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Hurricane Rapid Intensification: In Brief

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Contents

Figures

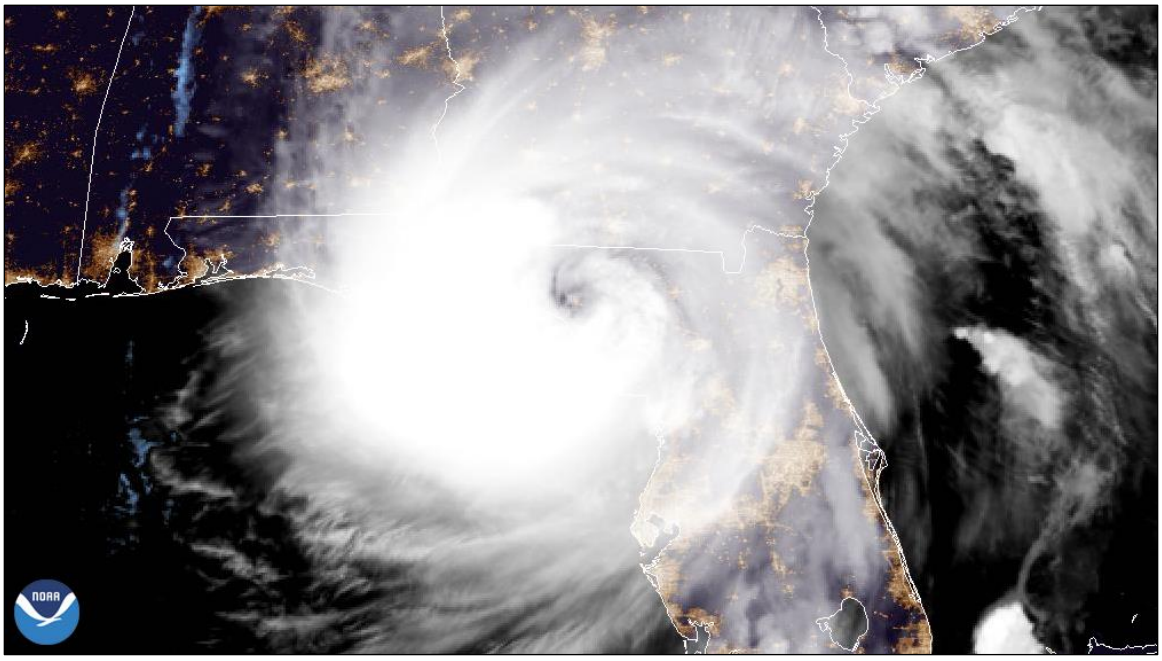
Contacts

Rapid Intensification and Coastal Communities

Hurricanes and other tropical cyclones cause destruction and fatalities in the United States and around the world. In recent years, the media and meteorologists have concentrated on the phenomenon of tropical cyclone rapid intensification (RI), where a tropical cyclone's maximum sustained winds increase at least 30 knots (~35 miles per hour [mph]) in a 24-hour period (a storm's maximum sustained wind speed defines its intensity).[1] For example, 2024's Hurricane Helene's maximum sustained wind speeds intensified from 45 mph to 80 mph in 24 hours; the hurricane made landfall with winds at 140 mph less than 36 hours after that (**Figure 1**).[2] Some scientists have found evidence of global and regional increases in the number of tropical cyclones that rapidly intensify in the recent past; however, scientific questions remain (see "Tropical Cyclone Intensities in the Recent Past").

Figure 1. Satellite Image of Hurricane Helene Making Landfall in Florida

(September 27, 2024)



Source: National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, "Hurricane Helene Makes Landfall in Florida," https://www.nesdis.noaa.gov/news/hurricane-helene-makes-landfall-florida.

Protecting a community before a tropical cyclone makes landfall takes time—time to prepare homes and properties for high wind and flooding, to stock supplies, to evacuate, and to move ships and cargo away from or around the storm. Depending on the location of a tropical storm when it rapidly intensifies (e.g., far offshore versus close to the coast), an individual or community may have less time to prepare or evacuate before an intensifying storm comes onshore. State, local, tribal and territorial emergency management officials may be less prepared

[1] National Oceanic and Atmospheric Administration (NOAA), National Hurricane Center and Central Pacific Hurricane Center (NHC), "Glossary of NHC Terms—Rapid Intensification," https://www.nhc.noaa.gov/aboutgloss.shtml.

[2] NOAA, NHC, "Hurricane Helene Advisory Archive," https://www.nhc.noaa.gov/archive/2024/HELENE.shtml?.

or unable to prepare for the magnitude of the storm and its impacts, potentially leading to longer response and recovery times, greater number of injuries and fatalities, as well as greater need for federal resources. Information on whether a storm may rapidly intensify—and to what extent—also affects maritime safety, with greater lead times allowing recreational and commercial ships to move their vessels and cargo away from or around hazardous conditions.

Concerns regarding preparation and evacuation before experiencing tropical cyclone conditions are especially salient in communities with fewer resources and more vulnerable individuals. Buildings in these communities may not be as resilient as buildings in other communities and may experience greater destruction once the storm arrives. In addition, residents in lower-resourced communities may need more time to evacuate safely and may be less able to adequately prepare.[3]

This report introduces tropical cyclone intensity forecasting, trends in storm intensity in recent decades, and projections of potential changes to storm intensity in the future.[4] The report ends with selected congressional considerations.

Forecasting, Trends, and Projections

Tropical cyclones are a rotating system of clouds and thunderstorms that originate over tropical and subtropical waters. Tropical cyclones need a preexisting weather disturbance (e.g., *tropical wave*),[5] warm water (over ~80^{O}F), thunderstorm activity that generates a low pressure area, and low wind shear (e.g., crosscutting winds that can disrupt a storm).[6]

Forecasting Tropical Cyclone Intensity

NOAA's National Weather Service (NWS) is the primary civilian federal agency responsible for forecasting tropical cyclones, including hurricanes in the Atlantic and eastern North Pacific Oceans, and issuing related watches and warnings.[7] NWS provides estimates of the storm's path or track, intensity or wind speed, size, and structure, as well as predictions of other hazards associated with a storm (e.g., storm surge, precipitation, flooding, tornadoes).[8] Storm forecasts involve many components and use a broad array of resources and capabilities within NOAA and

[3] For example, CRS Report R47280, *Defining FEMA's Approach to Equity and Emergency Management: Policy Considerations*, coordinated by Erica A. Lee; Insurance Institute for Business and Home Safety, "Vulnerable Populations," https://ibhs.org/public-policy/vulnerable-populations/; NOAA, National Centers for Environmental Information, "In Harm's Way: Hurricane Ida's Impact on Socially Vulnerable Communities," https://storymaps.arcgis.com/stories/780e11bd19cc4dfca54ac8fb1d5e926f.

[4] For more in-depth information about tropical cyclone forecasting, see CRS Report R46416, *Forecasting Tropical Cyclones: Overview and Issues for Congress*, by Eva Lipiec.

[5] NOAA defines a *tropical wave* as a "low pressure area that moves through the moisture-rich tropics, possibly enhancing shower and thunderstorm activity." NOAA, National Ocean Service (NOS), "How Do Hurricanes Form?," https://oceanservice.noaa.gov/facts/how-hurricanes-form.html.

[6] Ibid.

[7] NOAA, NHC, "About the National Hurricane Center," https://www.nhc.noaa.gov/aboutintro.shtml. The National Hurricane Center is part of the National Weather Service. The Air Force 557th Weather Wing provides similar services to the Department of Defense and military services, among other entities (https://www.557weatherwing.af.mil/About-Us/).

[8] University of Rhode Island Graduate School of Oceanography (URI GSO), "National Hurricane Center Forecast Process," http://www.hurricanescience.org/science/forecast/forecasting/forecastprocess/. Hereinafter URI GSO, "National Hurricane Center Forecast Process."

NWS and at other federal agencies.[9] The process begins with observations from satellites, aircraft, ships, buoys, radar, automated weather stations, and other sources. NWS uses the observational data to generate a series of forecast computer model simulations. Using the data as a baseline, the model uses mathematical equations to determine whether a tropical cyclone may form and, if so, to predict its characteristics.[10] Tropical cyclone forecast model simulations typically predict a storm's track (path) and intensity (wind speeds) over a period of three to five days. NWS forecasters analyze the model results and use their experience and expertise in the strengths and weaknesses of the various models to develop official public forecast products.[11] NWS produces and issues official public forecast products every six hours after a storm forms and more frequently if a tropical storm or hurricane watch or warning is issued. It also provides briefings to emergency managers, the media, and the public and cooperates with meteorological services in other countries (e.g., Mexico, countries in the Caribbean).[12] Local Weather Forecast Offices use the information from the official forecast to tailor their forecasts, accounting for local conditions and effects.[13]

According to NOAA, tropical cyclones include the following:

- **Tropical Depression**—a tropical cyclone with maximum sustained winds of 38 mph or less
- **Tropical Storm**—a tropical cyclone with maximum sustained winds of 39-73 mph
- **Hurricane**—a tropical cyclone with maximum sustained winds of 74 mph or higher. Hurricanes are called *typhoons* in the western North Pacific Ocean and *cyclones* in the Indian Ocean and South Pacific Ocean
- **Major Hurricane**—a tropical cyclone with maximum sustained winds of 111 mph or higher, corresponding to a category 3, 4, or 5 on the Saffir-Simpson Hurricane Wind Scale[14]

NWS issues a hurricane watch when conditions—sustained winds of 74 mph or greater—are possible within a specified coastal area, usually issued 48 hours in advance of the onset of tropical-storm-force winds. NWS issues a hurricane warning when hurricane conditions are expected somewhere within the specified coastal area in 36 hours or less.[15] Tropical storm watches and warnings have similar timeframes but for tropical storm conditions.

[9] The National Hurricane Operations Plan outlines various agency responsibilities across the federal government. See Interagency Council for Advancing Meteorological Services, *National Hurricane Operations Plan*, May 2024, FCM-P12-2024, https://www.icams-portal.gov/resources/ofcm/nhop/2024_full_nhop_change_2.pdf.

[10] URI GSO, "National Hurricane Center Forecast Process."

[11] John P. Cangialosi, Robbie Berg, and Andrew Penny, "Skill or Luck? How NHC's Hurricane Track Forecasts Beat the Models," NOAA, *Inside the Eye: Official Blog of the National Hurricane Center (NHC)*, April 9, 2020, https://noaanhc.wordpress.com/2020/04/09/skill-or-luck-how-nhcs-hurricane-track-forecasts-beat-the-models/.

[12] URI GSO, "National Hurricane Center Forecast Process"; URI GSO, "National Hurricane Center Forecast and Warning Products," https://www.hurricanescience.org/science/forecast/forecasting/forecastproducts/index.html; and NOAA, NWS, National Centers for Environmental Prediction, NHC, *National Hurricane Center Product Description Document: A User's Guide to Hurricane Products*, May 2024, https://www.nhc.noaa.gov/pdf/NHC_Product_Description.pdf.

[13] URI GSO, "National Hurricane Center Forecast Process."

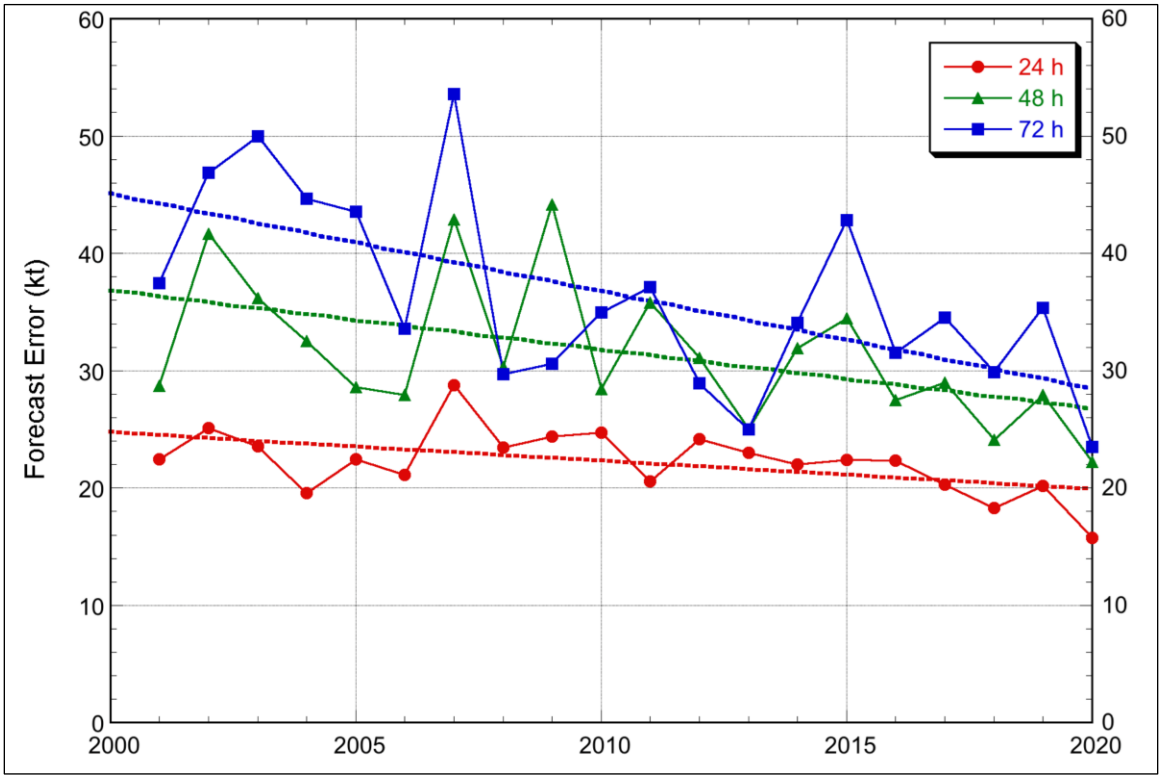
[14] NOAA, NHC, "Saffir-Simpson Hurricane Wind Scale," https://www.nhc.noaa.gov/aboutsshws.php.

[15] NOAA, NWS, "Hurricane and Tropical Storm Watches, Warnings, Advisories and Outlooks," https://www.weather.gov/safety/hurricane-ww.

Broadly, NWS has decreased *errors* (or the difference between the forecasted wind speed and the actual wind speed) associated with intensity forecasts over the past few decades.[16] To better understand NWS skill in forecasting a storm's rapid intensification one to three days out, researchers created a new metric.[17] Over the 2000-2020 time period in the Atlantic and eastern North Pacific basins, researchers found a downward trend in forecast errors at the 24, 48 and 72 hour forecasts during rapid intensification events (**Figure 2**).

Figure 2. Atlantic and Eastern North Pacific Basin Annual Average Intensity Errors When Rapid Intensification Was Observed or Forecast

(2000-2020)



Source: Mark DeMaria et al., Figure 15, in "Operational Forecasting of Tropical Cyclone Rapid Intensification at the National Hurricane Center," *Atmosphere, Special Issue: Rapid Intensity Changes of Tropical Cyclones*, vol. 12, no. 6 (May 26, 2021), p. 683, https://doi.org/10.3390/atmos12060683.

Notes: kt = knots (1 knot = 1.2 miles per hour; 30 knots = 35 mph). The categories in the Saffir-Simpson Hurricane Wind Scale differ in wind speeds by 15-27 mph.

The figure shows historical annual average performance of the National Oceanic and Atmospheric Administration's (NOAA's) National Hurricane Center's official forecast at 24, 48, and 72 h for the combined Atlantic and eastern North Pacific basins for the sample of cases when rapid intensification was either observed or forecast by NHC. Trend lines are shown by dashed lines. According to the authors, the verifications for the

[16] John P. Cangialosi et al., "Recent Progress in Tropical Cyclone Intensity Forecasting at the National Hurricane Center," *Weather and Forecasting*, vol. 35, no. 5 (October 1, 2020), pp. 1913-1922. For information about forecast errors in the 2023 hurricane season, see John P. Cangialosi, Brad J. Reinhart, and Jonathan Martinez, *NHC Forecast Verification Report: 2023 Hurricane Season*, June 3, 2024, https://www.nhc.noaa.gov/verification/pdfs/Verification_2023.pdf.

[17] Mark DeMaria et al., "Operational Forecasting of Tropical Cyclone Rapid Intensification at the National Hurricane Center," *Atmosphere, Special Issue: Rapid Intensity Changes of Tropical Cyclones*, vol. 12, no. 6 (May 26, 2021), p. 683, https://doi.org/10.3390/atmos12060683. Hereinafter DeMaria et al., "Operational Forecasting."

2020 season are preliminary, as not all of NWS's post-storm best track analyses were complete at the time this article was prepared.

NOAA defines *forecast intensity error* as "the absolute value of the difference between the forecast and best track intensity at the forecast verifying time," or more simply the difference between the forecasted wind speed and the actual wind speed (John P. Cangialosi, Brad J. Reinhart, and Jonathan Martinez, *NHC Forecast Verification Report: 2023 Hurricane Season*, June 3, 2024, https://www.nhc.noaa.gov/verification/pdfs/Verification_2023.pdf).

Tropical Cyclone Intensities in the Recent Past

How and why tropical cyclones may or may not have changed in intensity since records have been kept is not clear.[18] Some of the changes may be due to natural variability, whereas others may be due to human-induced climate change.[19] NOAA scientists have highlighted findings in the broader literature, including

- a poleward shift of maximum intensity storms in the northwest Pacific basin since 1980, meaning more intense storms are reaching higher latitudes;[20]
- a decrease in the number of Category 1-5 tropical cyclones (primarily due to a reduction in the number of Category 1 storms), with an increase in proportion of Category 3-5 storms, between 1979 and 2017;[21] and
- an increase in RI in the Atlantic, northwest Pacific, and other global basins between 1982 and 2017 compared with one climate model's simulation of climate variability. Other researchers also found an increasing trend in intensification rates in the Atlantic basin since the 1970s.[22]

According to some estimates, the number of tropical cyclones that experience RI of 50 knots (58 mph) or greater per year increased between 1990 and 2021 globally, with much of the increase in the western North Pacific, and North and South Indian basins.[23] Other researchers found variation in the average number of storms that rapidly intensified per five-year period between 1986 and 2020, with greater numbers of storms experiencing RI in the eastern Pacific basin than the Atlantic basin.[24]

Still others note changes in RI near coasts and the impacts of intensified storms once onshore. Research suggests an increase in global average intensification rates in regions close to the coast from 1979 to 2020;[25] with fewer than 5 storms experiencing RI per year in the 1980s to about 15

[18] NOAA, Geophysical Fluid Dynamics Laboratory (GFDL), "Global Warming and Hurricanes," https://www.gfdl.noaa.gov/global-warming-and-hurricanes/. Hereinafter NOAA, GFDL, "Global Warming and Hurricanes."

[19] Ibid.

[20] Ibid; and Thomas Knutson et al., "Tropical Cyclones and Climate Change Assessment: Part 1: Detection and Attribution," *Bulletin of the American Meteorological Society*, vol. 100, no. 10 (October 1, 2019), pp. 1987-2007, https://doi.org/10.1175/BAMS-D-18-0189.1.

[21] Ibid; and Stephen Jewson and Nicholas Lewis, "Statistical Decomposition of the Recent Increase in the Intensity of Tropical Storms," *Oceans Special Issue: Tropical Cyclone Future Projections*, vol. 1, no. 4, (December 11, 2020), pp. 311-325, https://doi.org/10.3390/oceans1040021.

[22] Ibid and Andra J. Garner, "Observed Increases in North Atlantic Tropical Cyclone Peak Intensification Rates," (October 19, 2023), *Nature Scientific Reports*, https://doi.org/10.1038/s41598-023-42669-y.

[23] Klotzbach et al., "Trends in Global Tropical Cyclone Activity: 1990-2021," *Geophysical Research Letters*, vol. 49, no. 6, (March 14, 2022), https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021GL095774.

[24] DeMaria et al., "Operational Forecasting," Table 5.

[25] Balaguru et al., "A Global Increase in Nearshore Tropical Cyclone Intensification," *Earth's Future,* vol. 12, no. 5, (May 2, 2024), https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023EF004230.

storms experiencing RI per year by 2020 within 400 kilometers (~250 miles) of the coast.[26] Some evidence exists of tropical cyclones slowing down in forward speed once onshore in the 1948-2017 time period, which might allow for increased precipitation and wind speeds over some areas compared to faster moving storms.[27]

Potential Tropical Cyclone Intensities in the Future

Experts have found RI to be more likely in future decades, due in part to climate change. According to NOAA, scientists have medium to high confidence that tropical cyclone intensities globally will likely increase on average under a 2°C of global surface temperature increase, and that the global proportion of tropical cyclones that reach very intense levels (Category 4 and 5) will also likely increase over the 21st century.[28] Scientists also project these changes for the Atlantic basin, specifically.[29] Additionally, some research suggests the potential for a tropical cyclone to experience RI within 24 hours of landfall in the north Atlantic basin increases from 15% to 28% under an intermediate climate scenario (2.1-3.5°C global surface temperature increase).[30]

Selected Congressional Considerations

Congress may consider whether to take various actions to further prepare for tropical cyclone RI and its potential impacts on life and property. Considerations may include whether and how Congress could support improvements to the prediction of RI, especially RI of landfalling tropical cyclones. Potential avenues include requiring agencies to perform more frequent observations and provide greater resolution broadly and of specific tropical cyclones; enabling agencies to increase the amounts of data incorporated into modeling, forecasts, and projections; supporting efforts to advance existing models or develop new modeling schemes; and supporting investment in increased high performance computing capabilities. Congress could direct NOAA and other federal agencies to invest in research to further clarify the "poorly understood" environmental, oceanic, and inner storm processes that may contribute to RI.[31] The 118th Congress has considered

[26] Yi Li et al., "Recent Increases in Tropical Cyclone Rapid Intensification Events in Global Offshore Regions," *Nature Communications*, vol. 14 (August 24, 2023), https://www.nature.com/articles/s41467-023-40605-2.

[27] NOAA, GFDL, "Global Warming and Hurricanes."

[28] Ibid. The Intergovernmental Panel on Climate Change (IPCC) defines *confidence* as "the robustness of a finding based on the type, amount, quality, and consistency of evidence … and on the degrees to agreement across multiple lines of evidence" (IPCC, "Annex VII: Glossary," in *Climate Change 2021: the Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the IPCC*, 2021).

[29] NOAA, GFDL, "Global Warming and Hurricanes" and Babak Salarieh, Izuchukwu A. Ugwu, and Abdullahi M. Salman, "Impact of Changes in Sea Surface Temperature Due to Climate Change on Hurricane Wind and Storm Surge Hazards Across U.S. Atlantic and Gulf Coast Regions," *SN Applied. Science*, vol. 5, no. 205 (July 9, 2023), https://doi.org/10.1007/s42452-023-05423-7.

[30] Lockwood et al., "Increasing Flood Hazard." The article uses the SSP2-4.5 greenhouse gas (GHG) emissions climate scenario; the IPCC defines SSP2-4.5 as a scenario with intermediate GHG emissions, with 2.1 to 3.5°C temperature difference between 2081-2100 relative to 1850-1900 (IPCC, "Summary for Policymakers," in *Climate Change 2021: the Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the IPCC*, 2021).

[31] Moraes et al., "Advances in Tropical Climatology – a Review," December 28, 2023, *Physical Geography*, https://doi.org/10.1080/02723646.2024.2313778; Lockwood et al., 2024; Falko Judt, Rosimar Rios-Berrios, and George H. Bryan, "Marathon Versus Sprint: Two Modes of Tropical Cyclone Rapid Intensification in a Global Convection-Permitting Simulation," *Monthly Weather Review*, vol. 151, no. 10 (October 4, 2023), https://doi.org/10.1175/MWR-D-23-0038.1; NOAA, "State of the Science;" Office of Naval Research, "Tropical Cyclone Rapid Intensification (TCRI) DRI," https://www.onr.navy.mil/organization/departments/code-32/division-322/marine-
(continued...)

some of these issues, in proposed and passed bills.[32] Congress may consider these issues as a part of a broader portfolio of research on characteristics of tropical cyclones, including their breadth and track.

Another avenue of action may include directing federal agencies to take on new or different roles or to continue authorized activities in preparation for or response to rapidly intensified tropical cyclones. Congress may consider the following questions, among others:

- How can federal agencies, such as NOAA, improve the public's understanding and response to tropical cyclone watches and warnings, especially in cases where it is unclear whether a storm may rapidly intensify?
- Should federal support of coastal state, local, tribal, and territorial long-term planning, response, and building code adoption and enforcement change if RI is observed or projected to occur more frequently along the coast? If so, how?[33]
- Evacuation orders are issued at the local level—what federal data and information would be most useful, and in what timeframe, to emergency managers deciding whether to issue a voluntary or mandatory evacuation with a tropical cyclone that may rapidly intensify right before landfall?
- What, if any, changes can be made to evacuation and shelter procedures and planning to account for increased tropical storm intensity by emergency managers and individuals, particularly those that may face particular risk during an intense tropical cyclone (e.g., individuals with disabilities, elderly individuals, children)?

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[32] For example, P.L. 115-25; H.R. 1715, H.R. 2995, H.R. 3560, H.R. 4069, H.R. 6093, H.R. 9498, S. 3642, S. 3888, and S. 4907.

[33] For example, Congress directed the National Institute for Standards and Technology and the Federal Emergency Management Agency to report on ways to make communities more hazard resilient to reduce losses of life, property, and economic/social/cultural disruptions from natural hazards, such as hurricanes. For more information, see CRS Report R47215, *Hazard-Resilient Buildings: Sustaining Occupancy and Function After a Natural Disaster*, by Linda R. Rowan; CRS Report R47665, *Building Codes, Standards, and Regulations: Frequently Asked Questions*, coordinated by Linda R. Rowan; and CRS Report R47666, *Infrastructure Codes, Standards, and Regulations: Frequently Asked Questions*, coordinated by Linda R. Rowan.

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