NATIONAL WINDSTORM IMPACT REDUCTION PROGRAM

BIENNIAL PROGRESS REPORT TO CONGRESS FOR FISCAL YEARS 2019 AND 2020

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

The National Windstorm Impact Reduction Program (NWIRP or Program) is a science- and engineering-based program whose stated mission is to achieve major measurable reductions in losses of life and property from windstorms, through a coordinated federal effort in cooperation with other levels of government, academia, and the private sector. The four designated Program agencies are the National Institute of Standards and Technology (NIST), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Federal Emergency Management Agency (FEMA). This progress report Program is submitted to Congress by the Interagency Coordinating Committee of NWIRP, as required by the National Windstorm Impact Reduction Act (NWIRA) of 2004 (Public Law 108-360, Title II), as amended by the NWIRA Reauthorization of 2015 (Public Law 114-52). This report fulfills the requirement for fiscal years (FY) 2019 and 2020.

Over the last 40 years, windstorms have caused over $1 trillion in economic losses and over 8,000 fatalities in the United States, with the vast majority of these losses occurring during the last two decades. Despite these sobering statistics, the NWIRP agencies have made significant progress during this time of unprecedented increases in the frequency and intensity of extreme weather and concomitant societal impacts. In 2018, the Program agencies released the NWIRP Strategic Plan, which sets forth a research-to-applications paradigm that integrates foundational research in understanding windstorm behavior, applied research to understand windstorm impacts, and applications and technology transfer to improve the windstorm resilience of the Nation. The various agency-specific contributions and accomplishments in advancing the NWIRP research-to-applications paradigm during FYs 2019-20 are documented in section 5 and presented as a function of the NWIRP strategic goals. Highlights of these agency contributions include significant improvements in hurricane forecasts and increased tornado warning times, advancements in the science of wind mapping to inform engineering-based design standards, improved coordination practices and increased resources for scientific research in support of post-windstorm investigations, and implementation of post-windstorm research-based recommendations into codes and standards development processes such as provisions for windstorm resistant construction, a new storm shelter standard, and proposed inclusion of tornado wind loading factors for structural design.

In addition to the agency-specific contributions to windstorm impact reduction during the reporting period, NWIRP has strengthened interagency coordination mechanisms amongst the designated Program agencies. In its 2015 authorizing legislation (Public Law 114-52), the U.S. Congress directs NIST to "coordinate all Federal post-windstorm investigations, to the extent practicable." In recognition of the need to devise formal guidance to implement this directive for landfalling tropical cyclones, in 2020 the NWIRP agencies developed a "Tropical Cyclone Coordination Plan for Science and Technology" – a living document that outlines the windstorm coordination roles of the NWIRP agencies across all phases of tropical cyclone (TC) disasters from pre- to post-landfall. Once fully implemented, this coordination plan will be used to guide scientific information sharing, agency decision making processes relevant to post-windstorm investigations, identification and development of scientific interagency collaborative opportunities, and information dissemination in the aftermath of TC disasters.

In 2020, NWIRP experienced significant challenges in efforts to reduce windstorm impacts due to operational and logistical challenges from restrictions related to the COVID-19 pandemic. The NWIRP agencies were unable to send scientific investigative teams to continue longitudinal data collection from previous disasters, or to assess the impacts from 2020's extreme weather events. In the midst of a record-breaking 2020 hurricane season, agencies often had minimal staffing on location, which led to challenges in optimizing coordination with stakeholders. Despite these challenges, the NWIRP agencies continued executing their missions to reduce windstorm impacts.

As windstorm impacts increase due to population and property valuation increases along the coast, and changing frequency and intensity of extreme weather events, it is critical that the NWIRP agencies continue to implement the NWIRP Strategic Plan and identify new opportunities for improved synergy across scientific disciplines, interagency engagement, and education and outreach to amplify awareness of NWIRP and support the development of the next generation of windstorm scientists and engineers. The path forward for NWIRP includes:

- expanding awareness of the NWIRP research-to-applications paradigm across the federal enterprise and beyond;
- strengthening NWIRP post-windstorm assessments by supporting federal coordination with university-based researchers;
- exploring the application of climate change model projections to inform the development of forward-looking national structural design standards, building codes, and other climate resilience applications;
- supporting the implementation of recommendations from interagency post-windstorm research; and,
- integrating scientific advances in real-time extreme weather event forecasting and social sciences to enhance emergency communication and life safety warning information to the public.

The NWIRP agencies are committed to advancing these priorities to reduce windstorm impacts across the Nation.

2. Background

Windstorms and associated flooding are the largest loss-producing natural hazards in the United States,[2] with hurricanes and tornadoes comprising a majority of losses related to life and property. From 1980-2020, windstorms caused over $1 trillion in economic losses and over 8,000 fatalities.[3] In recognition of the need to significantly decrease economic costs and loss of life, Congress established NWIRP.[4]

NWIRP is a federal interagency science- and engineering-based Program focused on achieving major measurable reductions in losses of life and property from windstorms, through a coordinated federal effort in cooperation with other levels of government, academia, and the private sector. The four designated Program agencies are NIST, NOAA, NSF, and FEMA.

Since NWIRP's inception in 2004, the Program has made notable progress. This includes significant improvements in hurricane forecasts and increased tornado warning times, advancements in the science of wind mapping to inform engineering-based design standards, improved coordination practices and research support for post-windstorm investigations, and implementation of post-windstorm research-based recommendations into codes and standards development processes such as provisions for

[2] Visit https://www.nist.gov/speech-testimony/calm-storm-reauthorizing-national-windstorm-impact-reduction-program.

[3] National Oceanic and Atmospheric Administration, National Centers for Environmental Information. Billion-dollar weather and climate disasters: Table of events. Retrieved from https://www.ncdc.noaa.gov/billions/events/US/1980-2020.

[4] 42 U.S.C. § 15703(a).

windstorm resistant construction, a new storm shelter standard, and proposed inclusion of tornado wind loading factors for structural design. Despite these achievements, the Nation continues to experience increasing losses of life and property due to extreme weather events, as evidenced by the devastating severe weather and tornado outbreaks in 2011, 2013, and 2020 and the recent catastrophic hurricane seasons of 2005, 2012, 2016-18, and 2020.

Continuing to improve windstorm impact reduction measures requires a research-to-applications paradigm featuring a sustained and robust interdisciplinary approach based on:

- meteorological and climate science research to better understand the short- and long-term changes in the behavior and impact of windstorms on society;
- 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.

The primary functions of NWIRP are carried out by two interagency coordinating bodies. The Windstorm Working Group (WWG), comprised of scientists and program/portfolio leaders, meets approximately once per month to implement the Program. The Interagency Coordinating Committee, comprised of the heads of the four designated Program agencies (FEMA, NIST, NOAA, and NSF), the Office of Management and Budget (OMB), and the Office of Science and Technology Policy (OSTP), meets annually to discuss the direction of the Program and make decisions regarding interagency implementation of the NWIRP Strategic Plan.[5] A detailed history of NWIRP statutory and technical Program activities from FYs 2005 through 2018 has been documented in a series of previous biennial reports to Congress.[6]

The structure of this report is as follows:

- Section 3 presents a brief overview of windstorm impacts during FYs 2019-20.
- Section 4 discusses NWIRP interagency post-windstorm coordination activities during the reporting period.
- Section 5 details agency specific activities in support of the three NWIRP Strategic Goals.
- Section 6 briefly articulates a shared vision for the path forward.
- Appendices include a listing of NWIRP strategic objectives and priorities, detailed descriptions of select agency technical activities, and recent interagency coordinated budget information.

3. Windstorms and Their Impacts in 2019 and 2020

Billion-dollar weather disasters are on the rise in the U.S. with severe weather and tropical systems (e.g., hurricanes) accounting for the majority of the increasing trend in economic losses from 1980-2020. After suffering historically destructive windstorm events in 2017 and 2018, the Nation experienced further increases in frequency and intensity of windstorm impacts in 2019 and 2020 (Figure 1). Over the course of those two years there were 30 windstorm disasters (21 severe storm and nine TC events) with losses

[5] https://www.nist.gov/system/files/documents/2018/09/24/nwirp_strategic_plan.pdf.

[6] NWIRP Biennial Reports to Congress, https://www.nist.gov/el/mssd/nwirp/biennial-reports-congress.

exceeding $1 billion (Consumer Price Index (CPI) adjusted for inflation[7]) for each event across the U.S. The 20 events in 2020 exceeding $1 billion is astonishingly high – nine more events than occurred during the historic years of 2011 and 2017.[8]

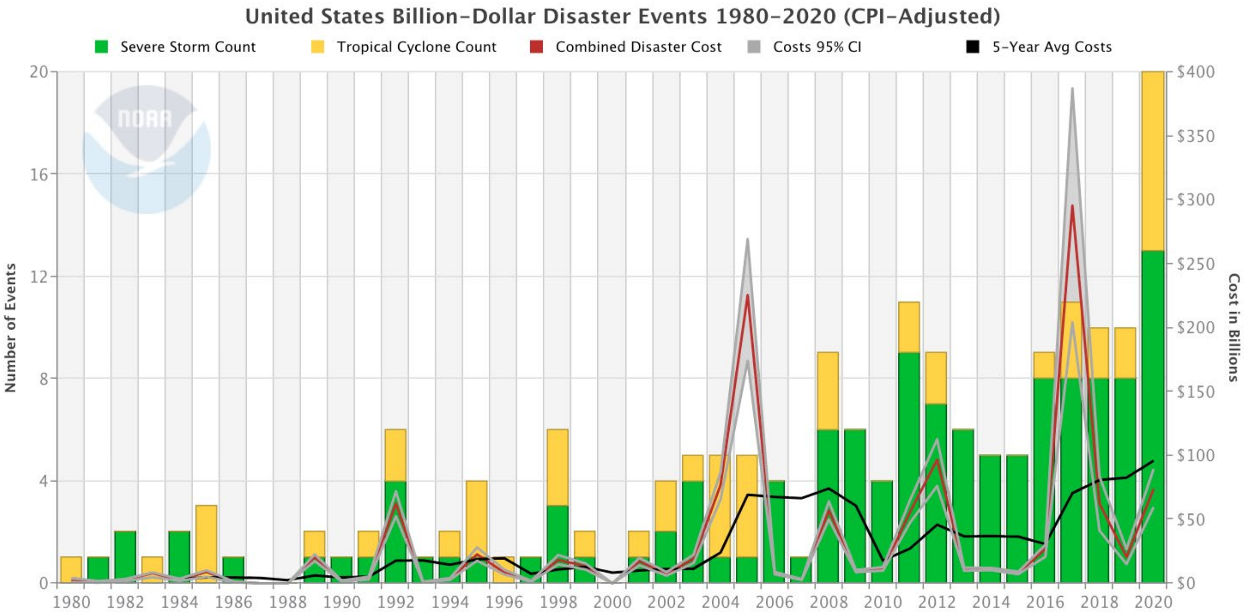


Figure 1. Number of tropical cyclone (yellow) and severe storm (green) events from 1980-2020 exceeding one billion USD (inflation adjusted). The annual cost is in gray and its five-year running mean in black. Source: NOAA.

3.1 2019

Eight severe weather events (e.g., derechos, thunderstorms, hailstorms, and tornadoes) exceeding one billion dollars affected the U.S. in 2019, with most of the activity confined to the east of the Rockies. Although 2019 had less overall TC activity when compared with the record-breaking 2017 and 2018 hurricane seasons during the previous NWIRP reporting period, it was still the fourth consecutive above-average season, with 18 named Atlantic basin storms (6 hurricanes, 3 major) that yielded $11.6 billion in losses and 15 fatalities in the U.S. Hurricane Dorian and Tropical Storm Imelda both exceeded $1 billion dollars in economic damage with Imelda producing up to 36 inches of rainfall over the same area impacted by Hurricane Harvey in 2017, while Hurricane Dorian narrowly missed rivaling the most destructive TCs in U.S. history. After a multiday trajectory toward the Florida coastline, Hurricane Dorian stalled over the Bahamas on September 1, raking the islands with category 5 winds and historic rainfall for over 24 hours before turning northward and impacting the outer banks of North Carolina as a weaker storm. Had Hurricane Dorian made landfall in eastern Florida, as some earlier forecasts had indicated, it would have been the second above design-level wind speed event experienced by the state of Florida in 10 months, the other being Hurricane Michael in October 2018.

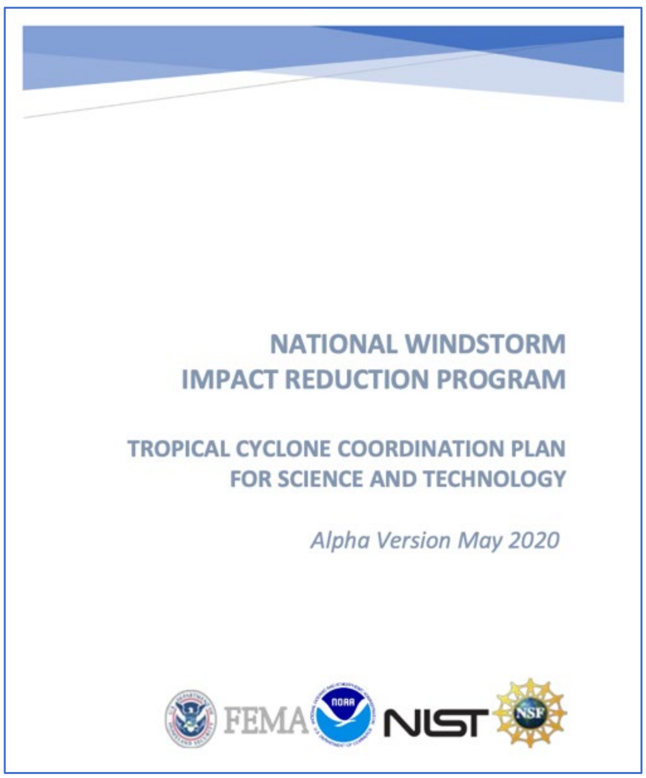
[7] Department of Labor Bureau of Labor Statistics. Historical Consumer Price Index for All Urban Consumers (CPI-U). https://www.bls.gov/cpi/tables/supplemental-files/historical-cpi-u-202109.pdf.

[8] This biennial progress report uses the billion-dollar disasters as the official NWIRP disaster impact metric as tracked by NOAA, a designated Program agency. By design, this metric may not include the totality of windstorm disaster losses in the U.S. However, it provides a comprehensive historical timeseries to track long term variability and trends in windstorm losses.

3.2 2020

The 2020 severe weather and hurricane seasons were both more intense than 2019 with a vast majority of the billion dollar events occurring while the country was being severely challenged by the COVID-19 pandemic. There were 13 separate billion dollar severe weather events (i.e., derechos, thunderstorms, hailstorms, and tornadoes) totaling $34 billion. The largest was the $11 billion August derecho event across the Midwest. The 2020 hurricane season was the fifth consecutive above-average hurricane season in a row and established a new record for most named storms in a season with 30 (14 hurricanes, 7 major), twelve of which made landfall in the U.S. causing 86 fatalities and $40 billion in economic damage. Among the most notable stories of the 2020 hurricane season was the occurrence of 2 hurricane landfalls 12 miles apart in Louisiana, separated by only 6 weeks. Category 4 Hurricane Laura was an above design-level wind speed event that caused significant damage to areas of the Louisiana coast and penetrating tens of miles inland. Six weeks later Hurricane Delta made landfall only 12 miles to the east of where the center of Hurricane Laura crossed the coast. Although Hurricane Delta was a category 2 storm, its impacts were likely magnified by increased societal vulnerability, given that the area was still recovering from Hurricane Laura.

4. Post-Windstorm Coordination During the Reporting Period



In NWIRP's 2015 authorizing legislation (Public Law 114-52) the U.S. Congress directs NIST to "coordinate all Federal post-windstorm investigations, to the extent practicable." Through the NWIRP WWG, several post-windstorm coordination activities were conducted during the reporting period. Chief among these were interagency NWIRP meetings that were held to provide an open forum for interagency information exchange in the aftermath of several weather disasters throughout FYs 2019 and 2020. Additionally, the NWIRP agencies developed an alpha version of a "Tropical Cyclone Coordination Plan for Science and Technology" – a living document that outlines the windstorm coordination roles of the NWIRP agencies across all phases of hurricane disasters from pre- to post-landfall. The TC coordination plan is also being implemented to support the development of interdisciplinary data and technology transfer mechanisms for future hurricane disasters. The record-breaking 2020 hurricane season amidst the COVID-19 pandemic offered an opportunity to test some elements of the plan and identify areas for improvement in future iterations. During the reporting period, the NWIRP agencies also engaged in post-windstorm coordination by collaborating and sharing research and operational products and procedures. Some examples follow.

Hurricane Michael

During Hurricane Michael, NOAA provided NWIRP with accurate storm track forecasts throughout the duration of the storm's lifecycle. NIST and FEMA deployed science and engineering teams in the aftermath of Hurricane Michael, and NIST received a Mission Assignment (MA)[9] from FEMA to produce wind speed hazard maps to support refined estimates of social and economic impacts through FEMA's Hazus catastrophe modeling system. The maps were also disseminated through FEMA's public disaster geodatabase website[10] and to the various Extreme Event Reconnaissance research groups supported by NSF engaged in conducting field studies in the aftermath of Hurricane Michael, through the NSF-supported DesignSafe-CI Recon Portal.[11] All four NWIRP agencies either developed or supported post-event science and technology reports on Hurricane Michael. The post-event NWIRP coordination call reinvigorated discussion regarding a longstanding issue with obtaining the requisite spatial and temporal resolution wind and water hazard measurements in landfalling hurricanes, and the impacts that these measurement science gaps have across the range of the NWIRP research-to-applications paradigm.

2019 and 2020 Tornado Outbreaks

NWIRP held interagency post-windstorm coordination meetings in the aftermath of the 2019 and 2020 spring tornado outbreaks. NOAA provided comprehensive meteorological overviews and furnished NWIRP with statistics of the event impacts, including a presentation on the meteorological characteristics of the tornadoes and an update on how NOAA is using social science research to improve tornado warnings and other communications related to tornado threats. NIST and FEMA shared information on their evaluations of the impacts to the built environment and compared aspects of these tornado outbreaks to what has been learned from past tornado investigations (e.g., the 2011 Joplin tornado), including the relevance to tornado design mapping for the U.S. University scientists also collected valuable wind measurement data as part of an NSF-supported field campaign.

Hurricanes Laura and Delta

On September 9, 2020 NWIRP held a special coordination meeting for Hurricane Laura – the second above design-level wind event to strike the Gulf Coast of the U.S. during the reporting period (see Appendix C). As opposed to Hurricane Michael, which had above design-level wind speeds extending from the coast into southwestern Georgia, the above design-level wind speeds from Hurricane Laura only occurred well inland of the coast, because the coastal areas of Louisiana have much stronger design wind speed standards when compared to the coastal regions of the Florida panhandle. The coordination meeting allowed the NWIRP WWG to share hazard and impact information and for the first time implement the alpha version of the NWIRP TC Coordination Plan for Science and Technology. A notable impact is that during Hurricane Laura the Lake Charles Doppler Radar System was destroyed, leaving the area challenged in detecting the intensity of subsequent extreme weather systems. Six weeks later the center of Hurricane Delta made landfall a mere twelve miles from the location where Hurricane Laura came ashore. To fill in the radar monitoring gap, a team from the University of Oklahoma, which originally planned to conduct critical wind measurement science research in landfalling hurricanes as part of a NIST-funded Disaster Resilience grant, deployed to

[9] https://www.fema.gov/sites/default/files/2020-04/MA_Policy_aug172018.pdf.

[10] https://disasters.geoplatform.gov/publicdata/NationalDisasters/2018/HurricaneMichael/Data/ARA_WindModel/.

[11] https://www.designsafe-ci.org/recon-portal/?event=2018%20Hurricane%20Michael.

Louisiana in advance of Hurricane Delta. The team volunteered to delay their critical research endeavors, opting instead to reconfigure their radar from research to operational mode to provide needed operationally-relevant observations to inform rainfall and wind hazard awareness and facilitate emergency communications throughout the storm.

Impact of the COVID-19 Pandemic

Federal agency responses to the extreme weather events in 2020 that included a combination of springtime severe weather events and a record-breaking hurricane season were significantly impacted by the COVID-19 pandemic. The pandemic yielded numerous unprecedented logistical, scientific research, and operational challenges. Due to travel restrictions across the Nation, NWIRP agencies were unable to send scientific investigative teams to continue longitudinal data collection from previous disasters (e.g., Hurricanes Matthew and Florence) or assess the impacts from 2020 extreme weather events, including tornado outbreaks in the southeastern states, the derecho in the Midwest, and the compound disaster in Louisiana from Hurricanes Laura and Delta. Additionally, NOAA noted that the National Hurricane Center (NHC) had minimal staffing on location during 2020, at times challenging optimal coordination with stakeholders. Given the unprecedented number of TCs in the Atlantic basin during 2020, NOAA had a record number of 58 P3 (hurricane mission storm) and 29 G4 (gulf storm) flights, about 45-50% above an average year.

5. Progress in Fiscal Years 2019 and 2020

The NWIRP agencies initiated implementation of the NWIRP Strategic Plan (released in late FY 2018) by focusing on advancing agency relevant strategic objectives across the Plan's three strategic goals. These goals form a two-way research-to-applications paradigm that focuses on improving fundamental understanding of windstorm morphology, advancing understanding of impacts to the built environment and related social and economic recovery mechanisms, and deployment of this basic and applied research to improve the resilience of communities nationwide. In this section of the report, the NWIRP agencies provide brief descriptions of activities that support the goals of the NWIRP Strategic Plan. Each entry also includes relevance to the 14 objectives and 8 strategic priorities which underpin the goals of the NWIRP Strategic Plan.[12] In addition to the agency-specific activities outlined below, the NWIRP agencies held two meetings of the NWIRP Interagency Coordinating Committee during FY 2020 to exchange information and support NWIRP principal decisions on programmatic strategy.

5.1 Goal A: Improve the Understanding of Windstorm Processes and Hazards

NIST: Topographic Effects on Wind Speeds. As part of its Hurricane Maria Program, NIST continued to make progress investigating the influence of topography on surface-level wind speeds in Puerto Rico. During FY 2020, NIST conducted wind tunnel testing and computational fluid dynamics (CFD) 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. NIST also deployed anemometers on three cell towers in the Yabucoa region of Puerto Rico, at sites where the surrounding topography produces significant increases in wind speeds, to provide real-world data for evaluation of topographic effects and for validation of the wind tunnel and computational models. *(Objectives 1, 2, 4, 6)*

[12] See Appendix B for list of NWIRP strategic objectives and priorities.

NIST/NRC: Tornado Hazard Maps. In collaboration with the Nuclear Regulatory Commission (NRC), NIST completed the methodology for development of a new generation of tornado hazard maps intended for use in tornado-resistant design of new buildings and structures and for risk assessment of existing facilities. The draft tornado hazard maps were presented at a stakeholder workshop in May 2019 and final versions of the maps were nearing completion by the end of the current reporting period. *(Objective 4)*

NIST: Windstorm Hazard Measurement Science. As part of its broader Disaster Resilience Grants Program, NIST awarded $2.24 million across four universities to deploy mobile and in situ observational systems to augment wind hazard data collection in extreme weather events and to conduct post-windstorm scientific analyses to improve understanding of the wind hazard environment at engineering relevant scales. Additionally, NIST held a virtual Windstorm Extreme Events Reconnaissance Workshop in July 2020 to explore strategies for a sustained effort to collect integrated observations of meteorological extremes. *(Objectives 1, 2, 3, 4, 5; Strategic Priorities 2, 3)*

NOAA: New Observing Technologies. New observing technologies such as the uncrewed aerial system that gathers data in the lower atmosphere, and the Doppler wind lidar, which provides the capability to sample winds in precipitation-free regions that radars cannot measure, were tested and demonstrated as a part of NOAA's Intensity Forecasting Experiment (IFEX) in FY 2019. Due to the global pandemic, NOAA was unable to continue testing these technologies in FY 2020. The National Severe Storms Laboratory (NSSL) is demonstrating the capabilities of the Phased Array Radar (PAR). The last few years of research and development have been focused on the installation, calibration, and initial data collection using the Advanced Technology Demonstrator, a full-scale demonstration radar capable of assessing the ability of phased array technology to address the operational meteorological requirements of the National Weather Service (NWS). (*Objective 2; Strategic Priority 2)*

NOAA/NIST/FEMA/NASA/NRC/ASCE/AMS: Tornado Wind Speed Estimation. NWS and NIST co-chair an American Society of Civil Engineers (ASCE)/Structural Engineering Institute (SEI)/American Meteorological Society (AMS) Tornado Wind Speed Estimation (TWSE) Standards Committee that developed a new standard on *Wind Speed Estimation in Tornadoes and Other Windstorms*. Other federal agencies include FEMA, NRC, and National Aeronautics and Space Administration (NASA). The TWSE committee is charged with developing improvements to the Enhanced Fujita (EF) Scale that cover concerns raised in the years following its inception, with a host of enhancements to the Scale's damage indicators to improve techniques for post-storm assessment and information gathering. Draft provisions for the EF Scale and other wind speed estimation methods covered in the standard have been developed and vetted through the committee approval process, with the goal of completing the public comment version within the next two years. (*Objective 2)*

NOAA: Toward Seasonal Prediction and Long-term Severe Weather Variability. Since 2012 the NWS Storm Prediction Center (SPC) has worked with the NWS Climate Prediction Center (CPC), academia, and the NOAA NSSL to improve understanding of the links between large-scale climate variability and windstorm and tornado activity. Studies of 40 years of high-resolution reanalyses[13] show that stronger convective inhibition has caused a decline in the frequency of thunderstorm environments over the southern

[13] https://journals.ametsoc.org/view/journals/bams/102/2/BAMS-D-20-0004.1.xml.

U.S., particularly in summer. Conversely, increasingly favorable conditions for tornadoes have been observed during winter across the Southeast. (*Objective 3)*

NOAA: Intensity Forecasting Experiment. NOAA's Hurricane Research Division continues to improve hurricane-intensity forecasting through the IFEX. In FY 2019, the focus was on sampling storms that underwent rapid intensification as this was an NHC science priority. FY 2020 proved to be a hyperactive hurricane season where NOAA aircraft sampled a record number of storms. *(Objective 3)*

NSF: Targeted Observation by Radars and UAS of Supercells (TORUS). NSF is funding a major field campaign aimed at understanding storm structures that may be attributed to tornadogenesis. The research team comprises scientists from multiple universities and NOAA. *(Objectives 1, 3; Strategic Priority 2)*

NSF: Major New Field Study of Extreme Rainfall. NSF is funding multiple universities to participate in an international field campaign examining the dynamics, thermodynamics, and microphysics of extreme rainfall generated in locations where hurricane/typhoon/monsoon flows occur frequently and interact with orography. *(Objectives 1, 3; Strategic Priorities 2 and 8)*

NSF: Field Study of how Wind Interacts with California Wildfires. NSF is funding the multi-university Sundowner Winds Experiment to improve understanding of downslope, gusty windstorms, which are recognized as important drivers of wildfire behavior in coastal settings. *(Objectives 1, 3)*

NSF: Rapid-Response Studies Following Windstorms. NSF funded researchers to undertake work that could only be conducted in the immediate aftermath of several major windstorms, including: the Easter Sunday 2020 tornadoes; wind-rainfall interaction in Hurricanes Florence and Michael; and the U.S. Midwest 2020 derecho. *(Objectives 1, 3, 4)*

NSF: Multi-year research projects examining fundamental principles in windstorms. NSF funded multi-year projects to improve understanding of supercell storms through data science: a study of hurricane-generated tornadoes; a wind-wave tank study of air-sea interaction in hurricanes; and an examination of how planetary boundary layer heterogeneities impact tornadic storms during storms/tornadoes. *(Objectives 1, 2, 3)*

NSF: Services and support for academic and agency atmospheric research. NSF funds the National Center for Atmospheric Research (NCAR) **(**https://ncar.ucar.edu/). NCAR provides essential services and support for the entire U.S. atmospheric research enterprise, both academic and federal. Of particular note during this reporting period, NCAR provided data services to NOAA for the Congressionally mandated VORTEX-SE program which studies tornadogenesis in the Southeast U.S. *(Objectives 1, 2, 3)*

NSF: New methods for windstorm hazard research. https://www.designsafe-ci.org/facilities/experimental/ Researchers using experimental facilities at the NSF-supported Natural Hazards Engineering Research Infrastructure (NHERI) demonstrated that real-time hybrid simulation methods, which have previously been applied to study seismic effects, are also appropriate for wind response simulation for tall buildings. This methodological advance will enable new types of studies of windstorm processes and hazards. *(Objectives 2, 4)*

5.2 Goal B: Improve the Understanding of Windstorm Impacts on Communities

FEMA: Mitigation Assessment Team (MAT) Program: FEMA conducts building performance studies after unique or nationally significant disasters to better understand how natural events affect the built environment. The 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 considering 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. FEMA conducted a MAT for Hurricane Michael and a final report was published in February 2020 (FEMA P-2077). In FY 2020, FEMA also deployed a MAT for Typhoon Yutu in the Commonwealth of the Northern Mariana Islands. Typhoon Yutu made landfall in October 2018, but still had damage left to investigate in 2020. *(Objective 5)*

FEMA: Hazus Hurricane Loss Estimation Model: FEMA develops and maintains the Hazus model, 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 damages from Hurricane's Irma and Maria, FEMA is developing 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 also will 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.

NIST received a MA from FEMA to develop hurricane wind speed maps based on available wind speed readings from instruments and observed levels of damage. These wind speed maps will ultimately improve the Hazus Hurricane Loss Estimation Model. *(Objective 9)*

NIST: Tornado Loads on Buildings. NIST developed a new methodology for determination of tornado loads on buildings, accounting for differences in hazard characteristics between tornadoes and other windstorms. Key parameters include revision to the exposure factor to address the bull-nose shaped velocity profile near the core of the tornado (as opposed to the boundary layer profile in straight line winds), an expanded internal pressure coefficient that accounts for the effects of atmospheric pressure change, and a new coefficient that reflects the increased roof uplift in tornadoes caused by strong updrafts. *(Objective 5)*

NIST: Science-Based Methodologies for Aerodynamic Simulation to Determine Wind Loads on Buildings and Structures. NIST is engaged in an effort to develop practical CFD methods for the numerical determination of aerodynamic forces on structures induced by strong winds. Progress during FYs 2019-20 included a review of verification, validation, and uncertainty quantification procedures in CFD simulations to produce more accurate, site-specific wind loads, resulting in safer and more economical structures. *(Objectives 5, 6)*

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 the response of these structures to extreme winds to advance performance-based design standards. During FYs 2019-20, in partnership with a private structural engineering firm, NIST developed preliminary ETABS-based software allowing the effective use of the Database-Assisted Design (DAD) procedures by structural engineering practitioners. *(Objectives 5, 6)*

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 NIST and 14 universities led by Colorado State University. During FYs 2019-20 multi-disciplinary models were developed for the 2011 Joplin tornado impacts and recovery. *(Objectives 5, 7; Strategic Priority 3)*

NIST: Longitudinal Study of the Recovery of Lumberton, NC, from Hurricane Matthew: NIST conducted its third data collection in FY 2019 focused on documenting the impacts of Hurricane Florence and the ongoing recovery from Hurricane Matthew for housing, businesses, and the public sector. The fourth data collection was delayed by the COVID-19 pandemic. *(Objectives 5, 7, 8)*

NIST: Hurricane Maria Program: In FYs 2019-20 NIST continued its multi-year investigation of the impacts of Hurricane Maria on Puerto Rico, including projects focused on performance of critical buildings, emergency communications, morbidity and mortality, and recovery of business supply chains, social functions, and infrastructure systems. The findings will support recommendations for changes to codes, standards and practices for the purpose of increasing community resilience in the face of hurricanes *(Objectives 1-14)*.

NOAA: State of Florida Public Hurricane Loss Model (FPHLM).[14] NOAA continues to work on the FPHLM, 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. NOAA researchers at the Atlantic Oceanographic and Meteorological Laboratory (AOML) and the Cooperative Institute for Marine and Atmospheric Studies partnered with Florida International University researchers to update and maintain the wind model. Analysis of Hurricanes Isaias and Sally that affected Florida are underway. *(Objective 9)*

NSF: Structural Extreme Events Reconnaissance (StEER).[15] This NSF-supported research network developed quick-response datasets and reconnaissance reports for 20 windstorm events (hurricanes, tornadoes and cyclones) during the FYs 2019-20 reporting period. The reports are free and available at https://www.steer.network/products. *(Objectives 5, 8; Strategic Priority 3)*

NSF: Wind Hazard and Infrastructure Performance (WHIP) Center.[16] NSF funded a new, multi-university Industry-University Cooperative Research Center (IUCRC) that addresses NWIRP-relevant research questions. The WHIP Center's Industry Advisory Board members are drawn from insurance, risk-modeling, and construction industries. The Board aims to ensure that WHIP research pertains to real-world

[14] https://fphlm.cs.fiu.edu/.

[15] https://www.steer.network/.

[16] https://www.whipc.org/.

problems, that transfer of new knowledge from research to practice is expeditious, and that long-term strategies to enhance windstorm resilience are developed. *(Objectives 5, 7, 9)*

NSF: Natural Hazards Engineering Research Infrastructure (NHERI). In the face of the 2020 COVID-19 pandemic, the NSF-funded NHERI network of major, disaster-relevant research facilities – including wind tunnels, cyberinfrastructure, post-disaster field equipment, and educational assets – undertook significant effort to ensure both continued operation and safety. NHERI developed and released a new, interdisciplinary data model for natural hazards field research. For the first time, social and behavioral scientists, engineers, and members of interdisciplinary teams have a data model they can use independently or in collaborative projects. The model can be used to share and publish qualitative, quantitative, and mixed-methods field research data specific to hazards and disasters. With the new data model, researchers can curate and publish preliminary field reports, field data, research protocols, and research instruments. NHERI's user workshops, summer institute, and public outreach were converted to on-line formats. *(Objectives 5, 6, 7)*

5.3 Goal C: Improve the Resilience of Communities Nationwide

FEMA: Improving Wind-Resistant Provisions. Significant improvements have been made to model building codes and national standards pertaining to design and construction of windstorm-resistant buildings and other structures as the result of Program activities. FEMA continually defends provisions that mitigate damage from all natural disasters including high winds and proposes changes based on findings from post-disaster investigations such as the MAT reports. (*Objective 5*)

FEMA developed 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 7-22, International Code Council (ICC) 500-2020: *Standard for the Design and Construction of Storm Shelters*, ICC 600-2020: *Standard for Residential Construction in High-Wind Regions*. FEMA will continue these and other efforts to improve wind-resistant provisions of codes and standards. *(Objective 11 and Strategic Priority 7)*

FEMA: Education, Outreach, and Information Dissemination. The FEMA website, http://www.fema.gov, serves as an important portal to emergency and disaster information. FEMA publications related to wind and coastal surge hazards are available for free on the web on FEMA's website, the Google Books website, and MADCAD. Conference participation, presentations, and outreach were limited in FY 2020 due to COVID-19. A virtual presentation was given highlighting the structural provisions of hurricane and tornado safe rooms and several presentations on the Building Codes Save study released in FY 2020. FEMA also provides in-person and online training based out of the Emergency Management Institute (EMI) in Emmitsburg, MD. FEMA has developed two new advanced wind-related modules for training courses at EMI. FEMA prepared fact sheets with resources for wind mitigation for the regions after the FY 2020 hurricanes and derecho in the Midwest. FEMA began planning for an increased fraction of education and outreach activities in subsequent fiscal years to be conducted virtually as the pandemic continued.

FEMA publications presenting design and construction guidance for safe rooms have been available since 1998 and were being updated during FY 2020 for release in early 2021. Over one million copies have been distributed and thousands of safe rooms have been built. A growing number of these safe rooms have already saved lives in actual events. There has not been a single reported failure of a safe room constructed to FEMA criteria. *(Strategic Priority 8)*

FEMA: Wind Resistant Construction. FEMA Building Science has promoted long-term wind resiliency in the USVI and Puerto Rico following major disaster declarations after Hurricane Irma (DR-4335) and Hurricane Maria (DR-4340) for the USVI, 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 that continued in FY 2020. *(Objective 12)*

NIST/FEMA: Storm Shelter Standard. NIST and FEMA staff serve on the committee (chaired by a NIST staff member) that is developing the third edition of the ICC/National Storm Shelter Association (NSSA) *Standard for the Design and Construction of Storm Shelters (ICC 500)*. NIST and FEMA submitted dozens of successful change proposals, including revisions to better address installation of shelters in existing buildings, loads from debris impact, load combinations, and a new appendix on storm shelter operations. *(Strategic Priority 7)*

NIST: Translating R&D Advances into Model Building Codes and Standards. The ASCE 7 Tornado Task Committee (chaired by a NIST staff member) developed a series of 25 proposals that together add tornado loads into the ASCE 7-22 Standard for Minimum Design Loads and Associated Criteria for Buildings and Other Structures, incorporating NIST's new tornado hazard maps (see Goal A) and tornado load methodology (see Goal B). NIST, in collaboration with private sector partners, proposed new ASCE 7 wind speed velocity profiles that incorporate the latest advances in boundary layer meteorology, important for design of tall buildings and towers. *(Objective 11)*

NIST: Emergency Communications. Continuing its research to develop the measurement science that provides the foundation for national codes, standards, and guidance on the creation and dissemination of clear, consistent, and accurate emergency communications for tornadoes and other hazards, NIST published peer-reviewed guidance on alerts and warnings using short messaging channels[17] and a study of impacts of the Joplin tornado on alerts and warnings in the U.S.[18] NIST guidance on the usage of outdoor siren systems and short message alerting systems was incorporated as a new Annex K in the 2019 edition of the National Fire Protection Association (NFPA) 1600: Standard on Continuity, Emergency, and Crisis Management. *(Objective 14)*

NOAA: Forecast Improvement Programs.

- The Hurricane Forecast Improvement Program (HFIP) major development focus in 2019 was on building the next generation Hurricane model - Hurricane Analysis and Forecast System (HAFS), primarily for track and intensity predictions. *(Objective 13)*

- Three new projects were conducted at the Joint Hurricane Testbed (JHT) in Miami, Florida – a NOAA testbed jointly managed by the NHC and AOML which involved testing of new techniques, applications, and ensemble model enhancements to improve the analysis and prediction of TCs. *(Objective 13)*

[17] J. Sutton, E. Kuligowski, Alerts and warnings on short messaging channels: guidance from an expert panel process, Nat. Hazards Rev. 20 (2019). https://doi.org/10.1061/(ASCE)NH.1527-6996.0000324.

[18] Kuligowski, E.D. Field research to application: a study of human response to the 2011, Joplin tornado and its impact on alerts and warnings in the USA. Nat Hazards 102, 1057–1076 (2020). https://doi.org/10.1007/s11069-020-03945-6.

- NSSL continues extensive work within NOAA testbeds and with operational units to evaluate an experimental Warn on Forecast (WoF) methodology, allowing forecasters to use thunderstorm-resolving computer models. *(Objective 13)*

- NOAA continues to develop a next generation hazardous weather forecast/warning paradigm called Forecasting a Continuum of Environmental Threats (FACETs), which will provide users a continuously updating suite of probabilistic information about hazardous weather threats. *(Objective 13)*

- Scientists at the NOAA Earth System Research Laboratories (ESRL)/Global Systems Laboratory (GSD) have developed a radar-initialized, thunderstorm-resolving, high-resolution, hourly-updating assimilation and modeling system, through the High Resolution Rapid Refresh (HRRR) model. Improvements will continue to be added in Version 3, including 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. *(Objective 13)*

- The StormReady Program supports a Weather-Ready Nation (WRN) by preparing communities for the occurrence of high impact environmental events, celebrating its 20 year anniversary back in 2018. Each year, the NWS targets 100 new StormReady communities, pending funding availability. In FY 2020 there were 106 new StormReady communities recognized. *(Objective 14)*

NSF: Social, Behavioral, and Economic insights for Resilience. NSF funded a number of multi-year projects to improve understanding of how social, behavioral, and economic factors influence decisions relevant to community resilience, including: factors that affect decisions to relocate from flood-prone locations; how certain traits of visualizations and media messages affect decisions about hazard mitigation and response; and how people make decisions when confronting multiple hazards simultaneously, as when they face both a pandemic and impending hurricanes. *(Objectives 7, 12, 14)*

NSF/NIST: New Joint Disaster Resilience Research Grants (DRRG) Program. NSF and NIST launched a joint competition – DRRG (NSF 20-581) -- to advance fundamental understanding of disaster resilience in support of improved, science-based planning, policy, decisions, design, codes, and standards. Of several hundred project ideas submitted, about a third were focused on windstorm and relevant to NWIRP goals. *(Objectives 1-14)*

NSF: Innovations for Improved Community Resilience. NSF opened a new funding opportunity -- the CIVIC Innovation Challenge (NSF 20-562) – which flips the usual community-university dynamic by asking communities to identify priorities ripe for innovation then partner with researchers to address those priorities. The initial stage-one planning grant competition attracted several hundred natural hazards/disasters proposals, including many that were focused on coastal storms, surge and inland flooding. *(Objectives 10, 12, 13, 14)*

NSF: Researchers and Communities Collaborating to Define Needs and Opportunities. The NHERI Computational Modeling and Simulation Center held a January 2020 workshop on “Simulation and Data Needs to Support Disaster Recovery Planning” where researchers and community stakeholders developed recommendations for future computational simulation tools to better support government agencies and other organizations as they promote resilience from natural disasters. Recommendations included a flexible computation workflow framework and testbed studies of natural disaster risk and recovery. *(Objectives 12, 14)*

6. The Path Forward

As windstorm impacts increase, it is critical that NWIRP agencies continue to implement the NWIRP Strategic Plan and identify new opportunities for improved synergy across scientific disciplines, interagency engagement, and education and outreach to amplify NWIRP awareness. Provided below are NWIRP priorities for advancing this shared vision.

- Expand awareness of the NWIRP research-to-applications paradigm across the federal enterprise by engaging in interagency councils, committees, and working groups with equities in windstorm impact reduction measures, including but not limited to, the interagency Council for Advancing Meteorological Services (ICAMS), the U.S. Global Change Research Program (USGCRP), the National Science and Technology Council (NSTC)'s Subcommittee on Resilience Science and Technology (SRST), and the Science for Disaster Reduction (SDR) interagency working group.
- Strengthen NWIRP post-windstorm assessments by supporting federal coordination with university-based researchers and leverage disaster reconnaissance data streams to advance interactive technology transfer based on the NWIRP TC Coordination Plan for Science and Technology. This will enable the identification of high priority applied research questions that are unique to the interdisciplinary windstorm disaster reduction field. Additionally, NWIRP post-disaster research guidance will acknowledge and support efficient and effective formal and informal collaborations and support investments to recruit and enable a world-class next generation of U.S.-based windstorm-relevant researchers.
- Strengthen cross disciplinary linkages between climate scientists and engineers by exploring the utility and application of fully-coupled climate model projections to understand climate change impacts on extreme weather to inform the development of forward-looking national structural design standards and model building codes, and to support NWIRP agency roles in national climate priorities.
- Support the implementation of recommendations from interagency post-windstorm research and development activities to improve hazard measurement science, advancing the Nation towards performance-based design, and strengthening the scientific foundation for the development of consensus codes and standards. For example, promoting life-safety protection measures for tornado impacts in products developed by national and international standards development organizations.
- Contribute to building a Weather-Ready Nation by integrating scientific advances in real-time extreme weather event forecasting and social science by delivering newly developed emergency communication and life safety warning information to the public through cell phone networks in support of impact-based decision support services.
- NWIRP will ensure that the U.S. non-governmental science and engineering communities are made aware of NWIRP-relevant Federal Science and Technology reports, studies, and priority-setting documents, while the NWIRP agencies will stay abreast of university-based findings and promising new research approaches to strengthen coordination and shared awareness to enable more impactful work.

Appendix A: Acronyms and Abbreviations

AMS	American Meteorological Society
AOML	Atlantic Oceanographic and Meteorological Laboratory
ASCE	American Society of Civil Engineers
CFD	Computational Fluid Dynamics
COVID-19	Coronavirus Disease of 2019
CPC	Climate Prediction Center
CPI	Consumer Price Index
DAD	Database-Assisted Design
DRRG	Disaster Resilience Research Grants
EF	Enhanced Fujita [Scale]
EMI	Emergency Management Institute
ESRL	Earth System Research Laboratories
FACETs	Forecasting a Continuum of Environmental Threats
FEMA	Federal Emergency Management Agency
FPHLM	Florida Public Hurricane Loss Model
FY	fiscal year
GSD	Global Systems Laboratory
Hazus	Hazards U.S., a Geographic Information System (GIS)-based natural hazard analysis tool developed and distributed by FEMA
HAFS	Hurricane Analysis and Forecast System
HFIP	Hurricane Forecast Improvement Project
HRRR	High Resolution Rapid Refresh
ICC	International Code Council
IUCRC	Industry-University Cooperative Research Center
IFEX	Intensity Forecasting Experiment
JHT	Joint Hurricane Testbed
MA	Mission Assignment
MAT	Mitigation Assessment Team
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCST	National Construction Safety Team
NFPA	National Fire Protection Association
NGGPS	Next Generation Global Prediction System
NHC	National Hurricane Center
NHERI	Natural Hazards Engineering Research Infrastructure
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	Nuclear Regulatory Commission
NSF	National Science Foundation
NSSA	National Storm Shelter Association

NSSL	National Severe Storms Laboratory
NSTC	National Science and Technology Council
NWIRP	National Windstorm Impact Reduction Program
NWS	National Weather Service
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PAR	Phased Array Radar
R2O	Research to Operations
SDR	Science for Disaster Reduction
SEI	Structural Engineering Institute
SIP	Strategic Implementation Plan
SPC	Storm Prediction Center
StEER	Structural Extreme Events Reconnaissance
TC	tropical cyclone
TORUS	Targeted Observation by Radars and UAS of Supercells
TWSE	Tornado Wind Speed Estimation
UFS	Unified Forecast System
U.S.	United States
USVI	U.S. Virgin Islands
VORTEX-SE	Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast
WHIP	Wind Hazard and Infrastructure Performance
WWG	Windstorm Working Group
WoF	Warn on Forecast
WRN	Weather-Ready Nation

Appendix B: NWIRP Strategic Goals, Objectives, and Priorities

Goal A. Improve the Understanding of Windstorm Processes and Hazards

Objective 1: Advance understanding of windstorms and associated hazards

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

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

Objective 4: Develop tools to improve windstorm hazard assessment

Goal B. Improve the Understanding of Windstorm Impacts on Communities

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

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

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

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

Objective 9: Develop advanced risk assessment and loss estimation tools

Goal C. Improve the Windstorm Resilience of Communities Nationwide

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

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

Objective 12: Promote the implementation of windstorm-resilient measures

Objective 13: Improve windstorm forecast accuracy and warning time

Objective 14: Improve storm readiness, emergency communications and response

Strategic Priorities

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 Field

Appendix C: Detailed NWIRP Agency Activities

NIST

NIST Hurricane Maria Program

On September 20, 2017, Hurricane Maria had a devastating impact on much of Puerto Rico, damaging buildings that its communities relied upon for medical care, safety, communications, education, business, and more. In 2018, NIST launched a multi-year effort to study this disaster across seven scientific research projects with the goal of making recommendations to encourage the widespread adoption of improved building codes, standards, and practices that would make communities in Puerto Rico and across the U.S. more resilient to hurricanes and other hazard events. The NIST Hurricane Maria Program is conducted under two authorities, the National Construction Safety Team Act (NCSTA) and the NWIRA. Figure 3 shows the grouping of the various research projects with the attendant legislative authority. However, as complementary components of the NIST

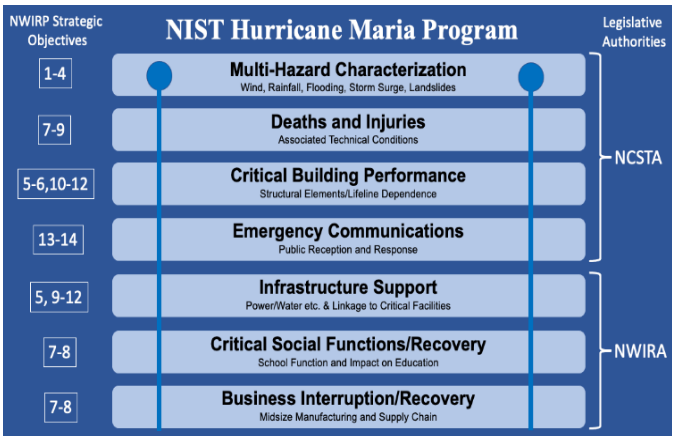


Figure 3. The projects comprising the NIST Hurricane Maria Program

Hurricane Maria Program, the National Construction Safety Team technical investigation and the NWIRP research study are closely coordinated and despite the distinct project groupings, the research foci span all 14 objectives contained within the NWIRP Strategic Plan, as indicated on the left side of Figure 3.

NIST Hurricane Wind Mapping Products

Since the 2017 hurricane season, NIST has collaborated with Applied Research Associates, Inc. (ARA) to develop surface wind speed mapping products showing the maximum estimated wind speed of hurricanes as they move inland. These maps are created through FEMA MAs. The wind speed maps serve as critical input data to FEMA's Hazus catastrophe modeling system. The maps and underlying data are also distributed to a broad group of disaster researchers throughout the public, private, and academic sectors.

During the reporting period, wind speed maps were produced for several hurricanes and notable improvements to the map product suite have occurred with each successive storm. Chief among these is the comparison of a given hurricane's event wind speeds with those from the ASCE 7-16 design level wind speed standard, which are broadly used to support and guide civil engineering design. Figure 4 shows the wind speed maps for two major hurricanes that made landfall along the Gulf Coast during the reporting period - category 5 Hurricane Michael and category 4 Hurricane Laura. Both of these storms are notable for causing catastrophic wind and storm surge damage and with the aid of the wind mapping products have been classified as above design-level events. The shaded areas (warm colors) in both of the maps depict where the estimated surface wind speed is estimated to be above that of the ASCE 7-16 design level. In Hurricane Michael, above design-level wind speeds were observed from the coast penetrating well into southwestern Georgia. Hurricane Laura had a different pattern, with winds slightly below design level near the coast (blue shading), however well above design level well inland (pink/red shading).

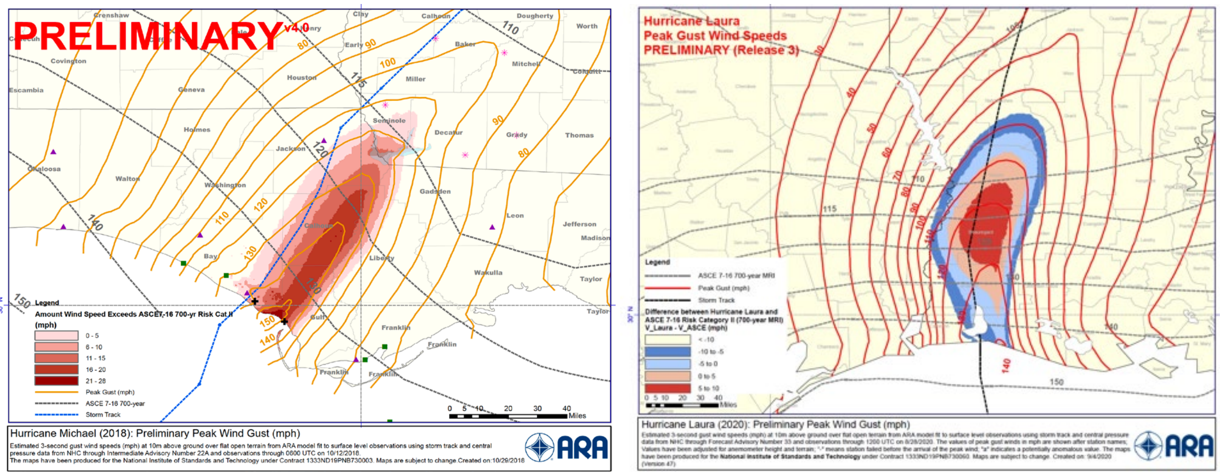


Figure 4. Surface wind speed mapping products for Hurricane Michael (left) and Hurricane Laura (right). Areas shaded in pink/red indicate where wind speed exceeded ASCE 7-16 design level for risk category II buildings.

NOAA

NOAA Hurricane Forecast Improvement Program. The HFIP was established within NOAA in 2007, in response to devastating hurricanes such as Charley in 2004, and Wilma, Katrina, and Rita in 2005 to accelerate the improvement of forecasts and warnings of TCs and to enhance mitigation and preparedness by increasing confidence in those forecasts. One of the key strategies defined in the revised HFIP plan in response to the proposed framework for addressing Section 104 of the Weather Research Forecasting Innovation Act of 2017, is to advance an operational HAFS at NOAA/NWS. HAFS will be a multi-scale model and data assimilation package capable of providing analyses and forecasts of the inner core structure of the TC out to seven days, which is key to improving size and intensity predictions, as well as the large-scale environment that is known to influence the TC's motion. HAFS will provide an operational analysis and forecast system out to seven days for hurricane forecasters with reliable, robust and skillful guidance on TC track and intensity, storm size, genesis, storm surge, rainfall and tornadoes associated with TCs. It will provide an advanced analysis and forecast system for cutting-edge research on modeling, physics, data assimilation, and coupling to earth system components for high-resolution TC predictions within the outlined Next Generation Global Prediction System (NGGPS)/Strategic Implementation Plan (SIP) objectives of the Unified Forecast System (UFS).

One of the major accomplishments of the 2020 hurricane season was the advancement and real-time testing of four basic configurations of FV3-based, NOAA’s next-generation HAFS including three regional configurations (including an 11 member-ensemble) and one global nested configuration. Led jointly by developers at NWS/NCEP and OAR/AOML and supported by NCAR/DTC, these efforts will efficiently and effectively transition the latest advances to operations for Hurricane models in 2021 and serve as prime examples of successful community-driven R2O efforts for the broader UFS community. More information on HFIP and HAFS real-time experimental products can be found at the HFIP website: http://hfip.org/.

NOAA Warn-on-Forecast Program. WoF is a NOAA research program tasked to increase tornado, severe thunderstorm, and flash flood warning lead times. Increasing the lead time and accuracy for hazardous weather and water warnings and forecasts, in order to reduce loss of life, injury, and damage to the economy, is one of the strategic goals of NOAA. Trends in yearly-averaged tornado warning lead time suggest that the present weather warning process, largely based upon a warn-on-detection approach using NWS Doppler radars, is reaching a plateau and further increases in lead time will be difficult to obtain. A new approach is needed to extend effective lead time. This will involve probabilistic hazard guidance provided by an ensemble of forecasts from convection-resolving numerical weather prediction models.

Researchers at NOAA's NSSL are developing WoF to improve forecasts, warnings, and decision support for high-impact thunderstorm events within the watch-to-warning time frame, 0-6 hours in advance of an event. WoF is designed to provide accurate predictions of thunderstorm hazards—like tornadoes, hail, wind, and flash flooding—to people who need them earlier than is currently possible with detection based techniques. The fundamental concept of WoF is to provide continuous, probabilistic predictions of hazards in individual thunderstorms. WoF is an important component of FACETs, or Forecasting a Continuum of Environmental Threats. FACETs aims to provide continuous probabilistic hazard information guidance to the public from time frames of multiple weeks through less than one hour. NOAA is using social and behavioral science to evaluate this probabilistic hazard information and how to best communicate this information to the public.

In addition to real-time demonstrations, WoF guidance has been tested within NOAA's Hazardous Weather Testbed by researchers, and forecasters as a part of the annual Spring Forecast Experiment, as a part of the Hydrometeorological Testbed, and presented to emergency managers within the HWT for the first time in spring 2019. The feedback provided by participants guides subsequent improvements to the WoF System as NOAA NSSL collaborates with partners to reduce the billions in economic impacts from severe storms. More information can be found at https://www.nssl.noaa.gov/projects/wof/.

NSF

NSF Overview of the Natural Hazards Engineering Research Infrastructure (NHERI). The NSF-supported NHERI is a distributed, multi-user, national facility that provides the natural hazards engineering community with access to research infrastructure (earthquake and wind engineering experimental facilities, cyber-infrastructure, computational modeling and simulation tools, post-disaster field equipment, and research data), coupled with education and community outreach activities, building upon the NHERI vision and operations goals and requirements for each NHERI-type award outlined in the program solicitations NSF 14-605 and NSF 15-598 that established NHERI. NHERI enables research and educational advances focused on earthquake and wind engineering that can contribute knowledge and innovation for the nation's civil infrastructure and communities to prevent natural hazard events from becoming societal disasters. NHERI also support NSF's core value to broaden opportunities and expand participation of groups, institutions, and geographic regions that are underrepresented in science, technology, engineering, and mathematics (STEM). Grand challenge research that can be conducted using NHERI resources is described in the *NHERI Science Plan* https://www.designsafe-ci.org/facilities/nco/science-plan/. Knowledge and innovations produced by research utilizing NHERI resources during 2016-2020 is described in the *NHERI Impact 2020* book https://www.designsafe-ci.org/community/nheri-impact-2020/.

NSF NHERI Awards as of FY 2020.

Facility	Institution	NSF Award Number
Network Coordination Office (NCO)	Purdue University	1612144
Cyberinfrastructure (CI)	University of Texas at Austin	2022469
Computational Modeling & Simulation Center (SimCenter)	University of California - Berkeley	1612843
Experimental Facility (RAPID Facility)	University of Washington	1611820
Experimental Facility (Wave Flume & Wave Basin)	Oregon State University	1519679
Experimental Facility (Geotechnical Centrifuges)	University of California - Davis	1520581
Experimental Facility (Hybrid Simulation)	Lehigh University	1520765
Experimental Facility (Mobile Field Shakers)	University of Texas at Austin	1520808
Experimental Facility (Wind Tunnel)	University of Florida	1520843
Experimental Facility (Wall of Wind)	Florida International University	1520853
Experimental Facility (Shake Table, currently undergoing upgrade to 6 DOF)	University of California-San Diego	1520904
Upgrade of the Large High Performance Outdoor Shake Table to Six Degrees of Freedom	University of California-San Diego	1840870
NHERI Resource: CONVERGE- Coordinated Social Science, Engineering, and Interdisciplinary Extreme Events Reconnaissance Research	University of Colorado, Boulder	1841338

Appendix D: NWIRP Coordinated Budget

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."[19]

The NWIRA Reauthorization of 2015 (Public Law 114-52) requires submission of a coordinated NWIRP budget to Congress each FY within 60 days after the date of the President's budget submission.[20] Descriptions of the planned activities for each of the four Program agencies (NIST, NSF, NOAA, and FEMA) are provided below, and the associated budgets are listed in the table at the end of this report.

National Institute of Standards and Technology

NIST was designated as the Lead Agency for NWIRP through the enactment of Public Law 114-52 on September 30, 2015. As such, NIST's responsibilities include planning and coordination as well as technical activities.

Lead agency activities include the following:

- 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 the following:

- Continue 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 are 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 approaches for wind hazards;
- Develop computational wind engineering capability for simulating turbulent atmospheric boundary layer flow and the resulting wind pressures on buildings;
- Continue development of tornado hazard maps and begin efforts to propose incorporation of the maps into building codes and standards;
- 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; and
- Continue technology transfer, translating windstorm impact reduction research to practice through participation in codes and standards development processes.

[19] 42 U.S.C. § 15703(a).

[20] 42 U.S.C. § 15703(e)(7).

National Science Foundation

NSF 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.

National Oceanic and Atmospheric Administration

NOAA activities fall under two categories: hurricane-related and local severe weather activities.

Planned hurricane related activities include the following:

- Continue the HFIP;
- Operate the National Hurricane Center/Joint Hurricane Testbed; and
- Operate the AOML Hurricane Research Division.

Planned local severe weather activities include the following:

- Operate the Storm Prediction Center, including Hazardous Weather Testbed;
- WoF development;
- Operate the National Severe Storms Laboratory Tornado and Severe Weather Research; and
- Research and deliver technologies developed by the Global System Laboratory that include the High-Resolution Rapid Refresh forecasts, Advanced Weather Interactive Processing System Hazard Services, renewable energy, and aviation tools and products.

Federal Emergency Management Agency

FEMA receives no appropriated funding for NWIRP; however, FEMA leverages available resources as appropriate to support NWIRP goals and objectives. An estimate of the leveraged resources is provided in the budget table. A high-level summary of the wind related activities that FEMA's Building Science Branch and Earthquake and Winds Programs Branch 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 Windstorm Impact Reduction Program (NWIRP)	FY 2019 Actuals ($K)	FY 2020 Enacted ($K)	FY 2021 Request ($K)
NIST [1]	5,595	5,320	5,320
NOAA [2]	16,964	16,848	16,309
NSF [3]	46,745	*	*
FEMA [4]	435	450	450
Total	69,739	22,618	22,079

1) NIST FY 2019 actuals and FY 2020 enacted reflect allocation to support the Hurricane Maria Investigation.

2) NOAA totals are not reflective of hurricane supplemental funds.

3) The NWIRA Reauthorization of 2015 authorized funding for NWIRP activities at NSF in the amount of $9,682 million in each of fiscal years 2015, 2016, and 2017. *As NSF has no dedicated NWIRP activities with their own solicitations, funding levels beyond the amounts authorized in the NWIRA Reauthorization of 2015 are calculated and reported only after each fiscal year's NWIRP-relevant awards across the Foundation are completed.

4) Due to the ad-hoc nature of how FEMA supports NWIRP activities, an estimated amount is included in the FY 2021 request, considering in prior years FEMA has been able to fund some level of activity by leveraging other resources.