NATIONAL WINDSTORM IMPACT REDUCTION PROGRAM

BIENNIAL PROGRESS REPORT TO CONGRESS FOR FISCAL YEARS 2017 AND 2018

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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).

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[1] Windstorm Working Group members are agency representatives serving during the reporting period.

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1. Background

Windstorms are the largest loss-producing natural hazards in the United States, with hurricanes and tornadoes comprising a majority of losses related to life and property. According to the National Oceanic and Atmospheric Administration (NOAA), between 1980-2018, windstorms caused over $1 trillion in economic losses and over 8,000 fatalities.[2] In recognition of the increasing economic costs and loss of life, Congress established a coordinated federal agency effort in 2004 – the National Windstorm Impact Reduction Program[3] (NWIRP or Program) – to accomplish significant reductions in windstorm-related losses of life and property. Improved windstorm impact reduction measures require an interdisciplinary 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.

Detailed history and NWIRP activities from fiscal years 2005 through 2016 have been documented in a series of biennial reports to Congress.[4] During fiscal years 2017-18, NWIRP carried out its statutory requirement to convene a Federal Advisory Committee[5] and develop a strategic plan for the interagency program.[6]

Structure of the Progress Report

A brief overview of the NWIRP Program is presented in Section 1. Section 2 of the report provides a short description of windstorms occurring during calendar years 2017 and 2018[7] and the resulting loss of life and property. Section 3 describes Program leadership and coordination, including development of the NWIRP Strategic Plan (Plan). Section 4 summarizes the major research, development, and implementation activities conducted by the Program agencies (the National Institute of Standards and Technology (NIST), National Science Foundation (NSF), NOAA, and Federal Emergency Management Agency (FEMA)), 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 in section 4 focus on activities that have taken place during the past biennial period, in this case fiscal years 2017-18 (also referred to in this document as the "reporting period"). Longer term projects may also include brief descriptions of prior years'

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[2] National Oceanic and Atmospheric Administration, National Centers for Environmental Information. (2019). Billion-dollar weather and climate disasters: Table of events. Retrieved from https://www.ncdc.noaa.gov/billions/events/US/1980-2017

[3] 42 U.S.C. §15703(a).

[4] National Windstorm Impact Reduction Program Biennial Reports to Congress. https://www.nist.gov/el/mssd/nwirp/biennial-reports-congress

[5] 42 U.S.C. §15704. National Windstorm Impact Reduction Program Office. National Advisory Committee on Windstorm Impact Reduction. https://www.nist.gov/el/materials-and-structural-systems-division-73100/national-windstorm-impact-reduction-program-1

[6] 42 U.S.C. §15703(e)(5). National Windstorm Impact Reduction Program Interagency Coordinating Committee. (2018). Strategic Plan for National Windstorm Impact Reduction Program. Retrived from https://www.nist.gov/el/materials-and-structural-systems-division-73100/national-windstorm-impact-reduction-program-0

[7] The summary of storm activities is provided for calendar years 2017 and 2018, rather than the fiscal years referred to elsewhere in this report, consistent with how storm and loss data are typically made available.

activities, to provide context. Section 5 provides a brief description of potential activities to implement the Plan.

2. Windstorms and Their Impacts in 2017 and 2018

Windstorm-related disasters such as hurricanes, tornadoes, and other forms of severe weather are the most destructive natural hazards in the U.S., causing significant loss of life and property each year. The years 2017 and 2018 were unprecedented in this regard.

2.1. 2017

The 2017 Atlantic hurricane season was one of the most deadly and destructive hurricane seasons on record. There were 17 named storms, 10 of which became hurricanes. Six of the storms attained major hurricane status (category 3 or greater), with three category 4 hurricane landfalls in the U.S. (Figure 1). In August, Hurricane Harvey made landfall in Rockport, Texas, with 58 m/s (130 mph) maximum sustained winds, and nearly stalled, which led to portions of the greater Houston area receiving approximately 1.52 m (60 inches) of rainfall, marking the single-storm rainfall total on record for the continental United States.[8] In early September, Hurricane Irma made landfall in Cudjoe Key, Florida, with maximum sustained winds of 58 m/s (130 mph). Irma made a second landfall on the western tip of the Florida Peninsula and progressed northward, impacting much of the state. On September 20th Hurricane Maria devastated the Commonwealth of Puerto Rico causing catastrophic damage to the built environment and an estimated 2,975 deaths.[9]

There were 1,522 tornadoes in 2017, which is 120 tornadoes more than the 2005-2015 average, according to the Storm Prediction Center.[10] Tornadoes claimed 35 lives and caused 516 injuries.[11] Locations of these tornadoes are mapped in Figure 2. Thunderstorms and other high-wind events claimed 50 lives and caused 213 injuries.[12] In total, windstorms that struck the United States in calendar year 2017 claimed over three thousand lives and injured thousands of people.[13]

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[8] National Oceanographic and Atmospheric Administration, National Hurricane Center. (2018). Tropical Cyclone Report – Hurricane Harvey (NHC Publication AL092017). Retrieved from https://www.nhc.noaa.gov/data/tcr/AL092017_Harvey.pdf
[9] The George Washington University Milken Institute School of Public Health. (August 28, 2018). Ascertainment of the Estimated Excess Mortality from Hurricane Maria in Puerto Rico. Retrieved from https://publichealth.gwu.edu/sites/default/files/downloads/projects/PRstudy/Acertainment%20of%20the%20Estimated%20Excess%20Mortality%20from%20Hurricane%20Maria%20in%20Puerto%20Rico.pdf (Report commissioned by Puerto Rico Governor, Ricardo Rosselló).
[10] National Oceanographic and Atmospheric Administration. (2017). Annual Trends in Local Storm Reports-Tornadoes. Retrieved from http://www.spc.noaa.gov/wcm/2017/torngraph-big.png
[11] National Oceanographic and Atmospheric Administration, National Weather Service. (2017). Summary of Natural Hazard Statistics for 2017 in the United States. Retrieved from http://www.nws.noaa.gov/om/hazstats/sum17.pdf
[12] Ibid.
[13] Estimated using information from the National Weather Service Summary of Natural Hazard Statistics for 2017 and National Oceanic and Atmospheric Administration, National Centers for Environmental Information. Retrieved from https://www.ncdc.noaa.gov/billions/events/US/2017-2018

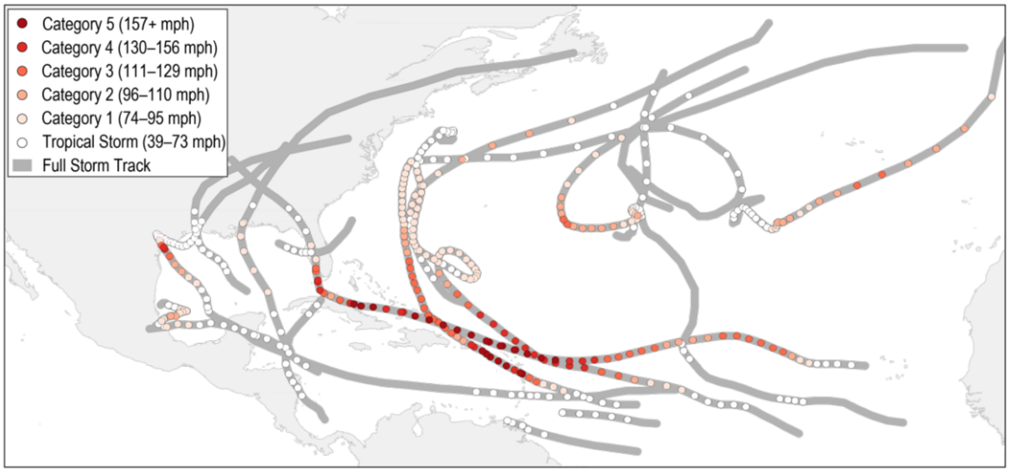

Figure 1. Atlantic Tropical Cyclones Occurring in 2017. Source: [U.S Global Change Research Program (USGCRP) 4th National Climate Assessment.]()

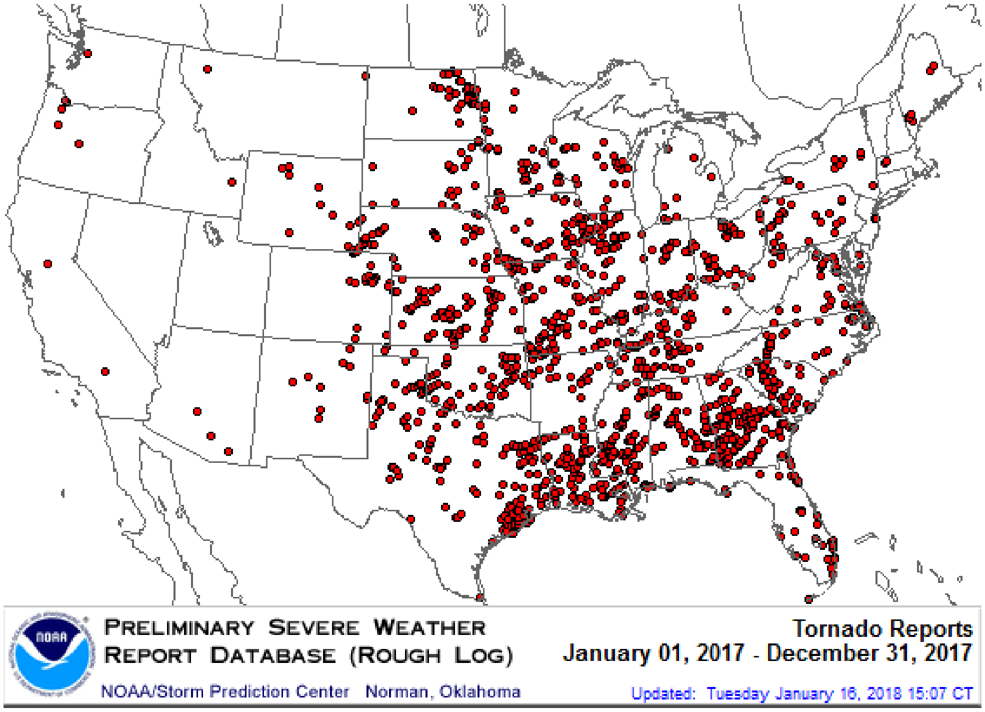

Figure 2. Tornadoes Occurring in 2017. Source: National Centers for Environmental Information, https://www.ncdc.noaa.gov/sotc/tornadoes/201713**.**

2.2. 2018

While the 2018 season had less overall activity than the record-breaking 2017 hurricane season, the damage was still catastrophic. The 2018 Atlantic hurricane season had 15 named storms, 8 of which became hurricanes, with two of those attaining major hurricane status (category 3 or greater). In 2018, Hurricanes Florence, Michael, and Yutu (Pacific) impacted the United States. Hurricane Florence made landfall on September 14, 2018, along the North Carolina coast. Despite making landfall as a category 1 hurricane with 40.2 m/s (90 mph) maximum sustained winds, Hurricane Florence produced up to 0.76m (30 inches) of rainfall over portions of North and South Carolina due to the storm's slow forward speed after landfall, similar to that of Hurricane Harvey in 2017. Hurricane Michael made landfall as a category 5 storm on October 10th with maximum sustained winds of 71.5 m/s (160 mph). Hurricane Michael caused catastrophic impacts along the panhandle of Florida, including the complete destruction of homes and businesses in Mexico Beach, Florida, and significant damage to Tyndall Air Force base. The estimated surface 3-second gust wind speeds from Hurricane Michael is 171 mph derived from 1-minute sustained wind speed of 161 mph.[14] This exceeded the most recent design standards for residential and commercial buildings in the Florida Panhandle (i.e., 144 mph for Risk Category IV).[15] Hurricane Yutu made landfall in the Northern Mariana Island U.S. territories of Saipan and Tinian on October 25, 2018, with satellite estimated winds of 80 m/s (180 mph) causing significant damage.

In 2018, there were 1,169 tornadoes and 13,206 reported wind events.[16] Figure 3 shows the locations where wind damage was reported from severe weather. In total, windstorms that struck the United States in calendar year 2018 claimed over 200 lives and injured 441 people.[17]

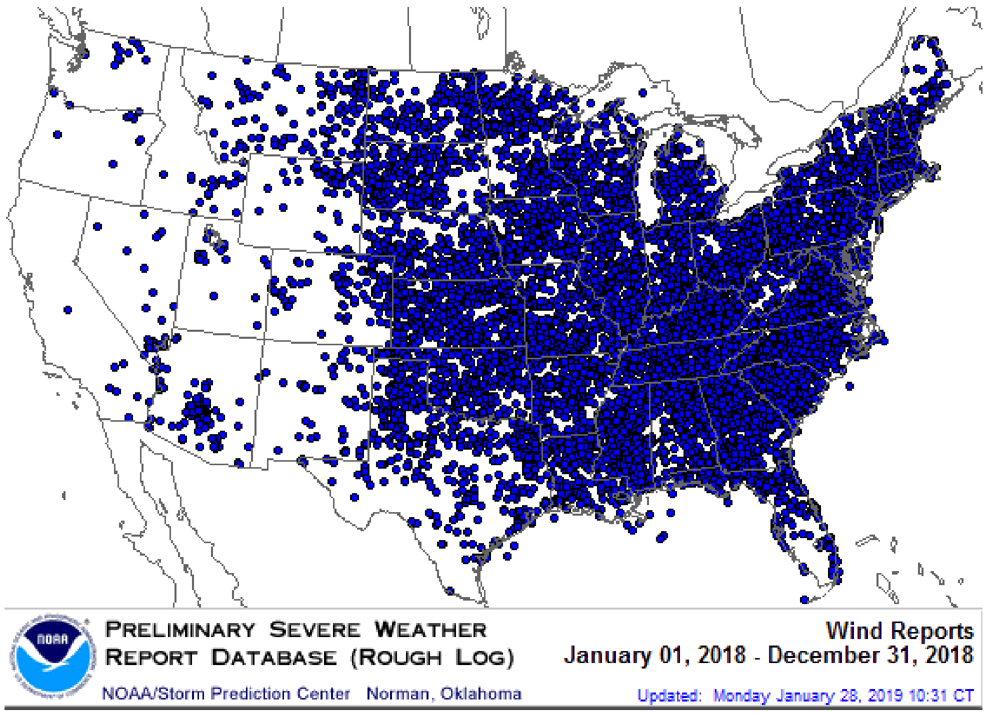

Figure 3. Wind Damage Reports Occurring in 2018. Excludes damage from tropical cyclones. Source: NOAA/Storm Prediction Center

[14] Benev, J., Ber, R., and Hagan, A. (2019). Tropical Cyclone Report: Hurricane Michael. National Oceanographic and Atmospheric Administration, National Hurricane Center.
[15] American Soceity of Civil Engineers (ASCE). (2016). Minimum design loads for buildings and other structures (ASCE/SEI 7-16), ASCE Standard ASCE/SEI 7-16, American Society of Civil Engineers, Reston, VA.
[16] National Oceanographic and Atmospheric Administration, Storm Prediction Center. (2018). Annual Severe Weather Report Summary. http://www.spc.noaa.gov/climo/online/monthly/2018_annual_summary.html#
[17] National Oceanographic and Atmospheric Administration, National Weather Service. (2017). Summary of Natural Hazard Statistics for 2016 in the United States. Retrieved from http://www.nws.noaa.gov/om/hazstats/sum16.pdf

Billion-dollar weather disasters are on the rise in the U.S. with severe weather and hurricanes comprising the majority of the increasing trend in economic losses from 1980-2017 (Figure 4). In addition to thousands of smaller windstorms over the course of the two-year period from 2017 to 2018, there were 16 severe storm events and five tropical cyclone events (Hurricanes Harvey, Irma, Maria, Florence, and Michael) with losses exceeding $1 billion (CPI-adjusted) each across the United States. Figure 5 shows the states impacted by these billion-plus dollar disasters.

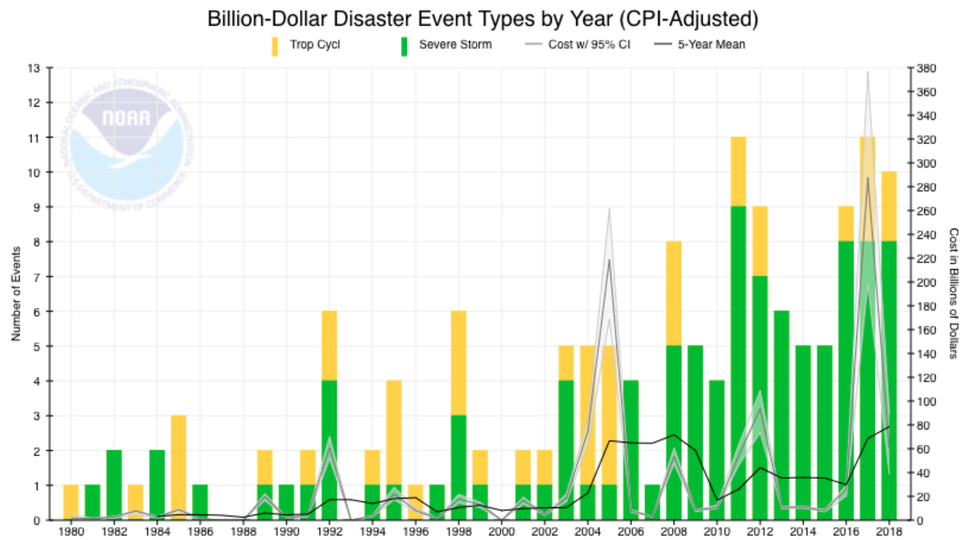

Figure 4. Number of tropical cyclone (yellow) and severe storm (green) events from 1980-2017 exceeding one billion USD. The annual cost is in gray and its 5-year running mean in black. Source: NOAA.

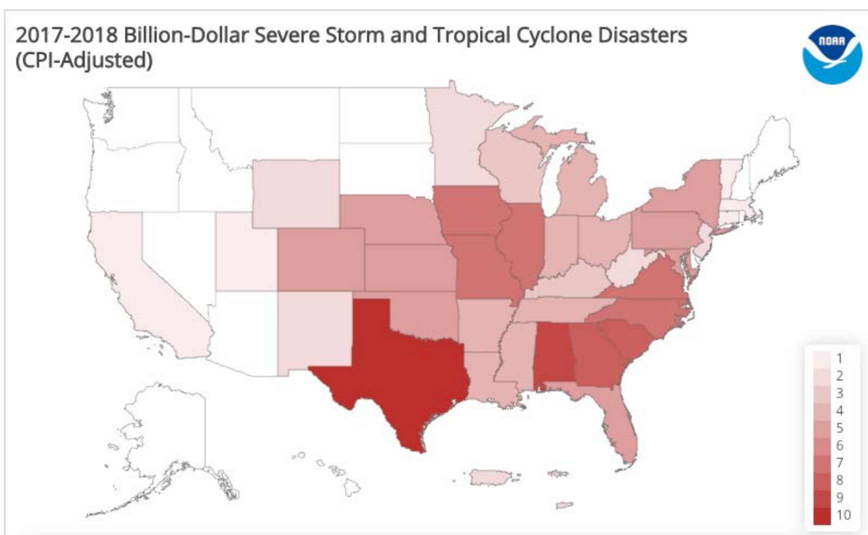

Figure 5. Severe Storm and Tropical Cyclone Disasters, by State, in 2017- (CPI adjusted). Note: the map reflects a summation of billion-dollar events for each state affected (i.e., it does not mean that each state shown suffered at least $1 billion in losses for each event. For example, two states could have each suffered a $500 million loss and it would still be counted as a billion-dollar event for each state). Source: NOAA.[18]

[18] National Oceanographic and Atmospheric Administration, National Centers for Environmental Information. (2018). U.S. Billion-Dollar Weather and Climate Disasters. Retrieved from https://www.ncdc.noaa.gov/billions/

3. Program Leadership, Management and Coordination

3.1. Interagency Coordinating Committee

NIST supports and organizes meetings of the NWIRP Interagency Coordinating Committee (ICC), which oversees the planning and coordination of the Program. The ICC consists of the heads or designees of FEMA, NOAA, NSF, Office of Science and Technology Policy (OSTP), and the Office of Management and Budget (OMB), and is chaired by the NIST Director or designee.[19] The ICC is charged with coordinating implementation of the Strategic Plan, developing annual coordinated budgets, and reporting to Congress on NWIRP Progress.[20] During this reporting period, the ICC approved the release of the Strategic Plan.

3.2. Windstorm Working Group

NIST leads a working group of federal employees, the Windstorm Working Group (WWG),[21] which met regularly throughout fiscal years 2017-18 to finalize the NWIRP Strategic Plan and coordinate Program research and activities as described in this report. The WWG also developed the Biennial Report to Congress for fiscal years 2015-16. Membership in the WWG consists of representatives from the NWIRP Program agencies, 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.[22]

3.3. Strategic Plan

NIST led the development of the NWIRP Strategic Plan (or Plan). NIST received significant input from the Program agencies and the WWG following review and assessment of national research needs and planning documents. NIST also incorporated input from the stakeholder community, through the NWIRP Strategic Planning Stakeholder Workshop held in June of 2016. Additionally, 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.[23] The National Advisory Committee for Windstorm Impact Reduction (NACWIR) provided valuable insight and recommendations. The NWIRP agencies considered all the public comments and NACWIR recommendations in developing the final version of the Plan, and it was released in August of 2018.[24]

The Plan establishes three overarching, long-term Strategic Goals: 1) Improve the understanding of windstorm processes and hazards; 2) Improve the understanding of windstorm impacts on communities; and 3) Improve the windstorm resilience of communities nationwide. There are 14 objectives underpinning the goals, broadly outlining the range of activities needed to achieve major reductions in the

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[19] 42 U.S.C. §15703(e)(2).
[20] 42 U.S.C. §15703(e).
[21] 42 U.S.C. §15703(a-c).
[22] Agency representatives serving on the WWG during the reporting period are listed at the front of this report.
[23] National Windstorm Impact Reduction Program Interagency Coordinating Committee. (2017). Strategic Plan for the National Windstorm Impact Reduction Program – Draft for Public Comment. Retrived from https://www.nist.gov/system/files/documents/2017/03/13/strategic_plan_for_national_windstorm_impact_reduction_program_-_draft_f.pdf
[24] National Windstorm Impact Reduction Program Interagency Coordinating Committee. (2018). Strategic Plan for National Windstorm Impact Reduction Program – Final Version. Retrived from https://www.nist.gov/el/materials-and-structural-systems-division-73100/national-windstorm-impact-reduction-program-0

losses of life and property from windstorms. . 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.

The Plan also identifies eight priority focus areas for new and enhanced efforts. These Strategic Priorities, 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: Improve Windstorm Resistance of Existing Buildings and Other Structures
- SP-6: Enhance Outreach and Partnerships to Improve Windstorm Preparedness and Hazard Mitigation
- SP-7: Enhance and Promote Effective Storm Sheltering Strategies
- SP-8: Develop the Nation's Human Resource Base in Windstorm Hazard Mitigation Fields

The Plan includes a mapping of each Program Agency's statutory responsibilities[25] to the Strategic Plan's goals, objectives, and Strategic Priorities, reproduced in this report as Appendix B. The diagram below shows how the elements of the Strategic Plan all work together to reduce loss of life and property from windstorms:

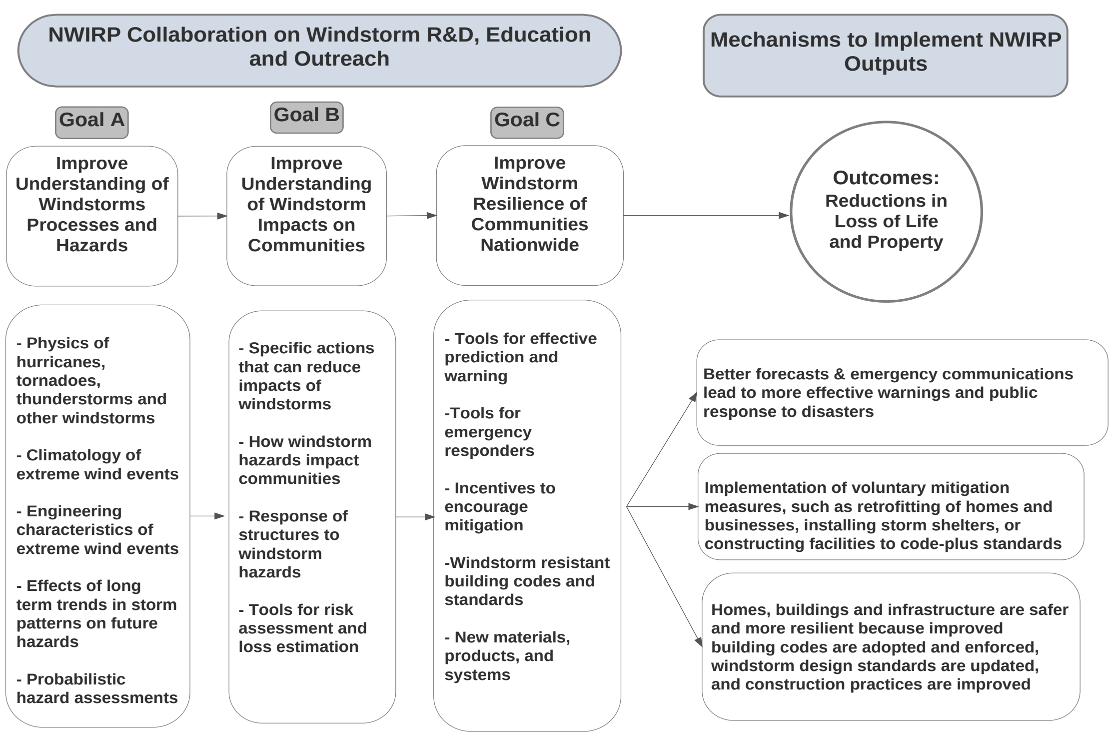

Figure 6: NWIRP Activities in Support of Goals, and Intended Outcomes

[25] 42 U.S.C. § 15703(b).

The goals, objectives, Strategic Priorities, and implementation strategies of the Plan 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 the level of resources that are available to Program agencies.

3.4. 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 fiscal year 2018 Coordinated Budget submitted to Congress is provided in Appendix C.

3.5. National Advisory Committee on Windstorm Impact Reduction

The National Windstorm Impact Reduction Act Reauthorization of 2015 (Public Law 114-52) called for the creation of the National Advisory Committee for Windstorm Impact Reduction (NACWIR or Committee).[26] It was charged with offering assessments and recommendations on the programmatic components of NWIRP, including the development of the NWIRP Strategic Plan.[27] In accord with NWIRP's authorizing statute, the Committee was composed of representatives of research and academic institutions, industry standards development organizations, emergency management agencies, state and local government, and business communities, including the insurance industry who were qualified to provide advice on windstorm impact reduction and represent related scientific, architectural, and engineering disciplines.[28] Consistent with the statutory requirements, none of the members were employees of the Federal Government.[29]

NIST organized six meetings of the NACWIR and the Committee completed their report within the statutorily required timeframe in fiscal year 2017.[30] They determined that the core agencies are making progress on key projects and programs that align with their missions and the NWIRP goals articulated in what was then the draft Strategic Plan.[31] They noted, however, that lack of resources and associated prioritization of the Program within the agencies is impeding the ability of the Program's goal "to achieve major measurable reductions in the losses of life and property from windstorms."[32] Despite limited funding, the Committee observed that the WWG was effectively coordinating activities at the staff level.

The Committee reviewed the Strategic Plan and submitted a report with their recommendations to the NIST Director. The Committee's report offered a number of recommendations which were incorporated into the Strategic Plan.

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[26] 42 U.S.C. § 15704.
[27] 42 U.S.C. § 15704(b). 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] 42 U.S.C. § 15704(a).
[29] *Ibid.*
[30] 42 USC § 15704(f).
[31] National Advisory Committee on Windstorm Impact Reduction. (2017). Assessments of and Recommendations for the National Windstorm Impact Reduction Program and its Implementation. Retrived from https://www.nist.gov/el/materials-and-structural-systems-division-73100/national-windstorm-impact-reduction-program-1
[32] *Ibid.* p. iii.

3.6. NIST Lead Agency Management and Coordination Activities

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.[33] NIST may also request assistance from other federal agencies to assist in carrying out the Program.[34] In fiscal years 2017-18, NIST sought additional assistance from NASA for their expertise in satellite imagery, and from HUD for their knowledge of manufactured housing and assessments of how such housing performed in recent wind events.

Three additional statutory Lead Agency responsibilities are to: 1) support the development of performance-based engineering tools;[35] 2) coordinate all federal post-windstorm investigations to the extent practicable;[36] and 3) issue recommendations to inform development of model building codes.[37] NIST activities supporting these responsibilities during fiscal years 2017-18 are described in the following sections. Statutory responsibilities for all Program agencies are listed in Appendix B.

3.6.1 Support for Performance-Based Engineering

Performance-based engineering uses specific performance metrics to drive the assessment, design, and construction of engineered facilities, as opposed to more traditional, prescriptive procedures. In furtherance of the statutory responsibilities, both NIST and FEMA worked with the American Society of Civil Engineers (ASCE) Ad Hoc Committee on Performance-based Design (PBD) for Wind Hazards. This effort focused on developing the overall framework and pre-standard provisions of PBD for all windstorms, including tornadoes. In addition, NIST identified research needed to develop an immediate occupancy building performance objective following natural hazard events (including windstorms).

3.6.2. Coordination of Federal Post-Windstorm Investigations

Consistent with its statutory responsibilities, NIST coordinates all federal post-windstorm investigations to the extent practicable.[38] In fiscal years 2017-18, NIST conducted post-windstorm coordination activities for several landfalling hurricanes, including Harvey, Irma, Maria, Nate and Florence. In addition to participation in pre- and post-landfall coordination calls led by other agencies, including NOAA, USGS, and FEMA, NIST conducted WWG coordination calls on an as-needed basis to address needs identified during other calls. For example, as multiple agencies were considering assessing the performance of manufactured housing following Hurricanes Harvey and Irma, coordination calls were conducted between NIST, FEMA, and HUD. Data collection plans were discussed prior to field deployments to help avoid gaps and overlaps, and results were shared following the fieldwork conducted by the three agencies.

Immediately following the landfall of Hurricane Harvey in August 2017, NIST collaborated with Applied Research Associates, Inc. (ARA) to develop maps showing the maximum estimated windspeed of the storm as it moved across Texas. For Hurricanes Irma, Maria, Nate, and Florence, NIST was mission assigned by FEMA to develop estimated windfields for input to their Hazus Hurricane Model, which is

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[33] 42 U.S.C. § 15703(b)(1)(A).
[34] 42 U.S.C. § 15703(b)(1)(C).
[35] 42 U.S.C. § 15703(b)(1)(B). Performance-based engineering uses specific performance metrics to drive the assessment, design, and construction of engineered facilities, as opposed to more traditional, prescriptive procedures.
[36] 42 U.S.C. § 15703(b)(1)(D).
[37] 42 U.S.C. § 15703(b)(1)(E).
[38] 42 U.S.C. § 15703(b)(1)(D).

used to estimate storm impacts. Initial windfield estimates were typically produced within one day following hurricane landfall, with improved versions published by day 3 and day 7, as more observation data from meteorological stations was obtained, processed, and analyzed. An example of one such windfield analysis is shown in Figure 7 for Hurricane Irma's landfall on the continental U.S. NIST leveraged these wind analyses to produce additional hurricane windfield products in support of post-storm data collection and analysis (as described in Section 4, Objective 8).

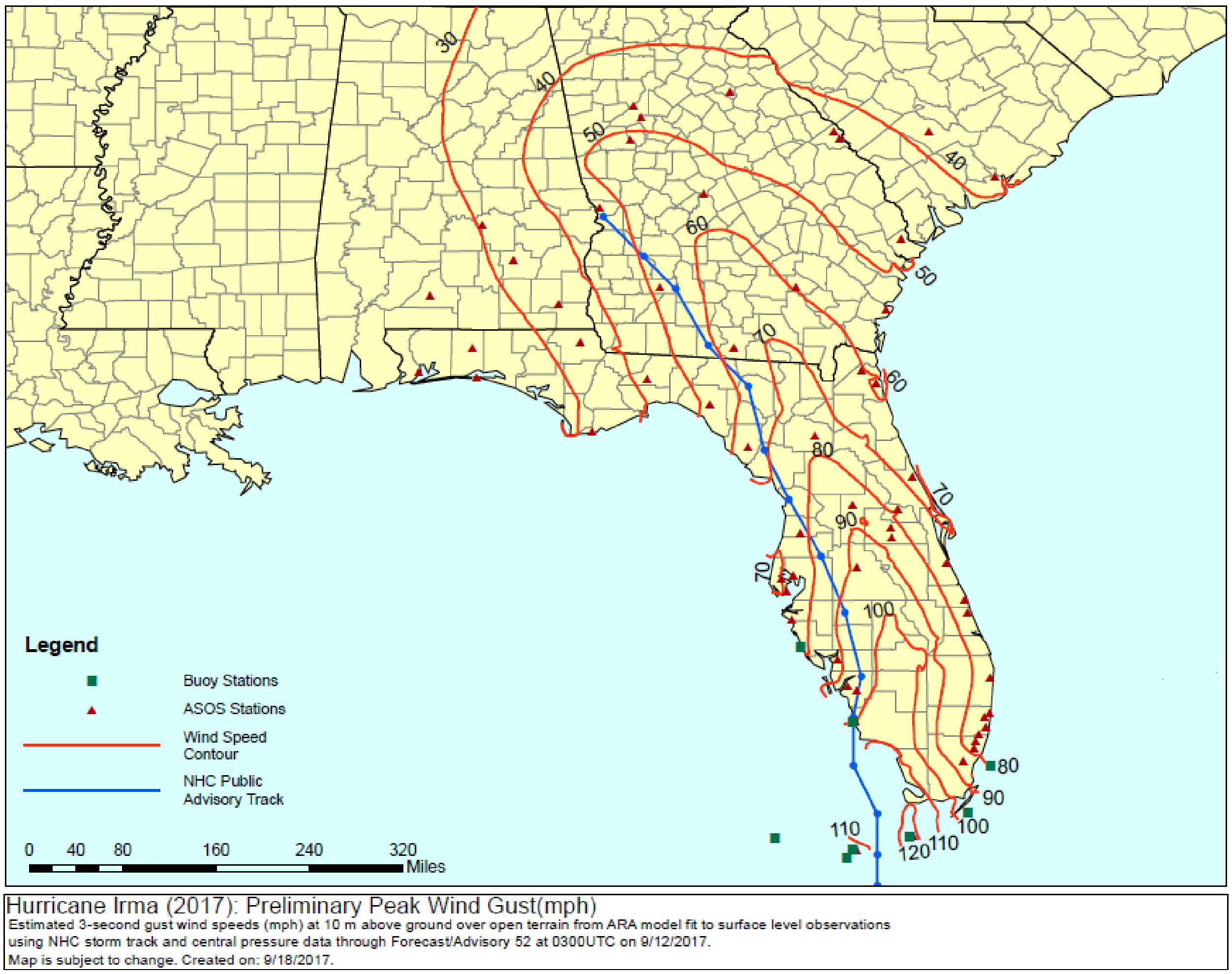

Figure 7. Wind Swath from Hurricane Irma over the Continental U.S. Produced by Applied Research Associates, Inc.

3.6.3 Recommendations for Model Codes

NIST issues recommendations to inform the development of model codes and keeps Congress apprised of such recommendations. NIST and FEMA have translated findings from research and investigations of recent storms into recommendations for improved codes and standards. Recent Program successes in making changes to national standards and model building codes are summarized in Section 5.2.

4. Progress in Fiscal Years 2017 and 2018

Progress made during fiscal years 2017-18 on windstorm impact reduction is summarized in this section. Activities supporting the eight Strategic Priorities identified in the NWIRP Strategic Plan[39] are presented in Section 4.1, and progress towards achieving the three broader Goals and associated 14 Objectives is described in Section 4.2.

4.1. Strategic Priorities

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

NIST: During fiscal year 2018, as part of NIST's Hurricane Maria Program (see Objective 5), work began on a new project to complete a quantitative assessment that attributes morbidity and mortality to building and infrastructure failures in Puerto Rico. The study results will provide guidance to improve building codes and standards, and inform future approaches to accurately attribute and predict life loss due to windstorm-caused building failures.

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

NOAA/NSF: Verification of the Origins of Rotation in Tornadoes Experiment. In fiscal years 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 other federal agencies, as well as forecasters from the National Weather Service (NWS) (including the Storm Prediction Center (SPC)), Environment Canada, the Australian Bureau of Meteorology, and the Finnish Meteorological Institute. 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. VORTEX-South East (SE) has continued to support a number of physical and social science research projects led by various university and government research organizations through fiscal year 2018, including several successful field observation programs in the Southeast United States. Researchers are beginning to share results from their initial projects, and are working to establish strong collaboration across the research and operational sectors to ensure results are integrated throughout the broader community.

NSF: **In-situ and Remote-Sensing Measurements of Storm-Scale and Low-Level Tornado and Hurricane Winds.** In fiscal year 2018, NSF funded a field campaign "Targeted Observation by Radars and UAS of Supercells (TORUS)" NSF-1824649, 1824609, 1824713, 1824811, awarded to University of Nebraska-Lincoln, Texas Tech University, University of Colorado-Boulder, and University of Oklahoma. TORUS is a successor to the VORTEX2 field campaigns in that some of

[39] National Windstorm Impact Reduction Program Interagency Coordinating Committee. (2018). Strategic Plan for National Windstorm Impact Reduction Program. Retrived from https://www.nist.gov/el/materials-and-structural-systems-division-73100/national-windstorm-impact-reduction-program-0

the main lessons learned from VORTEX2 and subsequent analysis will be put to the test in the TORUS campaign. Specifically, the researchers will make heavy use of Unmanned Aerial Systems (UAS) in addition to surface and mobile radar observations to answer questions about the thermodynamics of the very near-supercell environment, which has implication for tornadogenesis. This will be a two-year campaign in 2019 and 2020.

In the two consecutive active hurricane seasons of 2017 and 2018, NSF issued Dear Colleague Letters to solicit research responding to urgent national needs, which will be discussed more in SP-3 below. In fiscal years 2017-18, NSF funded a significant number of Rapid Response awards as a result of the devastating hurricane seasons, including deploying mobile radars, and collecting and analyzing data for Hurricanes Harvey and Irma. An early result of those investments has been the confirmation of the role of small, tornado-scale features in the hurricane wind field that can lead to damaging gusts. The Rapid Response Research (RAPID) awards for Hurricane Florence and Michael are works in progress.

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 which increase understanding of weather-related high impact events. NSF's federally funded research and development center, NCAR, has played a crucial role collaborating with the U.S. research community, especially academic researchers in large-scale field campaigns, to gather critical observations. NCAR has several roles. First, they help deploy research facilities, such as aircraft, radar, and lidar, into the field. Second, they serve as a central repository for all collected data for the research community. Third, they provide large-scale, high performance computers and develop community models to assist the U.S. atmospheric research community. Examples of NCAR-supported projects include VORTEX-SE and its predecessors, TORUS, and a number of field campaigns (see Strategic Priority 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), is a collaborative effort between 12 universities led by Colorado State University. It conducts extensive field studies in collaboration with NIST to collect data on resilience and recovery from disasters for validation of community disaster resilience models. During fiscal years 2017-18, the Center collected multi-disciplinary longitudinal data in Lumberton, North Carolina, on the continuing impacts of, and recovery from, Hurricane Matthew in 2016.

NSF: Rapid Response Research Facility. The NSF-supported Natural Hazards Engineering Research Infrastructure (NHERI) post-disaster, rapid response research (RAPID) facility, is a five-year project, initially funded in September 2016. The scientific goal of the project is to support natural hazard researchers to conduct next generation RAPID research. Researchers accomplish this goal by acquiring and sharing high-quality, post-disaster data sets that will enable characterization of civil infrastructure performance under natural hazard loads (including windstorms); evaluating the effectiveness of current and previous design methodologies; calibrating computational models used to predict civil infrastructure component and system responses to natural hazards, and developing 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 has been developing tools to support data collection and analysis (see Objective 8). Collected data will be archived by the NHERI Cyberinfrastructure facility (see Objective 5). As of the end of fiscal year 2018, this research facility has completed the two-year development and equipment acquisition phase and is now operational for field deployment through August 2021.

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 are creating design frameworks for satisfying performance requirements that go beyond prescriptive building code provisions. Principles of PBD have been adopted in earthquake engineering, and NSF-funded projects are extending this to wind engineering. An NSF award to Texas Tech University is formulating computational models for characterizing rotating tornado wind loading and impact on low-rise buildings. These models can be used to conduct performance-based evaluations of low-rise buildings to reduce damage and fatalities.

NIST: Performance-based Design for Wind. During fiscal years 2017-18, NIST began development of PBD for tornadoes, including new tornado hazard maps (see Objective 4). Both NIST and FEMA worked with the American Society of Civil Engineers (ASCE) Ad Hoc Committee on PBD for Wind Hazards. This effort focused on developing the overall framework and pre-standard provisions for PBD for all windstorms, including tornadoes. NWIRP adapted some elements of PBD for earthquakes, developed through efforts of the National Earthquake Hazards Reduction Program (NEHRP).[40] During fiscal year 2018, the Ad-Hoc Committee was replaced by a PBD Task Committee within the new ASCE 7 Wind Load Subcommittee, charged with developing Wind PBD provisions and commentary for the 2022 edition of the ASCE 7 standard.[41] NIST and FEMA continue to participate in this new Task Committee.

SP-5: Improve Windstorm Resistance of Existing Buildings and Other Structures

FEMA: Recommendations for improving windstorm resistance of existing buildings are discussed in several of the Recovery Advisories published after Mitigation Assessment Teams assessed building performance after Hurricanes Harvey, Irma, and Maria in Texas, Florida, Puerto Rico, and the U.S. Virgin Islands.[42] Some examples of the Recovery Advisories that provide this information are:

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[40] National Institute of Standards and Technology, National Earthquake Hazards Reduction Program. Performance-Based Design. Retrived from https://www.nehrp.gov/library/guidance_pbsd.htm

[41] American Society of Civil Engineers. ASCE 7 and SEI Standards. ASCE 7 2-22 Deveopment Cycle. Retrived from: https://www.asce.org/structural-engineering/asce-7-and-sei-standards/

[42] U.S. Department of Homeland Security, Federal Emergency Management Agency. Recovery Advisories. https://www.fema.gov/media-library/resources-documents/collections/24

- FL – RA 3 – Mitigation Triggers for Roof Repair and Replacement in the 6th Edition (2017) Florida Building Code
- USVI – RA 2 – Attachment of Rooftop Equipment in High-Wind Regions
- USVI – RA 3 – Installation of Residential Corrugated Metal Roof Systems
- USVI – RA 4 – Design Installation and Retrofit of Doors Windows and Shutters
- USVI – RA 5 – Rooftop Solar Panel Attachment: Design, Installation, & Maintenance
- PR – RA 1 – Rooftop Equipment Maintenance and Attachment in High-Wind Regions
- PR – RA 5 – Protecting Windows and Openings in Buildings
- PR – RA 6 – Repair and Replacement of Wood Residential Roof Covering Systems

SP-6: Enhance Outreach and Partnerships to Improve Windstorm Preparedness and Hazard Mitigation

NOAA: Weather-Ready Nation. The purpose of NOAA's Weather Ready Nation (WRN) initiative is to save lives and protect 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. The NWS is leveraging its vast nationwide network of partners and incorporating new ones including: other U.S. government agencies and emergency managers, researchers, the media, insurance industry, non-profits, the private sector, the weather enterprise, and more. During fiscal years 2017-18, the WRN program initiated: a new project for simplifying the way hazards are communicated (hazards simplification); a new NOAA water model for better predictions of streamflow at neighborhood scales of resolution for protecting life and property from localized flooding; constant social media engagement using infographics highlighting wind hazards and mitigation actions; and engagement with over 8,500 organizations recognized by NOAA as "Weather-Ready Nation Ambassadors." These are organizations that act as force multipliers sharing preparedness information with others.[43] Further description of the functions of WRN Ambassadors can be found at: https://www.weather.gov/wrn/ambassadors. Additional information about WRN, publications, initiatives, and news and events can be found at: https://www.weather.gov/wrn/.

FLASH/NOAA: #HurricaneStrong. *#HurricaneStrong* is a national resilience initiative led by the Federal Alliance for Safe Homes (FLASH)® to save lives and homes by collaborating with leading organizations in the disaster safety movement.[44] It was launched during the 2016 hurricane season. The collaboration with NOAA and the National Hurricane Center (NHC) provides 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". During fiscal years 2017-18 *#HurricaneStrong* has had an online readership of 804 million hits, adding an additional 68 pieces of coverage, 17,000 Tweets, 7,000 unique contributors on Twitter, and an estimated audience reach exceeding 24 million.

IBHS: FORTIFIED Home™ Program. The Insurance Institute for Business & Home Safety's (IBHS) FORTIFIED Home™ program provides a uniform, voluntary, superior set of science-based standards to help improve a home's resilience by adding system-specific upgrades beyond code

[43] Further descriptions of the functions of WRN Ambassadors can be found at: https://www.weather.gov/wrn/ambassadors. Additional information about WRN, publications, initiatives, news and events can be found at: https://www.weather.gov/wrn/.
[44] For more information, visit www.hurricanestrong.org.

requirements. The 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.[45] During fiscal years 2017-18, IBHS authored a post-disaster study of the coastal wind damage caused by Hurricane Harvey.[46] The study unveiled new guidance for consumers with homes exposed to hurricane wind, and also offered new quantitative data to inform architects and building designers, insurers and catastrophe modelers. This report will be useful in guiding home repairs, roofing and construction considerations in wind-prone and wind-damaged areas.

IBHS also has a FORTIFIED Commercial program. During fiscal years 2017-18, IBHS Commercial developed hurricane standards which help building owners improve their commercial structure's ability to resist damage from hurricanes and tropical storms.[47] These standards employ an incremental approach toward making new and existing commercial buildings more resistant to damage from severe weather. Similar to the IBHS FORTIFIED Home program, builders can work with owners to choose a desired level of protection that best suits their budgets and resilience goals. IBHS Commercial also developed High Wind and Hail Standards.[48] These standards help building owners improve their commercial structure's ability to resist damage from thunderstorms, winds at the edges of tornadoes, and hail events. The recommendations can be incorporated either during new construction or retrofitting existing buildings.

SP-7: Enhance and Promote Effective Storm Sheltering Strategies

NIST/FEMA: Storm Shelter Standard. NIST and FEMA staff serve on the Consensus Committee on Storm Shelters, which is chaired by a NIST staff member. NIST and FEMA are participating in the consensus update process for the third edition of the ICC 500, *Standard for the Design and Construction of Storm Shelters*, and commentary. The Consensus Committee on Storm Shelters, which is writing this new edition, began meeting late in fiscal year 2018.

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 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*). FEMA also monitors a Safe Room Helpline to answer questions about their safe room guidance from people such as home and

[45] U.S. Department of Homeland Security, Federal Emergency Management Agency. (December 2010). Wind Retrofit Guide for Residential Buildings, FEMA P-804. Retrived from https://www.fema.gov/media-library/assets/documents/21082
[46] Insurance Institute for Business & Home Safety. (July 2018). Hurricane Harvey Wind Damage Investigation. Retrived from https://disastersafety.org/hurricane/hurricane-harvey/
[47] Insurance Institute for Business & Home Safety. (2017). FORTIFIED Commercial Hurricane Standards. Retrived from http://fortifiedhome.org/wp-content/uploads/2019/08/FORTIFIED-Commercial-Factsheet.pdf
[48] Insurance Institute for Business & Home Safety. (2017). FORTIFIED Commercial High Wind & Hail Standards. Retrived from https://fortifiedhome.org/commercial/high-wind-hail/

building owners, building officials, builders, engineers, and architects. During fiscal years 2017-18, FEMA continued developing and publishing technical guidance materials. Examples include:

- Numerous Recovery Advisories[49] supporting safe room design and construction, including:
  - TX – RA 2 – Asphalt Shingle Roofing for High-Wind Regions
  - FL – RA 2 – Soffit Installation in Florida
  - FL – RA 3 – Mitigation Triggers for Roof Repair and Replacement in the 6th Edition (2017) Florida Building Code
  - USVI – RA 2 – Attachment of Rooftop Equipment in High-Wind Regions
  - USVI – RA 3 – Installation of Residential Corrugated Metal Roof Systems
  - USVI – RA 4 – Design, Installation and Retrofit of Doors, Windows, and Shutters
  - USVI – RA 5 – Rooftop Solar Panel Attachment: Design, Installation, & Maintenance
  - PR – RA 1 – Rooftop Equipment Maintenance and Attachment in High-Wind Regions
  - PR – RA 3 – Safe Rooms and Storm Shelters for Life-Safety Protection from Hurricanes
  - PR – RA 5 – Protecting Windows and Openings in Buildings
  - PR – RA 6 – Repair and Replacement of Wood Residential Roof Covering Systems
- Fact Sheets supporting safe room design, construction and maintenance, including:
  - Community Tornado Safe Room Doors: Installation and Maintenance
  - Residential Tornado Safe Room Doors (update)

SP-8: Develop the Nation's Human Resource Base in Windstorm Hazard Mitigation Fields

NSF: Research Awards. During the reporting period, NSF awards supporting NWIRP typically provided research funding for academic faculty, as well as graduate and undergraduate students. These awards provided an invaluable learning experience for graduate and undergraduate students. Some NSF awards supported post-doctoral early career researchers as well.

NSF: Research Experiences for Undergraduates (REU). The REU program[50] supports active research participation by undergraduate students in any of the areas of research funded by the NSF. During the reporting period, REU projects involved 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 operated by the NSF Natural Hazards Engineering Research Infrastructure (NHERI) Network Coordination Office.[51] This REU is a 10-week summer research program and annually brings about 30 students together with faculty to conduct research on topics such as: multi-hazard engineering, cyberinfrastructure, data management and site simulations. The research is conducted through projects and direct interactions with researchers working at the leading edge of understanding the impacts of windstorms on civil infrastructure. This REU site successfully attracts a diverse group of

[49] U.S. Department of Homeland Security, Federal Emergency Management Agency. Recovery Advisories. https://www.fema.gov/it/media-library/collections/24
[50] National Science Foundation. Research Experiences for Undergraduates. https://www.nsf.gov/crssprgm/reu/
[51] National Science Foundation, DesignSafe-CI, NHERI. Network Coordination Office. https://www.designsafe-ci.org/facilities/nco/organization/

students to participate in the program and to increase their interest in conducting research in the field of windstorm impact reduction.

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 NHC developed new tools to improve communication and public understanding of storm surge, including a new NWS Storm Surge Watch and Warning that highlights areas at greatest risk for life-threatening storm surge inundation ahead of landfalling tropical storm and hurricanes. These watches and warnings debuted in the United States during the destructive 2017 hurricane season and there were no known storm surge fatalities in the United States despite the landfall of 3 major hurricanes in 2017. These watches and warnings were also issued before hurricanes Florence and Michael during the 2018 hurricanes season. In addition, NHC continues to partner with FEMA to educate emergency managers about the hazards of storm surge. The NHC also provides extensive storm surge outreach material on their website, including a series of YouTube videos that help explain the dangers of storm surge.[52] The NOAA Hurricane Awareness Tour was conducted in 2017 and 2018 to bring awareness to coastal and inland communities about the hazards of hurricanes. The tours included U.S. Air Force Reserve and NOAA Hurricane Hunter Aircraft that conducted “stops" in various locations along the East and Gulf Coast of the United States. The tours were held during National Hurricane Preparedness Week to discuss hurricane preparedness and mitigation. The 2017 East Coast Awareness Tour made stops in Islip, New York, Washington, D.C., Raleigh, North Carolina, Orlando, Florida, and Miami, Florida. The 2018 Gulf Coast Tour made stops in Brownsville, Texas, Beaumont, Texas, Baton Rouge, Louisana, Birmingham, Alabama, and Lakeland, Florida. More than 100 media interviews were conducted on each tour and thousands of school children and the public toured the aircraft. Partners such as the Federal Alliance for Safe Homes (FLASH) also participated and discussed the latest in home and business mitigation.

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 FEMA’s media library website, the Google Books website, and MADCAD (http://www.madcad.com/). Following the 2017 hurricane season, FEMA continued to partner with communities and community organizations to teach design professionals and local officials the concepts of mitigation and safe room design. Many of these presentations and trainings were focused on hurricane wind mitigation in areas that are currently rebuilding. FEMA also provides in-person and online training based out of the Emergency Management Institute (EMI) in Emmitsburg, Maryland. FEMA is currently developing two new advanced wind-related modules for in-person training courses at EMI.

FEMA has maintained its partnership with external organizations such the Federal Alliance for Safe Homes (FLASH), NOAA, and the Hurricane Hunters which hosted the Hurricane Awareness Tour that FEMA participated in. The tour went to five different coastal towns from Texas to Florida and provided school children with demonstrations, tours of the aircraft, and information about hurricanes. FEMA provided safety and preparedness guidance geared towards children and reached

[52] National Oceanic and Atmospheric Administration, National Hurricane Center. Storm Surge Resources. https://www.nhc.noaa.gov/surge/resources.php

approximately 500 children per stop. Flash drives with all FEMA Building Science publications were available for teachers and parents that attended.

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. 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). More than five hands-on training courses[53] have been developed and provided to students and practitioners during previous reporting periods.

4.2. Objectives

As described in Section 3.3, three overarching, long-term Strategic Goals were established to accomplish the NWIRP mission, consistent with identified needs and the statutory requirements of the program. Within each goal, the NWIRP identified specific objectives. NWIRP Agency activities toward accomplishing those objectives during fiscal years 2017-18 are described here:

GOAL A. IMPROVE THE UNDERSTANDING OF WINDSTORM PROCESSES AND HAZARDS

Objective 1: Advance understanding of windstorms and associated hazards

NSF: Prediction of and Resilience against Extreme Events (PREEVENTS). In fiscal years 2017-18 the Directorate for Geosciences at NSF hosted a program[54] specific to natural hazards and extreme events. PREEVENTS included both a direct solicitation and an internal co-funding component. Windstorms were heavily represented, with a number of tornado and hurricane-related research projects funded. PREEVENTS will continue through fiscal year 2020.

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 fiscal years 2017-18, NSF funded studies on the fundamental aspects of hurricane intensification, laboratory observations of how extreme wind speed affects air-sea interaction in hurricanes, and the implication of gravity wave propagation from tropical cyclones.

NSF: Understanding of physical processes for the formation and maintenance of hurricanes and tornadoes using high-performance computer models. A number of funded research projects involved computer modeling of tornadoes and hurricanes. These studies typically compared simulated storms with actually observed storms and tried to deduce the physical mechanisms controlling the development of storms. One of the examples representing this type of research is an

[53] Argonne National Laboratory, Transportation Research and Analysis Computing Center. Computational Fluid Dynamics Training. https://www.tracc.anl.gov/index.php/computational-fluid-dynamics-training
[54] National Science Foundation. (2016). A closer Look at PREEVENTS: Prediction of and Resilience Against Extreme Events. Retrieved from https://www.nsf.gov/geo/ear/updates/oct2016/preevents-oct2016.jsp

award: “Understanding tornado development and maintenance in supercells with an emphasis on ‘high-end’ events”, NSF-1832327, 1832326, and 1832346, awarded to University of Wisconsin-Madison, Saint Louis University, and High Impact Weather Research & Consulting, LLC. This research is intended to improve our understanding of tornado formation and maintenance by simulating tornado-producing supercells at ultra-high temporal and spatial resolutions.

NIST: Tornado Climatology. In order to develop more accurate tornado hazard maps (Objective 4) and tornado loss estimation tools (Objective 9), NIST developed methodologies to quantify and correct for population bias (where more tornadoes are observed and reported in populated areas); developed a methodology for identifying regions of the U.S. having similar tornado climatology; and conducted analyses to provide better correlation between damage and wind speed, the relationship that provides the basis for tornado ratings in the Fujita (F) and Enhanced Fujita (EF) scales.

NIST: Topographic Effects on Wind Speeds. As part of its Hurricane Maria Program (see Objective 5), NIST initiated work to investigate the influence of topography on surface level wind speeds in Puerto Rico. During fiscal year 2018, NIST developed plans for wind tunnel testing and computational wind engineering analyses, to better understand the wind speed-up effects, and to determine if they are adequately represented by the topographic factors used in modern building codes and standards.

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

NSF: New Observational Tools and Techniques. In fiscal years 2017-18, NSF provided funding for two new observing technologies intended to assist researchers in studying fundamental aspects of windstorms. One of these tools was the development of a high-resolution radar for hurricane landfall and supercell thunderstorm studies, among others. NSF also invested in a new technique for retrieving thermodynamics within supercell thunderstorms using a constant pressure balloon. In this technique, two balloons carry a sensor package. When the balloons reach a relevant altitude and storm-relative location, one of the balloons is jettisoned and the other balloon follows the storm inflow and records crucial temperature and moisture data in areas that are unreachable by manned or unmanned aircraft.

NOAA: New Observing Technologies. New observing technologies are being tested and demonstrated as a part of NOAA’s 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 is demonstrating the capabilities of the Multifunction Phased Array Radar (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 of phased array radar (which has long been used to track aircraft) to perform as a weather radar. Research conducted at NSSL has shown 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 fiscal years 2017-18, engineering activities have primarily centered on the design and development of the Advanced Technology Demonstrator (ATD). The purpose of the ATD system is to gain knowledge and reduce the technical risks associated with the engineering and development of dual polarization phased array radar technology. The ATD is a full-scale demonstration radar that will be capable of assessing the ability of phased array technology to address the operational meteorological requirements of the NWS. Installation of the ATD began during this reporting period.[55]

NOAA/NIST/ASCE/AMS: 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. NIST staff 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 comprises representatives from academia and the private sector, and multiple units within NOAA and NIST, along with other federal agencies including FEMA, NRC, and NASA. During the current reporting period, the American Meteorological Society (AMS) was brought on as a co-developer of the standard. Draft provisions for each of the methods have been developed and are currently going through the internal standards committee approval process.

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

NOAA: Toward Seasonal Prediction and Long-term Severe Weather Variability. Since 2012 the NWS SPC has worked 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. In fiscal year 2018, the NSSL carried out research to measure how well observed values of important environmental variables for severe storms are represented in reanalysis estimates and has used those values to demonstrate an increase in the frequency of favorable conditions in the mid-South region of the United States over the last 40 years.

Objective 4: Develop tools to improve windstorm hazard assessment

NIST: Wind Speed Maps (nontornadic). NIST completed work during the current reporting period on development of new design wind speed maps intended for adoption in current U.S. building codes

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[55] National Oceanic and Atmospheric Administration, National Severe Storms Laboratory. Advanced Technology Demonstrator. https://www.nssl.noaa.gov/tools/radar/atd/

and standards (see also Objective 11). The project incorporated several technical advances over previous generations of maps.[56] In addition to using more years of data from more weather stations around the U.S., NIST made adjustments to account for terrain conditions at anemometer locations, peak gusts at each station were classified by storm type (thunderstorm, non-thunderstorm, and tropical) and analyzed separately, and a peaks-over-threshold technique was used 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.

NIST: Tornado Hazard Maps. Building on the advances from the NIST tornado climatology research (Objective 1), NIST continued developing 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. During fiscal years 2017-18 NIST developed an improved tornado database for the years 1950-2016, including cleansed and augmented data; developed and tested a method to account for under-reporting of true tornado occurrence rates for most parts of the U.S.; and developed an approach for explicit consideration of uncertainties in the models. NIST also started planning another stakeholder workshop to roll out draft tornado hazard maps for a range of intervals, to be held in fiscal year 2019.

GOAL B. IMPROVE THE UNDERSTANDING OF WINDSTORM IMPACTS ON COMMUNITIES

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

HUD: The U.S. Department of Housing and Urban Development (HUD) amended the Federal Manufactured Home Construction and Safety Standards (Standards) in July 1994 to improve the wind resistance of manufactured homes in the areas prone to hurricane-strength winds. In the aftermath of Hurricane Irma, a team was assembled to conduct a damage survey of manufactured homes produced after 1994. The team visited 23 communities inspecting a total of 78 manufactured homes. The majority of the homes displayed minimal wind damage and none of the manufactured homes displayed any visible foundation damage or shifts from the original positions. This observation can be attributed to the adequacy of the post 1994 Standards performance, prescriptive requirements, and the results of the quality control-focused environment that requires an acceptable level of workmanship to produce compliant manufactured homes. Despite these successes, it is important to note that manufactured homes in the subject area selected for inspection were located in HUD Wind Zone III and designed to resist a wind speed of 110 mph. Given that Hurricane Irma produced a maximum design wind speed of approximately 85 mph in that region, the manufactured homes inspected in Florida were not subjected to the design wind loads referred to in the HUD Standards.

NSF: Natural Hazards Engineering Research Infrastructure (NHERI). The scientific purposes for NHERI are to:

- Understand, model, and predict the lifecycle performance of civil infrastructure, from component to holistic system levels, under different natural hazard events;

[56] Pintar, A., Simiu, E., Lombardo, F., and Levitan, M. (2015). 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. *NIST Special Publication 500-301*, 54.

- 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 STEM workforce to conduct and translate research into an innovation ecosystem for multi-hazard resilient and sustainable civil infrastructure and communities.

The operations of the NSF-supported NHERI originally began with 11 awards made in fiscal years 2015-16 and has continued through the current FY 17-18 reporting period. Currently active NHERI awards include the Network Coordination Office (NCO), Cyberinfrastructure (CI), the Computational Modeling and Simulation Center (SimCenter), and eight earthquake and wind engineering experimental facilities (including a post-disaster RAPID facility).

Complementing the NHERI facilities, the CONVERGE project at the University of Colorado, Boulder, funded by NSF in fiscal year 2018, establishes and supports a new Extreme Events Reconnaissance Research Leadership Corps designed to connect engineering and social science researchers. These connections will help foster the development of best practice guidelines for post-disaster, reconnaissance research and public communications in the event of a major disaster.

The NSF-supported NHERI cyberinfrastructure award continues to host 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 U.S. or abroad.

NIST: Tornado Loads on Buildings. Under its Disaster Resilience Research Grants Program,[57] NIST funded a cooperative agreement with ARA titled *Development of Tornado Design Criteria for Buildings and Shelters Subject to Tornado Induced Loads*. The goal of this project is to develop improved wind loading criteria for structures to resist tornadoes. During fiscal year 2018, ARA worked with Western University's Wind Engineering, Energy and Environment (WindEEE) Dome to design and conduct a large series of experiments in their new hexagonal wind tunnel. These experiments collected exterior surface and internal pressure data on building models subject to tornado-like vortices.

NSF: RAPID Awards - Collection of Perishable Data Following Windstorms. The NSF has a standing funding mechanism, e.g., the post-disaster, rapid response research (RAPID) mechanism, to

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[57] National Institute of Standards and Technology. (2017). NIST Funds 12 Projects to Make Communities More Resilient to Disasters. Retrieved from https://www.nist.gov/news-events/news/2017/08/nist-funds-12-projects-make-communities-more-resilient-disasters

provide funding to researchers to collect perishable research data from the field after a significant windstorm or other hazard event. During fiscal years 2017-18, NSF made over 50 RAPID awards related to windstorms, such as: two awards, one related to Hurricane Irma and one related to Hurricane Matthew went to the University of Notre Dame; seven awards were in response to the effects of Hurricane Harvey; an award to Auburn University collected data on wind and surge induced residential building damage; one award to the University of Utah collected information on the trajectories of social vulnerability of the Houston area households through a study of pre- and post- events; and West Texas A&M University received an award to preserve 3D damage data for enhanced modeling of engineered steel structures on the Texas coast. This data can facilitate the analysis of steel for developing new fragility methods and provides a means to evaluate the effectiveness of wind design provisions along the U.S. coast.

NIST: Preliminary Reconnaissance Hurricane Deployments. T hrough collaboration between the Disaster and Failure Studies and NWIRP programs at NIST, research staff conducted preliminary reconnaissance missions to collect perishable data for three hurricanes in the fall of 2017. For Hurricane Harvey, reconnaissance teams were deployed to study 1) coastal wind and storm surge damage near landfall in Rockport, Texas, and 2) inland rainfall flooding impacts in the west Houston area. The coastal team co-deployed with FEMA's preliminary MAT. One NIST staff member continued on to participate in the full MAT for Hurricane Harvey (see FEMA entry below). NIST sent two teams to Florida for Hurricane Irma, one focused on wind and storm surge damage in the Florida Keys and the other concentrating on a broader range of storm impacts across South Florida, including damage and loss of functionality of critical facilities due to interruption of lifeline utilities. Two NIST teams also deployed to Puerto Rico following Hurricane Maria, one embedded with and part of the full FEMA MAT (see below), and the other gathering data emergency communications and storm impacts on buildings, infrastructure, and communities.

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 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 resistance 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 fiscal years 2017-18, FEMA deployed MATs for Hurricanes Harvey, Irma, and Maria in Texas, Florida, Puerto Rico and the U.S. Virgin Islands, and follow-on work related to previous MATs is ongoing. Subsequent MAT reports were published for each location that include findings from the MAT investigations along with conclusions and recommendations for preventing damage.

- FEMA P-2020, *Mitigation Assessment Team Report: Hurricanes Irma and Maria in Puerto Rico*.

- FEMA P-2021, *Mitigation Assessment Team Report: Hurricanes Irma and Maria in the U.S. Virgin Islands*.
- FEMA P-2022, *Mitigation Assessment Team Report: Hurricane Harvey in Texas*.
- FEMA P-2023, *Mitigation Assessment Team Report: Hurricane Irma in Florida*.

NIST: Hurricane Maria Program: In fiscal year 2018 NIST completed initial planning for a multi-year investigation of the impacts of Hurricane Maria on Puerto Rico, including projects focused on damage to critical facilities (schools, hospitals, and shelters) and the role of infrastructure in their support, e.g., delivering power and telecommunications services to a hospital. The findings will be part of a final report, which will include recommendations for changes to codes, standards and practices for the purpose of increasing community resilience in the face of hurricanes.

NSF: Infrastructure Resilience. The electric power infrastructure in the United States, especially in coastal areas, faces substantial risk from wind hazards. Through an NSF Faculty Early Career Development Program (CAREER) award,[58] researchers at Iowa State University are investigating the underlying design and assessment of transmission line systems to increase resiliency of electric power networks under windstorm effects. This research is investigating key attributes contributing to the resiliency of transmission systems within electric power networks and is developing risk-informed design methodology to increase this resiliency. Another NSF-supported project at the University of Chicago and the University of Wisconsin-Madison is increasing resilience and efficiency of electric power and computing infrastructures by understanding how to exploit and maximize emerging relationships between the two structures. Research on computing and power grids will lead to improved resilience and efficiency enabling better windstorm design of power and computing infrastructures.

FHWA: Full Scale Measurement of Structural Dynamic Properties. In an ongoing program to characterize the dynamic properties of bridge stay cables – which are critical to structural performance and aerodynamic stability – the analysis of data from full-scale, forced vibration tests on selected major structures continued during fiscal years 2017-18. Tests had been previously performed on the Zakim (Massachusetts), Emerson (Missouri), and Penobscot Narrows (Maine) bridges. During this reporting period, a technical report[59] on the Emerson study was published and a technical report[60] on the Zakim study finalized in preparation for publication. These reports document the behavior of large, ungrouted bridge cables and illustrate 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.

[58] National Science Foundation. Faculty Early Career Development Program (CAREER). https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503214

[59] Bosch, H.R. and Pagenkopf, J.R., U.S. Departmnet of Transportation, Federal Highway Administration. (2018). Dynamic Properties of Stay Cables on the Bill Emerson Bridge. Report No. FHWA-HRT-17-037.

[60] Bosch, H.R. and Pagenkopf, J.R., U.S. Departmnet of Transportation, Federal Highway Administration. Dynamic Properties of Stay Cables on the Leonard P. Zakim Bunker Hill Bridge. Report No. FHWA-HRT-xx-xxx. (Pending Publication).

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, wind tunnel tests were performed (during the previous reporting period) at NRCC on small-scale section models representative of "out-of-round" bridge stay cables. Static tests were performed in simulated wind conditions over a broad range of wind speeds to evaluate the influence of cable roundness on overall performance and aerodynamic stability. During the current reporting period, a comprehensive technical report[61] was finalized for publication. As noted in the report, the imperfect shape of high-density polyethylene pipe (HDPE) used on bridge stay cables can play an important role in the aerodynamic stability and performance of cables. To further investigate this area of wind and cable interaction, dynamic wind tunnel tests and numerical simulations were planned for and completed in the current reporting period and a comprehensive report[62] was prepared. The design of these tests required information regarding the roundness of typical HDPE used in bridge construction. To obtain this information, detailed field measurements had to be undertaken at select bridge sites and an automated robotic device was designed and fabricated for this purpose. A comprehensive report[63] on robot development and results of the full-scale cable test program (mentioned in the previous section) was finalized during this performance period. In addition, four technical papers documenting the results of this research on bridge stay cables were presented at and published in the proceedings of an international symposium.

Large Variable Message Signs can and have exhibited sensitivity to the effects of wind and truck gust loadings resulting in performance problems and structural failures. Wind tunnel testing in the FHWA Aerodynamics Laboratory and computational modeling in the Argonne National Laboratory are ongoing. Traffic signal standards and high light towers have also exhibited sensitivity to the effects of wind and structural failures have been observed. Research on this subject has been conducted under the National Cooperative Highway Research Program (NCHRP), and American Association of State Highway and Transportation Officials (AASHTO) standard specifications for these structures have been significantly updated. To evaluate and further build upon these improvements in design, analysis of measurements from wind tunnel testing in the FHWA Aerodynamics Laboratory has been resumed. During this reporting period, analysis of data from more than 100 section models of multi-sided, tapered cylinders (representative of components from highway support structures) has continued and a report is in preparation.

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) is to provide the natural hazards engineering research and education community with access to next generation

[61] Christiansen, H. and Larose, G.L. U.S. Departmnet of Transportation, Federal Highway Administration. (Pending Publication). Wind Tunnel Investigations of the Aerodynamics of Bridge Stay Cable Cross-Sectional Shapes. Report No. FHWA-HRT-xx-xxx.
[62] Larose, G.L., Stoyanoff, S., and Dunn, B., U.S. Departmnet of Transportation, Federal Highway Administration. (Pending Report). Aerodynamic Stability of Bridge Stay Cables – Dynamic Tests and Simulations. Report No. FHWA-HRT-xx-xxx.
[63] Bosch, H.R. and Pagenkopf, J.R., U.S. Departmnet of Transportation, Federal Highway Administration. Development of a Cable Robot and Measurement of Stay Cable Roundness. (Pending Publication). Report No. FHWA-HRT-xx-xxx.

computational modeling and simulation software tools, user support, and educational materials needed to advance the nation's capability to simulate the impact of natural hazards on structures, lifelines, and communities. These simulations will help users make informed decisions about the need for and effectiveness of potential mitigation strategies. Many of these tools have been made publicly available on the NHERI CI's DesignSafe-ci.org Discovery Workspace during fiscal years 2017-18. The SimCenter provides 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 engaged in an effort to develop practical Computational Fluid Dynamics (CFD) methods for the numerical determination of 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 fiscal years 2017-18, 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.[64] NIST developed a physics-based methodology for simulating turbulent atmospheric flows for structural engineering applications,[65] and established its effectiveness through comparisons with turbulent flows defined in standards and achieved in wind tunnel simulations.[66]

To begin developing 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[67] and evaluated the sensitivity of the aerodynamic pressures to simulation parameters using experimental design techniques.[68] NIST performed wind tunnel tests to support the validation of pressures in the CFD simulations.

FHWA: Numerical Modeling of Wind Effects on Highway Structures. During fiscal years 2017-18, existing interagency agreements continued between the U.S. Department of Transportation and the U.S. Department of Energy for modeling the effects of natural hazards, such as windstorms, hydraulics, and flooding, on infrastructure. The agreements have enabled FHWA to utilize high-performance computing and support staff from the Argonne National Laboratory (ANL). Resources located at the TRACC are being used to model wind effects on highway users as well as highway structures. Research has continued in this area to further refine and streamline the model to develop a "virtual wind tunnel," that will complement physical testing facilities. A comprehensive technical

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

[65] Shi, L. and Yeo, D., National Institute of Standards and Technology. (2016). OpenFOAM Large-Eddy Simulations of Atmospheric Boundary Layer Turbulence for Wind Engineering Applications. NIST Technical Note 1944. Retrived from http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1944.pdf

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

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

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

report[69] was published in fiscal year 2017. This improved model is being tested and validated using results of physical tests in the laboratory.[70] ANL staff is developing tools that have been used to develop and refine models to study the interaction of wind with inclined bridge stay cables as well as wind (or truck-induced gust) interaction with large message sign and signal structures. FHWA and ANL staff have also developed a computational model for studying the wind "shielding" effects of large bridge towers on trucks crossing elevated bridge structures.[71]

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 fiscal years 2017-18 included improvements in analysis methods for wind pressures on building components and cladding. An improved procedure and software for estimating peaks of stationary wind pressure time series over 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.

NIST: Coastal Inundation Events in Developed Regions. NIST issued a grant to Oregon State University under the NIST Disaster Resilience Grants Program and the University of Notre Dame to develop practical methodologies to determine how storm waves and tsunamis vary in built environments when compared to the 'bare earth' methodologies presently in use. Progress on this front has the potential to greatly improve predictions of wave and tsunami loading in developed regions, which will help both design and planning. Work is underway to bring all of the results together to strengthen buildings at risk of collapse from storm waves and tsunamis. NIST and partners are also preparing laboratory experiments to validate numerical simulations of wave inundation and loading. The experiments are being conducted during fiscal year 2018 at the Oregon State University O.H. Hinsdale Wave Research Laboratory.

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 fiscal years 2017-18, NSF made numerous awards that will advance knowledge on economic and social factors influencing risk reduction measures. A wide range of NSF programs have supported this research. 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 exploring the residents' attitudes and beliefs regarding sheltering, with the goal of developing and testing communications leading to better informed sheltering decisions.

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[69] Sitek, M.A., Lottes, S.A., and Bojanowski, C., Argonne National Laboratory. (2017). Air Flow Modeling in the Wind Tunnel of the FHWA Aerodynamics Laboratory at the Turner-Fairbank Highway Research Center. Report No. ANL/NED/17/2 .

[70] Sitek, M.A. and Lottes, S.A., Argonne National Laboratory. (2018). CFD Simulation of Wind Tunnel Tests of the Deer Isle – Sedgwick Bridge Model. Part 1. Static Tests. Report No. ANL/NED/18/1.

[71] H.R. Bosch and N. Zhang, U.S. Departmnet of Transportation, Federal Highway Administration. (Pending Publication). CFD Simulation and Evaluation of Bridge Tower and Deck Wake Effects on the Stability and Safety of Traffic. Report No. FHWA-HRT-xx-xxx.

Individual NSF programs can use the RAPID mechanism 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 fiscal years 2017-18, the Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) competition supported a project at the University of Illinois at Urbana-Champaign focusing on human-sensor data for characterizing windstorm damage. This project is addressing how to quantify the confidence in crowdsourced damage assessment and designing a tool for reliable crowdsourcing given unreliable participants. Through the use of citizen science crowdsourcing, rapid identification of damage areas could help decision makers allocate resources for response and recovery efforts. This rapid response allows for targeted damage assessments which can improve the design of buildings in regions susceptible to windstorms. The final results of this research will be shared with NOAA to be used in surveyor training to assess wind damage and for public tutorials.

Through the core NSF program Human, Disasters, and the Built Environment (HDBE), an award to the University of Colorado, Boulder is developing two new platforms and corresponding networks to help researchers respond to and overcome long standing challenges in the advancement of the hazards and disaster field. The Social Science Extreme Events Reconnaissance (SSEER) and the Interdisciplinary Science and Engineering Extreme Events Reconnaissance platforms will leverage databases and information resources to build capacity of the social science, engineering, and interdisciplinary hazards and disaster research communities to conduct post-disaster reconnaissance.

NIST: Longitudinal Study of the Recovery of Lumberton, NC, from Hurricane Matthew: In early October of FY 2017, Hurricane Matthew crossed North Carolina as a Category 1 storm, with some areas receiving 0.38 m to 0.46 m (15 to 18 in) of rainfall on already saturated soil. The NIST funded Center for Risk-Based Community Resilience Planning teamed with researchers from NIST's Engineering Laboratory to conduct field studies focused on impacts of the Lumber River flooding in Lumberton, North Carolina. Lumberton is a racially and ethnically diverse community with higher than average poverty and unemployment rates, a typical civil infrastructure for a city of 22,000 residents, and a city council form of government. The longitudinal field study is focused on documenting the impacts and subsequent recovery processes of the local community following the FY 2017 riverine flooding in Lumberton.

This type of interdisciplinary longitudinal research is critical to better understand community processes in the face of disasters and ultimately provide data and inform best practices for enhancing resilience to natural hazards in U.S. communities. The initial data collection in early FY 2017 had two major objectives: (1) document initial conditions after the flood for the longitudinal study of

Lumberton's recovery, with a focus on improving flood-damage and population-dislocation models, and (2) develop multidisciplinary protocol providing a quantitative linkage between engineering-based flood damage assessments and social science-based household interviews that capture socio-economic conditions (e.g., social vulnerabilities related to race, ethnicity, income, tenancy status, and education levels). The second data collection effort in FY 2018 focused on documenting the recovery of housing, businesses, and the public sector in Lumberton.

NIST: Hurricane Maria Program – Economic and Social Factors: In fiscal year 2018, NIST began collecting data and started planning for a multi-year study of the impacts of Hurricane Maria on Puerto Rico. There are two projects within the Hurricane Maria Program that will attempt to identify the linkage(s) between economic and social functions and windstorm impact reduction.

- Recovery of Critical Social Functions: This project will identify the underlying characteristics and conditions associated with recovery of critical social functions in Puerto Rico and will examine the recovery trajectories of sampled schools and hospitals. This project may also include investigation of the interdependencies of the households and the social functions provided by schools and hospitals.

- Business Interruption and Supply Chain Recovery: Provide greater understanding of business continuity resilience planning and supply chain continuity and how this may differ between industries and affected regions. Additionally, understanding the relationship between these areas of economic significance to the social functions and the infrastructure that supports them will help strengthen business continuity in the future.

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 of the NWIRP Strategic Plan) provides 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: (1) supports acquisition of an unprecedented amount of perishable, post-disaster, high-quality, open data by the natural hazards community; (2) provides learning and training opportunities in post-disaster reconnaissance; (3) promotes public engagement with science and technology through a citizen science data collection initiative; and (4) develops new and strengthens existing international research partnerships by establishing collaborations with foreign organizations during global deployments. In addition to the RAPID facility, the

Reconnaissance Portal on the NHERI CI's DesignSafe ci.org website[72] collects and categorizes data within a geospatial framework.

During fiscal years 2017-18, the Georgia Institute of Technology, University of Illinois at Urbana-Champaign, University of Colorado at Boulder, and University of California-Los Angeles received awards to the Geotechnical Extreme Events Reconnaissance (GEER) Post Disaster Reconnaissance. Since 2015, GEER has documented the geotechnical effects of 18 extreme events, including hurricanes Irma and Harvey, among others. The GEER Post Disaster Reconnaissance will work with the NSF RAPID facility to coordinate critical activities including development and delivery of training efforts. It will continue to perform the primary objectives: documenting geotechnical effects of important extreme events to identify important topics in need of research; employing innovative technologies for post-event reconnaissance; and advancing the capabilities of individuals performing research based on field observations.

NIST: Post Disaster Data Collection with UAV's. NIST funded a project through a Disaster Resilience Grant, titled "Improving Disaster Resilience Through Scientific Data Collection with UAV Swarms." The award supports the development of swarms of small-unmanned aerial vehicles (sUAVs) equipped with lightweight navigation and sensing instruments that can detect the health of critical infrastructure before, during and after a natural disaster. The methodology developed through this multi-disciplinary effort will transform health diagnostics approaches, by swiftly providing the right type and quantity of trusted field data, needed in support of science-based decision making. The ability to disperse and coordinate unmanned airborne sensor systems to support perishable data collection will amplify the potential of sUAVs for the collection of data in otherwise inaccessible regions impacted by a hazard. The methodology is extensible to a variety of intelligent multi-sensing health diagnostic systems.

Objective 9: Develop advanced risk assessment and loss estimation tools

NSF: Hurricane Resilience of Electric Power Transmission Infrastructure. An NSF-supported project at Purdue University is developing a new risk assessment method to investigate the complexities associated with linking outages to societal costs due to extreme events. This method will help estimate the risk of major power outages, estimate compounding economic losses due to infrastructure failure from power outages, and optimize techniques for determining best practices for addressing uncertainties.

FEMA: Maintain Hazus-MH Hurricane Loss Estimation Model. FEMA develops and maintains the Hazards – U.S., 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, infrastructure, and social impacts of disasters and graphically illustrates communities of high-risk 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 mitigation, preparedness, response, and recovery phases of the emergency management decision making process. Based on substantial damage inspections and observed

[72] National Science Foundation, DesignSafe-CI, NHERI. Cyberinfrastructure Description. https://www.designsafe-ci.org/community/cyberinfrastructure/

damages from Hurricanes Irma and Maria, FEMA is currently researching new wind damage estimation formulas representative of building construction practices common in Puerto Rico and the U.S. Virgin Islands (USVI). This will increase the accuracy of FEMA's Hazus loss estimations for Puerto Rico and USVI for future storms and will also benefit other FEMA risk reduction programs. FEMA is also researching cloud computing technologies to decrease processing times required for future hurricane response Hazus loss estimation efforts.

NOAA: State of Florida Public Hurricane Loss Model. NOAA continued to work with the state of Florida during fiscal years 2017-18 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 during the relevant fiscal period to update and maintain the wind model within the FPHLM. In fiscal years 2017-18, researchers started the implementation of changes to the FPHLM (Flood Hazard Model) that was necessary to comply with the Report of Activities (ROA) 2017 Flood Standards. Changes to the FPHLM (Wind Hazard Model) were made to meet the ROA 2017 Standards; this includes an update to the ZIP Code centroids and roughness databases, and an update to the probability distribution functions to reflect changes and revisions to the revised Atlantic hurricane database (HURDAT2). Analysis of major Hurricanes Irma and Michael that affected Florida in 2017/2018 are underway.

NOAA: Develop a Tornado and Severe Thunderstorm Impact Estimation Model. In FY 2017-18 NOAA/NWS Storm Prediction Center continued its ongoing development of a nationally applicable standardized method that contains models for probabilistically estimating aggregate potential impacts from tornadoes. This model, called IMPACTS (Integrated Machine-based Predictive Analytics of Convective Threats to Society), creates estimates of physical and societal impacts of tornadoes. Work is ongoing to extend IMPACTS to include severe thunderstorm wind and hail.

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: Structural Extreme Events Reconnaissance. An NSF-funded project at the University of Notre Dame is operationalizing a network to coordinate the structural engineering research community's rapid response to natural disasters across the country. The goal of the Structural Extreme Events Reconnaissance (StEER) is to collect perishable extreme event data that can be used for subsequent research investigations to reduce risks to civil infrastructure and promote national welfare by saving lives and reducing property losses in future disasters. StEER work will be coordinated with the NHERI RAPID facility, GEER, SSEER, and CONVERGE, and the data will be available on the NHERI DesignSafe Reconnaissance Portal.

NIST: Database-assisted Design. Database-assisted design (DAD) methods can provide more accurate results than more simplified procedures in building codes and standards. During the current reporting period, 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. A novel DAD computational framework applicable to flexible structures experiencing significant wind-induced dynamic effects was also developed.[73]

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

NIST: Translating R&D Advances into Model Building Codes and Standards. During fiscal years 2017-18, NIST developed an improved set of design basis wind speed maps for wind design of buildings and other structures in the United States and worked with the American Society of Civil Engineers (ASCE) and the International Code Council (ICC) to have these maps incorporated into ASCE 7-16 standards and IBC-2018 building codes. Additionally, NIST developed a set of probabilistic tornado hazard maps for the contiguous United States for use in tornado-resistant design of buildings and other structures. NIST is actively working with the Wind Load Sub-Committee of the ASCE 7 standards committee to have these tornado hazard maps incorporated into ASCE 7-22 to facilitate tornado-resistant design for the first time in the U.S.

FEMA: Improving Wind-Resistant Provisions. During fiscal years 2017-18, 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 develops supporting commentary and improvements to reference standards for wind-resistant design. FEMA supported the development of provisions for designing for tornado wind loads in ASCE 7 and the next edition of the ICC 500: *Standard for the Design and Construction of Storm Shelters* (see SP-7). FEMA continues to work with NOAA, NIST, and ASCE to create 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.

[73] Park, S. and Yeo, D., National Institute of Standards and Technology. (2016). Database-Assisted Design and Second-Order Effects on the Wind-Induced Structural Behavior of High-Rise Steel Buildings. NIST Technical Note 1940. Retrived from http://ws680.nist.gov/publication/get_pdf.cfm?pub_id=921073

FHWA: Development of Design Guidelines and Specifications. Research continued in fiscal years 2017-18 on the issue of wind- and rain-induced vibration of bridge stay cables. Results of research on bridge cables have been made available to the Post-Tensioning Institute's DC-45 Cable-Stayed Bridge Committee for consideration during periodic updates of their guide specification on cables. During this reporting period, FHWA continued to work closely with the Transportation Research Board (TRB) on the project NCHRP 12-111 "Evaluating the Effectiveness of Vibration Mitigation Devices for Structural Supports of Signs, Luminaires, and Traffic Signals." FHWA also worked with TRB on the project NCHRP 15-67 "Improved Methodology to Accurately Determine Wind Drag Coefficients for Highway Signs and Their Support Structures." Both projects are aimed at updating American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Specifications for Structural Supports for Signs, Luminaires, and Traffic Signals (AASHTO LRFD SLTS Specifications).

Objective 12: Promote the implementation of windstorm-resilient measure

FEMA: Wind Resistant Construction. FEMA Building Science has promoted long-term wind resiliency in the U.S. Virgin Islands (USVI) and Puerto Rico following major disaster declarations after Hurricane Irma (DR-4335) and Hurricane Maria (DR-4340) for the U.S. Virgin Islands, and Hurricane Irma (DR-4336) and Hurricane Maria (DR-4339) for Puerto Rico, through products which will strengthen the resiliency of structures against windstorms. These products provided understanding and recommendations for wind mitigation and building science guidance. FEMA assisted the USVI in updating the residential home guidance document, Construction Information for a Stronger Home (4th Edition) which is relied upon by locals for home construction. The latest edition will provide local designers and builders with a reference point for increased wind loads and prescriptive details to apply in their design and construction projects. This product promotes the implementation and usage of the latest model building code wind provisions as provided in the 2018 International Building Code and 2018 International Residential Code. FEMA delivered successful trainings and subject matter consultation within USVI and Puerto Rico to educate governmental and private groups on wind hazards and mitigation with courses discussing residential coastal construction, wind retrofit, safe rooms, and fundamentals of building science. Also, FEMA provided topographic wind maps which can be used to determine wind loads.

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 hurricane track and intensity errors by 20% in 5 years and 50% in 10 years and extending the useful range of hurricane forecasts to 7 days. Under HFIP, there have been significant improvements to NOAA's operational hurricane prediction model, the Hurricane Weather Research and Forecasting (HWRF) system, resulting in increased accuracy in the model-based guidance for tropical cyclone intensity predictions. In fiscal year 2017, HFIP continued to provide funding to numerous efforts within NOAA, other federal agencies, and universities to support the development, testing, and evaluation of an enhanced HWRF model prediction system, better use of existing observations, evaluation of new potential observations, and support for improved forecasting techniques. Sustained developments in the HWRF system led to further improvements in intensity predictions. These upgrades resulted in further improvements in model intensity guidance in nearly all basins. The operational HWRF was the best deterministic intensity forecast model in the Atlantic basin. It outperformed statistical models based on climatology.

Preliminary assessment of NWS NHC performance in the Atlantic average track forecast errors were near or a little below the 5-year (2013-2017) mean errors through 48 hours, with the largest improvement seen at 36 and 48 hours where the 2018 average errors were nearly 10% below the 5-year means. NHC's track forecast errors were slightly above the 5-year mean errors at days 3-5. NHC's preliminary Atlantic intensity errors for 2018 were generally lower than the 5-year means, except at 72 hours. The largest reduction in errors was seen at day 4, where the 2018 errors were about 15% below the 5-year averages, and at day 5, where the 2018 errors were more than 20% below the 5-year mean.

Shifting to the NWS Central Pacific Hurricane Center (CPHC), a preliminary assessment of their performance in the Central Pacific average track forecast errors were below the 5-year (2011-2015) mean errors through 120 hours, with the largest improvement seen at 96 and 120 hours where the 2018 average errors were nearly 40% and 30% below the 5-year means, respectively.

NOAA: Joint Hurricane Testbed. During fiscal year 2017, the U.S. Weather Research Program within the NOAA Office of Oceanic and Atmospheric Research Office of Weather and Air Quality supported six 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 ensemble model enhancements to improve the analysis and prediction of tropical cyclones. The JHT is designed to transfer 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 Colorado-Colorado Springs, Florida State University, University of Wisconsin-Milwaukee, Mississippi State, Colorado State University, and Florida International University), and U.S. government laboratories (NOAA's Cooperative Institute for Research in the Atmosphere and Northern Gulf Institute).

NOAA: Intensity Forecasting Experiment. NOAA's Hurricane Research Division continues to improve hurricane-intensity forecasting. The Intensity Forecasting Experiment (IFEX) is collecting observations that span the tropical cyclone (TC) life cycle in a variety of environments for improvements in the next-generation Hurricane Weather Research and Forecasting 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. When possible, IFEX partners with other federal agencies such as NASA, Office of Naval Research (ONR), and NSF to accomplish a more complete sampling of TC structure and intensity. 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 Hurricanes Matthew in 2016, and Irma and Maria in 2017. The NOAA P-3 Orion[74] and the Gulfstream IV-SP (G-IV) research aircraft[75] gathered mission critical data that were implemented in the operational hurricane weather research model. Prior to making landfall, the NOAA P3 aircraft successfully launched six unmanned aircraft called Coyote into Hurricane Maria. The Coyote collected data in the lowest part of the atmosphere, as low as 300 feet above the ocean surface.

NOAA: Warn-on-Forecast. NOAA's National Severe Storms Laboratory (NSSL) is working with the NWS to develop a new vision for the watch-to-warning decision process, which is aimed at increasing the continuity, timeliness, and specificity of high-impact weather information available to users during this time frame. This effort includes increasing tornado warning lead time, reducing the false alarm ratio, and providing reliable probabilistic hazard information that users of local warnings can use in formulating a best response for their situation. Toward this end, NSSL scientists and collaborators are developing an on-demand, probabilistic, fine resolution weather model-based analysis and forecast system. The NSSL continues to investigate various model parameterization schemes, impacts of assimilating radar data, satellite data and other observations on the veracity of forecasts.

In fiscal years 2017-18, the NSSL began working within NOAA testbeds and with operational units to evaluate an experimental Warn on Forecast1(WoF) methodology, allowing forecasters to use thunderstorm-resolving computer models to guide severe weather outlooks, forecaster discussion products, and probabilistic short-term forecasts for tornadoes, winds, hail, and flash floods to advance from what is possible today with the current Doppler radar systems. Evidence suggests that these enhancements to operational weather capabilities will lead to a more accurate warning system, increase lead time, and provide probabilistic information to the public to support risk-wise actions during severe weather events. The WoF program is being conducted in collaboration with the NOAA Earth System Research Laboratory Global Systems Division (ESRL/GSD), the NWS Environmental Prediction Center, the NWS SPC, the NWS Weather Prediction Center, and the NWS Forecast Office in Norman, Oklahoma (OUN).

NOAA: Hazardous Weather Testbed. In FY 2017-18, 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 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 partners such as the NCAR, the Geophysical Fluid Dynamics Laboratory, other universities,

[74] National Oceanographic and Atmospheric Institute. P3 Orion research airplane. https://www.nssl.noaa.gov/projects/torus/p3.php
[75] National Oceanographic and Atmospheric Institute. NOAA IV- SP Gulfstream Jet. https://www.omao.noaa.gov/learn/aircraft-operations/aircraft/gulfstream-iv-sp-g-iv

various NOAA agencies, broadcast meteorologists, emergency managers, 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, broadcast meteorologists and emergency mangers in the 2017 and 2018 HWT experiments. 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. Broadcast meteorologists and emergency managers received the warning-scale PHI while performing typical job functions in simulated work environments. A primary result was that the FACETs paradigm enabled NWS forecasters to provide a continuous flow of information that provided significant benefits to decision making. PHI was also found to provide a more focused alert area than the current storm-based polygon warning 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.

NOAA: High-Resolution Rapid Refresh Model and the Rapid Refresh Model. 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 High-Resolution Rapid Refresh (HRRR) model to advance the prediction of weather changes in the environment. The HRRR provides hourly weather updates at 3 km resolution (i.e., a 3.5 square-mile area), which increases the protection of lives and property, helps to improve the efficiency and effectiveness of wind and solar energy of the U.S. energy sector, and provides air traffic managers with rapidly updated projections of developing severe weather.

Version 2 of the HRRR was implemented in NWS operations in late fiscal year 2016 and continued to provide benefits during the reporting period. 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 to 18 hours. Following version 2, HRRR Version 3 has improved simulation of convective storms and clouds, reduced high bias for precipitation in both warm and cold seasons, improved 2-m temperatures including over snow cover, extended length to 36 hours four times per day, and coverage over Alaska.

The Rapid Refresh Model (RAP) is a coarser version of the HRRR assimilation and modeling system, providing forecasts for the North American domain and updated hourly. The RAP provides the boundary conditions used to execute the HRRR model Version 3 of the RAP, was implemented in NWS operations in fiscal year 2016 and included a larger domain and hourly forecasts out to 21 hours. Building on these enhancements, RAP version 4 (RAPv4) was implemented into operations with the HRRR model on July 12, 2018. RAPv4 improves the depiction of cloud fields and reduces a high precipitation and reflectivity bias most notable during the first several forecast hours. It also extends forecast guidance out to 39 hours four times daily.

Objective 14: Improve storm readiness, emergency communications and response

NOAA: StormReady Program. The StormReady program supports a Weather-Ready Nation (WRN) by preparing communities for the occurrence of high impact environmental events. On an annual basis NOAA/NWS targets 100 new StormReady communities pending funding availability. In FY18 there were 136 new StormReady communities recognized. S tormReady supports NWS' disaster risk reduction strategy and is offered to provide guidance and incentive 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 identified 3234 county or county-equivalents in the United States. During the reporting period, we were 44 percent of the way there with 1425 county or county-equivalents recognized as StormReady. Overall, there are nearly 2900 communities recognized as StormReady in the U.S.

NOAA: Forecasting a Continuum of Environmental Threats (FACETs). As part of ongoing research in support of the FACETs paradigm, NOAA has supported 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). New measures were developed and tested for tornado warning reception, comprehension, and response in a pilot survey of about 3,000 Oklahomans. Results of the pilot survey were then used to develop and field a corollary national survey tailored to provide a demographically representative result. This survey found that a large majority of respondents did understand the basics of the current tornado WWA system, but regional differences were noted and details of the WWA system such as warning sizes and times were less well understood. This survey also provided important baseline information about how the public understands probabilistic information and might interpret future hazard information based on PHI.

NIST: Emergency Communications. NIST conducts emergency communication research to develop the measurement science that provides the foundation for national codes, standards, and/or guidance on the creation and dissemination of clear, consistent, and accurate emergency communications for tornadoes. NIST's current focus is on development of 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 fiscal year 2017 included: 1) a published review of outdoor siren systems: a review of technology, usage and public response during emergencies;[76] and 2) a NIST- and Fire Protection Research Foundation-sponsored workshop for those with responsibilities/roles as communicators (e.g., National Weather Service warning coordination meteorologists, emergency management coordinators, public information officers, press secretaries, and engagement specialists) from locations across the U.S. to provide feedback on NIST-developed interim guidance on the usage of short message alerting systems (e.g., Wireless Emergency Alerts [WEAs] and Twitter). Progress in fiscal year 2018 included: 1) a published review

[76] Kuligowski, E., and Wakeman, K., National Institute of Standards and Technology. (2017). Outdoor Siren Systems: A Review of Technology, Usage, and Public Response During Emergencies. NIST Technical Note 1950. https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1950.pdf

of the public's response to short message alerts under imminent threat;[77] 2) a published guidance document on alerts issued by outdoor siren and short message alerting systems;[78] 3) newly developed short message templates for 280-character and 360-character WEA messages, with Jeannette Sutton, from the University of Kentucky's Communication Department, and 4) proposed incorporation of guidance on the usage of outdoor siren systems and short message alerting systems for the next edition (2019) of NFPA 1600: Standard on Disaster/ Emergency Management and Business Continuity/Continuity of Operations Programs.

5. The Path Forward

The next step for NWIRP is to implement the Strategic Plan. Implementation activities may include the following elements:

- Develop technical information and support research to improve surface wind measurements in extreme windstorm events. NWIRP's post storm coordination and assessment activities continue to document serious technical and logistical issues with the Nation's wind observation capabilities in extreme windstorms, especially during landfalling hurricanes. A lack of high resolution, continuous measurements of surface wind speeds inhibits our understanding of extreme wind effects on the built environment.

- Develop plans, budgets and project milestones for baseline studies on loss of life and property due to windstorms, including identification of causes, trends, and factors underlying the trends in windstorm fatalities and property damage. When funding becomes available this effort will provide improved methods and data for tracking future windstorm impacts and will enable further identification and prioritization of NWIRP research and development, technology transfer, and outreach activities, once the key drivers of fatalities and losses are better understood.

- Engage in measurement science research to better understand the characteristics and utility of space-based precipitation measurement platforms in landfalling hurricanes to support post windstorm investigations and overall windstorm disaster risk reduction. Rainfall in landfalling hurricanes causes more than three times as many fatalities as wind. However, different land-based measurement systems may produce highly variable rainfall estimates in hurricane disasters, complicating flood and landslide assessments and attribution.

- Expand engagement with federal agencies and stakeholder organizations, including other levels of government, academia and the private sector.

- Enhance stakeholder communication, through creation of a mobile-friendly Program website, newsletters, and increased participation in windstorm-related conferences and other appropriate events.

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[77] Kuligowski, E., and Doermann, J. (2018). A Review of Public Response to Short Message Alerts under Imminent Threat. NIST Technical Note 1982. Retrived from https://doi.org/10.6028/NIST.TN.1982

[78] Kuligowski, E., and Kimball, A. (2018). Alerting under Imminent Threat: Guidance on Alerts Issued by Outdoor Siren and Short Message Alert Systems. NIST Technical Note 2008. Retrived from https://doi.org/10.6028/NIST.TN.2008

Lastly, it should be noted that while the Strategic Plan addresses 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

AMS - American Meteorological Society
AOML - Atlantic Oceanographic and Meteorological Laboratory
ASCE - American Society of Civil Engineers
ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers
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
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
NVOAD - National Voluntary Organizations Active in Disasters
NWIRA - National Windstorm Impact Reduction Act of 2004
NWIRP - National Windstorm Impact Reduction Program
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 provide a mapping from the statutory responsibilities (42 U.S.C. § 15703) of the four Program agencies 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	9	1, 7
	C	10	
Support windstorm-related data collection and analysis. 42 U.S.C. § 15703(b)(5)(A)(ii).	A	2, 4	2, 3
	B	7, 8, 9	
	C	12	
Support public outreach and information dissemination. 42 U.S.C. § 15703(b)(5)(A)(iii).	C	12, 14	6, 7, 8
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	6, 7
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, 7

Table B.1: 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, 5
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	2	3
	B	8	
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, 7
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	1, 2, 4	All
	B	5, 6, 8, 9	
	C	10, 11	

Table B.2: 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	1, 2, 3, 4	1, 2, 3, 8
	B	5, 6, 8	

Table B.3: 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	1, 2, 3, 4	1, 2, 3, 4, 7, 8
	B	5, 6, 8, 9, 10	
Support research in economic and social factors influencing windstorm risk reduction measures. 42 U.S.C. § 15703(b)(3)(B).	B	7, 8	1, 3, 8
	C	10, 11, 12	

Appendix C: NWIRP Coordinated Budget

The fiscal year 2019 NWIRP Coordinated Budget, provided below, was submitted to Congress on May 7, 2018.

Background on the 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 measures to reduce those impacts." 42 U.S.C. § 15703(a).

The National Windstorm Impact Reduction Act Reauthorization of 2015 (PL 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.[79] Descriptions of the planned activities for each of the four program agencies (National Institute of Standards and Technology, National Science Foundation, National Oceanic and Atmospheric Administration, and Federal Emergency Management Agency) are provided below, and the associated budget requests are listed in the attached table.

National Institute of Standards and Technology (NIST)

NIST has been designated as the Lead Agency for NWIRP through the enactment of PL 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; and
- Coordinate all federal post-windstorm investigations, to the extent practicable.

Planned technical activities include:

- Initiate efforts on the NIST Technical Investigation of the effects of Hurricane Maria on the U.S. territory of Puerto Rico. The goals of the investigation will be to characterize: (1) the wind environment and technical conditions associated with deaths and injuries; (2) the performance of representative critical buildings, and designated safe areas in those buildings, including their dependence on lifelines; and (3) the performance of emergency communications systems and the public's response to such communications;
- 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;
- Continue work on development of site-specific risk estimation tools for assessment of joint hurricane hazards of wind, storm surge, and waves;
- 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.

[79] 42 USC 15703(e)(7).

National Oceanic and Atmospheric Administration (NOAA)

NOAA activities fall under two categories: hurricane-related and locally severe weather activities. Planned hurricane related activities include the following:

- Continue the Hurricane Forecast Improvement Project;
- Operate the National Hurricane Center Joint Hurricane Testbed; and
- Operate the Atlantic Oceanographic and Meteorological Laboratory Hurricane Research Division.

Planned locally severe weather activities include the following:

- Operate the Storm Prediction Center, including Hazardous Weather Testbed;
- "Warn on Forecast" Development;
- Operate the National Severe Storms Laboratory Tornado and Severe Weather Research; and
- Operate the Earth Systems Research Laboratory, Global Systems Division, including High-Resolution Rapid Refresh forecasts.

Federal Emergency Management Agency (FEMA)

FEMA receives no appropriated funding for specific wind related projects. However, FEMA leverages available resources as appropriate to support NWIRP goals and objectives. The values shown in the budget report table represent an estimate of the leveraged resources.

A high-level summary of the wind related activities FEMA Building Science has or will be pursuing includes: post-windstorm related data collection and analysis; development of risk assessment tools and guidance for effective mitigation; integration of mitigation measures into consensus codes and standards; and public outreach, training, and information dissemination consistent with the Agency's all-hazards approach.

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 buildings, structures, and lifelines; and research in the economic and social factors influencing windstorm risk reduction measures.

NWIRP Budget Report for Fiscal Year 2017 Actual, Fiscal Year 2018 Actual, and Fiscal Year 2019 Enacted

Windstorm ($K)	FISCAL YEAR 2017 Actuals	FISCAL YEAR 2018 Actuals	FISCAL YEAR 2019 Enacted
NIST	3,475	6,612	5,696
NOAA	15,444	18,804	20,504
NSF	9,682	9,682	9,682
FEMA	450	300	300
Total Windstorm	29,051	35,398	36,182