new knowledge about economic and social factors influencing risk reduction measures. A wide range of programs such as Anthropology; Decision, Risk and Management Sciences; Economics; Geography and Spatial Sciences; Infrastructure Management and Extreme Events; Law and Social Science; Perception, Action and Cognition; and Sociology have supported this research through a variety of mechanisms.

Individual programs fund projects through their open undefined competitions. For example, the Sociology Program funded research on messages that explain mitigation decisions related to wind hazards among different populations. In another project aimed at understanding why almost half of the deaths from tornadoes involve residents of mobile homes, NSF-funded work at the University of South Carolina. That work explores the residents' attitudes and beliefs regarding sheltering, with the goal of developing and testing communications leading to better sheltering decisions.

Individual programs can use the RAPID mechanism that allows NSF to provide immediate funding for projects that involve ephemeral data (and therefore cannot be funded through a standard competition). Individual programs also co-fund projects as more than one NSF program reviews proposals submitted in open undefined competitions. For example, the Economics Program and the Decision, Risk and Management Sciences Program combined to support a project on understanding the influence of economic and other incentives on wind hazard mitigation decisions. An NSF-supported project at the Louisiana State University is studying the role of social media in disaster resilience. Knowledge gained from the project will help develop strategies to create effective social media campaigns and emergency management practices to promote resilience to wind storms.

Special competitions provide another mechanism by which NSF supports research on windstorm impact reduction. During the FYs 2015 and 2016 period, these special competitions include Interdisciplinary Research in Hazards and Disasters (Hazards SEES), Dynamics of Coupled Natural and Human Systems (CNH), and Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP). For example, an NSF-funded project at the Johns Hopkins University, Georgetown University, and the University of Michigan is studying the effects of repeated hurricanes through integrating individual and organizational behavioral studies, economic models, public health data, infrastructure engineering, and spatial landscape analysis. The project is yielding a significant advance in understanding regional resilience under repeated hazards. The work includes direct interaction with government and utility emergency response executives and should contribute to helping reduce regional vulnerability and increase regional resilience in areas subjected to repeated hurricanes.

Another NSF-supported project at the University of Delaware is studying how to optimize evacuations and sheltering from hurricanes through integrating the methods and perspectives of engineers and social, behavioral, and economic scientists. The work identifies multiple objectives such as minimizing the loss of lives and costs and then considers the full range of sheltering strategies designed to meet the objectives. By cooperating with state and local emergency management departments and the American Red Cross, the research results are being disseminated to practitioners as quickly and effectively as possible.

Objective 8: Develop tools to improve post-storm impact data collection, analysis, and archival

NSF: Rapid Response Research Facility. The NHERI post-disaster, RAPID facility (see also Strategic Priority 3 and Objective 5) will provide many resources to improve post-windstorm data collection, analysis, and archival, including:

(1) a portfolio of state-of-the-art data collection tools (including geomatics technologies; image capture and laser scanning equipment; seismological, wind, and inundation instruments; and unmanned aircraft systems, among others);

(2) new software tools to aid in data collection and processing;

(3) education, outreach, and training services;

(4) advisory services to assist reconnaissance teams with the planning of safe and successful field missions for data collection; and

(5) a headquarters that includes a 3D mini Computer Automated Virtual Environment (CAVE) for viewing and preliminary analysis of the various forms of image data collected during field campaigns.

As a community resource, the facility will:

(1) support acquisition of an unprecedented amount of perishable, post-disaster, high-quality, open data by the natural hazards community;

(2) provide learning and training opportunities in post-disaster reconnaissance;

(3) promote public engagement with science and technology through a citizen science data collection initiative; and

(4) develop new and strengthen existing international research partnerships by establishing collaborations with foreign organizations during global deployments.

Objective 9: Develop advanced risk assessment and loss estimation tools

NSF: Hurricane Resilience of Electric Power Transmission Infrastructure. An NSF-supported project at the Ohio State University is investigating a new approach to system reliability and resilience assessment of power transmission systems. The goal of the project is to identify vulnerable transmission lines and provide cost-effective retrofit solutions to reduce the likelihood of damage, prevent service loss, and improve recovery time during hurricanes.

FEMA: Maintain Hazus-MH Hurricane Loss Estimation Model. FEMA develops and maintains the Hazards – United States Multi-Hazard model (Hazus), a nationally applicable standardized methodology that contains models for estimating potential losses from multiple hazards, including hurricane winds. Hazus 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 FY 2015 and FY 2016, the Hazus program was undergoing major modernization efforts that focused primarily on general Hazus code and data and the flood module. Updates to Hurricane-specific elements during this time period were minimal, but included minor enhancements and fixes, keeping up with ArcGIS versions, and improvements to data, database engine, and reports.

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. NOAA researchers at the Atlantic Oceanographic and Meteorological Laboratory (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. In FY 2015, researchers worked on extending the historical database to include tropical storms below hurricane strength. An evaluation of the wind model to determine suitability for modeling weak tropical systems that can cause significant flooding was also performed.

GOAL C. IMPROVE THE WINDSTORM RESILIENCE OF COMMUNITIES NATIONWIDE

Objective 10: Develop tools to improve the performance of buildings and other structures in windstorms

NSF: Optimal Design of Structures. An NSF-funded project at the University of Maryland is taking a cyber-physical approach to the optimal design of structures for wind hazards by combining wind tunnel testing results from the University of Florida facility with computational design and optimization. The goal of the project is to enable rapid creation of structural designs that meet specified objectives, advancing the capability to build stronger, lighter, and more resilient structures in the face of wind hazards.

NIST: Database-assisted Design. Database-assisted design (DAD) methods can provide more accurate results than more simplified procedures in building codes and standards. During FYs 2015 and 2016, a methodology and software were developed to directly calculate member demand-to-capacity indexes used in sizing structural members of rigid structures, using as input extreme wind speeds and aerodynamic pressure time histories available in wind engineering databases.[53] NIST also developed a novel DAD computational framework applicable to flexible structures experiencing significant wind-induced dynamic effects.[54]

Objective 11: Support the development of windstorm-resilient standards and building codes

NIST: Translating R&D Advances into Model Building Codes and Standards. Following R&D of the technical basis for improvements in voluntary standards and model building codes to enable windstorm-resilient construction, NIST worked to move the research results into practice by proposing changes to these codes and standards. During FYs 2015 and 2016, the new wind speed maps developed by NIST (see Objective 4) were approved for inclusion in the 2016 edition of the ASCE 7 Standard *Minimum Design Loads for Buildings and Other Structures* and the 2018 edition of the International Building Code (IBC). Unlike their predecessors, these new maps clearly reflect the significant differences between the extreme wind climates of non-hurricane prone regions of the conterminous United States, which will result in more rational, risk-consistent designs throughout the country. A new wind speed map for design of hurricane shelters developed by NIST was incorporated into the ICC 500 standard, and NIST provided major contributions to the new ICC 500 Commentary, including the chapter on structural design criteria (see SP-6).

FEMA: Improving Wind-Resistant Provisions. During FYs 2015 and 2016, 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's 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.

In addition to championing improvements to the wind-resistant provisions of the IBC, FEMA developed supporting commentary and improvements to reference standards for wind-resistant design. During FY 2015 and 2016, FEMA has supported the development of first ever commentary for the ICC 500: *Standard for the Design and Construction of Storm Shelters* (see SP-6) and new tornado commentary for ASCE 7-16: *Minimum Design Loads for Buildings and Other Structures.* FEMA also began working with NOAA, NIST, and ASCE on creation of a tornado wind speed estimation standard (see Objective 2). FEMA will continue these and other efforts to improve wind-resistant provisions of codes and standards.

FEMA/NIST: Building Code Requirements for Storm Shelters. As a result of the 2011 spring tornadoes MAT recommendations, FEMA proposed two code changes. Both changes were approved for publication in the 2015 IBC. The code changes call for mandatory storm shelters in tornado prone

[53] *The Use of Demand-to-Capacity Indexes for the Iterative Design of Rigid Structures for Wind*, by Habte, F., Chowdhury, A.G., and Park, S. NIST Technical Note 1908, 2016. http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1908.pdf.
[54] *Database-Assisted Design and Second-Order Effects on the Wind-Induced Structural Behavior of High-Rise Steel Buildings*, by Park, S. and Yeo, D., NIST Technical Note 1940, 2016. http://ws680.nist.gov/publication/get_pdf.cfm?pub_id=921073

regions (where the shelter design wind speed for tornadoes is 250 mph) for schools and first-responder facilities as follows:

- All new kindergarten through 12th grade schools with 50 or more occupants in total per school shall have an ICC 500-compliant storm shelter.
- All new 911 call stations, emergency operation centers, and fire, rescue, ambulance and police stations shall have an ICC 500-compliant storm shelter.

Implementing recommendations resulting from its studies of deadly EF-5 tornadoes in Joplin, Missouri (2011)[55] and Moore, Oklahoma (2013),[56] NIST, with support from FEMA, successfully proposed code changes for the 2018 IBC and 2018 International Existing Building Code (IEBC). These changes expand the requirements for storm shelters in schools and associated construction in tornado-prone regions as follows:

- New construction for 50 or more occupants at new and existing kindergarten through 12th grade schools shall have an ICC 500 compliant storm shelter capable of housing all the occupants of the school. When the new construction is not of sufficient size to accommodate the entire school, it shall at least accommodate the occupants of the new building or the addition to the existing building.
- This requirement includes associated indoor assembly facilities on the school sites, such as gymnasiums with bleachers, multipurpose rooms, theaters, and libraries.

FHWA: Development of Design Guidelines and Specifications. FHWA continued its research on wind- and rain-induced vibration of bridge stay cables and made the results 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 12-111 "Evaluating the Effectiveness of Vibration Mitigation Devices for Structural Supports of Signs, Luminaires, and Traffic Signals" aimed at updating AASHTO LRFD Specifications for Structural Supports for Signs, Luminaires, and Traffic Signals (AASHTO LRFD SLTS Specifications).

Objective 12: Promote the implementation of windstorm-resilient measures

FLASH/FEMA: Building Code Commentaries. The Federal Alliance for Safe Homes (FLASH®) in partnership with FEMA Building Science Branch, developed a series of building code focused commentaries to help inform community officials and other stakeholders of the need for and benefits of adopting disaster-resilient building codes. For more information, visit http://newsroom.flash.org/news/commentary/.

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[55] *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. t http://www.nist.gov/manuscript-publication-search.cfm?pub_id=915628

[56] *Preliminary Reconnaissance of the May 20, 2013, Newcastle-Moore Tornado in Oklahoma*, by E. Kuligowski, L. Phan, M. Levitan, and D. Jorgensen, NIST SP 1164. December 2013. http://ws680.nist.gov/publication/get_pdf.cfm?pub_id=914721

FLASH: Texas State Collaborative. The Texas State Collaborative is a private-public collaboration to: 1) Increase public safety through enhanced awareness of Texas weather risks; 2) foster strong, modern state and local building codes; and 3) support effective enforcement of state and local building codes by well-trained and adequately resourced professionals. Developed in partnership with FEMA Building Science Branch, State Farm Insurance Companies, the Texas Department of Insurance, and the Building Officials Association of Texas, local leaders and the FLASH® brings national support and resources to assist with achieving agreed upon goals. While specific to Texas, the model program can be implemented in jurisdictions across the U.S. For more information, visit www.texasstatecollaborative.org.

FLASH: Protect Your Home in a FLASH. The FLASH® using FEMA Building Science Branch guidance documents, developed four do-it-yourself videos and other online resources that provide steps consumers should take to ensure their homes are protected in the event of hurricane or other potentially damaging storms. Each *Protect Your Home in a FLASH* video is fast-paced, simple to follow, and packed with valuable information for safeguarding homes. The videos showcase activities that can be completed in one hour, one day, and one weekend. For more information, visit www.flash.org/protect.php.

Objective 13: Improve windstorm forecast accuracy and warning time

NOAA: Hurricane Forecast Improvement Program. NOAA established the 10-year Hurricane Forecast Improvement Project (HFIP) to accelerate the improvement of forecasts and warnings of tropical cyclones and to enhance mitigation and preparedness by increased confidence in those forecasts. Specific goals include reducing track and intensity errors by 20 percent in five years and 50 percent in 10 years and extending the useful range of hurricane forecasts to 7 days. Under HFIP, NOAA has made significant improvements to its operational hurricane prediction model, the Hurricane Weather Research and Forecasting (HWRF) system, resulting in increased accuracy in the numerical guidance for tropical cyclone intensity predictions. In fact, HWRF was the best intensity forecast guidance model in 2015 for the North Atlantic Basin.[57] HWRF also showed some significant improvements in detecting rapid intensity (RI) and structure changes, hence improving the probability of detection for RI forecasts

NOAA: Joint Hurricane Testbed. During FYs 2015 and 2016, the U.S. Weather Research Program within the NOAA OAR Office of Weather and Air Quality supported eight new projects conducted at the Joint Hurricane Testbed (JHT) in Miami, Florida – a NOAA testbed jointly managed by the NHC and AOML. These projects involved testing of new techniques, applications, and model enhancements to improve the analysis and prediction of tropical cyclones. The JHT is designed to facilitate the transfer of 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 and Florida International University), and federal

[57] 2015 HFIP R&D Activities Summary: Recent Results and Operational Implementation. http://www.hfip.org/documents/HFIP_AnnualReport_FY2015.pdf

government laboratories (Naval Research Laboratory, NOAA's Cooperative Institute for Research in the Atmosphere, and NOAA's Cooperative Institute for Meteorological Satellite Studies).

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 goals of the Intensity Forecasting Experiment (IFEX) are 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 such as NASA, ONR, and NSF to accomplish a more complete sampling of TC structure and intensity. For example, recent experiments with which IFEX partnered include NASA's Hurricane and Severe Storm Sentinel (HS3) Project, ONR's Tropical Cyclone Intensification and Structure (TCI) Project, and NSF's Pre-Depression Investigation of Cloud-systems in the Tropics (PREDICT). 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. These innovative interactions provide the opportunity for extensive monitoring of tropical cyclones undergoing significant changes in their structure and intensity such as Hurricane Patricia in 2015, a poorly forecasted storm which broke records for intensification rate, peak intensity, and warm core amplitude. The NOAA P-3 (IFEX) and ONR WB-57 (TCI) aircraft sampled Patricia prior to and during its unprecedented intensification, at peak intensity, and during its unprecedented rapid weakening just prior to landfall on the Mexican coast.

NOAA: Warn-on-Forecast. NOAA's NSSL is working with the NWS to develop a new vision for the warning decision process. This new vision is is aimed at increasing tornado warning lead time, reducing the false alarm ratio, and providing quantified uncertainty and/or probabilistic hazard information that users of local warnings can use in formulating the best response for their situation. Toward this end, NSSL scientists and collaborators are developing on-demand, probabilistic, NWP-based convection-resolving analysis and forecast system. The NSSL continues to investigate various model parameterization schemes, impacts of the assimilation of radar data, satellite data and other observations on probabilistic forecasts, and techniques to improve model initialization through three- and four-dimensional data assimilation. In FY 2015, the NSSL continued to receive funding to support the Warn-on-Forecast (WoF) project.

NOAA: Hazardous Weather Testbed. In FYs 2015 and 2016, 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 NCAR, other universities, various NOAA agencies, private industry, and leading research scientists and forecasters from around the world.

NOAA: Forecasting a Continuum of Environmental Threats (FACETs). NOAA tested a prototype of the FACETs Probabilistic Hazard Information (PHI) tool with forecasters in the 2016 HWT experiment. Forecasters evaluated 4-hourly probabilistic calibrated hazard guidance and produced their own warning-scale PHI for tornadoes, lightning and severe thunderstorms utilizing the prototype tool. A primary result was the PHI provided a more focused warning than the current polygon system, with less false alarm area in proximity to the hazard area and more lead time for the projected path of threat (i.e., warnings extend farther than polygon). It was also noted that forecasters can have difficulty issuing probabilistic forecasts at warning scales because of a lack of calibration and comprehension, such that a human-machine mix is crucial for producing warning scale PHI. HWT activities also included the participation of emergency managers and broadcasters in an Integrated Warning Team paradigm.

NOAA: High-Resolution Rapid Refresh Model (HRRR) and the Rapid Refresh Model (RAP). There is a longstanding need for 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 HRRR model to advance the prediction of weather changes in the environment. The HRRR provides hourly weather updates at three 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 American energy sector, and provides air traffic managers with rapidly updated projections of developing severe weather. During FY 2014, NOAA ESRL/GSD and NOAA National Centers for Environmental Prediction (NCEP) 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 was implemented in NWS operations in late FY 2016. This significant upgrade increased the use of satellite data, ingests new data from lightning sensors, radar, surface stations, and cloud observations, and extends hourly forecasts from XX to 18 hours. The 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. NOAA implemented Version 3 of the RAP in FY 2016, which included a larger domain and hourly forecasts out to 21 hours.

Objective 14: Improve storm readiness, emergency communications and response

NOAA: StormReady Program. The StormReady program supports a WRN by preparing communities for the occurrence of high impact environmental events. On an annual basis NWS targets 100 new StormReady communities if funds are available. StormReady supports NWS's disaster risk reduction strategy and provides guidance and incentives to emergency management officials who want to improve their hazardous weather and flood operations. A long-term goal for the program is to make every county or county-equivalent in the United States StormReady. The 2010 U.S. Census identifies 3234 county or county-equivalents in the United States. We are 38 percent of the way there with 1235 county or county-equivalents currently recognized as StormReady. Overall, there are nearly 2600 communities recognized as StormReady in the U.S. A StormReady Community is defined as a local government entity or facility that has the authority and ability to adopt the StormReady recognition guidelines for the residents and visitors within its jurisdiction. The StormReady web site, http://www.stormready.noaa.gov, was completely updated in FYs 2015 and 2016, greatly exceeding the FY 2016 Annual Operating Plan milestone of 189 counties becoming StormReady. NOAA also partnered with the Simon Property Group on recognizing all of their 209 Regional Malls, The Mills and Premium Outlets locations as StormReady Supporters (and WRN Ambassadors).

NOAA: Forecasting a Continuum of Environmental Threats (FACETs). The FACETs program conducted a baseline watch, warning, and advisory (WWA) survey to assess current methods of communicating threats to the public. This survey included a systematic analysis of previous research on tornado warning reception, comprehension, and response (database of 108 studies). FACETs developed and tested new measures for tornado warning reception, comprehension, and response in a pilot survey of about 3,000 Oklahomans. One survey goal was to evaluate new measures and compare them with the old ones. A second goal was to address important gaps in previous research and answer basic questions, e.g., to determine how many people actually receive a warning when it is issued for a given area. Both of these goals were achieved during the FY 2015 and FY 2016 reporting period.

NIST: Emergency Communications. NIST conducts emergency communication research to develop the measurement science that provides the foundation for national codes, standards, and guidance on the creation and dissemination of clear, consistent, and accurate emergency communications for tornadoes. NIST's current focus is on developing evidence-based guidance for communities on the creation and provision of public alerts, including both outdoor siren (warning) systems and social media (including mobile alerts). Progress in FY 2016 included: 1) a review of current technology for outdoor siren systems, siren usage, and public response to sirens; 2) a NIST and Fire Protection Research Foundation sponsored workshop for emergency managers and NWS representatives from 13 jurisdictions located in tornado-prone areas within the U.S. The outcome of the workshop provided feedback on NIST-developed interim guidance on the usage of outdoor siren systems; and 3) beginning development of guidance on the usage of outdoor siren systems for the next edition (2019) of NFPA 1600: Standard on Disaster/ Emergency Management and Business Continuity/Continuity of Operations Programs. Additionally, NIST developed guidance on 1) public alerts and warnings, and 2) application of social media to support emergency communications, was successfully proposed for incorporation into the new NFPA 1616 Standard on Mass Evacuation, Sheltering, and Re-entry Programs.

5. Outcomes Achieved

NWIRP has continued to make progress towards achieving the goals and objectives of the Program, which is to significantly reduce the losses of life and property due to windstorms. Section 5.1 addresses outcomes achieved by the Program for the goals identified in the Strategic Plan: improving the understanding of windstorm processes, hazards, and impacts; and using this knowledge to make improvements to windstorm resilience of communities.

The Program has been successful in using research and investigative findings to inform the development of model building codes and national standards. Over thirty recently approved changes to building and emergency management codes and standards resulting from Program activities are summarized in Section 5.2.

5.1. Strategic Goals

Highlights of successes achieved in the areas of each of the three Strategic Goals are summarized below.

Goal A. Improve the Understanding of Windstorm Processes and Hazards

- 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.
- Results from the NOAA and NSF-supported second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX2) are advancing the understanding of tornado formation, improving prediction, and offering prospects for increased warning lead-times.
- Improvements in tornado intensity estimation (developed jointly by NIST, NOAA, and Texas Tech University) allowed the EF tornado scale to be adopted and used by the NWS in 2007 for more accurate rating of tornado intensity.

Goal B. Improve the Understanding of Windstorm Impacts on Communities

- NSF created national, multi-user facilities to provide the natural hazards engineering community with access to research infrastructure (earthquake and wind engineering experimental facilities, cyberinfrastructure, computational modeling and simulation tools, and research data), coupled with education and community outreach activities through NSF's NHERI program, including three facilities dedicated to supporting experimental research in wind and coastal engineering.
- New knowledge from NSF awards helped risk communicators improve the effectiveness of warning messages, zoning boards understand opportunities to increase resilience, and emergency managers to address the concerns of evacuees.
- Results of wind engineering research by FHWA 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, and updates of design guides and specifications for wind.

Goal C. Improve the Windstorm Resilience of Communities Nationwide

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. 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. In FY 2015, FEMA published the 4th edition of FEMA P-320, *Taking Shelter from the Storm: Building a Safe Room for Your Home and Small Business* (December 2014) which includes safe room designs for multiple material types and 3rd edition of FEMA P-361, *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms* (March 2015). FEMA also provided training on the latest editions of the publications to engineers, architects, builders, and emergency managers.

- Successful building code change proposals by FEMA for the 2015 IBC will result in ICC 500-compliant storm shelters in new schools and first-responder facilities in the areas of the nation with the highest tornado risk.

- NIST successfully proposed changes to the 2018 IBC and 2018 IEBC to extend the tornado shelter requirements to new buildings and additions to buildings on existing school campuses, including indoor assembly occupancies (e.g. theaters) associated with school facilities. Shelters are required to have enough capacity to protect the entire population of the school, if the new building or addition is large enough.

- New wind speed maps for the design of buildings and structures developed by NIST have been incorporated in the 2016 edition of the ASCE 7 Standard for Minimum Design Loads for Buildings and Other Structures and approved for inclusion in the 2018 IBC. The new wind speed maps provide more risk consistent design wind speeds and better incorporate regional differences in extreme wind climate across the country.

- NOAA's advances in satellite-based observations, supercomputers, and data assimilation and modeling have reduced average hurricane forecast track errors significantly—about half of what they were 15 years ago.

- NOAA's NWS used Doppler radar and better understanding of radar indicators for tornado threat, as well as forecasting and prediction to double the average warning time for tornadoes over the past two decades to 13 minutes.

- NOAA's WRN program is readying communities for extreme weather, water, and climate events. NOAA's NWS is transforming its operations to help America respond. Offices now provide forecast information in a way that better supports the ability of emergency managers, first responders, government officials, businesses and the public to make fast, smart decisions to save lives and property and enhance livelihoods.

- The StormReady program is supporting a WRN by preparing communities for the occurrence of high impact environmental events, including windstorms. Overall, there are nearly 2,600 communities NOAA recognized as StormReady in the U.S.

- A new collaboration, #HurricaneStrong, offers empowering hurricane safety and mitigation information for families and practitioners through business summits, digital channels, home improvement store workshops, kids programming, media outreach, school lesson plans, special events, and a social media campaign. The program was created by the (FLASH®) in partnership with NOAA and FEMA.

5.2. Changes to Model Building Codes and National Standards

Significant improvements have been made to model building codes and national standards pertaining to design and construction of windstorm-resistant buildings and other structures as the result of Program activities. The Program also provided significant contributions to the development of a new emergency planning and operations standard. Successful recommendations for changes (i.e., successful change proposals) were made to the following six model building codes and standards, and one emergency management standard:

- ICC 500-2014 Standard and Commentary: ICC/ National Storm Shelter Association (NSSA) Standard for the Design and Construction of Storm Shelters;
- 2015 International Building Code (2015 IBC);
- 2015 International Residential Code (2015 IRC);
- ASCE 7-16, Minimum Design Loads and Associated Criteria for Buildings and Other Structures;
- 2018 International Building Code (2018 IBC);
- 2018 International Existing Building Code (2018 IEBC); and
- NFPA 1616-2017, Standard on Mass Evacuation, Sheltering, and Re-entry Programs

Highlights of these codes and standards successes include:

- New design wind speed maps in ICC 500-2014, ASCE 7-16, and the 2018 IBC;
- Requirements for incorporation of storm shelters in new K-12 schools and emergency responder facilities located in the most tornado-prone parts of the country (2015 IBC);
- Requirements for incorporation of storm shelters in new buildings (2018 IBC) and additions to buildings (2018 IEBC) on existing K-12 school campuses;
- Strengthening of peer-review and special inspection requirements for design of community storm shelters in ICC 500-2014;
- Strengthening of oversight on prefabricated storm shelters in ICC 500-2014;
- Better establishment of limits of the prescriptive fastening requirements for wall coverings (2015 IRC);
- Requirements and guidance for building safety considerations in selection of emergency shelters and best available refuge areas for multiple hazards, including hurricanes and tornadoes (NFPA 1616-2017); and
- Guidance on public alerts and warnings, and application of social media to support emergency communications (NFPA 1616-2017).

The following table summarizes 28 approved changes to windstorm-related provisions in existing building codes and standards that resulted from Program activities during the current reporting period, or resulted from prior proposals to documents that were published during this reporting period. More information on the activities supporting many of these change proposals is provided in Section 4 (particularly in SP-4, SP-6, and Objectives 4, 5, and 11) and in prior NWIRP Biennial Reports. Another 15 proposals were submitted to these building codes and standards that were disapproved.

Table 1: Successful Changes to Model Building Codes and National Standards

CODE / STANDARD	MAIN SECTION(S)	DESCRIPTION OF CHANGE
ICC 500-2014	106.1.1	Reduce the peer review occupancy trigger from 300 to 50 occupants.
ICC 500-2014	106.1.1	Expand the peer review by requiring designs be reviewed for compliance with additional chapters of ICC 500. 2008 edition of ICC 500 requires a peer review to be conducted for compliance with Chapter 3 (Structural Design Criteria). FEMA's proposal added Chapter 5 (Occupancy, Means of Egress, Access and Accessibility) and Chapter 7 (Shelter Essential Features and Accessories) to the items that must be covered by the peer review. Chapter 6 (Fire Safety) was added by the ICC committee.
ICC 500-2014	106.1.2	Require the peer review to be submitted to the authority having jurisdiction along with the construction documents identified in Section 107 of ICC 500.
ICC 500-2014	106.1.1	Require that all shelters in Risk Category IV buildings (essential facilities) as defined in the IBC, as well as elementary schools, secondary schools, and day care facilities (with an occupant load greater than 16), have the design peer reviewed by a design professional.
ICC 500-2014	106.3	Require special inspections for certain storm shelter applications with the goal of targeting storm shelters installed on existing slabs that are not sufficient to carry the load. This proposal went through extensive debate and eventually evolved into a special inspection for anchors post-installed into hardened concrete. The ICC 500 requirement was subsequently expanded to include masonry as well. FEMA's proposal also included the addition of the 2015 IBC definitions for "special inspection" and "special inspector" into Chapter 2 (Definitions).
ICC 500-2014	107.2.1	Require more information within storm shelter plans. The proposal was heavily debated and modified, but retained the original intent. The accepted proposal requires storm shelter plans to also provide minimum foundation capacity requirements and shelter installation requirements, including anchor location and minimum required capacity for each anchor. The final ICC 500 language requires these items for all types of storm shelters.

CODE / STANDARD	MAIN SECTION(S)	DESCRIPTION OF CHANGE
ICC 500-2014	107.3.1	Strengthen oversight on prefabricated storm shelters. The proposal adds the following to the list of items for which a community storm shelter quality assurance plan must be provided: foundation design, prefabricated storm shelter installation requirements (including anchor location and minimum required capacity for each anchor), and the minimum foundation capacity requirements for a prefabricated storm shelter.
ICC 500-2014	303.1, 703.8	Change the rainfall rate and other provisions for design of hurricane shelters to more accurately reflect rain load and drainage-related hazards.
ICC 500-2014	304.2	Replace design wind speed map for hurricane shelters with one developed using an improved hurricane simulation methodology.
ICC 500-2014	301-304	Revise the load requirements for consistency with ASCE 7-10 load provisions.
ICC 500-2014	305.1.2	Change the horizontal hurricane test missile speed from 0.4 times the shelter design wind speed to 0.5 times the design wind speed to align with FEMA P-361.
ICC 500-2014	308	Add an existing slab on grade subsection that describes the special inspection, evaluation, and testing criteria for existing slabs. The proposal was not accepted as a new section, but the section (formerly 309) was updated to specifically include new or existing slabs.
ICC 500-2014	309	Modify the language of Section 309.1 (formerly 310.1) of ICC 500 to clarify what types of penetrations are required and address the issue of door undercuts.
ICC 500-2014	401	Numerous proposals related to flood elevation criteria that resulted in ICC 500 adopting elevation criteria that now more closely reflects the criteria found in FEMA P-361. See Chapter B4 of the 2015 edition of FEMA P-361 for a detailed list of the flood elevation criteria found in ICC 500 and the few remaining differences between it and FEMA P-361.
ICC 500-2014	404	Restrict flood hazard siting for residential and community storm shelters. Residential restrictions were not accepted but community section was added to prevent community storm shelters being sited in high-risk flood hazard areas, including areas subject to high-velocity wave action (Zone V), and floodways; an exception was included to allow siting in high-risk flood hazard areas where permitted by the Board of Appeals in accordance with the provisions in the IBC.

CODE / STANDARD	MAIN SECTION(S)	DESCRIPTION OF CHANGE
ICC 500-2014	806.4.1	Require glazed opening testing for tornado shelters to be performed at a pressure of at least 1.2 times the design wind pressure.
ICC 500-2014	Commentary	Wrote several chapters of the commentary for the ICC 500-14 standard and made significant contributions to the rest of the document.
2015 IBC	3102.7	Establishes clearly that there are two categories of membrane structures supported by a rigid framework: 1) Membrane-Covered Frame Structures – for which the membrane does not participate in the lateral restraint of the frame members. The membrane shall not be considered to provide lateral restraint in the calculation of the capacities of frame members 2) Tensile Membrane Structures – wherein the membrane is considered to participate in the lateral restrain of the frame members. With the passage of G186-12, Tensile Membrane Structures are now to be designed in accordance with the new ASCE 55 standard.
2015 IBC	423.3 (new)	Adds requirement for storm shelter in critical emergency operations facilities (911 call stations, emergency operation centers, fire, rescue, ambulance and police stations) where located in 250 mph tornado storm shelter wind zone per ICC 500 Figure 304.2(1).
2015 IBC	423.4 (new)	Adds requirement for storm shelter in K-12 schools with more than 50 occupants where located in 250 mph tornado storm shelter wind zone per ICC 500 Figure 304.2(1). Exceptions apply for day care facilities and occupancies accessory to places of religious worship.
2015 IRC	R703.4	Better establishes the current limits of the prescriptive fastening table for wall coverings. New charging language, new and modified tables capture Exposure C & D and mean roof heights greater than 30'.
ASCE 7-16	26.5	Provide new design wind speed maps that better represent regional variations in extreme wind climate. Provide separate wind speed map for use in design of Risk Category IV structures (critical and essential facilities).
ASCE 7-16	31.4.3	Add requirements for consideration of wind directionality as part of the wind tunnel procedure for determination of wind loads.
ASCE 7-16	C26.5.1	Update the information on correlation between ASCE 7 design wind speeds and the Saffir-Simpson Hurricane Wind Scale.

CODE / STANDARD	MAIN SECTION(S)	DESCRIPTION OF CHANGE
2018 IBC	423	Require installation of storm shelters in new buildings on existing school campuses in tornado prone areas. This requirement includes providing shelters for indoor assembly occupancies (e.g. theaters and gymnasiums with bleachers) associated with Group E occupancies. Shelters are required to have enough occupant capacity to protect the full occupant load of the school or the assembly area, whichever is greater, if the new building is large enough to accommodate that capacity. Maximum travel distance to the shelter from the building being served is also specified.
2018 IBC	1609	Add the same new design wind speed maps that were developed for ASCE 7-16.
2018 IEBC	1106 (new)	Require installation of storm shelters when constructing additions to existing school buildings in tornado prone areas. Occupant capacity and travel distance requirements are added consistent with IBC Section 423.

Additionally, the Program made significant contributions to a new emergency planning and operations standard during the current reporting period, the NFPA 1616 Standard on Mass Evacuation, Sheltering, and Re-entry Programs. Materials were developed and successfully proposed in the areas of 1) building safety considerations in the selection of emergency shelters for multiple hazards, including windstorms, and 2) improvement of emergency communications related to mass evacuation and sheltering. These contributions are summarized in Table 2. Additional information is provided in Section 4.1 (SP-6) and 4.2 (Objective 14) on shelter safety and emergency communications considerations, respectively.

Table 2: Successful Changes to Emergency Planning and Operations Standards

STANDARD	MAIN SECTION(S)	DESCRIPTION OF CHANGE
NFPA 1616-2017	5.6 and Annex A5.6	Requirements for consideration of building safety in the selection of facilities for mass sheltering before, during, and after windstorms and other hazards.
NFPA 1616-2017	Annex E	Guidance for consideration of building safety in the selection of mass shelters for windstorms and other hazards.
NFPA 1616-2017	Annex J	New annex with guidance on public alerts and warnings.
NFPA 1616-2017	Annex K	New annex with guidance on application of social media to support emergency communications.

5.3. The Path Forward

At the time of publication of this document, the NWIRP Strategic Plan has been finalized. Initial planning for implementation of the Strategic Plan includes the following elements:

- Expand the network of federal agencies that collaborate on windstorm impact reduction by adding NASA, USGS, and others to build a stronger scientific understanding of the causes and impacts of windstorms, and to ensure that there is no duplication of efforts between agencies. In addition, expand engagement with stakeholder organizations, including other levels of government, academia and the private sector, so that research outcomes on prevention efforts can be disseminated through existing communication networks and reach a wider public audience.

- Improve communication of the NWIRP's progress through developing a more user-friendly Program web site, a newsletter, and increased participation in windstorm-related conferences. and publishing our work and accomplishments widely through established FEMA networks that reach schools, community leaders, and home-owner organizations.

Lastly, it should be noted that while the Strategic Plan is believed to address the key elements necessary to achieve major measurable reductions in the losses of life and property from windstorms, progress on implementation of the Plan and the rate of future Program accomplishments are highly dependent on the level of resources available to NWIRP agencies.

Appendix A: Acronyms

- ASCE - American Society of Civil Engineers
- ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers
- AOML - Atlantic Oceanographic and Meteorological Laboratory
- CFD - Computational Fluid Dynamics
- CIMAS - Cooperative Institute for Marine and Atmospheric Studies
- CPI - Consumer Price Index
- DHS - Department of Homeland Security
- DoE - Department of Energy
- EF - Enhanced Fujita Scale
- FEMA - Federal Emergency Management Agency
- FHWA - Federal Highway Administration
- FLASH - Federal Alliance for Safe Homes
- FY - Fiscal Year
- GSA - General Services Administration
- Hazus® - Hazards U.S., a Geographic Information System (GIS)-based natural hazard analysis tool developed and distributed by FEMA
- Hazus®-MH - Hazus Multi-Hazard
- HUD - Department of Housing and Urban Development
- HWT - Hazardous Weather Testbed
- IBC - International Building Code
- IBHS - Insurance Institute for Business and Home Safety
- ICC - International Code Council
- IEBC - International Existing Building Code
- LiDAR - Light Detection and Ranging
- MAT - Mitigation Assessment Team
- NACWIR - National Advisory Committee on Windstorm Impact Reduction
- NASA - National Aeronautics and Space Administration
- NCAR - National Center for Atmospheric Research
- NEHRP - National Earthquake Hazards Reduction Program
- NHERI - Natural Hazards Engineering Research Infrastructure
- NIST - National Institute of Standards and Technology
- NOAA - National Oceanic and Atmospheric Administration
- NPDIA - National Plan for Disaster Impact Assessments
- NRC - Nuclear Regulatory Commission
- NSF - National Science Foundation
- NSSA - National Storm Shelter Association
- NSTC - National Science and Technology Council
- NWIRA - National Windstorm Impact Reduction Act of 2004
- NWIRP - National Windstorm Impact Reduction Program
- NVOAD - National Voluntary Organizations Active in Disasters

- NWS - National Weather Service
- OMB - Office of Management and Budget
- OSTP - Office of Science and Technology Policy
- PBD - Performance-Based Design
- R&D - Research and Development
- SDR - Subcommittee on Disaster Reduction
- USACE - U.S. Army Corps of Engineers
- USGS - United States Geological Survey
- VA – U.S. Department of Veterans Affairs
- WG/DIAP - Working Group for Disaster Impact Assessments and Plans
- WWG - Windstorm Working Group

Appendix B: NWIRP Agency Statutory Responsibilities

Tables B.1 through B.4 show the relationship among the statutory responsibilities (42 U.S.C. § 15703) of the four Program agencies, respectively, to the Strategic Plan goals, Objectives, and Strategic Priorities. Many other activities within the Program agencies, conducted under different statutory authorities, also support the NWIRP mission and specific goals and objectives. For example, while NOAA's assigned NWIRP responsibility is atmospheric science research (Table B.3), many other NOAA activities provide critical support for windstorm impact reduction, such as storm data collection and archival, forecasting, warning communications, and education and outreach programs. Other Program agency capabilities beyond those supporting the statutory responsibilities will be engaged by NWIRP as needed.

Table B.1: Federal Emergency Management Agency

Program Agency Responsibilities	Strategic Plan Goal	Strategic Plan Objective	Strategic Priority SP #
Support development of risk assessment tools and effective mitigation techniques. 42 U.S.C. § 15703(b)(5)(A)(i).	B C	9 10	1, 6
Support windstorm-related data collection and analysis. 42 U.S.C. § 15703(b)(5)(A)(ii).	A B C	2, 4 7, 8, 9 12	2, 3
Support public outreach and information dissemination. 42 U.S.C. § 15703(b)(5)(A)(iii).	C	12, 14	5, 6, 7
Support promotion of the adoption of windstorm preparedness and mitigation measures, including for households, businesses, and communities, consistent with the agency's all-hazards approach. 42 U.S.C. § 15703(b)(5)(A)(iv).	C	12, 14	5, 6
Work closely with national standards and model building code organizations, in conjunction with NIST, to promote implementation of research results and promote better building practices within the building design and construction industry, including architects, engineers, contractors, builders, and inspectors. 42 U.S.C. § 15703(b)(5)(B).	C	11, 12, 14	4, 6

Table B.2 National Institute of Standards and Technology

Statutory Responsibilities	Strategic Plan Goal	Strategic Plan Objective	Strategic Priority SP #
Lead Agency Responsibilities			
Ensure the Program includes necessary components to promote implementation of windstorm risk reduction measures by federal, state, and local governments, national standards & model building code organizations, architects and engineers, and others with roles in planning & constructing buildings & lifelines. 42 U.S.C. § 15703(b)(1)(A).	**All**	**All**	**All**
Support development of performance-based engineering tools, & work with appropriate groups to promote commercial application of such tools, including wind-related model building codes, voluntary standards, and construction best practices. 42 U.S.C. § 15703(b)(1)(B).	**C**	**11, 12**	**4**
Request assistance of federal agencies other than the Program agencies, as necessary to assist in carrying out the Act (Program). 42 U.S.C. § 15703(b)(1)(C).	**All**	**All**	**All**
Coordinate all federal post-windstorm investigations, to the extent practicable. 42 U.S.C. § 15703(b)(1)(D).	**A** **B**	**2** **8**	**3**
When warranted by research or investigative findings, issue recommendations to assist informing development of model codes & inform Congress on use. 42 U.S.C. § 15703(b)(1)(E).	**C**	**11**	**4, 6**
Program Agency Responsibilities			
In addition to the lead agency responsibilities, carry out R&D to improve model building codes, voluntary standards, and best practices for design, construction, and retrofit of buildings, structures, and lifelines. 42 U.S.C. § 15703(b)(2).	**A** **B** **C**	**1, 2, 4** **5, 6, 8, 9** **10, 11**	**All**

Table B.3: National Oceanic and Atmospheric Administration

Program Agency Responsibilities	Strategic Plan Goal	Strategic Plan Objective	Strategic Priority SP #
Support atmospheric sciences research to improve understanding of behavior of windstorms and their impact on buildings, structures, and lifelines. 42 U.S.C. § 15703(b)(4).	A B	1, 2, 3, 4 5, 6, 8	1, 2, 3, 7

Table B.4: National Science Foundation

Program Agency Responsibilities	Strategic Plan Goal	Strategic Plan Objective	Strategic Priority SP #
Support research in engineering and atmospheric sciences to improve understanding of behavior of windstorms and their impact on buildings, structures, and lifelines. 42 U.S.C. § 15703(b)(3)(A).	A B	1, 2, 3, 4 5, 6, 8, 9, 10	1, 2, 3, 4, 6, 7
Support research in economic and social factors influencing windstorm risk reduction measures. 42 U.S.C. § 15703(b)(3)(B).	B C	7, 8 10, 11, 12	1, 3, 7

Appendix C: NWIRP Coordinated Budget

The Fiscal Year 2016 NWIRP Coordinated Budget, provided below, was submitted to Congress on October 20, 2016.

NWIRP Coordinated Budget Report

The **National Windstorm Impact Reduction Program (NWIRP)** was established by Congress in 2004 "…to achieve major measurable reductions in the losses of life and property from windstorms through a coordinated federal effort, in cooperation with other levels of government, academia, and the private sector, aimed at improving the understanding of windstorms and their impacts and developing and encouraging the implementation of cost-effective mitigation."

The National Windstorm Impact Reduction Act Reauthorization of 2015 (P.L. 114-52) requires submission of a coordinated NWIRP budget to Congress each fiscal year within 60 days after the date of the President's budget submission.

National Institute of Standards and Technology (NIST)

NIST has been designated as the Lead Agency for NWIRP through the enactment of P.L. 114-52 on September 30, 2015. As such, NIST's responsibilities include both leadership and technical activities.

Planned lead agency activities include:

- Plan and coordinate NWIRP, in cooperation with other federal agencies and the broader stakeholder community
- Lead development of a public comment draft of the strategic plan for NWIRP, supported by input gathered from a stakeholder's workshop
- Develop the charter, solicit nominations, and begin the membership appointment process for the National Advisory Committee on Windstorm Impact Reduction
- Coordinate all federal post-windstorm investigations, to the extent practicable.

Planned technical activities include:

- Continue development of performance-based design approach for wind hazards
- Develop computational wind engineering capability for simulating wind pressures on simple prismatic shapes, as the first step towards simulation of wind loads on real structures
- Continue development of tornado hazard maps for use in design of buildings and structures
- Subject to the availability of funds, solicit grant proposals for research aimed to improve resilience of buildings and infrastructure against windstorm hazards, including storm surge
- Continue technology transfer, translating windstorm impact reduction research to practice through participation in codes and standards processes.

National Science Foundation (NSF)

The National Science Foundation will support research in engineering and the atmospheric sciences to improve the understanding of the behavior of windstorms and their impact on building, structures, and lifelines; and research in the economic and social factors influencing windstorm risk reduction measures.

National Oceanic and Atmospheric Administration (NOAA)

NOAA will conduct research into windstorms and work to improve our wind-related forecasts and warnings. NOAA activities contributing to the goals of NWIRP fall under two categories, hurricanes and local severe weather.

- **Hurricanes -** This includes funding for hurricane forecast improvement, hurricane research-to-operations (R2O) integration, and operationally-focused hurricane research.
- **Local Severe Weather, including Tornadoes, Derechoes, and Severe Thunderstorms -** This includes R&D and R2O activities related to these areas, including hazardous weather and aviation weather forecast improvement.

Federal Emergency Management Agency (FEMA)

While FEMA receives no appropriated or dedicated funding for wind related projects, a high-level summary of the wind related activities FEMA Building Science has or will be pursuing includes: supporting the development of risk assessment tools and effective mitigation techniques, post-windstorm related data collection and analysis, public outreach, information dissemination, and implementation of mitigation measures consistent with the agency's all-hazards approach.

NWIRP BUDGET REPORT

NWIRP ($K)	FY 2015 Enacted	FY 2016 Enacted	FY 2017 Cong Request
NIST	1,350	3,475	3,475
NOAA	18,843	19,344	16,343
NSF	9,682	9,682	9,682
FEMA	450	100	300
Total NWIRP	30,325	32,601	29,800