NATIONAL WINDSTORM IMPACT REDUCTION PROGRAM

BIENNIAL PROGRESS REPORT TO CONGRESS FOR FISCAL YEARS 2021 AND 2022

FEMA

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NIST

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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 (NWIRA) of 2004 (Public Law 108-360, Title II), as amended by the NWIRP Reauthorization of 2015 (Public Law 114-52).

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1. Executive Summary

The National Windstorm Impact Reduction Program (NWIRP or Program) is a science- and engineering-based coordinating 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 for the Program is submitted to Congress by the NWIRP Interagency Coordinating Committee, as required by the 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 (FYs) 2021 and 2022.

From 1982-2022, severe thunderstorms and tropical cyclones (TCs) caused over $1.7 trillion in economic losses and over 8,000 fatalities in the United States (U.S.), with the vast majority of these losses occurring during the last two decades[2]. Yet, 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 2021-2022 are documented in Section 5 and organized around the NWIRP strategic goals.

Highlights of agency contributions include significant improvements to the understanding of hurricane intensification processes which led to improved hurricane forecasts, progress in the understanding of tornadic vs. non-tornadic storms, advancements in Warn-on-Forecast and other storm scale modeling, 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 inclusion of tornado wind loading factors into a new standard for high occupancy and essential use buildings.

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 TCs, 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 TC disasters from pre- to post-landfall. This coordination plan was used following Hurricane Ian in 2022 to guide scientific information sharing, agency decision making processes relevant to post-windstorm investigations, identification and

[2] Visit https://www.ncei.noaa.gov/access/billions/time-series

development of scientific interagency collaborative opportunities, and information dissemination in the aftermath of TC disasters.

In 2022, after two years of largely remote-only coordination due to the COVID-19 pandemic, NWIRP agencies returned to more normal operations. For the first time in two years, NWIRP agencies have ramped up travel to collect data, both longitudinally and in immediate response to severe weather events. All NWIRP agencies have been able to increase their on-site decision support and data collection activities immediately preceding and following major tornado events and TCs including major Hurricanes Ida and Ian.

As windstorm impacts grow due to a variety of factors, including increases in population and changing frequency and intensity of extreme weather events, it is critical that the NWIRP agencies continue to implement the NWIRP Strategic Plan. Furthermore, NWIRP identifies 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 represents visions in which NWIRP would become active should they be supported:

- 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;
- contribute to building a Weather Ready Nation by integrating scientific advances in real-time impact-based extreme weather event forecasting and delivery, informed by social science and engineering disciplines, to elicit the appropriate responses by individuals and organizations;
- 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, along with associated flooding, hail, and wildfires, produce more losses in the U.S. than any other hazard.

Windstorms and associated flooding, hail, and wildfires comprise the majority of individual loss-producing natural hazard events that exceed $1 billion in the U.S.,[3] with hurricanes and tornadoes comprising the majority of losses related to life and property. From 1982-2022, severe thunderstorms and TCs caused over $1.7 trillion in economic losses and over 8,000 fatalities.[4] The trends in losses from wind and related hazards continues to rise. In recognition of the need to significantly decrease economic costs and loss of life, Congress established NWIRP.[5]

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

Since NWIRP's inception in 2004, the participating agencies have made notable progress. Some of the improvements include:

- the understanding of hurricane intensification processes which led to improved hurricane forecasts;[6]
- progress in the understanding of tornadic vs. non-tornadic storms;
- advancements in Warn-on-Forecast and other storm scale warn-on-forecast modeling;
- 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 inclusion of tornado wind loading factors into a new standard for high occupancy and essential use buildings.

However, challenges in windstorm impact mitigation efforts remain. The Nation continues to experience increasing property losses due to extreme weather events, as evidenced by the devastating severe weather and tornado outbreaks in 2011, 2013, 2020, and 2021 and the recent set of damaging hurricane seasons from 2017 to 2022. The loss of life and property from Hurricane Ian's storm surge of 2022 highlighted the vulnerability of coastal residents even when storm surge warnings were issued a day in advance. The increased losses originate from two major causes. First, only 36% and 26% of U.S. communities have adopted hazard resistant building codes for FY 2021 and FY 2022, respectively, leaving many areas where new and existing buildings remain vulnerable to severe storms (Figure 1).[7] These are percentages of tracked jurisdictions that adopted the 2015 or later IBC and IRC for FY21 and 2018 or later IBC and

[3] Visit https://www.ncei.noaa.gov/access/billions/time-series/US

[4] National Oceanic and Atmospheric Administration, National Centers for Environmental Information. Billion-dollar weather and climate disasters: Table of events. Retrieved from https://www.ncei.noaa.gov/access/billions/events/US/1982-2022

[5] 42 U.S.C. § 15703(a).

[6] https://www.nhc.noaa.gov/verification/verify8.shtml

[7] https://www.fema.gov/emergency-managers/risk-management/building-science/bcat

IRC for FY22 without removing or weakening the hazard resistant provisions of the codes for any of five hazards (flood, seismic, damaging wind, hurricane wind, and tornado) which present a high risk to the given community. Second, population (Figure 2A) and wealth are increasing in states vulnerable to severe wind storms, including hurricanes, severe thunderstorms, and tornadoes (Figure 2B).[8] This phenomenon is also known as the expanding bullseye effect which means more assets (e.g., homes) are subject to damage, even in areas with adopted building codes.[9] More than twice as many housing units could be exposed to TCs in 2100 compared to today in the largest urban areas along the Atlantic and Gulf coasts even if the climatological threat from these storms remain the same. Increasing population in areas exposed to wildfire and severe thunderstorms is likely to follow the same pattern of increasing damage costs.

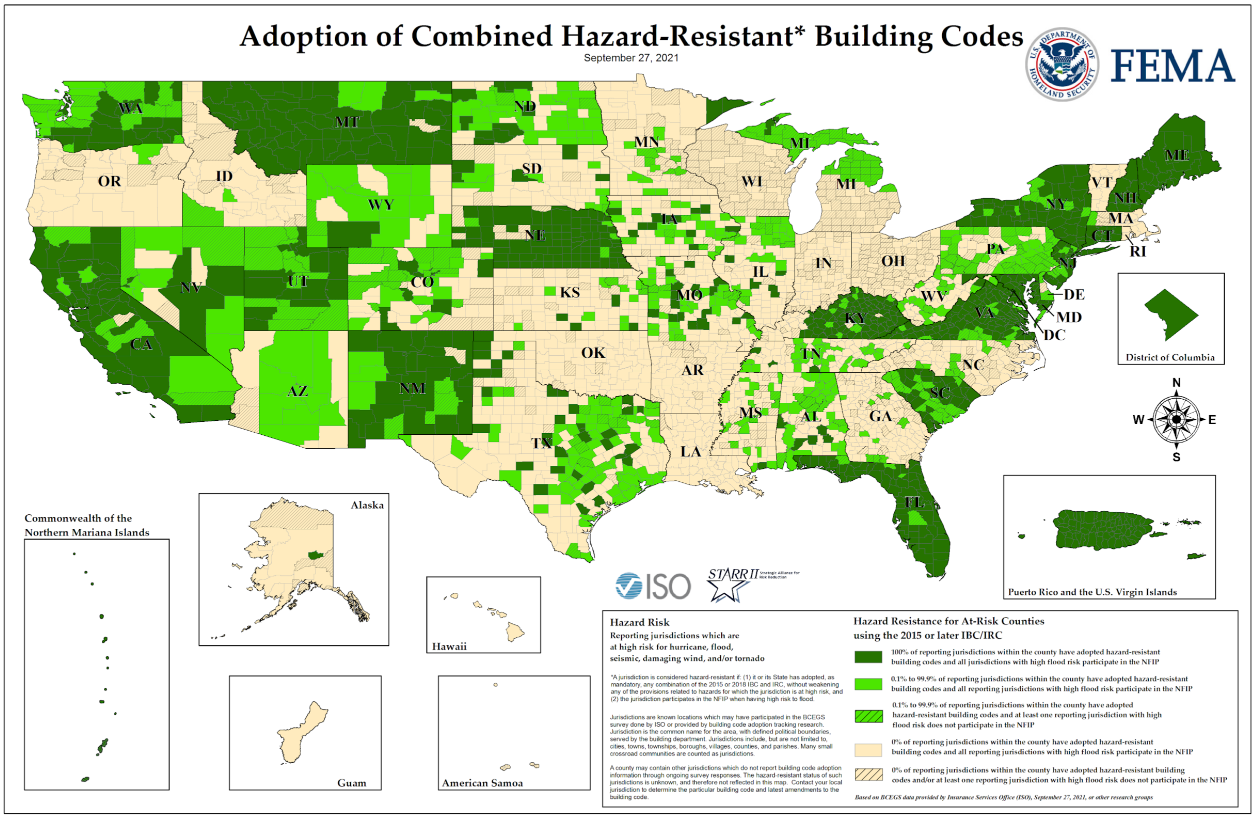
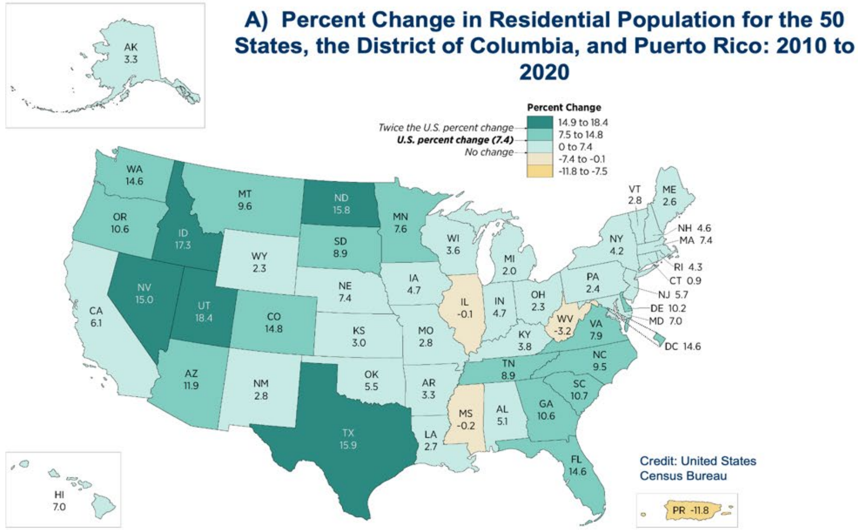


Figure 1. *Building code adoption levels as of 2021 identified in the FEMA nationwide building code adoption tracker courtesy of a survey by the Building Code Effectiveness Grading Schedule.[10]. Each county is colored green where greater than 0% of jurisdictions reported adopting hazard-resistant building codes. Source: FEMA.*

[8] Klotzbach and co-authors, Continental U.S. Hurricane Landfall Frequency and Associated Damage: Observations and Future Risks, 2018, https://journals.ametsoc.org/view/journals/bams/99/7/bams-d-17-0184.1.xml

[9] Freeman and Ashley, Changes in the US hurricane disaster landscape: the relationship between risk and exposure, 2017, Natural Hazards DOI 10.1007/s11069-017-2885-4

[10] https://www.isomitigation.com/bcegs/



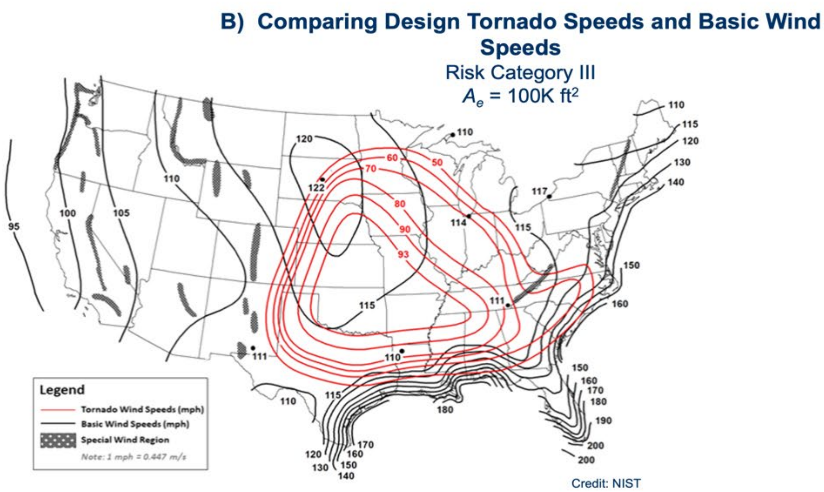


Figure 2A. Change in state population from 2010 to 2020 identified by the US Census Bureau. Source: https://www.census.gov/library/visualizations/2021/dec/2020-percent-change-map.html

Figure 2B. Design Tornado Wind Speeds (red contours) and Basic Wind Speeds (black contours) for Risk Category III buildings occupying an 100 Kft2 developed by NIST for the ASCE 7-22 Building Loads Standard. Higher wind speeds reflect higher risk levels of winds from tornadoes and other phenomena (e.g., tropical cyclones).

Furthermore, other challenges remain to be addressed.

- In terms of the metrics for performance, operational tornado warning accuracy values have consistently plateaued since the historic outbreak season of 2011,[11] after years of gradual increasing annual accuracy values following the National Weather Service (NWS) modernization in the 1990's and early 2000's. After the 2011 season, there was a community-wide emphasis on the

[11] Correia and Brooks, 2018: Long-Term Performance Metrics for National Weather Service Tornado Warnings. https://doi.org/10.1175/WAF-D-18-0120.1

messaging of known tornado threats and reductions in false alarms which over time was reflected in a slight decrease in mean tornado warning lead times to around 10 minutes, annually.

- Wildfires are burning more acreage now than before, from an average of 3,000,000 acres per year in the late 1980s to 8,000,000 acres burned per year in the 2020s. Of note, the largest fires since 2020 were recorded in the states of California, Colorado, and New Mexico. Many of these fires featured explosive wind-driven growth rates such as with the Camp, CA fire of 2018 and Marshall, CO fire of 2021. These fires are also creating more fire-generated tornadoes, such as the one in the Carr, CA fire of 2018 where a firefighter was killed and a neighborhood was damaged well outside the burn zone.[12] A later fire near Loyalton, CA resulted in the first ever tornado warning issued by the NWS for a fire-generated tornado.[13] Fire tornado research is young relative to research on traditional tornadoes and the NWS has little guidance to support fire-related tornado or other fire-generated windstorm warnings. Yet, the combined hazards of wind-driven wildfire, and fire-generated tornadoes represent an increasing concern as population and wealth accumulate in areas of increasing fire risk.[14]
- Wind-generated storm surges are also resulting in rising losses as the previously noted increasing amount of coastal wealth and population are exposed to rising sea levels.[15] The rising surge-related property damage highlights a vulnerability of our population along coastlines and the need to improve our understanding of all of the mechanisms of storm surge that affect buildings and infrastructure including inundation depth, water current velocity, wave action and debris impacts. Subsequently, building surge resistance standards need to be updated to address new research findings.
- Global warming challenges our efforts to mitigate wind-induced losses, partly due to a limited understanding of the likely spatial and temporal changes in the wind and related hazards. As global warming continues, the confidence is high for increasing wildfire risk,[16] is medium for TC intensity,[17] and is low for severe local storms, including tornadoes.[18] Research is needed to continue to firm up the confidence of past and future trends of severe winds and related hazards. Parallel research needs to evaluate how building performance standards would need to change in the next century assuming continued global warming.

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;

[12] Lareau, N. J., and co-authors, Fire-Generated Tornadic Vortices, 2022: Bulletin of the American Meteorological Society, https://doi.org/10.1175/BAMS-D-21-0199.1

[13] https://www.washingtonpost.com/weather/2020/08/16/california-fire-tornado-warning/

[14] https://www.nist.gov/news-events/news/2021/02/new-timeline-deadliest-california-wildfire-could-guide-lifesaving-research

[15] Masters, F., How sea level rise contributes to billions in extra damage during hurricanes, Yale Climate Connections, https://yaleclimateconnections.org/2022/10/how-sea-level-rise-contributes-to-billions-in-extra-damage-during-hurricanes/

[16] https://www.pnas.org/doi/full/10.1073/pnas.1607171113

[17] Walsh and Co-authors, 2015: Hurricanes and Climate: The U.S. CLIVAR Working Group on Hurricanes, Bulletin of the American Meteorological Society, https://doi.org/10.1175/BAMS-D-13-00242.1

[18] Taszerak and Co-authors, 2021: Differing Trends in United States and European Severe Thunderstorm Environments in a Warming Climate, Bulletin of the American Meteorological Society, https://doi.org/10.1175/BAMS-D-20-0004.1

- 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), composed of scientists and program/portfolio leaders, meets approximately once every two months 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. A detailed history of NWIRP statutory and technical Program activities from FYs 2005-2018 has been documented in a series of previous biennial reports to Congress.[19]

The structure of this report is as follows:

- Section 3 presents a brief overview of windstorm impacts during FYs 2021-2022.
- Section 4 discusses NWIRP interagency post-windstorm coordination activities during the reporting period.
- Section 5 details agency specific activities in support of the NWIRP strategic priorities and 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 2021 and 2022

The number of individual severe storm, TC and wildfire events with losses exceeding $1 billion fell slightly in FYs 2021-2022 from their peak in 2020 (Figure 3). However, they align with the overall trend of increased events occurring each year since 1980. Thirty-one events related to wind occurred over these two years – 22 of them from severe thunderstorms, seven from TCs and two from wildfires – each with losses exceeding $1 billion (Consumer Price Index (CPI) adjusted for inflation).[20] As in 2020, these numbers exceeded the totals in any year prior to 2020.[21]

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

[20] 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.

[21] 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. Conversely, the contribution of wind to total wildfire losses is poorly documented. However, it provides a comprehensive historical time series to track long term variability and trends in windstorm losses.

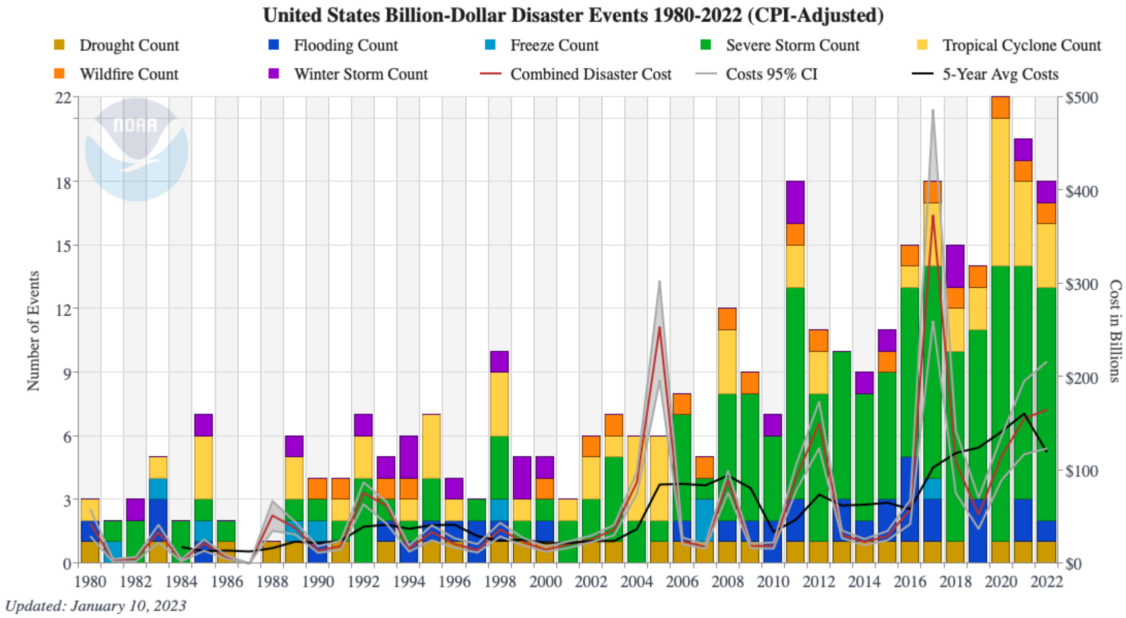


Figure 3*. Number of individual tropical cyclone (yellow), severe storm (green) and wildfire (orange) events from 1980-2022 exceeding one billion USD (inflation adjusted) comprise the majority of all $1 billion hazards. The annual cost is in gray and its five-year running mean in black. Source: NOAA.*

3.1 2021

As in the previous four years, 2021 was a more active hurricane season than usual with 21 named storms and seven hurricanes, four of them reaching major hurricane status. About $80.4 billion of the season's losses of $84 billion came from one storm, Hurricane Ida, as its center directly struck Port Fourchon, LA at category 4 status. This ties losses from Ida with Hurricane Laura in 2020 and the Last Island, LA hurricane of 1856 as the strongest to make landfall in LA.[22] Grand Island, LA, just east of landfall, was severely impacted as 40% of all buildings were destroyed with wind gusts exceeding 120 miles per hour (mph) and a 10-foot storm surge.[23] Hurricane wind conditions extended to the northern shoreline of Lake Pontchartrain. As Ida moved into the northeastern U.S., it became extratropical and produced Enhanced Fujita (EF) 2 tornadoes near Annapolis, MD and Montgomery County, PA, and an EF3 tornado in Gloucester County, NJ. These were the strongest of 35 tornadoes associated with Ida. Finally, severe flash flooding was reported from Philadelphia to New York City as rainfall exceeded 10" in some areas. Central Park, in New York City, reported 7.19" of rain where 3.04" fell in one hour, a record for the station.

Other remarkable windstorm events occurred in 2021. The December 10-11, 2021 Quad-State Tornado Outbreak resulted in 93 fatalities, $4 billion in losses and 800 miles of tornado tracks (Figure 4). The most severe tornado traveled 166 miles with a peak EF4 intensity, and would have been by far the longest tornado track in history had there not been a five-mile gap between it and a previous 80-mile-long tornado track produced by the same parent storm. The towns of Mayfield, Dawson Springs, and Bremen in Kentucky were especially hit hard, among other smaller communities, resulting in 57 deaths and over 500 injuries.

[22] Hurricane Ida summary, https://www.nhc.noaa.gov/data/tcr/AL092021_Ida.pdf
[23] https://www.weather.gov/lix/pshhurricaneida

Another tornado struck Bowling Green, KY damaging neighborhoods and an industrial park, resulting in 17 fatalities and 53 injuries. Tornadoes also impacted areas around St. Louis including one that hit an Amazon warehouse in Edwardsville, IL causing six fatalities at the site. The December 15 derecho from Kansas to Minnesota resulted in the farthest north tornado outbreak on record for so late in the year. More than 50 tornadoes caused $1.9 billion in damage and one fatality. Severe winds from the derecho's parent storm produced wind gusts up to 100 mph in north central Kansas resulting in a severe dust storm, building damage, vehicle rollovers, and numerous wildfires.[24] The year accumulated 1314 tornadoes according to the Storm Prediction Center.[25]

As for wildfires, more acres were burned in 2021 than on average due to severe drought in the western U.S. An especially notable wildfire on December 30 west of Marshall, CO, just south of Boulder burned 6000 acres, destroying more than 1000 homes as it rapidly spread out of control as downslope winds exceeded 100 mph.[26] A cessation of the severe winds and firefighting efforts prevented this fire from consuming even more homes. Much larger fires occurred farther west, including the Dixie Fire in California (960,000 acres and 1000 structures lost), the Caldor Fire in California (220,000 acres) and several other huge fires in Oregon, Montana, and Arizona. These fires and others burned 7.21 million acres and resulted in $11.4 billion in losses.[27]

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[24] https://www.cjonline.com/story/news/2021/12/15/kansas-weather-high-wind-storms-hail-tornado-possible-dangerous-fire-conditions-wednesday/8906410002/

[25] https://www.spc.noaa.gov/climo/torn/STAMTS21.txt

[26] https://assets.bouldercounty.gov/wp-content/uploads/2023/06/marshall-fire-investigative-summary.pdf

[27] https://www.ncei.noaa.gov/access/billions/events/US/2021

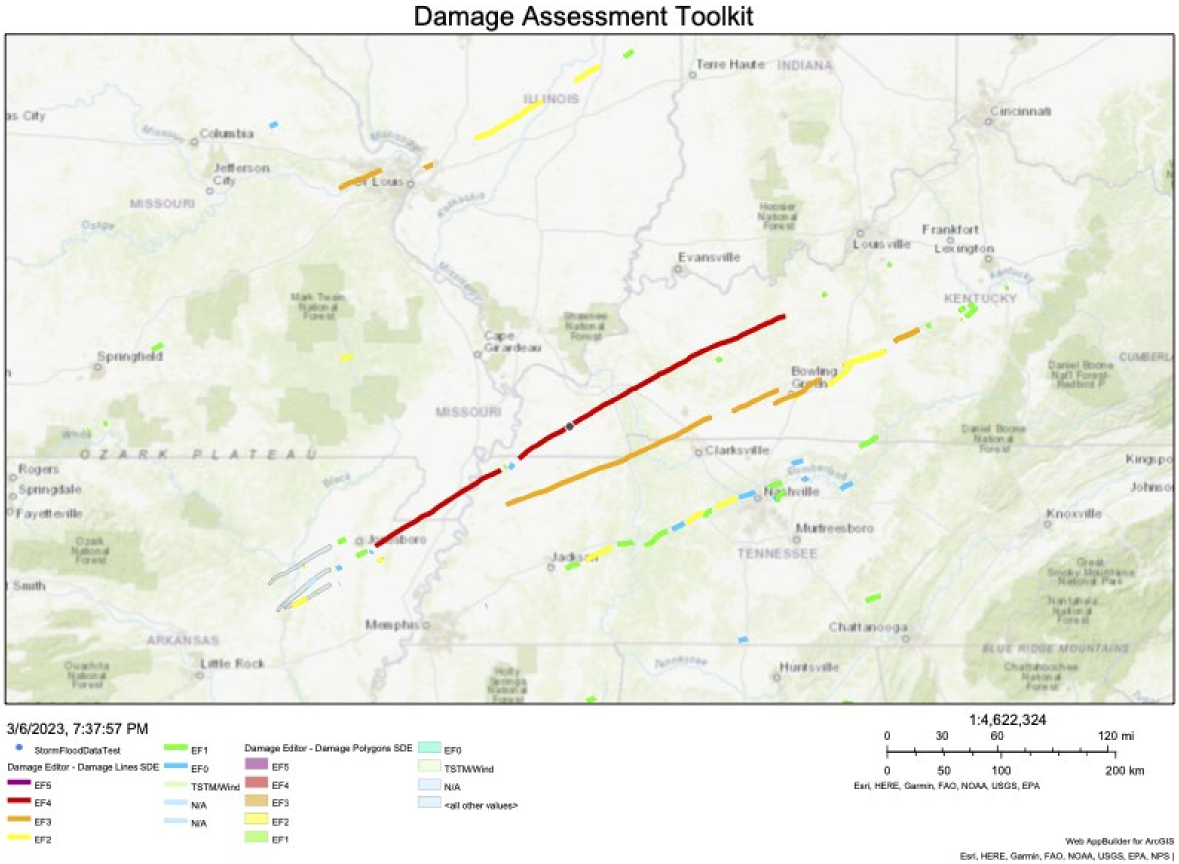

Figure 4. A damage track map from the 10 December 2021 tornado outbreak. The red tracks represent violent (EF4) tornadoes, including the easternmost one that struck Mayfield, KY.

3.2 2022

The TC-induced losses in 2022 were dominated by one event. Hurricane Ian exemplified the saying "it only takes one storm" when it roared ashore in southwest Florida on September 29 as a high-end category 4 storm, the only major hurricane to make landfall in the U.S. in 2022.[28] The storm crossed the Florida Peninsula, exiting the east coast near Cape Kennedy only to make a second landfall near Myrtle Beach, SC as a category 1 hurricane.[29] In what had been a below normal hurricane season in terms of impacts on the U.S. up to late September, "Ian" produced the second largest CPI-adjusted losses from a U.S. hurricane landfall on record (Hurricane Katrina was the costliest). "Ian" also was responsible for 152 fatalities, ranking number 21 of the deadliest U.S. mainland landfalling hurricanes on record.[30] Many of the fatalities were older residents and/or residents with restricted mobility, as a 7- to 15-foot storm surge inundated large

28 https://www.nhc.noaa.gov/data/tcr/AL092022_Ian.pdf

29 https://www.ncei.noaa.gov/access/billions/events/US/2022

30 https://www.wunderground.com/hurricane/articles/deadliest-us-hurricanes

areas of populated lowland.[31] The surge, compounded by strong currents, wave action and debris impacts, also resulted in the destruction of wood-frame and manufactured housing. The wind, on the other hand, revealed the benefits of modern building codes in resisting damage. Buildings built to these codes suffered minor damage compared to older buildings lacking modern retrofits. Despite the improved building resilience and the increase in numbers of new homes and other buildings since 2004, when Hurricane Charley roared ashore in the same area, there were still large property losses.[32]

The tornado count in 2022 was lower than average with a preliminary count of 1331.[33] The most active period was from mid-March to mid-April and then in November. While none of the tornadoes in 2022 approached the strength and longevity of the most intense tornadoes of 2021, there were some worthy of mention. For instance, on March 22, an EF3 tornado struck districts on the east side of New Orleans, with Arabi being hardest hit. Numerous homes were destroyed with two fatalities; however, ironically, the damage could have been worse were it not for the high number of lots remaining empty following Hurricane Katrina. On December 14, another tornado struck the east and south sides of New Orleans, including Arabi. A strong tornado struck Gaylord, Michigan on May 20 and plowed through shopping centers and neighborhoods, killing two and injuring 44. It was the first EF3 or stronger tornado since 1991 for the northern portion of lower Michigan. There were four EF4 tornadoes in 2022 that resulted in seven fatalities. One struck Pembroke, GA on April 5, starting near Fort Stewart. Two EF4 tornadoes formed on November 4 starting in northeast Texas and moving into southeast Oklahoma. One of them came close to hitting Idabel, OK. Perhaps the anomalous violent tornado of the year was a very early season EF4 tornado that traveled for 70 miles and resulted in seven deaths in southern Iowa on March 5. This tornado carved the longest track in Iowa since 1984 and came close to striking the Des Moines metro area.[34] This year also featured three multi-state organized intense derechos.

On May 12, a derecho developed over Nebraska and moved into eastern South Dakota and western Minnesota, bringing a wall of dust and wind gusts of greater than 100 mph south of Sioux Falls, resulting in estimated losses of $2.5 billion. On June 13, thunderstorms produced severe winds from Chicago, southeastward into West Virginia. Supercell thunderstorms produced winds exceeding 90 mph in Chicago and Ft. Wayne. Total losses from these events exceeded $3.2 billion.[35]

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. These included interagency NWIRP meetings that were held to provide an open forum for interagency information exchange in the aftermath of several weather disasters throughout FYs 2021-2022, and a data sharing workshop for the Quad-State Tornado Outbreak. Some examples follow.

[31] https://www.nytimes.com/2022/10/21/us/hurricane-ian-victims.html
[32] https://www.washingtonpost.com/climate-environment/2022/09/28/florida-population-growth-hurricane-ian-path/
[33] https://www.spc.noaa.gov/climo/torn/STAMTS22.txt
[34] https://www.weather.gov/dmx/March5th2022Tornadoes
[35] https://www.ncei.noaa.gov/access/billions/events/US/2022?disasters[]=severe-storm

Hurricane Ida

Hurricane Ida made landfall southwest of New Orleans in August 2021, following the devastating twin impacts of Hurricanes Laura and Delta, farther west in Louisiana in 2020. NIST produced rapid estimates of the surface level peak gust winds under a Mission Assignment (MA) from FEMA to support their Hazus Hurricane Model loss estimates (Figure 5). NIST widely distributed these results to federal and academic hurricane researchers as well as private sector stakeholders, through FEMA's public disaster geodatabase website,[36] the NSF-supported DesignSafe-CI Recon Portal,[37] the NSF-supported Structural Extreme Events Reconnaissance (StEER) Network Hurricane Ida Slack Channel, and stakeholder emails and briefings.

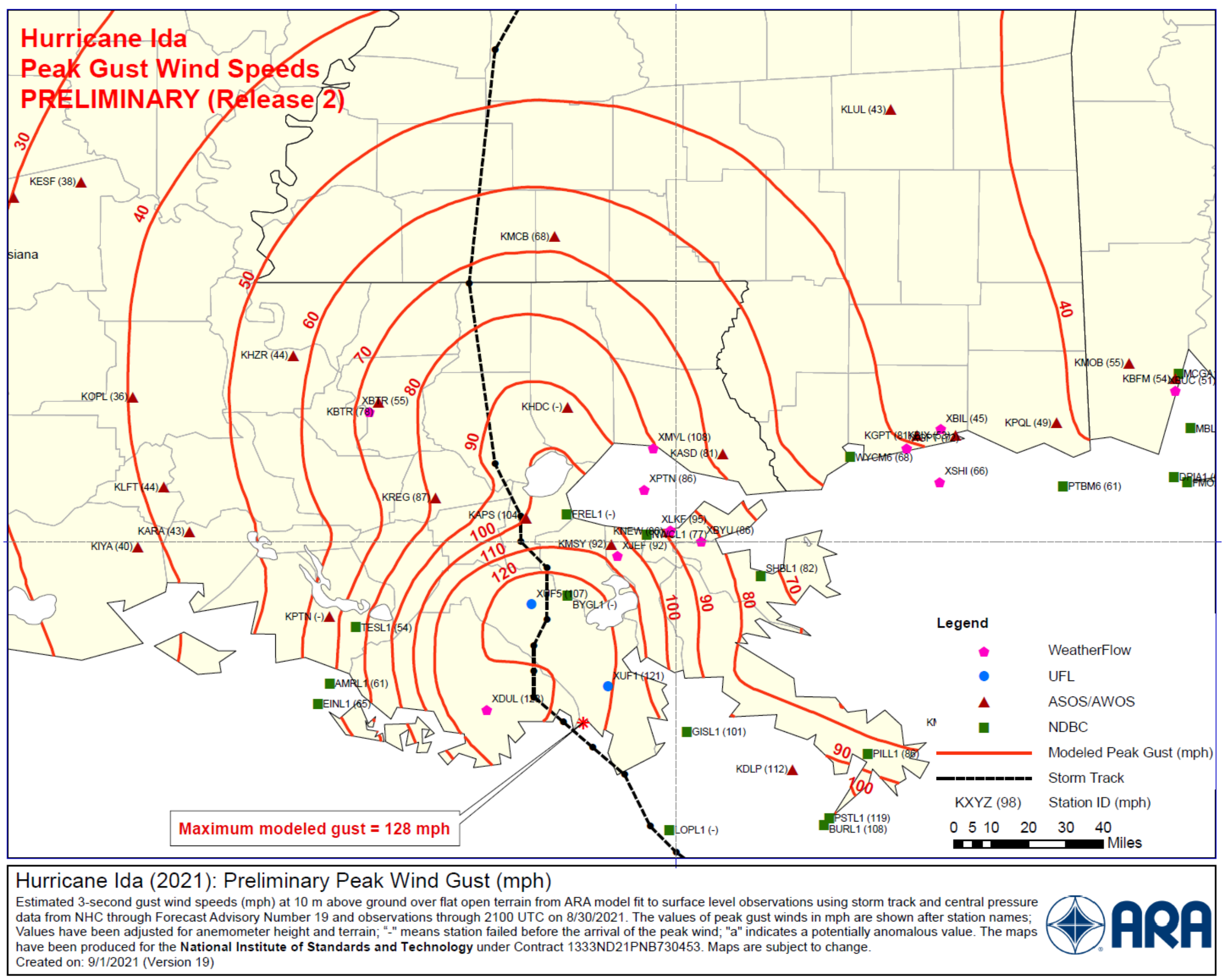

***Figure 5**. A map of preliminary peak wind gusts for Hurricane Ida in 2021 adjusted to a common exposure setting similar to an open grass field. This product was developed by NIST, in conjunction with Applied Research Associates.*

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[36] https://disasters.geoplatform.gov/publicdata/NationalDisasters/2021/HurricaneIda_August2021/NIST_Windfield/

[37] https://www.designsafe-ci.org/data/browser/public/designsafe.storage.community/Recon%20Portal/2021%20Hurricane%20Ida%20New%20Orleans%20Louisiana%20USA/Windfield%20Map

Quad-State Tornado Outbreak

After the historic Quad-State Tornado Outbreak of December 10-11, 2021, NIST held a meeting of the WWG on this outbreak – with briefings regarding agency activities and sharing of data collection and research plans. This was followed up with a half-day virtual workshop on data and information sharing on March 7, 2022, for the dozen or so federal and federally-supported research teams studying the tornadic wind fields, building performance, emergency response, and recovery. Feedback from the participants indicated that the workshop was very beneficial to their research and planning for additional field deployments.

The Quad-State Outbreak included an EF4 tornado that hit northwest Tennessee and western Kentucky and another EF3 tornado in Kentucky. FEMA deployed a pre-Mitigation Assessment Team (pre-MAT) to Kentucky from 19 to 23 December 2021 to investigate building damage and look for safe rooms or storm shelters that may have been hit along those two paths, focusing on the EF4 track. A couple of important conclusions from this investigation were that rural areas would benefit from residential safe rooms due to the distance and time to get to a community safe room and that proper enforcement of building codes would help mitigate some of the damages they saw that were preventable.

Hurricane Ian

Hurricane Ian prompted a number of responses among the NWIRP agencies. NOAA's National Severe Local Storms Laboratory sent ground-based mobile weather stations, precipitation disdrometer sensors, and two mobile radars to collect wind and precipitation data. NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) collected a wide variety of data, from sail drones to data collected via reconnaissance aircraft. The NWS's operational radar, surface, upper air, and polar and geostationary satellites documented the evolution of Ian, which was analyzed in gridded products such as the Real-Time Mesoscale Analysis.

NIST produced rapid estimates of the surface level peak gust winds under MA from FEMA to support their Hazus Hurricane Model loss estimates (Figure 6). NIST widely distributed these results to federal and academic hurricane researchers as well as private sector stakeholders through FEMA's public disaster geodatabase website,[38] the NSF-supported DesignSafe-CI Recon Portal,[39] the NSF-supported StEER Network Hurricane Ida Slack Channel, and stakeholder emails and briefings.

The NSF-supported StEER Network deployed several teams to document the impacts from Ian. Virtual data gathering began from before landfall to more than one week afterward. Teams initially collected street-level panorama data throughout Lee and Charlotte Counties. A follow-up team assessed the integrity of structures; flew large, fixed wing drones; and collected high-water mark data. The data was made available online for quick perusal by researchers, and practitioners.[40]

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[38] https://disasters.geoplatform.gov/publicdata/NationalDisasters/2021/HurricaneIda_August2021/NIST_Windfield/

[39] https://www.designsafe-ci.org/data/browser/public/designsafe.storage.community/Recon%20Portal/2021%20Hurricane%20Ida%20New%20Orleans%20Louisiana%20USA/Windfield%20Map

[40] https://www.steer.network/hurricane-ian

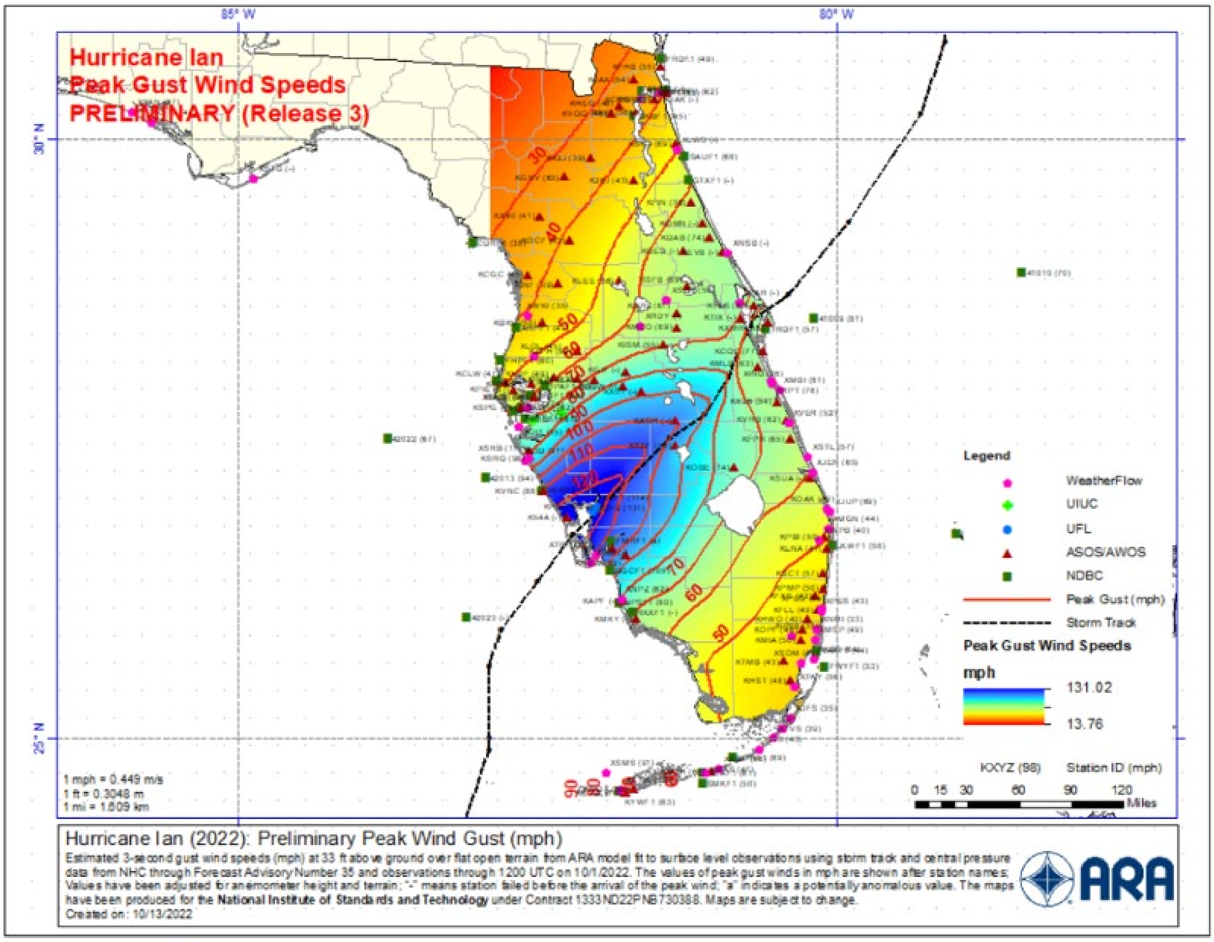

Figure 6. *Similar to Figure 4 except for Hurricane Ian and the shaded background indicating peak wind gusts.*

5. Progress in Fiscal Years 2021 and 2022

The NWIRP agencies initiated implementation of the NWIRP Strategic Plan[41] (released in late FY 2018) by focusing on advancing agency-relevant objectives across the Plan's three strategic goals and eight strategic priorities. The 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. These goals are well-suited to address the challenges presented in Section 2 of this report. In this section of the report, the NWIRP agencies provide brief descriptions of key activities that support the three goals of the NWIRP Strategic Plan. Each entry also includes its relevance to 14 objectives and eight strategic priorities listed in Appendix B, which underpin the goals of the NWIRP Strategic Plan.

[41] See Appendix B for a complete list of NWIRP strategic goals, objectives and priorities.

5.1 Strategic Priorities

FEMA: 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. The current Hazus model runs as a standalone program. However, FEMA is also researching cloud computing technologies to decrease processing times required for future hurricane response Hazus loss estimation efforts. This effort is known as OpenHazus. (*Strategic Priority 1*)

FEMA: Education, Outreach, and Information Dissemination. 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. In FY 2021, FEMA updated their safe room guidance publications and multiple fact sheets. The two main publications included FEMA's most popular publication, FEMA P-320,[42] *Taking Shelter from the Storm: Building or Installing a Safe Room for Your Home*, and FEMA P-361,[43] *Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Room*s. FEMA will continue these and other efforts to improve wind-resistant provisions of codes and standards. (*Strategic Priorities 5, 6 and 7*)

NIST/FEMA: Storm Shelter Standard. NIST and FEMA staff serve on the committee (chaired by a NIST staff member) responsible for development of the International Code Council (ICC)/National Storm Shelter Association (NSSA) *Standard for the Design and Construction of Storm Shelters*. The third edition of the standard (ICC 500-2020) was completed and published during this reporting period, including a new appendix on storm shelter operations. Numerous change proposals submitted by NIST and FEMA were incorporated. The separate commentary to the third edition was also completed, and work began on the fourth edition of the standard. *(Objective 11; Strategic Priority 7)*

NIST: Windstorm Hazard Measurement Science. Four university awardees of NIST FY 2019 Disaster Resilience Research Grants[44] continued to deploy mobile remote sensing and in-situ observation 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 (much of the planned fieldwork during the previous reporting period was delayed due to the pandemic). Data were collected for: Hurricanes Delta and Ian, thunderstorms during May-July 2021 in several locations in Texas, Oklahoma, Kansas and Illinois, and in Kentucky following the Quad-State Tornado Outbreak in December 2021**.** *(Objectives 1, 2, 3, 4, 5; Strategic Priorities 2, 3)*

NIST: Performance-Based Design for Windstorm Hazards. NIST awarded a contract to the American Society of Civil Engineers (ASCE) in FY 2022 to conduct a stakeholder workshop to review the current

[42] https://www.fema.gov/sites/default/files/documents/fema_taking-shelter-from-the-storm_p-320.pdf
[43] https://www.fema.gov/sites/default/files/documents/fema_safe-rooms-for-tornadoes-and-hurricanes_p-361.pdf
[44] https://www.nist.gov/news-events/news/2019/08/nist-awards-66-million-research-help-structures-better-withstand

state-of-the-art in Performance-Based Wind Design and identify research needs and priorities. The workshop will be held in FY 2023, followed by publication of a report. *(Strategic Priority 4)*

NSF: Estimating Loss of Life due to Windstorms. Coordinating with the Centers for Disease Control, NSF funded a study of excess mortality associated with Hurricane Maria. The number of fatalities associated with that hurricane had become a point of debate, so a team from the NSF-funded Natural Hazards Center examined death certificates for six months following the hurricane to ascertain excess deaths and attribute causes. The methodology can be used in future events. (Strategic Priority 1)

NSF: Rapid Response Research (RAPID). NSF has the capability to issue awards quickly, based on internal review only, when there is severe urgency with regard to availability of or access to data. Most often, these grants for RAPID are issued when disasters strike and researchers need to get into the field quickly in order to gather data before it disappears or degrades in such a way that a scientific opportunity would be lost. During this reporting period, NSF issued more than 20 RAPID awards pertinent to NWIRP, including projects addressing the behavior and impacts of multiple tornadoes as well as Hurricanes Laura, Hanna, and Ida. RAPID research topics, which were proposed by university-based researchers, ranged from meteorological observations to measurement of impacts on natural and built environments, to evacuation behaviors, to effects on buildings and businesses (*Strategic Priorities 1, 2*).

NSF: Research Experiences for Undergraduates (REU) Sites Program. NSF funds many research opportunities through its REU Sites program. An REU Site consists of a group of 10 or so undergraduates who work actively with faculty and other researchers on a shared research project. REU Sites aim to provide the kinds of exciting, engaging experiences that attract students to a career in science. They provide financial and housing support to the recipients and actively recruit students from schools where Science, Technology, Engineering, and Mathematics (STEM) research opportunities are limited or who are from groups typically underrepresented in STEM fields. During FYs 2021-2022, NSF funded at least five REU Sites particularly relevant to NWIRP: two dedicated to coastal resilience and research; one in partnership with NOAA dedicated to remote sensing; one on big data research for social change; and the long-standing Natural Hazards Engineering Research Infrastructure (NHERI) summer REU program that places students in each of its experimental facilities (including wind tunnels, wave research facilities, and simulation facilities) as well as into extreme event reconnaissance facilities. *(Strategic Priority 8)*

NSF: Faculty Early Career Development (CAREER) Program. NSF's prestigious CAREER program supports early-career faculty who have the potential to serve as role models in research and education and to lead advances in the mission of their department or organization. CAREER awards are five-year investments in extended research and education projects that free promising early-career faculty to concentrate on their work rather than writing proposals for funding. In this reporting period NSF made 23 CAREER awards to scholars working on NWIRP-relevant research and education topics. *(Strategic Priority 8)*

NOAA: Education, Outreach, and Information Dissemination. NOAA continues to be actively engaged in outreach. The joint initiative, #HurricaneStrong, between the Federal Alliance for Safe Homes (FLASH®) and NOAA continues its goal to save lives and homes by providing 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".[45] In addition to the aforementioned Weather-Ready ambassador program, NWS has been very active in preparedness activities with the public and its core partners. A small example of the activities appears here to reinforce the breadth of activities that occur.

- The NWS conducted training for emergency managers at the 2022 Florida Governor's Hurricane Conference.
- The Shreveport, LA NWS conducted a press conference heralding the 2022 severe weather season.
- The NWS offices of Boston and Jacksonville conducted tabletop severe storm and hurricane exercises with their partners.
- The NWS Goodland, KS staffed booths at state fairs to educate attendees about severe weather safety.
- The NWS Morehead City, NC hosted a pre-season hurricane community forum for the public and core partners.
- The National Hurricane Center (NHC) installed a pole at the front entrance, color coded to demonstrate how various storm surge depths appear to visitors.

These kinds of activities occur across all NWS offices in advance of severe storm, fire, and hurricane seasons. (*Strategic Priorities 6, 7*)

NOAA: Advances in Severe Storm Data Collection. The NWS has been improving its high-resolution post-storm data collection of severe wind data since 2011 with the advent of new GIS tools and improved access to aerial and satellite imagery. In FY 2022, the NWS introduced a Post-Storm Data Acquisition (PSDA) Readiness and Recognition Program to improve consistency of post-storm survey practices among all weather forecast offices.

The NWS is also testing the collection of high-resolution storm surge and flood impact and water level information to better support forecast product verification efforts. The data will not be released to publicly viewable sites until this effort has been made operational. (*Strategic Priorities 2, 3*)

5.2 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 FYs 2021-2022, NIST completed wind tunnel testing of topographic models representing Mayaguez and Yabucoa regions of Puerto Rico where the surrounding topography produces significant increases in wind speeds. NIST developed a computational fluid dynamics (CFD) procedure for modeling forests on topographic terrain using vegetation data from satellites, in order 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 has also successfully recorded field wind velocity and direction data from anemometers on three cell towers in the Yabucoa region since March 2021 for evaluation of topographic effects and for validation of the wind tunnel and computational models. *(Objectives 1, 2, 4, 6)*

NIST/U.S. Nuclear Regulatory Commission (NRC): Tornado Hazard Maps. NIST completed a multi-year effort to develop the first-ever engineering-derived probabilistic tornado wind speed maps, which also

[45] https://hurricanestrong.org

account for the dependency of tornado risk on the plan size of a building or structure. These maps have been published in the ASCE 7-22 design load standard (see Goal C). The NRC provided financial support for explicit evaluation of epistemic (modeling) uncertainty, which was incorporated into the map development process. *(Objective 4)*

NOAA: New Observing Technologies. New observing technologies such as the Uncrewed Aerial Systems (UAS) that gathers data in the lower atmosphere and the Saildrone technology that sails in the open ocean gathering data were demonstrated as a part of NOAA's Advancing the Prediction of Hurricanes Experiment (APHEX) in FYs 2021-2022. The National Severe Storms Laboratory (NSSL) has utilized UAS to gather atmospheric data and conduct tornado damage assessments as part of VORTEX-USA[46] supported field programs. NSSL is also 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, which 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. In FYs 2021-2022 the Weather Program Office supported extramural research to advance observations needed for substantial improvement in forecasting and prediction of high-impact weather events. (*Objective 2*)

NOAA/NIST/FEMA/NASA/NRC/ASCE/AMS: Wind Speed Estimation (WSE) Standards Committee. The ASCE/Structural Engineering Institute (SEI)/American Meteorological Society (AMS) WSE is continuing the work on developing a new standard on wind speed estimation in tornadoes and other windstorms from several methods. These include a significantly expanded EF-Scale, three tree-fall pattern analysis techniques, engineering forensics, Doppler radar measurements, and in-situ measurements involving anemometry. An additional supporting technique involving post-storm remote sensing-based condition analysis is also under development to support the other methods. Members of the ASCE/AMS WSE committee come from multiple affiliations, including NIST, NOAA, NASA, FEMA, NRC, non-profit agencies, private companies, and academic institutions. The WSE committee is in the midst of balloting draft content and will likely continue its balloting process for two more years. (*Objective 2)*

NOAA: Toward Seasonal Prediction and Long-term Severe Weather Variability. For nearly a decade, 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. Overall, although work and research on long-term prediction continues on several fronts, actionable progress that could lead to useful seasonal forecasts remains incremental. One such study of 40 years of high-resolution reanalyses (Taszarek et al 2020) showed that stronger convective inhibition has caused a decline in the frequency of thunderstorm environments over the southern U.S., particularly in summer. Conversely, increasingly favorable conditions for tornadoes have been observed during winter across the Southeast. (*Objective 3)*

NOAA: Advancing the Prediction of Hurricanes Experiment. NOAA's Hurricane Research Division continues to improve hurricane-intensity forecasting through the Advancing the Prediction of Hurricanes Experiment. In FYs 2021-2022, the focus was on sampling storms through most of their lifecycle to understand their evolution including whether storms underwent rapid intensification. *(Objective 3)*

[46] VORTEX-USA is the successor to VORTEX-SE.

NSF/NOAA: Field campaign to study tornadogenesis in the southeast U.S. NSF and NOAA collaborated to conduct a large field campaign (NSF-2020462; NSF-2020588) called PERiLS (Propagation, Evolution and Rotation in Linear Storms) in the states of Alabama and Mississippi in the spring of FYs 2021 and 2022. The field campaign will continue in the spring of FY 2023. This work is aligned with another Congressionally mandated program called VORTEX-USA. The analyses of the data collected during the FYs 2021-2022 campaigns are currently underway, in parallel with the FY 2023 field campaign. *(Objectives 1,2, 3, 8, 13; Strategic Priorities 1, 2, 3)*

NSF/NOAA: In-situ and Remote-Sensing Measurements of Storm-Scale and Low-Level Tornado and Hurricane Winds. In FY 2022, the NSF and NOAA funded the field campaign "Targeted Observation by Radars and UAS of Supercells (TORUS)"[47] awarded to University of Nebraska-Lincoln, Texas Tech University, University of Colorado-Boulder, and University of Oklahoma. The TORUS field campaign's goal is to collect data to assist in improving the understanding of supercell thunderstorms and how they produce severe winds, hail and tornadoes. The researchers make heavy use of UAS, NOAA's P3 aircraft, and surface and mobile radar observations to accomplish TORUS's objectives. (*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, 8)*

NSF: Field Study of Wind Interactions 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: Multi-Year Research Projects Examining Fundamental Principles in Windstorms. NSF funded multi-year projects to improve understanding of supercell storms and formation of tornadoes through observations, modeling, and data science; new technology based on scientific theories and computer visualizations in four dimensions to improve the prediction of tornadoes and derechos; an examination of how severe thunderstorms and tornadoes may change in a future, warmer climate; investigations of various aspects of TC pathways, including development of a storm, rapid intensification, secondary eyewall cycle, as well as prediction of hurricane size and intensity; and studies on weather and wildfire interactions. *(Objectives 1, 2, 3)*

NSF: Services and Support for Academic and Agency Atmospheric Research. NSF's National Center for Atmospheric Research (NCAR), provides necessary support for the U.S. academic community and collaborations with other federal agencies. In particular, during the reporting period, NCAR has provided data services to NOAA for the Congressionally-mandated program, VORTEX-USA, that studies tornadogenesis in the Southeast U.S. and now, elsewhere. In collaboration with NOAA, DOD, DOE and many other agencies, NCAR also continues to lead the development of community climate and weather prediction models that are widely used throughout the federal and private sectors and in the academic community. These models include CESM (Community Earth System Model); WRF (Weather Research

[47] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1824649

and Forecast Model); MPAS (Model for Prediction Across Scales); and UFS (Unified Forecast System). *(Objectives 1, 2, 3)*

5.3 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 requested by the state or territory. The findings and recommendations derived from field observations and analyses are used to provide design and construction guidance that will improve the disaster resistance of the built environment in the affected state or region and often prove to 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, Fact Sheets, and Design Guides made available to communities to aid in their rebuilding effort and to enhance the disaster resistance of building improvements and new construction. In FY 2020, FEMA deployed a MAT for Typhoon Yutu (from October 2018) in the Commonwealth of the Northern Mariana Islands, which resulted in two Recovery Advisories, two Fact Sheets, and a MAT report published in FY 2021. FEMA deployed a pre-MAT to Kentucky for the Quad State Tornado Outbreak in December 2021 and will be publishing two Recovery Advisories, a Fact Sheet, and a Design Guide in FY 2023 based on findings from the deployment. MAT deployments for Hurricane Ian that made landfall at the end of FY 2022 will occur in FY 2023. *(Objective 5)*

FEMA: Hazus Hurricane Loss Estimation Model: Based on substantial damage inspections and observed damages from Hurricanes Irma and Maria, FEMA enhanced Hazus by developing new wind damage functions and updated structural data specifically representative of building construction practices common in Puerto Rico and the U.S. Virgin Islands (USVI). This increases 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. (*Objective 9*)

NIST: Hurricane Wind Field Analysis Mission Assignments: NIST conducted MAs for FEMA to develop rapid estimates of the surface-level wind fields for Hurricanes Delta, Ida, and Ian, in support of operational applications of the Hazus Hurricane Model and other disaster response needs. (*Objective 9*)

NIST: Tornado Loads on Buildings. NIST completed the development of a new tornado load methodology that accounts for differences between tornadic and straight-line winds, and tornadic and straight-line wind-structure interaction. This methodology is the basis for the tornado load procedure in the ASCE 7-22 standard, as described in Goal C. *(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 2021-2022 included development of a quantification procedure for numerical uncertainties in CFD simulation results 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 2021-2022, in partnership with a private structural engineering firm, NIST developed ETABS-based software for steel high-rise buildings allowing the effective and practical 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 2021-2022, the center released version 3.7.0 of IN-CORE (Interdependent Networked Community Resilience Modeling Environment). IN-CORE models the impact of a user-designed natural hazard (e.g., a tornado) on a community to evaluate user-modified physical and socio-economic attributes of a community. This allows community planners to test different models of disaster resilience planning with the goal of optimizing disaster response. *(Objectives 5, 7; Strategic Priority 3)*

NIST: Longitudinal Study of the Recovery of Lumberton, NC, from Hurricane Matthew: NIST conducted its fifth data collection in FY 2022 focused on documenting the impacts of COVID-19 and the ongoing recovery from Hurricane Florence and Hurricane Matthew for housing, businesses, and the public sector. The team also expanded the collection of forward leaning actions for preparedness, mitigation, and resilience to future events. With the fifth data collection, the team was able to resume in-person data collection. NIST also published the report from its third data collection in FY 2022. *(Objectives 5, 7, 8)*

NIST: Hurricane Maria Program: In FYs 2021-2022 NIST completed several important data collection activities as part of its multi-year National Construction Safety Team (NCST) investigation and NWIRP research study of the impacts of Hurricane Maria on Puerto Rico, including wind tunnel testing of building and topographic models to better understand the effects of topography on wind loads, information provider interviews and household surveys about the public's response to emergency communications, hospital interviews and medical record abstraction to study hurricane-related deaths, collection and review of documentation on building design and performance for selected hospitals and buildings used as shelters, and surveys of manufacturing and retail service businesses on hurricane impacts and subsequent recovery. 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. NOAA continues to work 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. NOAA researchers at the AOML and the Cooperative Institute for Marine and Atmospheric Studies partnered with Florida International University researchers to update and maintain the wind model. Analyses of Hurricanes Isaias and Sally that affected Florida were completed. *(Objective 9)*

NSF: Structural Extreme Events Reconnaissance (StEER) Network.[48] This NSF-supported research network developed quick-response datasets and reconnaissance reports for 11 windstorm events

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

(hurricanes, tornadoes and cyclones) during the FYs 2021-2022 reporting period. The reports are free and available for download at https://www.steer.network/products. *(Objectives 5, 8; Strategic Priority 3)*

NSF: Nearshore Extreme Events Reconnaissance (NEER) Network. NEER deployed fast-response research teams following Hurricane Ida in September of 2021 and Winter Storm Kenan in January 2022. The teams gathered pre-, during- and post-storm data relevant to ecosystems impacted by significant storms, including interactions between waves, surge, currents, sediments, and structures. *(Objectives 5, 8; Strategic Priorities 2, 3)*

NSF: SUstainable Material Management Extreme Events Reconnaissance (SUMMEER) Network. During this reporting period, the SUMMEER network created and made publicly available a set of training webinars to aid researchers seeking to collect data about debris following disasters as well as webinars to help municipalities make decisions about disaster waste management. The training videos are free and available at https://www.youtube.com/channel/UClK3eBAc-nhPejZLiv4URHw. *(Objectives 5, 8; Strategic Priority 6)*

NSF: Wind Hazard and Infrastructure Performance Center (WHIP-C). This multi-university Industry-University Cooperative Research Center (IUCRC) addresses NWIRP-relevant research questions. The WHIP-C's Industry Advisory Board members are drawn from insurance, risk-modeling, and building and construction industries, and NIST joined as a member in FY 2022. In this reporting period, the WHIP-C initiated new studies of anchor requirements for roof systems, better field data about damage to improve risk models, and development of new fragility curves for tornado loads on low-rise buildings, among other topics. *(Objectives 5, 7, 8, 9; Strategic Priorities 3, 4, 5)*

NSF: Natural Hazards Engineering Research Infrastructure (NHERI). During this reporting period, all of NHERI's major experimental facilities dedicated to natural hazards research (see Appendix C), including several specifically pertinent to NWIRP topics, were renewed for an additional five years, ensuring continuity and support for the relevant research communities. In addition, NHERI began planning for a new wind, wave, and surge testing facility (known as the National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events (NICHE)), and the NHERI Simulation Center established two new hurricane testbeds for the study of potential storm impacts, one for Atlantic County, NJ, and one for Lake Charles, LA. *(Objectives 5, 6, 7, 9)*

5.4 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 NWIRP 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*)

Through a collaborative effort with stakeholders, FEMA makes available to the public a substantial library of guides and resources aimed at mitigating building damage[49] and promoting safe construction and usage of shelters[50] from severe windstorms and associated hazards. More FEMA publications, related to wind and

[49] https://www.fema.gov/emergency-managers/risk-management/building-science

[50] https://www.fema.gov/emergency-managers/risk-management/safe-rooms/resources

coastal surge hazards, are available for free on FEMA's media library website, the Google Books website, and MADCAD (http://www.madcad.com/). Many of these presentations and training interventions 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, MD. FEMA includes advanced wind-related modules for in-person training courses at EMI. *(Objective 11)*

NIST: Translating R&D Advances into Model Building Codes and Standards. NIST-led efforts to incorporate the new tornado hazard maps and load methodology into the national load standard were successfully concluded with the inclusion of a new *Chapter 32-Tornado Loads* in the *ASCE 7-22 Standard-Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. NIST collaborated with ASCE and FEMA to develop and submit a successful proposal to the ICC for inclusion of the ASCE 7-22 Tornado Load requirements into the 2024 International Building Code (IBC). A collaborative proposal between NIST and industry to revise the velocity pressure profiles was also accepted in ASCE 7-22, improving safety for taller buildings. NIST made significant contributions to improvements in provisions for approach flow characteristics, testing procedures, and acceptance criteria in the *ASCE 49-21, Standard for Wind Tunnel Testing for Buildings and other Structures. (Objective 11)*

NOAA: Forecast Improvement Programs.

- The Hurricane Forecast Improvement Project (HFIP) major development focus in FYs 2021-2022 was on building the next generation Hurricane model, Hurricane Analysis and Forecast System (HAFS), and adding multi-storm telescoping nest capabilities that provides a higher model resolution over the storm for track and intensity predictions. The storm-following telescopic moving nests are designed to satisfy the requirements of the resolution to resolve the TC's large-scale structure and forecast efficiency. *(Objective 13)*
- During FYs 2021-2022, the development and the eventual opening of the new testbed at NOAA's NHC was realized. The Hurricane and Ocean Testbed will offer a physical place to bridge researchers with forecasters. It builds upon the work outlined by NOAA's Joint Hurricane Testbed and will expand its focus to look at marine forecasts testing of new techniques, applications, and ensemble model enhancements to improve the analysis and prediction of TCs. *(Objective 13)*
- 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 FACETs, which will provide users a continuously updating suite of probabilistic information about hazardous weather threats. Near term experimental probabilistic guidance for severe storm hazards (tornadoes, hail, wind and lightning) is being evaluated with NWS forecasters through the NOAA Hazardous Weather Testbed. As a first step, a project called Threats In Motion (TIM), where current polygon-based warnings are allowed to move with severe local storms, has undergone testing at the NWS Operations Proving Ground as well as the Hazardous Weather Testbed. Once implemented, there is a strong likelihood that TIM will improve the equitability of tornado and severe thunderstorm warning lead times. *(Objective 13)*
- The StormReady Program supports a Weather-Ready Nation (WRN) by preparing communities for the occurrence of high impact environmental events. Each year, the NWS targets a set number of

new StormReady communities, pending funding availability. In FY 2021, there were 55 new StormReady communities added (FY 2021 milestone was 50). Through September 19, 2022 there were 76 new StormReady sites across the country for FY 2022 (FY 2022 milestone was 60). (*Objective 14*)

NSF/NIST: Joint Disaster Resilience Research Grants (DRRG) Program. DRRG aims to advance fundamental understanding of disaster resilience in support of improved, science-based planning, policy, decisions, design, codes, and standards. In FY 2022, 20 DRRG awards were issued, including 11 NWIRP-relevant projects. *(Objectives 1-14)*

NSF: Innovations for Improved Community Resilience. The CIVIC Innovation Challenge, which is run in partnership with the Department of Homeland Security (DHS) and the Department of Energy (DoE), flips the usual community-university dynamic by asking communities to identify priorities ripe for innovation then partner with researchers to address those priorities. In this reporting period, CIVIC made six NWIRP-relevant awards in which researchers are working directly with communities to solve important disaster-related problems. *(Objectives 10, 12, 13, 14)*

NSF: Large-Scale Investments in Coastal Resilience. NSF's Coastlines and People (CoPe) program issued two cohorts of large-scale "hub" awards during FY 2021 and FY 2022. Each CoPe Hub engages with communities vulnerable to storm and sea-level rise risks to jointly identify research priorities and co-produce knowledge, tools, and new interventions to reduce vulnerabilities and improve resilience to natural hazards. During this time period, CoPe issued seven new Focused Hub awards and four Large-Scale Hub awards, including a $20 million hub in an Established Program to Stimulate Competitive Research (EPSCoR) state that is developing a decision support tool that incorporates equity, economic conditions, anticipated losses and resilience variables (i.e., not just anticipated losses, which is common) to support mitigation and recovery decisions. *(Objectives 10, 12, 13, 14)*

NSF: Researchers and Communities Collaborating to Define Needs and Opportunities. The NSF's NHERI Program has funded a Decadal Visioning Project 2026-2035, to engage the relevant research communities in deliberations about what types of research infrastructure and resources will be most valuable to advance an understanding that can improve the Nation's resilience to natural disasters going forward. Also, the NHERI Coordination Office is engaging with the relevant research communities to update its Five-Year Science Plan. These reports will help the decentralized U.S. natural hazards research communities to share priorities, findings, and resources for maximum effectiveness. *(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 visions in which the WWG has agreed are worthy elements of the strategic plan should they be supported and resources become available. These visions will be visited by the WWG and updated in the NWIRP Strategic Plan when the opportunity arises.

- 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.
- Advance research into identifying needed building code and infrastructure adaptations as the global climate continues to warm over the next century. To do this, a connection must be made between the characteristics of a warming world resolvable on a global scale to the trends in natural hazards on a local scale that more directly affect building and infrastructure performance. Upon this, research can inform implementation and then subsequent adoption by local communities. The path to this adoption can take significant time and must begin with actionable information that can be used on the local scale. Thus, a memorandum of understanding between NOAA, NIST, and the ASCE has been signed to convene a series of workshops to identify best practices in utilizing climate projection information in community resilience planning and designs of resilient buildings and infrastructure. Actions that the workshops identify will likely evolve into broader cross-disciplinary research and development between NOAA, NIST, and ASCE. NWIRP agencies, and their collaborators, should be involved to enhance the ability to advance research into mitigating adverse outcomes from severe windstorms and associated hazards. Furthermore, these activities should be backed by sufficient funding to maximize the probability of success.
- Contribute to building a Weather-Ready Nation by integrating scientific advances in real-time impact-based extreme weather event forecasting and delivery, informed by social science and engineering, to elicit the appropriate responses by individuals and organizations, in alignment with the weather. The development of probabilistic forecasts and warnings should continue to be a high priority, along with methods to ensure such information is made available and actionable by individuals and organizations. The social science role informs the content of the forecasts and warnings to elicit the appropriate response while the engineering informs the process of relating the hazard intensity to predict the impacts upon the built environment and infrastructure. NWIRP organizations should continue their efforts to improve the suite of options to provide forecast and warning information and guidance to take action, including promoting more options for shelters to accommodate the diverse portfolio of exposure and vulnerabilities among the public and organizations. NWIRP stands ready to support the development of short-term warnings and decision support information for wildfire hazards, by providing guidance for predicting wildfire

spread in high winds, fire-generated windstorms, and tornadoes and subsequent impacts.[51,52,53] In addition, NWIRP can be leveraged to improve the verification of probabilistic warnings and forecasts which then feeds back to supporting warning improvements as well as community resilience.

- 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.
- 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.

[51] https://www.dhs.gov/sites/default/files/publications/wui_fire_report_of_findings_july_24_2019v2_508.pdf
[52] https://www.usfa.fema.gov/downloads/pdf/publications/wui-issues-resolutions-report.pdf
[53] https://www.nwcg.gov/sites/default/files/committee/docs/fenc-satellite-data-task-team-final-report.pdf

Appendix A: Acronyms and Abbreviations

AMS	American Meteorological Society
AOML	Atlantic Oceanographic and Meteorological Laboratory
APHEX	Advancing the Prediction of Hurricanes Experiment
ASCE	American Society of Civil Engineers
CAREER	Faculty Early Career Development
CESM	Community Earth System Model
CFD	Computational Fluid Dynamics
CoPe	Coastlines and People
COVID-19	Coronavirus Disease of 2019
CPC	Climate Prediction Center
CPI	Consumer Price Index
DAD	Database-Assisted Design
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
DRRG	Disaster Resilience Research Grants
DTC	NCAR's Developmental Testbed Center
EF	Enhanced Fujita [Scale]
EMI	Emergency Management Institute
EPSCoR	Established Program to Stimulate Competitive Research
FACETs	Forecasting a Continuum of Environmental Threats
FEMA	Federal Emergency Management Agency
FPHLM	Florida Public Hurricane Loss Model
FY	fiscal year
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
HWT	Hazardous Weather Testbed
IBC	International Building Code
ICAMS	Interagency Council for Advancing Meteorological Services
ICC	International Code Council
IN-CORE	Interdependent Networked Community Resilience Modeling Environment
IUCRC	Industry-University Cooperative Research Center
MA	Mission Assignment
MAT	Mitigation Assessment Team
MPAS	Model for Prediction Across Scales
mph	miles per hour
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Center for Environmental Prediction
NCST	National Construction Safety Team
NCSTA	National Construction Safety Team Act
NEER	Nearshore Extreme Events Reconnaissance
NGGPS	Next Generation Global Prediction System
NHC	National Hurricane Center
NHERI	Natural Hazards Engineering Research Infrastructure
NICHE	National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	U.S. Nuclear Regulatory Commission

NSF	National Science Foundation
NSSA	National Storm Shelter Association
NSSL	National Severe Storms Laboratory
NSTC	National Science and Technology Council
NWIRA	National Windstorm Impact Reduction Act
NWIRP	National Windstorm Impact Reduction Program
NWS	National Weather Service
OAR	NOAA’s Oceanic and Atmospheric Research
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
PAR	Phased Array Radar
PERiLS	Propagation, Evolution and Rotation in Linear Storms
PSDA	Post-Storm Data Acquisition
RAPID	Rapid Response Research
REU	Research Experiences for Undergraduates
R2O	Research to Operations
SDR	Science for Disaster Reduction
SEI	Structural Engineering Institute
SIP	Strategic Implementation Plan
SPC	Storm Prediction Center
SRST	Subcommittee on Resilience Science and Technology
StEER	Structural Extreme Events Reconnaissance
STEM	Science, Technology, Engineering, and Mathematics
SUMMEER	SUstainable Material Management Extreme Events Reconnaissance
TC	tropical cyclone
TCs	tropical cyclones

TIM	Threats In Motion
TORUS	Targeted Observation by Radars and UAS of Supercells
UAS	Uncrewed Aerial System
UFS	Unified Forecast System
U.S.	United States
USGCRP	U.S. Global Change Research Program
USVI	U.S. Virgin Islands
VORTEX-SE	Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast
VORTEX-USA	Verification of the Origins of Rotation in Tornadoes EXperiment-United States of America
WHIP-C	Wind Hazard and Infrastructure Performance Center
WoF	Warn-on-Forecast
WoFS	Warn-on-Forecast System
WRF	Weather Research and Forecast
WRN	Weather-Ready Nation
WSE	Wind Speed Estimation
WWG	Windstorm Working Group

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 technical projects with the goal of making recommendations to encourage the

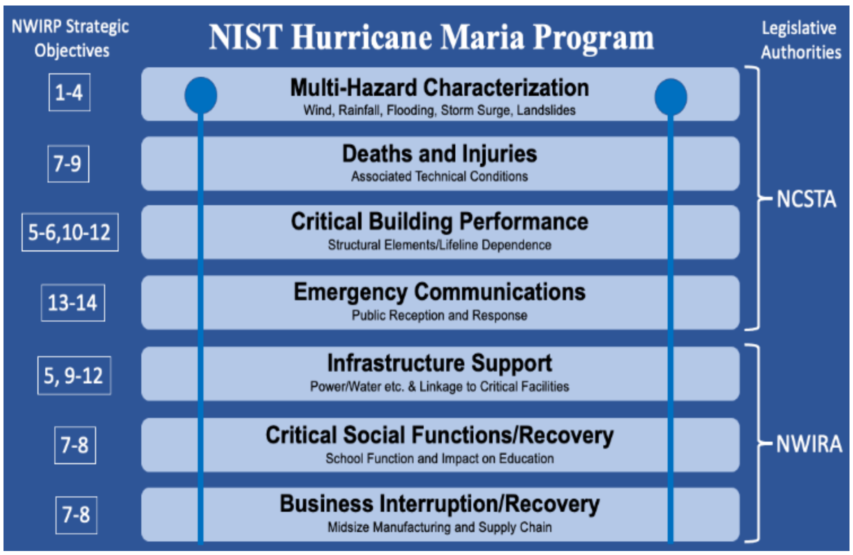

***Figure** 7. An outline of projects comprising the NIST Hurricane Maria Program*

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 NCSTA and the NWIRA. Figure 7 shows the grouping of the various research projects with the attendant legislative authority. As complementary components of the NIST Hurricane Maria Program, the NCST technical investigation and the NWIRP research study are closely coordinated, and the foci of the seven projects span all 14 objectives contained within the NWIRP Strategic Plan, as indicated on the left side of Figure 7.

Tornado Load Requirements for Conventional Buildings. Following years of research and development on tornado hazards and tornado-structure interaction, NIST engagement with the building standards and codes processes resulted in the first-ever probabilistic tornado hazards maps and tornado load methodology for tornado-resistant design of buildings being incorporated into the ASCE 7-22 national load standard and approved for inclusion in the 2024 IBC. This accomplishment represents a paradigm shift in design for windstorms (the only prior mention of tornadoes in the IBC was for design of storm shelters). As these new tornado provisions get adopted into state and local building codes, essential facilities (e.g., hospitals, fire and police stations) and facilities that represent a substantial hazard to human life (e.g., high occupancy buildings, schools, nursing homes) in much of the U.S. can now be designed for tornado loads in addition to wind loads from hurricanes, thunderstorms, Nor'easters, and other extreme wind events. The tornado load requirements apply to buildings and other structures in the conterminous U.S. east of the Continental Divide, where most U.S. tornadoes occur.

Design tornado speeds vary from 60 to 138 mph, or approximately EF0-EF2 on the Enhanced Fujita Scale, depending on geographic location, building function, and plan size and shape of the building or facility. It is important to note that these code requirements reflect design for the most common tornadoes, not the most intense. Approximately 97% of all tornadoes in the past few decades have been rated EF2 or less. For life safety protection from more intense tornadoes, storm shelters and safe rooms should be used. The design tornado speed will be less than the design wind speed for most buildings; however, the design loads for tornadoes will often be greater than the design wind loads, due to other differences in tornado wind and wind-structure interaction characteristics. For example, uplift loads in building roofs will typically increase more than loads on other parts of the building, due in part to the strong updrafts in tornadoes that are not present in other types of windstorms. In some cases, the tornado loads may be double or more compared to wind loads required by the current version of the code. While these large load increases will translate into buildings with significantly more capacity to resist wind loads from tornadoes and other storm types, the increase in construction costs is expected to be minimal. From a study led by the NIST Office of Applied Economics,[54] considering construction cost impacts on archetype elementary and high school buildings, the maximum increases were approximately 0.14% of the total construction budget, in cities such as Kansas City, Dallas, and Memphis. Locations farther away from the central U.S. had much smaller increases or no cost increases at all.

NOAA

Hurricane Forecast Improvement Program (HFIP). The HFIP was established within NOAA in 2007, in response to devastating hurricanes such as Charley in 2004, and Wilma, Katrina, 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 is 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 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 the NWS/National Center for Environmental Prediction (NCEP) and NOAA’s Oceanic and Atmospheric Research (OAR)/AOML and supported by the NCAR/Developmental Testbed Center (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 Research to Operations (R2O) efforts

[54] Economic Analysis of ASCE 7-22 Tornado Load Requirements. NIST TN 2214. March 2022. https://doi.org/10.6028/NIST.TN.2214

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/.

Warn-on-Forecast (WoF). WoF is a NOAA research project tasked to increase tornado, severe thunderstorm, and flash flood warning lead times by connecting high spatial and temporal resolution model output with confidence levels from warning forecasters. 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 times 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 more updated approach whereby model output and the observational network are used together to effectively extend lead times on hazardous weather events. This will involve probabilistic hazard guidance provided by an ensemble of forecasts from convection-allowing numerical weather prediction models.

Researchers at NOAA's National Severe Storms Laboratory are developing the Warn-on-Forecast System (WoFS) 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 and warnings of thunderstorm hazards—like tornadoes, hail, wind, and flash flooding—with more lead-time than is currently possible with detection-based warning techniques. The fundamental concept of WoFS is to provide continuous, probabilistic predictions of hazards in individual thunderstorms. WoFS is an important component of Forecasting a Continuum of Environmental Threats (FACETs). FACETs aims to provide continuous probabilistic hazard information guidance to the public from time frames of multiple weeks up through less than one hour prior to a given event. 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, WoFS guidance has been tested by forecasters and researchers within NOAA's Hazardous Weather Testbed (HWT), the annual Spring Forecasting Experiment and within the Hydrometeorological Testbed. WoFS was presented to emergency managers within the HWT in 2019 and again in 2022. The feedback provided by participants guides subsequent improvements to WoFS as NOAA NSSL collaborates with partners to reduce the billions in economic impacts from severe storms and flash floods. More information can be found at https://www.nssl.noaa.gov/projects/wof/.

NSF

NSF Overview of NHERI. The NSF- supported NHERI is a multi-hazards research community focused on mitigating the impact of earthquakes, windstorms, tsunamis, storm surge and other water-related hazards on our nation's civil infrastructure and society. NHERI enables research and educational advances 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 supports NSF's core value to broaden opportunities and expand participation of groups, institutions, and geographic regions that are underrepresented in 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/. Findings from research using NHERI resources during FYs 2021-2022 can be found in the State of Technology Transfer in the Natural Hazards Infrastructure Research: 2021 Annual Report (https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/PRJ-3332) and 2022 (https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/PRJ-3469).

NSF NHERI Awards as of FY 2022.

Facility	Institution	NSF Award Number
Network Coordination Office (NCO)	Purdue University	2129782
Cyberinfrastructure (CI)	University of Texas at Austin	2022469
Computational Modeling & Simulation Center (SimCenter)	University of California - Berkeley	2131111
Experimental Facility (RAPID Facility)	University of Washington	2130997
Experimental Facility (Wave Flume & Wave Basin)	Oregon State University	2037914
Experimental Facility (Geotechnical Centrifuges)	University of California - Davis	2037883
Experimental Facility (Hybrid Simulation)	Lehigh University	2037771
Experimental Facility (Mobile Field Shakers)	University of Texas at Austin	2037900
Experimental Facility (Wind Tunnel)	University of Florida	2037725
Experimental Facility (Wall of Wind)	Florida International University	2037899
Experimental Facility (Large Outdoor Shake Table)	University of California-San Diego	2227407
NHERI Resource: CONVERGE - Coordinated Social Science, Engineering, and Interdisciplinary Extreme Events Reconnaissance Research	University of Colorado-Boulder	1841338
NHERI Decadal Visioning for FYs 2026-2035	Nexight Group LLC	2227014
Mid-scale RI-1 (M1:DP): National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events (NICHE)	Florida International University	2131961

NSF Multi-year Research Projects as of FYs 2021-2022 (Geoscience).

Research Projects	Institution	NSF Award Number
Storm-environment interactions controlling the probability of supercell tornadogenesis	North Carolina State University	2130936
Identifying the Physical Drivers and Radar Signatures of Fire-Generated Tornadic Vortices	University of Nevada - Reno	2114251
Combining Self-organized Maps and Idealized Storm-scale Simulations to Investigate the Effect of Future Climate Change on Severe Convective Storms	Purdue University; University of Washington	2209052; 2209699
Detection and Estimation of Multi-Scale Complex Spatiotemporal Processes in Tornadic Supercells from High Resolution Simulations and Multiparameter Radar	University of Wisconsin; University of Oklahoma; University of California – San Diego	2114757; 2114817; 2114860
EAGER: Progressive Derecho Initiation and Propagation in Specific Physical Corridors as Determined by Mesoscale D-PSI Vectors	Desert Research Institute	2231695
On the Intensity and Size Relationship of Tropical Cyclones	Florida State University; University of Maryland	2202875; 2202766
Improving Our Understanding of Supercells from Convection Initiation to Tornadogenesis via Innovative Observations, Simulations, and Analysis Techniques	Pennsylvania State University; University of Oklahoma	2150792; 2150793
The Vorticity Dynamics of Tornadoes: Formation and Maintenance Mechanisms	Texas Tech University	2152537

Continued Fundamental Studies on Secondary Eyewall Formation, Contraction and Dissipation	**Naval Postgraduate School**	**2201246**
Mechanisms and Variability of Tropical Cyclone Formation under the Upper-Tropospheric Influence	**University of Illinois**	**2116804**
Understanding the Turbulent Dynamics of Convective Bursts and Tropical Cyclone Intensification Using Large Eddy Simulations and High-Order Numerics	**University of Maryland Baltimore County; New Jersey Institute of Technology**	**2121366; 2121367**
RAPID: Multi-Scale Investigation into the Storm Processes of the 10 August 2020 Midwest Derecho	**University of Oklahoma; University of Nebraska-Lincoln; University of Illinois**	**2054677; 2054688; 2054706**
RAPID: Dual-Doppler Analysis of the Boundary Layer in Category-4 Hurricane Laura	**University of Illinois**	**2112980**
RAPID: The Influence of Terrain on Tornado Characteristics Following the 10-11 December 2021 Tornado Outbreak	**University of Nebraska-Lincoln; University of Georgia; University of Illinois; University of North Carolina at Asheville**	**2221974; 2221975; 2221976; 2221977**
Convective Upscale Growth Processes during RELAMPAGO	**University of Wisconsin; Colorado State University; University of Washington**	**2146708; 2146709; 2146710**
EAGER: Observing Extreme Fire Behavior in Canyons	**San Jose State University**	**2230778**

CAREER: Role of Canopy Turbulence in Wildland Fire Behavior	**University of California - Irvine**	**2146520**
Propagation, Evolution and Rotation in Linear Storms (PERiLS)	**University of Illinois; North Carolina State University**	**2020462; 2020588**
Rapid-scan Polarimetric Radar Data Collection and Analysis of the Wind Field in Severe Convective Storms and Tornadoes	**University of Oklahoma**	**2214926**
Downshear Reformation of Tropical Cyclones	**State University of New York - Albany**	**2225604**
Understanding Downdrafts in Deep Convection	**Pennsylvania State University; Texas A&M University; Columbia University**	**2149353; 2149354; 2149355**

Appendix D: NWIRP Coordinated Budget

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.[55] 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;
- Develop tornado resistant designs for risk category II buildings;
- 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.

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.

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[55] 42 U.S.C. § 15703(e)(7).

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 NHC/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 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 2021 Actuals ($K)**	**FY 2022 Actuals ($K)**	**FY 2023 Enacted ($K)**
NIST [1]	5,320	5,320	5,481
NOAA [2]	17,992	17,371	16,995
NSF [3]	41,181	83,010	9,682
FEMA [4]	450	600	0
Total	**64,943**	**106,301**	**32,158**

1) NIST FY 2021 actuals and FY 2022 actuals reflect allocation to support the Hurricane Maria Investigation.
2) NOAA totals are not reflective of hurricane supplemental funds.
3) NSF has no dedicated NWIRP activities with its own solicitation. 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, a presumed amount is not included in FY 2023, although in prior years FEMA has been able to fund some level of activity by leveraging other resources.