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The National Hurricane Center and Forecasting Hurricanes: 2017 Overview and 2018 Outlook

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Summary

The National Hurricane Center (NHC), part of the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), is responsible for forecasting hurricanes in the Atlantic Ocean and the eastern Pacific Ocean. The NHC provides estimates of the path of a storm (i.e., hurricane track), the intensity, and the size and structure of the storm, as well as predictions of storm surge, rainfall, and even tornadoes. Depending on the storm's status, this information may be used to create a hurricane watch or a hurricane warning and public advisories, which are issued on an increasingly frequent basis if a storm strengthens and approaches the U.S. coastline.

Three major hurricanes struck the continental United States, the U.S. Virgin Islands, and Puerto Rico in 2017, causing severe damage: Harvey, Irma, and Maria. Hurricane Harvey was the first major hurricane to strike the continental U.S. coast since 2005, achieving category 4 strength before making landfall along the Texas coast on August 25, 2017. According to the NHC, Harvey "was the most significant tropical cyclone rainfall event in United States history, both in scope and peak rainfall amounts, since reliable records began around the 1880s." Hurricane Irma was the second major hurricane to strike the continental U.S. coast in 2017, making landfall in the Florida Keys on September 10. Irma's large wind field produced significant storm-surge flooding along the northeastern coast of Florida, even though the storm made landfall in southwestern Florida. Puerto Rico was still recovering from damage caused by Hurricane Irma when Hurricane Maria made landfall on September 20. Maria was the deadliest storm of 2017 and is widely regarded as the worst natural disaster on record to strike Puerto Rico.

For the 2018 hurricane season, the Climate Prediction Center (CPC), within the NWS, predicted 10-16 named storms, 5-9 hurricanes, and 1-4 major hurricanes in its May 24, 2018 announcement. The August 9, 2018, update to the seasonal prediction lowered those estimates to 9-13 named storms, 4-7 hurricanes, and 0-2 major hurricanes. The updated forecast indicated a less active Atlantic hurricane season in 2018 compared to the May prediction.

In general, forecasts of the 2017 hurricanes' tracks were better than the previous five-year average for track forecasts. The ability to forecast hurricane tracks has improved steadily since the 1960s, increasing the likelihood of more accurately predicting landfall location. Better instruments aboard weather satellites, such as the GOES (geostationary) series and the polar-orbiting weather satellites, have contributed to these improvements, together with more sophisticated hurricane forecast models and vastly improved computing capabilities, among other factors.

These factors also have improved forecasts of hurricane intensity, but they have done so in smaller increments per decade compared to improvements in track forecasts (at least until the last decade). Forecasts of intensity for Hurricanes Harvey, Irma, and Maria proved more difficult than forecasts of tracks; some errors in intensity forecasts for these hurricanes exceeded the previous five-year averages for forecast errors.

Indeed, perhaps the biggest challenge for the NHC is how to improve the ability to predict hurricane intensity. Furthermore, hurricane intensity itself is generally measured as highest sustained wind speeds, but that measurement does not take into consideration the storm-surge or precipitation-caused flooding, both of which may be among the most dangerous elements of a hurricane. Superstorm Sandy, for example, produced a storm surge that inundated the heavily populated coastline in New Jersey and New York to cause enormous damage.

On April 18, 2017, Congress enacted P.L. 115-25, the Weather Research and Forecasting Act of 2017, which provides direction to NOAA and NWS on a range of weather-related activities,

including hurricanes. The legislation's broad aim is to improve weather forecasts and warnings, and Section 104 of Title 1 specifically aims to improve hurricane forecasting. At an April 12, 2018, hearing before the Senate Committee on Commerce, Science, and Transportation, the acting Administrator for NOAA stated that NOAA would continue to follow guidelines outlined in P.L. 115-25 to improve the agency's hurricane predictions. Congress likely will continue to oversee implementation of P.L. 115-25 and may consider other legislation regarding the federal effort to improve hurricane forecasting, especially in response to active and destructive hurricane seasons, such as the one in 2017.

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In 2017, three hurricanes—Harvey, Irma, and Maria—caused extensive damage to several states within the continental United States and to the U.S. Virgin Islands (USVI) and Puerto Rico. The three storms were part of an active 2017 Atlantic hurricane season (June 1-November 30) that produced 17 named storms, of which 10 reached hurricane strength.[1] Six of the 10 hurricanes achieved sustained wind speeds of at least 111 miles per hour (mph) and were classified as major hurricanes (categories 3, 4, or 5 on the Saffir-Simpson Hurricane Wind Scale).[2] Hurricanes Harvey and Irma were the first storms with winds at major hurricane strength to make landfall in the continental United States since 2005. Hurricane Maria also had major hurricane strength winds when it struck Puerto Rico.

The potential for widespread destruction to parts of the U.S. coastline underscores the value of timely hurricane forecasts as a means for providing early and accurate warnings to affected communities. This report first provides a synopsis of the role of the National Hurricane Center (NHC), part of the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), in forecasting hurricanes, and it discusses some of the advances and remaining challenges in hurricane forecasting. The report then provides an overview of the 2017 hurricane season, with a focus on the three destructive hurricanes named above, and includes a brief summary of the hurricane outlook for 2018.

Hurricane forecasting has been improving for decades and is one of a number of weather-related ongoing issues of interest to Congress. A number of weather- and hurricane-related bills were introduced over the past several Congresses, and on April 18, 2017, Congress enacted P.L. 115-25, the Weather Research and Forecasting Act of 2017, which provides direction to NOAA and NWS on a range of weather-related activities, including hurricanes. The broad aim of the legislation is to improve weather forecasts and warnings, and Section 104 of Title 1 of P.L. 115-25 specifically aims to improve hurricane forecasting. At the April 12, 2018, hearing, the acting Administrator for NOAA stated that NOAA would continue to follow guidelines outlined in P.L. 115-25 to improve the agency's hurricane predictions.[3]

Congress likely will continue to conduct oversight and consider legislation regarding the federal effort to improve hurricane forecasting, especially in response to active and destructive hurricane seasons, such as the one 2017.

Forecasting Hurricanes: Role of the National Hurricane Center

The National Hurricane Center (NHC), part of the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), is responsible for forecasting

[1] Storms are named when they reach tropical storm status and have sustained winds above 39 miles per hour.

[2] National Oceanic and Atmospheric Administration (NOAA), National Hurricane Center (NHC), "Saffir-Simpson Hurricane Wind Scale," at https://www.nhc.noaa.gov/aboutsshws.php. Category 1: 74-95 miles per hour (mph); Category 2: 96-110 mph; Category 3: 111-129 mph; Category 4: 130-156 mph; Category 5: 157 mph or higher.

[3] Written testimony of Rear Admiral Tim Gallaudet, Assistant Secretary of Commerce for Oceans and Atmosphere and Acting Under Secretary of Commerce for Oceans and Atmosphere, NOAA, in U.S. Congress, Senate Committee on Commerce, Science, and Transportation, *Are We Ready for the Next Hurricane Season?*, Status of Preparation and Response Capabilities for 2018, 115th Cong., 2nd sess., April 12, 2018.

tropical cyclones,[4] including hurricanes in the Atlantic Ocean and the eastern Pacific Ocean.[5] The NHC provides estimates of the path or track of a tropical cyclone, the intensity, and the size and structure of the storm, as well as predictions of storm surge, rainfall, and even tornadoes.[6] Depending on the status of the tropical cyclone, this information may be used to create a hurricane watch or a hurricane warning and public advisories, which are issued on an increasingly frequent basis if a storm strengthens and approaches the U.S. coastline.[7]

How the Process Works

A hurricane forecast involves many components and uses a broad array of resources and capabilities within NOAA and the NWS, all of which must be coordinated and interpreted by the NHC.[8] The process begins with observations: satellites, aircraft, ships, buoys, radar, and other sources provide data used to create storm-track and intensity predictions. Most Atlantic hurricanes, for example, begin to form just west of the African continent over the ocean.[9] NOAA weather satellites primarily provide the remote-sensing observations during the early stages of tropical storm development in the eastern Atlantic. NOAA's Geostationary Operational Environmental Satellites (GOES) are stationed over the same location spanning North America (two satellites make up the active GOES constellation, often referred to as GOES East and GOES West) and provide continuous data as the storms form and intensify during their journey across the Atlantic from Africa to North America.[10]

Approaching the Coast

If an Atlantic hurricane is judged to pose a threat to the U.S. coastline, NOAA hurricane aircraft and U.S. Air Force aircraft (often referred to as *Hurricane Hunters*[11]) fly directly into the storm

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[4] A tropical cyclone is defined as a warm-core nonfrontal synoptic-scale (i.e., horizontal length of about 620 miles or more) cyclone, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center. Cyclones rotate counter-clockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

[5] NOAA, NHC, "About the National Hurricane Center," at https://www.nhc.noaa.gov/aboutintro.shtml.

[6] University of Rhode Island Graduate School of Oceanography, Hurricanes: Science and Society, "National Hurricane Center Forecast Process," at http://www.hurricanescience.org/science/forecast/forecasting/forecastprocess/. Hereinafter University of Rhode Island, "National Hurricane Center Forecast Process."

[7] A *hurricane watch* is an announcement that hurricane conditions are possible within a specified coastal area, usually issued 48 hours in advance of the onset of tropical storm force winds. A *hurricane warning* is issued when hurricane conditions—sustained winds 74 mph or greater—are expected somewhere within the specified coastal area. University of Rhode Island, "National Hurricane Center Forecast Process."

[8] The entire federal hurricane forecast effort is broader than NOAA and its sub-agencies; however, the NHC is a focal point and this report focuses on its role. The National Hurricane Operations Plan outlines various agency responsibilities across the federal government. See https://www.ofcm.gov/publications/nhop/nhop2.htm.

[9] This report focuses on Atlantic basin hurricanes as those storms typically inflict the greatest damage to the United States. For more information about why hurricanes threaten the U.S. east coast and not the U.S. west coast, see "Why do Hurricanes Hit the East Coast of the U.S. but Never the West Coast?", Scientific American, at https://www.scientificamerican.com/article/why-do-hurricanes-hit-the-east-coast-of-the-u-s-but-never-the-west-coast/.

[10] University of Rhode Island, "National Hurricane Center Forecast Process."

[11] NOAA Hurricane Hunters are specially equipped aircraft that collect data during hurricanes. The NOAA fleet includes two Lockheed WP-3d Orion four-engine turboprop aircraft and one Gulfstream IV-SP jet aircraft. The WP-3D aircraft fly directly into hurricanes during the storms and collect in-situ data on winds and atmospheric pressures, among other measurements. The Gulfstream jet flies at higher altitudes and collects critical information on the "steering" winds that affect the hurricane track, among other data. See NOAA, Office of Marine and Aviation Operations, "NOAA Hurricane Hunters," at https://www.omao.noaa.gov/learn/aircraft-operations/about/hurricane-

and above the storm to collect real-time data. It is the responsibility of the Chief, Aerial Reconnaissance Coordination, All Hurricanes (CARCAH),[12] unit to coordinate all tropical cyclone operation reconnaissance in accordance with the National Hurricane Operations Plan (NHOP).[13] Data collected from the Hurricane Hunters and other aircraft (e.g., the NASA Global Hawk)[14] are checked at CARCAH and provided to NHC forecasters. If the storm gets closer, approximately 280 miles from the coast, land-based radars begin to provide the NHC with precipitation and wind-velocity data. Additional ground-based measurements are provided by the Automated Surface Observation Systems instruments when the storm is close to shore or makes landfall.[15]

Analyzing the Data

The NHC gathers all the observational data as a tropical cyclone approaches the U.S. coastline and uses the data to generate a series of hurricane forecast computer model simulations.[16] The principal purpose of hurricane forecast model simulations typically is to predict the hurricane *track* (the hurricane path) and *intensity* (the hurricane wind speeds) over a period of three to five days.[17] Essentially, the model uses the observational data to understand the state of the atmosphere and then uses mathematical equations to produce forecasts.

Not all hurricane forecast models are the same; they may differ in how they process information, such as when observations are fed into the model, which equations are used, how the solutions to the equations are used to make forecasts, and other factors. These differences explain why NHC hurricane forecasts may differ from those of other countries or institutions that also produce hurricane forecasts (e.g., the European Center for Medium-Range Forecasts produces Atlantic hurricane forecasts,[18] as do some research institutions within the United States, such as the National Center for Atmospheric Research).[19]

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hunters. The 53rd Weather Reconnaissance Squadron, a component of the 403rd Wing of the U.S. Air Force located at Keesler Air Force Base, Biloxi, MS, flies 10 WC-130J Hercules aircraft into hurricanes during weather reconnaissance missions. See http://www.403wg.afrc.af.mil/About/Fact-Sheets/Display/Article/192529/53rd-weather-reconnaissance-squadron-hurricane-hunters/.

[12] CARCAH is a subunit of the 53rd Weather Reconnaissance Squadron, U.S. Air Force (also referred to as the Hurricane Hunters).

[13] Office of the Federal Coordinator for Meteorology, *National Hurricane Operations Plan*, at https://www.ofcm.gov/publications/nhop/nhop2.htm.

[14] NASA, Armstrong Flight Research Center, "Global Hawk," at https://www.nasa.gov/centers/armstrong/aircraft/GlobalHawk/index.html.

[15] University of Rhode Island Graduate School of Oceanography, Hurricanes: Science and Society, "Automated Surface Observation Systems (ASOS)," at http://www.hurricanescience.org/science/observation/landbased/automatedsurfaceobssystems/.

[16] University of Rhode Island Graduate School of Oceanography, Hurricanes: Science and Society, "Hurricane Forecast Models," at http://www.hurricanescience.org/science/forecast/models/. Hereinafter University of Rhode Island, "Hurricane Forecast Models."

[17] Hurricane intensity generally is measured as highest sustained wind speeds. However, that measurement does not take into consideration the storm-surge or precipitation-caused flooding, both of which may be among the most dangerous elements of a hurricane.

[18] The European Centre for Medium-Range Weather Forecasts (ECMWF) is an independent intergovernmental organization supported by 34 countries. It produces global numerical weather forecasts using weather models, including the EMXI model referenced in the text. See ECMWF, "Advancing Global NWP Through International Collaboration," at https://www.ecmwf.int/.

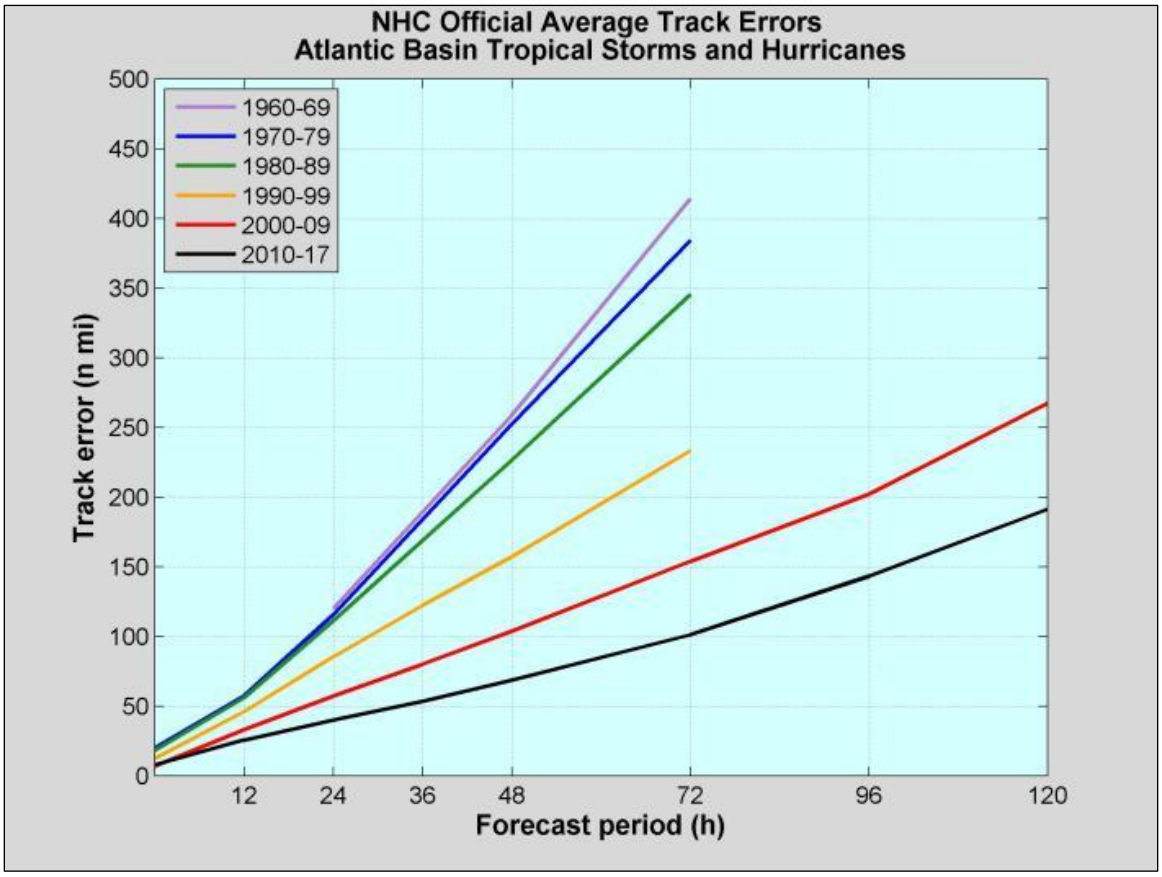
[19] University of Rhode Island, "Hurricane Forecast Models."

Hurricane Track and Intensity Forecasts: Improvements and Challenges

Hurricane forecasts generally are divided into two categories: hurricane track (the path of the hurricane) and hurricane intensity (the sustained wind speed). The ability to forecast hurricane tracks has improved steadily since the 1960s (**Figure 1**), increasing the likelihood of more accurately predicting landfall location. **Figure 1** shows that the track errors in the current decade are less than half of what they were in the 1990s. Also, through the 1990s, the forecasts extended out for only three days; today, forecasts typically extend out for five days.[20] That increased accuracy and extended timeframe provides useful information to local, state, and federal emergency managers faced with decisions about evacuating coastlines and the need to stage emergency equipment and supplies. Better instruments aboard weather satellites, such as the GOES series and the polar-orbiting weather satellites, have contributed to those improvements, as have more sophisticated hurricane forecast models and vastly improved computing capabilities.

Figure 1. NHC Official Average Track Errors Comparison

(by decade for Atlantic Basin tropical storms and hurricanes)



Source: CRS from John Cangialosi, "The State of Hurricane Forecasting," *Inside the Eye: Official Blog of the National Hurricane Center*, March 9, 2018, at https://noaanhc.wordpress.com/2018/03/09/the-state-of-hurricane-forecasting/.

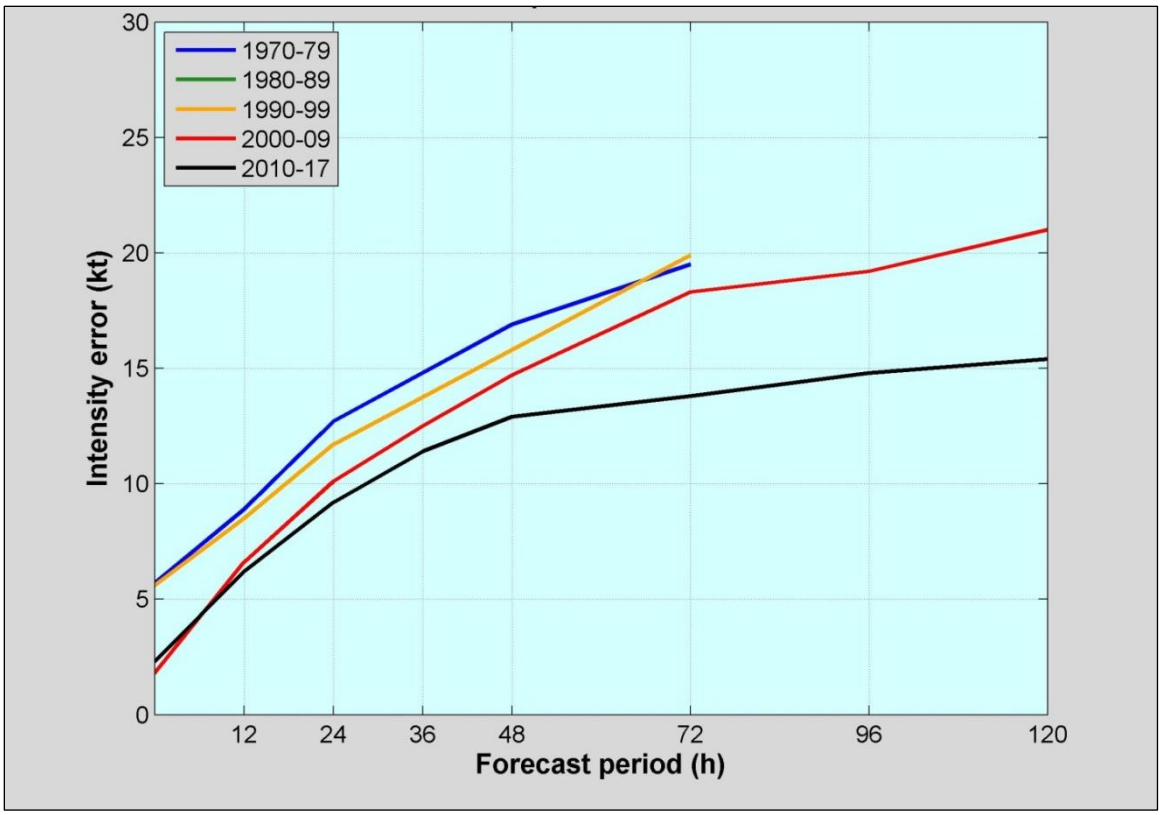
Notes: Forecast errors indicate the difference between the forecast track and the actual track in nautical miles; (h) is hours.

[20] In other words, five-day forecasts today are as good as three-day forecasts were 25 years ago, in terms of their skill at matching forecasts with actual events.

Until the last decade, hurricane intensity forecasts had improved in smaller increments than hurricane track forecasts (see **Figure 2**). Intensity forecast errors from 2010 to 2017, the black line in **Figure 2**, are about 15 knots (17 miles per hour), between 72 and 120 hours (3-5 days). That is the largest incremental improvement since the 1970s; however, that margin of error corresponds roughly to a difference of one hurricane category on the Saffir-Simpson Hurricane Wind Scale. The NHC reports that it often encourages those who could be affected by a tropical cyclone to prepare for a storm one category stronger than the forecast.[21]

Figure 2. NHC Official Average Intensity Errors Comparison

(by decade for Atlantic Basin tropical storms and hurricanes)



Source: CRS from John Cangialosi, "The State of Hurricane Forecasting," *Inside the Eye: Official Blog of the National Hurricane Center*, March 9, 2018, at https://noaanhc.wordpress.com/2018/03/09/the-state-of-hurricane-forecasting/.

Notes: Intensity errors expressed as wind speed measured in knots. Forecast period shown in hours. The NHC issues official forecasts every 6 hours, and each forecast has projections valid 12, 24, 36, 48, 72, 96, and 120 hours (h) after the forecast's initial time.

Forecasts and Warnings

Using the results from hurricane forecast models, different components within and outside of the NHC contribute to the hurricane forecast process. These components include the Hurricane Specialist Unit (HSU), the Tropical Analysis and Forecast Branch (TAFB), and the Hurricane

[21] NHC, *Inside the Eye*, the State of Hurricane Forecasting, March 9, 2018, https://noaanhc.wordpress.com/2018/03/09/the-state-of-hurricane-forecasting/.

Liaison Team (HLT).[22] Of these, the HSU produces the final, official public forecast products, issued every six hours after a storm forms and more frequently if a hurricane watch or a hurricane warning is issued.[23] The HSU also provides briefings on tropical storms to emergency managers and to the public, and it cooperates with meteorological services in other countries (e.g., Mexico, as well as Central American and Caribbean countries). The TAFB supports the HSU by providing tropical cyclone position and intensity estimates, conducting media interviews, and assisting in tropical cyclone operations.[24]

The HLT is sponsored through the Federal Emergency Management Agency (FEMA) and is comprised of federal, state, and local emergency managers, FEMA personnel, and NWS forecasters and hydrologists. On or before the beginning of hurricane season, the NHC director requests that FEMA activate the HLT, which remains active throughout hurricane season. If a tropical cyclone in the Atlantic or eastern Pacific basin threatens the United States or its territories, then the NHC can request that NWS meteorologists or hydrologists be assigned to the HLT until the storm threat has passed.[25]

The HLT serves as a liaison between the NHC forecasters and local emergency managers facing a threat of tropical cyclones. One of the HLT's main functions is to communicate the threat level to federal, state, and local officials. Neither the HLT nor the NHC assumes any responsibility for issuing evacuations, however; those decisions are the responsibility of state or local officials.[26]

The NWS, as delegated by the Secretary of Commerce, has statutory authority for weather forecasting and for issuing storm warnings (15 U.S.C. §313). Forecasts and warnings generally are coordinated between the NWS national centers and the local forecast offices. When the NHC issues its forecast, local NWS Weather Forecast Offices use the information for their own forecasts, which take into consideration local conditions and help disseminate the forecast through its established local networks.[27]

Storm Surge

In addition to the hurricane forecast models that predict intensity, winds, and precipitation, other forecast models are designed specifically to forecast *storm surge*. Storm surge is defined as an abnormal rise in sea level accompanying a hurricane or other intense storm. It generally refers to the difference between the measured level of the sea surface during the storm compared to what the sea level would have been without a storm. (See **Figure 3**.) Storm surge, combined with high precipitation from a hurricane, can create dangerous flood conditions for coastal communities during tropical cyclones and other intense storms. (Superstorm Sandy, for example, produced a storm surge that inundated the heavily populated coastline in New Jersey and New York to cause enormous damage, despite the storm itself being a relatively weak hurricane immediately prior to landfall.) The combination of a storm surge and high tide produces what is referred to as a *storm*

[22] The TAFB and HSU are within the NHC; the HLT is within FEMA.

[23] For more on hurricane watches and hurricane warnings, see footnote 7.

[24] University of Rhode Island, "National Hurricane Center Forecast Process."

[25] NOAA, NHC, "About the National Hurricane Center," at https://www.nhc.noaa.gov/aboutintro.shtml.

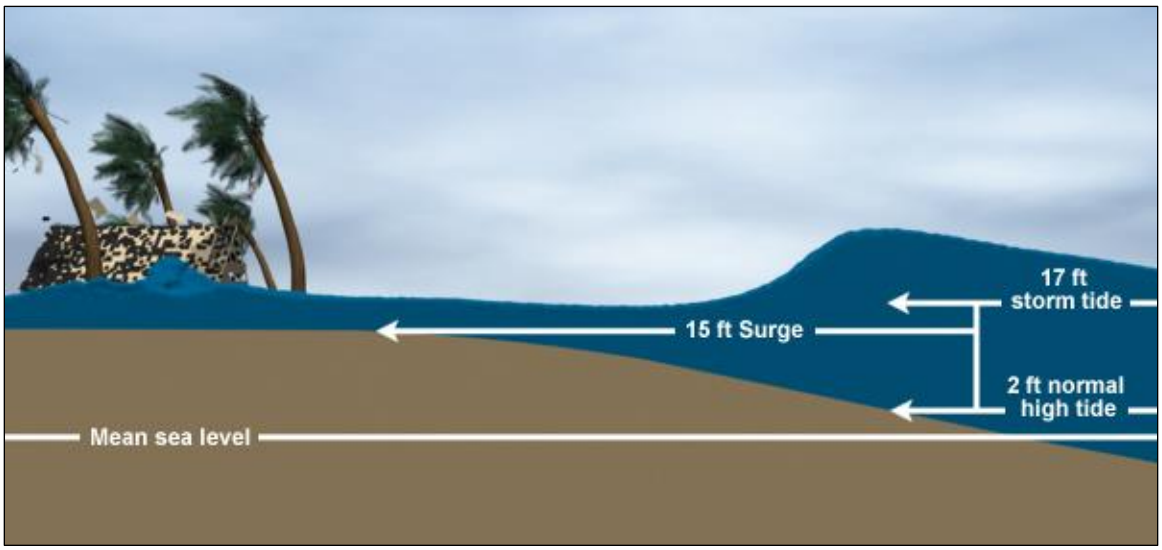
[26] For more information about the Hurricane Liaison Team, see NOAA, National Weather Service, "National Hurricane Center Hurricane Liaison Team," National Weather Service Instruction 10-603, September 21, 2016, at http://www.nws.noaa.gov/directives/sym/pd01006003curr.pdf.

[27] For general information on how severe weather warnings are communicated to the public, see Forecasting and Warning: The Role of the National Weather Service, in CRS Report R40097, *Severe Thunderstorms and Tornadoes in the United States*, by Peter Folger.

tide (**Figure 3**). A large high tide coinciding with a large storm surge can produce a large storm tide and may cause extreme flooding in coastal areas.[28]

The Storm Surge Unit, part of the NHC, models and predicts storm-surge vulnerability over the U.S. Atlantic and Gulf Coasts, Hawaii, Puerto Rico, and the U.S. Virgin Islands (USVI).[29] The Storm Surge Unit typically commences its operations when a hurricane warning is issued and, if the hurricane threatens to make landfall, the unit continues 24 hours per day until the storm-surge threat subsides.

Figure 3. Storm Surge and Storm Tide



Source: National Hurricane Center at https://www.nhc.noaa.gov/surge/. (Modified by CRS.)

Notes: The 17 foot storm tide (top arrow) indicates the sum of the 2-foot normal astronomical high tide and the 15-foot storm surge.

Improvements and Challenges

Perhaps the biggest challenge for the NHC is how to improve the ability to predict hurricane intensity—basically, how strong a hurricane will become and when and where it will reach its maximum intensity (its highest sustained wind speeds). However, that measurement does not take into consideration the storm-surge or precipitation-caused flooding, both of which may be among the most dangerous elements of a hurricane.

Flooding resulting from high rainfall events during hurricanes could be responsible for the majority of fatalities caused by a storm. Some studies show, however, that the amount of rainfall produced by a storm may not necessarily be related to the intensity—the sustained wind speed—of the hurricane. Record levels of precipitation and subsequent flooding during Harvey, for example, continued even after the storm made landfall and was downgraded from a hurricane to a tropical storm. Improving the ability to accurately forecast the timing, amount, and location of high rainfall periods would advance the value of hurricane forecasting significantly.

[28] NOAA, NHC, *Storm Surge Overview*, at https://www.nhc.noaa.gov/surge/.

[29] NOAA, NHC, *Storm Surge Unit*, at https://www.nhc.noaa.gov/surge/ssu.php.

2017 Atlantic Hurricane Season Overview

NOAA releases its outlook for hurricane season prior to June 1 of each year and typically provides an update as conditions evolve for the Atlantic basin. **Table 1** shows that the number and strength of actual hurricanes slightly exceeded the upper range of NOAA's seasonal outlook for an active hurricane season in 2017.

Table 1. 2017 Atlantic Hurricane Season: Comparison Between Seasonal Outlook and Actual Storms

NOAA Seasonal Outlook (May 2017)	NOAA Seasonal Outlook (August 2017)	Actual
Named Storms: 11-17	Named Storms: 14-19	Named Storms: 17
Hurricanes: 5-9	Hurricanes: 5-9	Hurricanes: 10
Major Hurricanes: 2-4	Major Hurricanes: 2-5	Major Hurricanes: 6

Source: National Oceanic and Atmospheric Administration (NOAA), "Extremely Active 2017 Atlantic Hurricane Season Finally Ends," November 30, 2017, at http://www.noaa.gov/media-release/extremely-active-2017-atlantic-hurricane-season-finally-ends.

Notes: A *hurricane* is a storm with sustained wind speeds of at least 74 miles per hour. A *major hurricane* is a storm with sustained wind speeds of at least 111 miles per hour (Category 3). Category 3, 4, and 5 hurricanes are deemed major hurricanes because of their potential for significant damage and loss of life. The NOAA Seasonal Outlook numbers were first released on May 25, 2017, then revised on August 9, 2017.

Three major hurricanes affected the continental United States, the USVI, and Puerto Rico in 2017, causing severe damage: Harvey (August 17-September 1), Irma (August 30-September 12), and Maria (September 17-September 30).[30] In general, forecasts of these hurricanes' tracks were better than the previous five-year average for track forecasts. However, forecasts of intensity were less accurate; some forecast errors for these hurricanes exceeded the previous five-year average for forecast errors. Track and intensity forecasts for each of the three major hurricanes are discussed below.

Hurricane Harvey

Hurricane Harvey was the first major hurricane to strike the continental United States since 2005, achieving category 4 strength before making landfall along the Texas coast on August 25, 2017, about 6 miles east of Rockport, Texas.[31] According to the NHC, Harvey "was the most significant tropical cyclone rainfall event in United States history, both in scope and peak rainfall amounts, since reliable records began around the 1880s."[32] The highest storm total rainfall reported was more than 60 inches near Nederland, TX, which exceeded the previous record of 52 inches in Hawaii during Hurricane Hiki in 1950.[33]

[30] The dates associated with each hurricane reflect the time from initial formation until storm dissipation. Email from Matthew Borgia, Congressional Liaison for Weather, NOAA, March 15, 2018.

[31] The last major hurricane to make landfall in the continental United States was Hurricane Wilma in 2005, which made landfall in Florida on October 25, 2005, as a category 3 hurricane.

[32] Eric S. Blake and David A. Zelinsky, *National Hurricane Center Tropical Cyclone Report: Hurricane Harvey*, NOAA, AL092017, January 23, 2018, p. 6. Hereinafter Blake and Zelinsky, *Hurricane Harvey*, 2018.

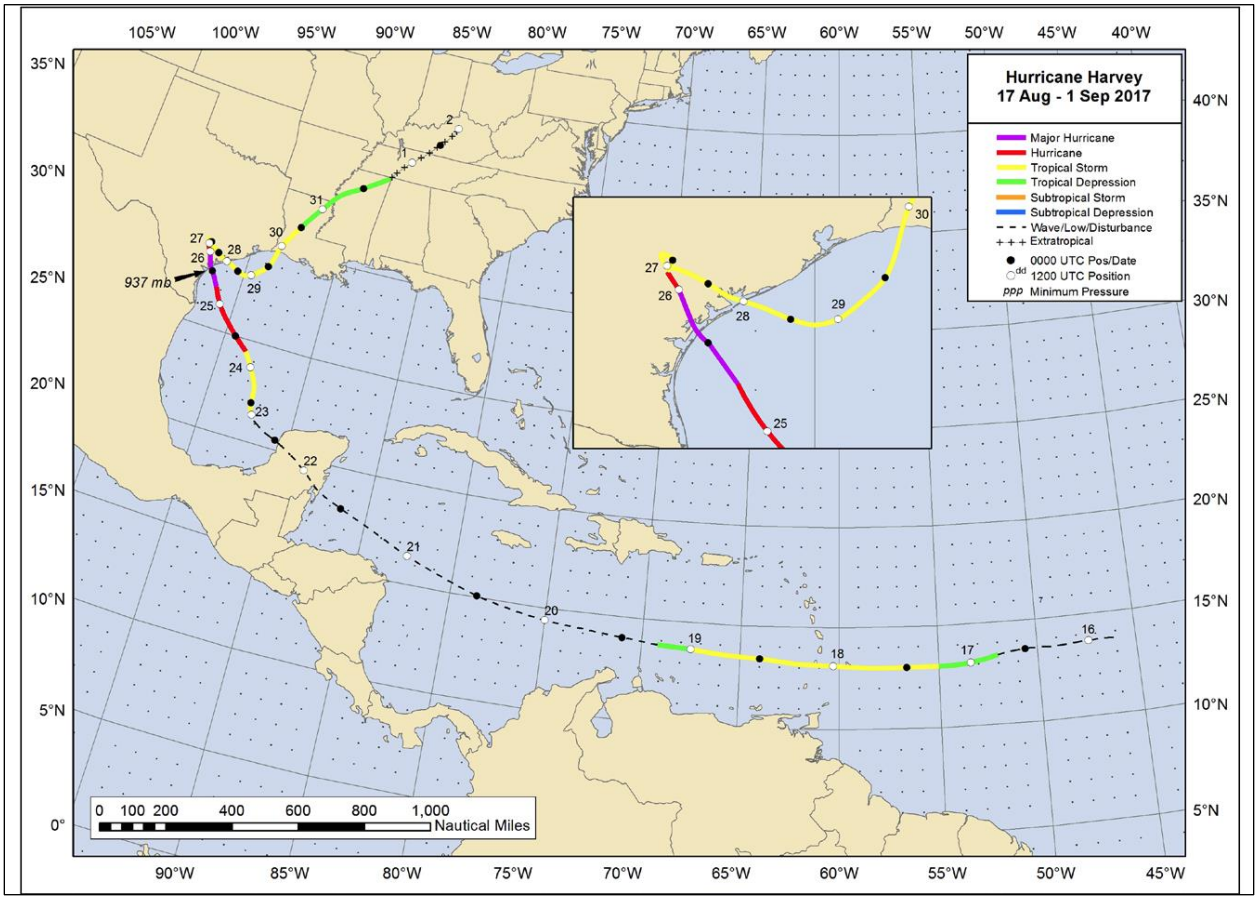
[33] Blake and Zelinsky, *Hurricane Harvey*, 2018, p. 6.

Hurricane Harvey also was remarkable for the areal extent of the intense flooding it caused. Large sections of southeastern Texas received 3 feet or more of rainfall during Harvey, and the NHC postulated that "it is unlikely the United States has ever seen such a sizable area of excessive tropical cyclone rainfall totals as it did from Harvey."[34]

Hurricane Harvey was a slow-moving storm once it made landfall in Texas, which explains why it produced such extreme rainfall. The cyclone was trending to the northwest as it made landfall but stopped its northwestern motion and made a slow loop from August 26 into August 27, then drifted southeastward for a few days before moving offshore again. However, the front did not move far between August 27 and August 28, allowing warm and humid air from the Gulf of Mexico to feed the storm, resulting in heavy rainfall over land even though the storm had diminished to tropical storm status. **Figure 4** shows Harvey's track from its genesis as a tropical depression in the Atlantic Ocean through its dissipation on September 1 over the Tennessee Valley.

Figure 4. Hurricane Harvey's Track

(August 17, 2017, through September 1, 2017)



Source: Eric S. Blake and David A. Zelinsky, *National Hurricane Center Tropical Cyclone Report*: Hurricane Harvey, NOAA, AL092017, January 23, 2018, Figure 2. (Hereinafter Blake and Zelinsky, *Hurricane Harvey*, 2018.)

Notes: Inset indicates that Harvey made landfall as a major hurricane, and then reversed course and slowly drifted southeastward over southeastern Texas and offshore for several days before heading northeastward over

[34] Blake and Zelinsky, *Hurricane Harvey*, 2018, p. 7.

land again. Numbers along the hurricane track indicate dates (e.g., 17 equals August 17, 2017). The small arrow indicating 937 mb (millibars) indicates the lowest pressure recorded for the storm along its track.

The record rainfall amounts created widespread flooding in Texas, and freshwater flooding was responsible for 65 of the 68 "direct" deaths in Texas attributed to the hurricane.[35] The fatality statistics make Harvey the deadliest U.S. hurricane in terms of direct deaths since Superstorm Sandy in 2012.[36] NOAA estimated that damage from Hurricane Harvey was approximately $125 billion, with more than 300,000 structures and up to 500,000 cars flooded in southeastern Texas.[37]

Forecasts

As **Figure 4** shows, Harvey formed as a tropical depression east of the Caribbean islands on August 17, 2017, diminished in strength as it moved west and crossed the Yucatan Peninsula, and then re-formed as a tropical storm in the Gulf of Mexico. According to the NHC, "the re-formation of Harvey was well-forecast by NHC ... and the remnants of Harvey in the Caribbean were given a high (>60%) chance of genesis in the 2-day outlook 42 h[ours] before re-formation occurred—an excellent forecast by current standards."[38]

Hurricane forecasts generally are divided into two categories: hurricane track and hurricane intensity. The NHC forecast for Harvey's track was better than average, meaning the forecast errors were lower than the average official forecast errors for hurricanes during the previous five-year period (**Table 2**). For each forecast period shown in **Table 2**, the official track forecast errors (expressed in nautical miles from the actual path of the hurricane) for Hurricane Harvey were lower than the five-year average forecasts made by the NHC during 2012-2016.

Table 2. National Hurricane Center (NHC) Official Track Forecast Errors for Hurricane Harvey Compared to the 2012-2016 Average

(in nautical miles)

Forecast	Forecast Period[a]						
	12 hours	24 hours	36 hours	48 hours	72 hours	96 hours	120 hours
NHC Official	18.8	28.8	38.9	49.7	81.2	124.5	168.7
2012-2016 Average	24.9	39.6	54.0	71.3	105.8	155.4	208.9

Source: Congressional Research Service (CRS), from Blake and Zelinsky, *Hurricane Harvey*, 2018, Table 6a.

Notes: Forecast errors indicate the difference between the forecast track and the actual track in nautical miles.

a. The NHC issues official forecasts every 6 hours, and each forecast has projections valid 12, 24, 36, 48, 72, 96, and 120 hours after the forecast's initial time.

[35] According to the NHC, deaths occurring as a direct result of the forces of a tropical cyclone are referred to as *direct deaths* and would include deaths caused by drowning in storm surge, rough seas, rip currents, freshwater floods, lightning, and wind-related events (such as collapsed structures). Deaths occurring from heart attacks, house fires, electrocution from downed power lines, car accidents, and other factors are considered *indirect deaths*. Harvey caused about 35 indirect deaths. Blake and Zelinsky, *Hurricane Harvey*, 2018, p. 8.

[36] For hurricanes making landfall in the continental United States.

[37] Blake and Zelinsky, *Hurricane Harvey*, 2018, p. 9. NOAA reports that the damage estimate is a range between $90 billion and $160 billion (90% confidence interval), with $125 billion as the central estimate.

[38] Blake and Zelinsky, *Hurricane Harvey*, 2018, p. 12.

The accuracy of the official NHC forecast for Harvey's intensity was mixed, compared to the previous five-year average forecasts (**Table 3**). The previous five-year average intensity forecasts (expressed in knots of wind speed) were better than the Harvey forecasts for the first 48 hours,[39] but the Harvey intensity forecasts were better than the five-year average after 48 hours and out to 120 hours (five days, **Table 3**). The NHC indicated that the dichotomy in intensity forecast errors likely was due to the cyclone weakening faster than expected over land between the 36- and 48-hour forecast intervals. In contrast, the NHC noted that it correctly forecast that Harvey would stay a weak cyclone at the long-range forecasts.[40] Additionally, the NHC reported that "initially, the rapid intensification (RI) of Harvey after its re-formation was not well-anticipated, but most of the guidance had Harvey near hurricane intensity before landfall in Texas.... A NHC Special Advisory issued at 1800 UTC 24 August, 33 h[ours] before landfall, forecast RI and verified within 5 kt of the intensity near landfall."[41]

Table 3. NHC Official Intensity Forecast Errors for Hurricane Harvey Compared to the 2012-2016 Average

(in nautical miles per hour, or knots)

Forecast	Forecast Period[a]						
	12 hours	24 hours	36 hours	48 hours	72 hours	96 hours	120 hours
NHC Official	5.8	8.9	12.0	15.0	6.5	3.5	6.3
2012-2016 Average	5.5	8.2	10.5	12.0	13.4	14.0	14.5

Source: CRS, from Blake and Zelinsky, *Hurricane Harvey*, 2018, Table 7a.

Notes: Forecast errors indicate the difference between the forecast intensity and the actual intensity in nautical miles per hour, or knots.

a. The NHC issues official forecasts every 6 hours, and each forecast has projections valid 12, 24, 36, 48, 72, 96, and 120 hours after the forecast's initial time.

Rainfall forecasts for Hurricane Harvey and the storm's actual rainfall were the highest on record. The Weather Prediction Center (WPC) within the National Weather Service is responsible for issuing precipitation forecasts. After Hurricane Harvey re-formed in the Gulf of Mexico, the initial WPC forecast was for 20 inches of precipitation in southeast Texas. The forecasts increased to 40 inches in the hours before Harvey made landfall and then increased again to 50 inches the day prior to Harvey's center exiting Texas.[42] **Figure 5** shows the progression of rainfall forecasts over time.

[39] A knot (kt) is 1 nautical mile per hour, equivalent to approximately 1.15 statute miles per hour.

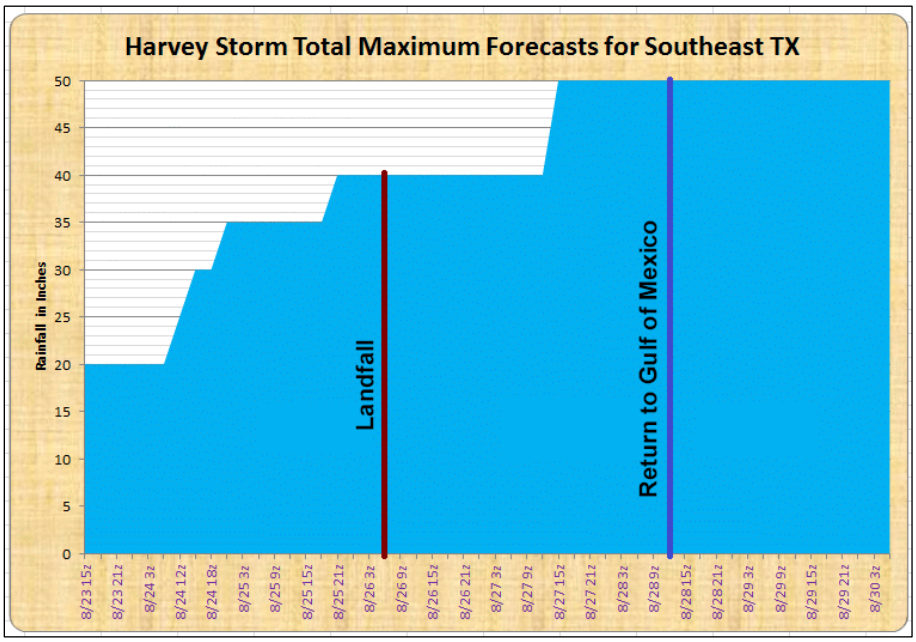
[40] Blake and Zelinsky, *Hurricane Harvey*, 2018, p. 13.

[41] Blake and Zelinsky, *Hurricane Harvey*, 2018, p. 13. UTC refers to Coordinated Universal Time (formerly Greenwich Mean Time) and is the primary time standard by which the world coordinates its clocks and time. 1800 UTC on August 24, 2017, would have corresponded to noon in Houston.

[42] Blake and Zelinsky, *Hurricane Harvey*, 2018, p. 14.

Figure 5. Rainfall Forecasts for Hurricane Harvey

(August 17, 2017, through September 1, 2017; for southeast Texas)



Source: Blake and Zelinsky, *Hurricane Harvey*, 2018, Figure 22. (Modified by CRS.)

Notes: Heaviest rainfall predictions and actual rainfall occurred in southeast Texas after Harvey was downgraded to tropical storm status. Bottom axis shows date and time of forecast (each tick mark indicates three hours).

Hurricane Irma

Hurricane Irma was the second major hurricane to strike the continental U.S. coast in 2017, making landfall in the Florida Keys near Cudjoe Key at category 4 strength on September 10 and striking southwest Florida near Marco Island later that day as a category 3 hurricane (**Figure 6**). After making landfall in Florida, the storm weakened but maintained hurricane strength as it moved north-northwestward just east of Naples and Ft. Myers, FL, on September 11, before becoming a tropical storm about 20 nautical miles west of Gainesville that same day. Before striking the U.S. mainland, Irma reached category 5 hurricane force and made landfall on the Caribbean islands of Barbuda, St. Martin, and Virgin Gorda of the British Virgin Islands on September 6.[43] Irma dissipated on September 12 as it moved across Alabama.

Hurricane Irma did not strike Puerto Rico or the USVI, but the tropical storm strength high winds located further out from the eye, rainfall, and storm surge created significant destruction, particularly on the islands of St. Thomas and St. John.[44] Widespread damage was reported on both islands, including collapsed fire and police stations and damaged hospitals.[45] St. Croix was not as severely affected as the other two USVI, but even so nearly 70% of the structures on St.

[43] John P. Cangialosi, Andrew S. Latto, and Robbie Berg, *National Hurricane Center Tropical Cyclone Report: Hurricane Irma*, NOAA, AL112017, March 9, 2018, pp. 1-4. Hereinafter Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018.

[44] *Storm surge* is defined as an abnormal rise in sea level accompanying a hurricane or other intense storm.

[45] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, p. 14.

Croix were damaged.[46] Three direct deaths in the USVI occurred as a result of Irma, and the storm was responsible for three indirect deaths in Puerto Rico, widespread power outages, and minor damage to homes and businesses. Other Caribbean islands where Irma made landfall took the full brunt of its category 5-strength winds, rain, and storm surge and suffered near-complete destruction.[47]

Hurricane Irma formed in the Atlantic as a tropical depression and reached hurricane strength quickly compared to Hurricane Harvey. Irma reached major hurricane force two days after storm genesis and maintained hurricane or major hurricane force for nearly 11 days, diminishing to tropical storm strength only after reaching northern Florida (**Figure 6**). According to the NHC, Irma's rapid intensification—marked by a wind speed increase of 70 knots within 48 hours—is rare for Atlantic tropical cyclones, occurring only about 1 in 30 times (about 3.3% of the time).[48] Irma also maintained sustained category 5 intensity for 60 hours, the second-longest period on record.[49] Irma's major hurricane force and repeated landfalls (seven landfalls in total) were responsible for widespread destruction.

[46] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, p. 14.

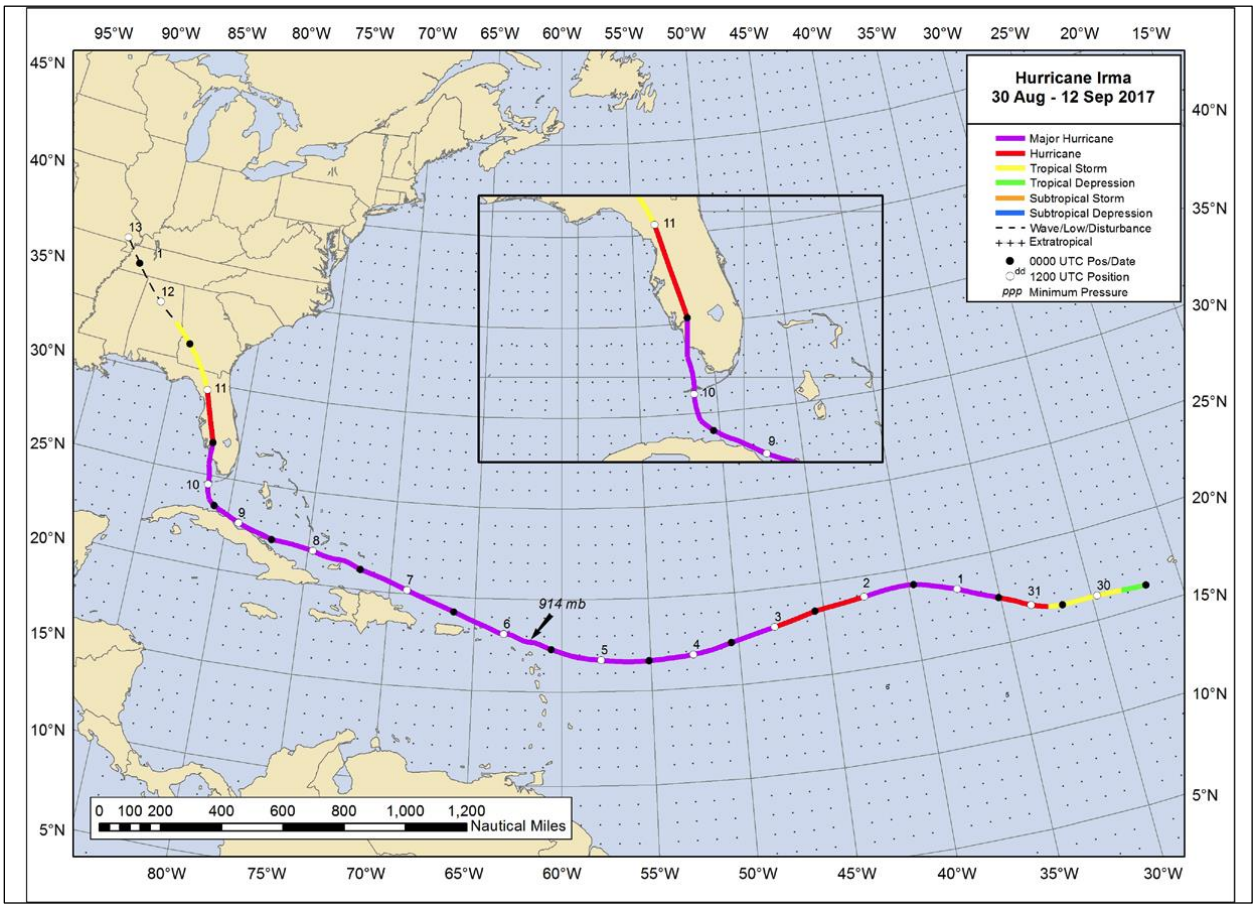
[47] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, pp. 13-14. For example, nearly 95% of all structures on Barbuda were destroyed, and the island was completely evacuated for the first time in nearly 300 years in the wake of Irma and in anticipation of Hurricane Jose. Hurricane Jose, September 5-25, 2017, also developed into a major hurricane but did not make landfall in the United States.

[48] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, p. 2.

[49] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, p. 2. Only the 1932 Cuba Hurricane of Santa Cruz del Sur exceeded Irma's duration at category 5 strength.

Figure 6. Hurricane Irma's Track

(August 30, 2017, through September 12, 2017)



Source: John P. Cangialosi, Andrew S. Latto, and Robbie Berg, *National Hurricane Center Tropical Cyclone Report: Hurricane Irma*, NOAA, AL112017, March 9, 2018, Figure 1. Hereinafter Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018.

Notes: Numbers along the hurricane track indicate dates (e.g., 10 equals September 10, 2017).

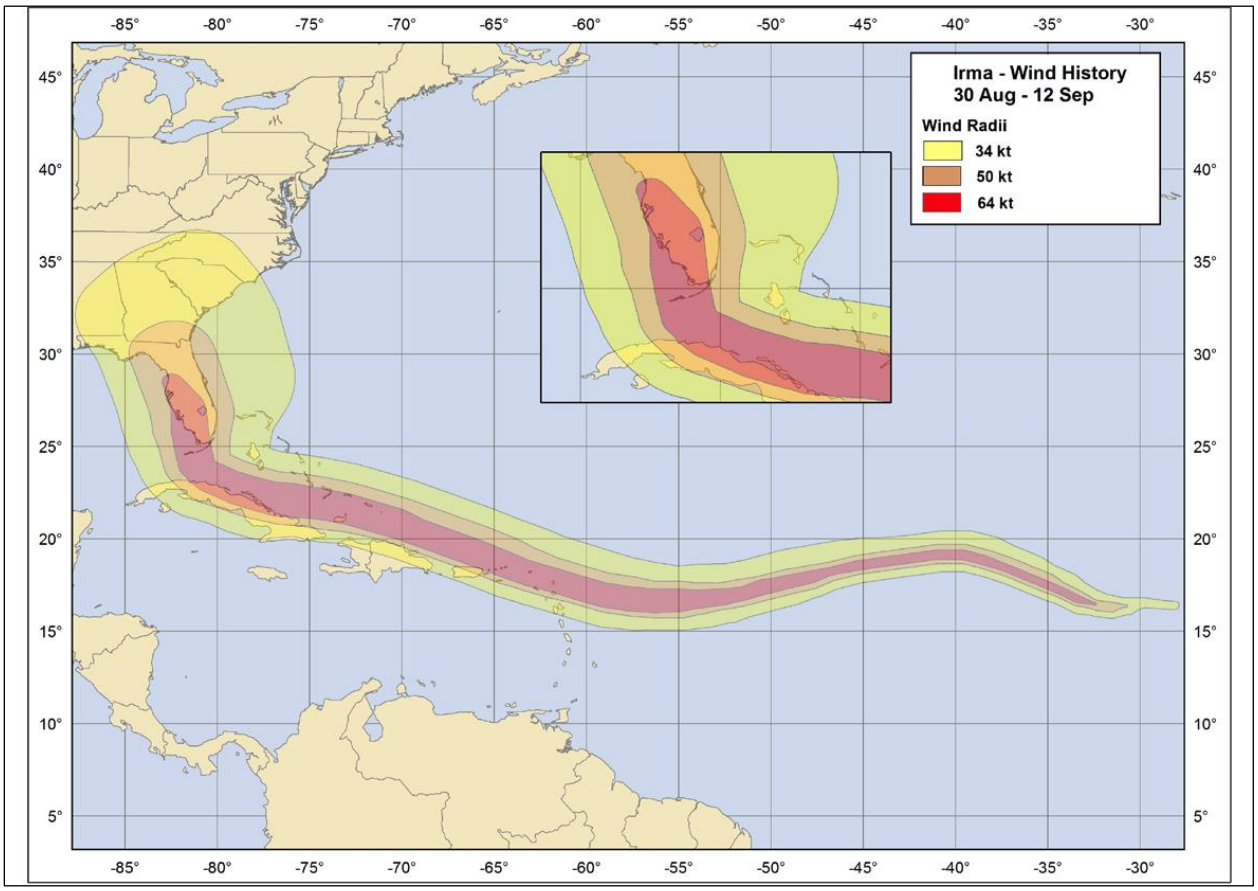
Figure 7 shows the swath of destructive winds along Irma's path, indicating that the radius of high winds enlarged as the storm moved west into the Caribbean, the Straits of Florida, and the southeastern United States. Irma's large wind field produced significant storm-surge flooding along the northeastern coast of Florida, even though the storm made landfall in southwestern Florida. The significant flooding along the banks of the St. Johns River near Jacksonville, FL, for example, resulted from the combination of storm-surge and rainfall runoff into the river, along with easterly winds ahead of Irma pushing seawater upstream, causing the water to rise initially.[50] The broad wind field and associated rainfall and storm surge created conditions that led to seven direct deaths in the southeastern United States because of Irma: four in Florida, two in Georgia, and one in South Carolina.[51]

[50] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, pp. 10-11.

[51] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, p. 15.

Figure 7. Hurricane Irma's Wind Field

(August 30, 2017, through September 12, 2017; wind speed in knots)



Source: Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, Figure 4.

Notes: The wide wind field shown over the Florida peninsula indicates why Irma caused flooding in northeastern Florida even though it made landfall in southwestern Florida. Wind speed is in knots.

Forecasts

The NHC noted that Irma became a cyclone earlier than predicted, but the official track forecast errors were generally 30%-40% lower than the average official forecast errors for the previous five-year period (**Table 4**). The only other forecast model that consistently predicted Irma's track better than the NHC model was the European Centre for Medium-Range Weather Forecasts model (EMXI).[52]

[52] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, p. 18.

Table 4. NHC Official Track Forecast Errors for Hurricane Irma Compared to the 2012-2016 Average

(in nautical miles)

Forecast	Forecast Period[a]						
	12 hours	24 hours	36 hours	48 hours	72 hours	96 hours	120 hours
NHC Official	14.8	25.5	37.6	50.5	73.9	101.8	135.0
2012-2016 Average	24.9	39.6	54.0	71.3	105.8	155.4	208.9

Source: CRS, from Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, Table 5a.

Notes: Forecast errors indicate the difference between the forecast track and the actual track in nautical miles.

a. The NHC issues official forecasts every 6 hours, and each forecast has projections valid 12, 24, 36, 48, 72, 96, and 120 hours after the forecast's initial time.

The NHC official intensity forecasts for Irma had errors larger than the forecast errors for the previous five-year period (**Table 5**). The NHC noted that Irma's intensity was more difficult to forecast than the intensity of a typical tropical cyclone due to Irma's quick formation and interaction with Cuba.[53]

Table 5. NHC Official Intensity Forecast Errors for Hurricane Irma Compared to the 2012-2016 Average

(in nautical miles per hour, or knots)

Forecast	Forecast Period[a]						
	12 hours	24 hours	36 hours	48 hours	72 hours	96 hours	120 hours
NHC Official	9.0	12.4	15.8	17.4	18.7	24.9	29.7
2012-2016 Average	5.5	8.2	10.5	12.0	13.4	14.0	14.5

Source: CRS, from Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, Table 6a.

Notes: Forecast errors indicate the difference between the forecast intensity and the actual intensity in nautical miles per hour, knots.

a. The NHC issues official forecasts every 6 hours, and each forecast has projections valid 12, 24, 36, 48, 72, 96, and 120 hours after the forecast's initial time.

Hurricane Maria

Hurricane Maria was the second category 5 hurricane to form in 2017. It was the deadliest storm of 2017 and is widely regarded as the worst natural disaster to strike Puerto Rico on record. Maria became a tropical storm on September 16, 2017, became a hurricane on September 17, and reached category 5 intensity on September 18.[54] The storm developed maximum wind speeds of

[53] Cangialosi, Latto, and Berg, *Hurricane Irma*, 2018, p. 18. The ECMWF also reported that it struggled with correctly predicting the intensity of both Hurricane Harvey and Hurricane Irma. See ECMWF, "Predictions of Tropical Cyclones Harvey and Irma," at https://www.ecmwf.int/en/newsletter/153/news/predictions-tropical-cyclones-harvey-and-irma.

[54] Richard J. Pasch, Andrew B. Penny, and Robbie Berg, *National Hurricane Center Tropical Cyclone Report: Hurricane Maria*, NOAA, AL152017), April 5, 2018, p. 2. Hereinafter Pasch, Penny, and Berg, *Hurricane Maria*,

175 mph over the eastern Caribbean on September 19, but weakened slightly to category 4 after making landfall on the island of Dominica. It then struck the southeast coast of Puerto Rico on September 20 with winds just below the threshold of a category 5 hurricane.[55] That same day, the storm passed close by the USVI, particularly the island of St. Croix, damaging 80%-90% of the power and transmission systems in the USVI.[56] The eye of the hurricane traversed Puerto Rico roughly diagonally from southeast to northwest for several hours and moved offshore into the Atlantic Ocean later on September 20. After crossing Puerto Rico, Maria headed north toward the eastern United States but remained offshore, passing about 130 nautical miles east of Cape Hatteras, NC, on September 27. Maria never made landfall in the continental United States before dissipating in the Atlantic Ocean on September 30.[57] **Figure 8** shows the hurricane track from genesis on September 16, 2017, through dissipation on September 30, 2017.[58]

2018.

[55] Pasch, Penny, and Berg, *Hurricane Maria*, 2018, p. 2.

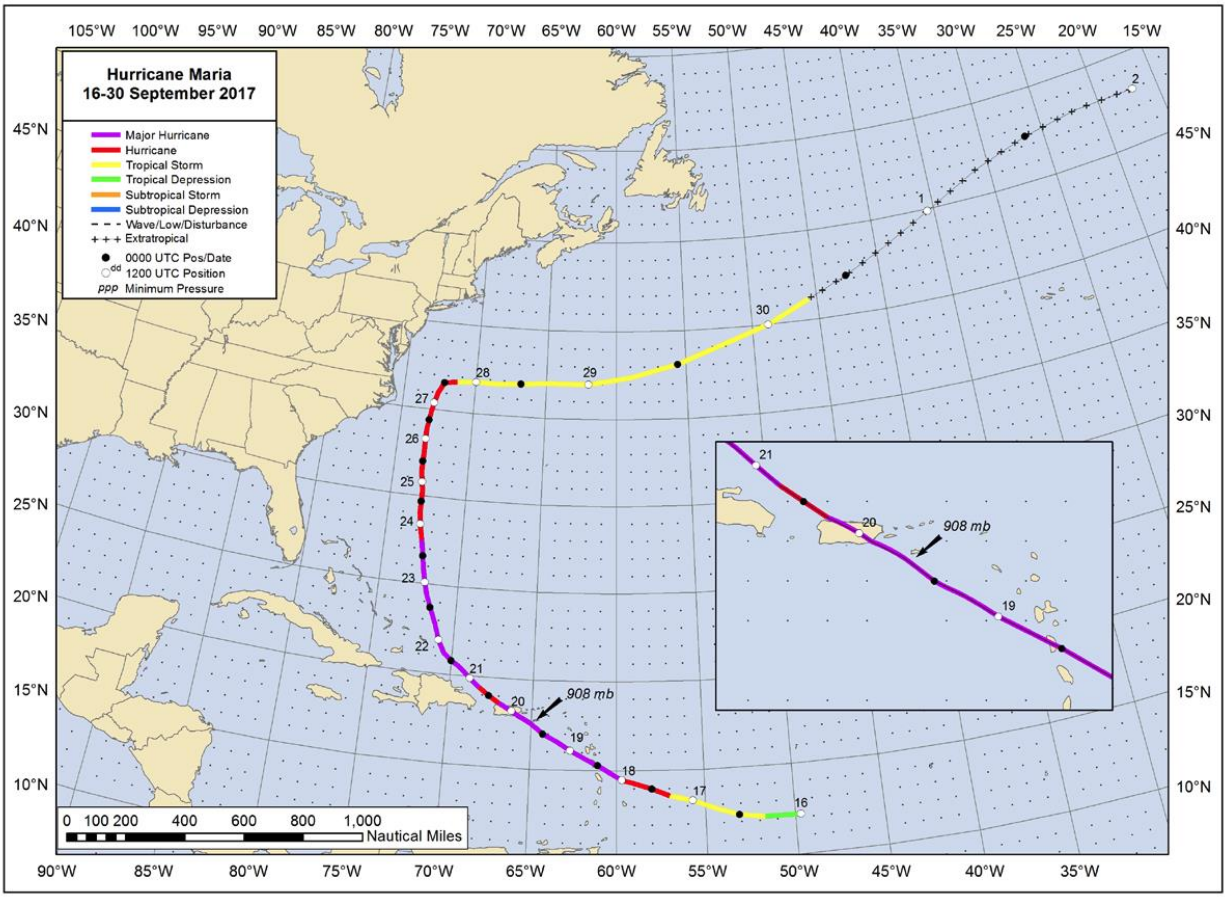
[56] For more information on damage to the U.S. Virgin Islands' power and water systems and recovery efforts, see CRS Report R45105, *Potential Options for Electric Power Resiliency in the U.S. Virgin Islands*, by Corrie E. Clark, Richard J. Campbell, and D. Andrew Austin.

[57] Pasch, Penny, and Berg, *Hurricane Maria*, 2018, p. 3.

[58] Pasch, Penny, and Berg, *Hurricane Maria*, 2018, p. 33.

Figure 8. Hurricane Maria's Track

(September 16, 2017, through September 30, 2017)



Source: Richard J. Pasch, Andrew B. Penny, and Robbie Berg, *National Hurricane Center Tropical Cyclone Report: Hurricane Maria*, NOAA, AL152017), April 5, 2018, Figure 1. Hereinafter Pasch, Penny, and Berg, Hurricane Maria, 2018.

Notes: Numbers along the hurricane track indicate dates (e.g., 18 equals September 18, 2017).

Puerto Rico was still recovering from damage caused by Hurricane Irma two weeks earlier when Maria made landfall. Hurricane Maria incapacitated the central electric power system on Puerto Rico, leaving the entire island without power and destroying much of the power grid.[59]

Direct and indirect death totals in Puerto Rico have been the subject of controversy, according to some journalists and news reports, with higher unofficial numbers contrasting with the lower numbers reported by the government of Puerto Rico.[60] The official death toll in Puerto Rico is 65; however, hundreds of indirect deaths may be attributed to Maria, pending results of a Puerto

[59] For more information about damage to the Puerto Rican power system, see CRS Report R45023, *Repair or Rebuild: Options for Electric Power in Puerto Rico*, by Richard J. Campbell, Corrie E. Clark, and D. Andrew Austin.

[60] See, for example, Eliza Barclay and Alexia Fernandez Campbell, "Data Shows Hurricane Deaths in Puerto Rico Could Be Over 1,000," Vox, December 8, 2017, at https://www.vox.com/policy-and-politics/2017/11/29/16623926/puerto-rico-death-toll-hurricane-maria-count.

Rican government review.[61] NOAA estimated that Maria caused about $90 billion of damage on Puerto Rico, making it the costliest hurricane in modern times for the island and the third-costliest hurricane in U.S. history (behind Katrina and Harvey).[62] The island of Dominica suffered 31 direct deaths due to Maria, which damaged or destroyed most of Dominica's structures.

Forecasts

According to NOAA, the genesis of Hurricane Maria was not well forecast, which the agency attributes to a failure of hurricane forecast models to predict tropical cyclone formation until very soon before the cyclone actually formed.[63] However, the track forecasts for Maria had fewer errors by about 50% than the mean official errors from the previous five-year period for all forecast intervals (**Table 6**).

Table 6. NHC Official Track Forecast Errors for Hurricane Maria Compared to the 2012-2016 Average

(in nautical miles)

Forecast	Forecast Period[a]						
	12 hours	24 hours	36 hours	48 hours	72 hours	96 hours	120 hours
NHC Official	12.9	20.5	26.8	35.8	58.3	85.0	122.2
2012-2016 Average	24.9	39.6	54.0	71.3	105.8	155.4	208.9

Source: CRS, from Pasch, Penny, and Berg, *Hurricane Maria*, 2018, Table 6a.

Notes: Forecast errors indicate the difference between the forecast track and the actual track in nautical miles.

a. The NHC issues official forecasts every 6 hours, and each forecast has projections valid 12, 24, 36, 48, 72, 96, and 120 hours after the forecast's initial time.

The NHC official intensity forecasts were mixed compared to the mean official errors from the previous five-year period. The errors for Maria were higher than the previous five-year average for the intervals up to 48 hours but lower than the five-year average for 72, 96, and 120 hours (**Table 7**). Of note, according to NOAA, is how poorly the models anticipated Maria's rapid intensification on September 18, under-predicting the storm's strengthening.[64] However, the NHC noted that every forecast beginning with the second official forecast after genesis for Maria indicated that the storm would reach major hurricane intensity before it struck Puerto Rico. Further, the NHC forecasts provided Puerto Rico with 54 hours of advance warning that Maria would make landfall as a category 4 hurricane.[65]

[61] Pasch, Penny, and Berg, *Hurricane Maria*, 2018, p. 6.

[62] Pasch, Penny, and Berg, *Hurricane Maria*, 2018, p. 7.

[63] Pasch, Penny, and Berg, *Hurricane Maria*, 2018, p. 8.

[64] Pasch, Penny, and Berg, *Hurricane Maria*, 2018, p. 9.

[65] Pasch, Penny, and Berg, *Hurricane Maria*, 2018, p. 9.

Table 7. NHC Official Intensity Forecast Errors for Hurricane Maria Compared to the 2012-2016 Average

(in nautical miles per hour, or knots)

Forecast	Forecast Period[a]						
	12 hours	24 hours	36 hours	48 hours	72 hours	96 hours	120 hours
NHC Official	6.6	10.6	13.0	14.5	12.2	8.8	8.1
2012-2016 Average	5.5	8.2	10.5	12.0	13.4	14.0	14.5

Source: CRS, from Pasch, Penny, and Berg, *Hurricane Maria*, 2018, Table 7a.

Notes: Forecast errors indicate the difference between the forecast intensity and the actual intensity in nautical miles per hour, or knots (kt). A nautical mile is about 1.15 statute miles.

a. The NHC issues official forecasts every 6 hours, and each forecast has projections valid 12, 24, 36, 48, 72, 96, and 120 hours after the forecast's initial time.

2018 Atlantic Hurricane Season Outlook

The Climate Prediction Center (CPC), within the NWS, annually issues a NOAA Atlantic Hurricane Season Outlook. The outlook for 2018, initially issued on May 24, predicted 10-16 named storms, 5-9 hurricanes, and 1-4 major hurricanes.[66] The CPC updated its outlook on August 9, predicting 9-13 named storms, 4-7 hurricanes, and 0-2 major hurricanes.[67]

According to the August CPC prediction, there is a 60% chance of a below-normal season (most likely), a 30% chance of a near-normal season, and a 10% chance of an above-normal season. These categories reflect the probabilistic nature of the annual outlooks, meaning they have a certain likelihood of occurring.[68] The outlook is based on (1) predictions of large-scale climate factors known to influence seasonal hurricane activity and (2) climate models that directly predict hurricane activity.[69] For comparison to the 2018 outlook, **Table 8** shows seasonal means and ranges for named storms, hurricanes, and major hurricanes, using data collected between 1981 and 2010.

In its August update, the CPC provided four main reasons why it expects the 2018 hurricane season to be less active than its May prediction:[70]

1. Exceptionally cool sea surface temperatures in the region of the Atlantic where tropical storms initially form;
2. An increased likelihood of an El Niño developing;

[66] NOAA, National Weather Service, Climate Prediction Center, "NOAA 2018 Atlantic Hurricane Season Outlook," May 24, 2018, at http://www.cpc.ncep.noaa.gov/products/outlooks/hurricane2018/May/hurricane.shtml.

[67] NOAA, National Weather Service, Climate Prediction Center, "NOAA 2018 Atlantic Hurricane Season Outlook," August 9, 2018, at http://www.cpc.ncep.noaa.gov/products/outlooks/hurricane2018/August/hurricane.shtml. Hereinafter NOAA, "NOAA 2018 Atlantic Hurricane Season Outlook."

[68] NOAA describes the probabilistic nature as follows "the seasonal activity is expected to fall within these ranges in 7 out of 10 seasons with similar climate conditions and uncertainties to those expected this year." NOAA, "NOAA 2018 Atlantic Hurricane Season Outlook."

[69] NOAA, "NOAA 2018 Atlantic Hurricane Season Outlook."

[70] NOAA, "NOAA 2018 Atlantic Hurricane Season Outlook."

3. Components of atmospheric circulation patterns that developed and are not conducive to hurricane formation; and
4. Consistent with the first three items, all hurricane models predict a less active season than they did in May.

Although the Atlantic hurricane season runs from June 1 to November 30, the CPC notes that most of the predicted activity is expected to occur during the peak hurricane months of August to October. Because ocean and atmospheric conditions may change, the CPC typically issues an update in August to its initial May outlook to coincide with the onset of the peak season.

Table 8. Seasonal Means and Ranges for Named Storms

(1981-2010)

Season Type	Mean Number of Tropical Storms	Range of Tropical Storms	Mean Number of Hurricanes	Range of Hurricanes	Mean Number of Major Hurricanes	Range of Major Hurricanes
Above Normal	16.5	12-28	9.7	7-15	4.8	3-7
Near Normal	12.3	10-15	6.3	4-9	2.3	1-4
Below Normal	6.7	4-9	3.3	2-4	1.0	0-2
All Seasons	12.1	4-28	6.4	2-15	2.7	0-7

Source: NOAA, National Weather Service, Climate Prediction Center, "Background Information: North Atlantic Hurricane Season," at http://www.cpc.ncep.noaa.gov/products/outlooks/NorATL_Background.shtml.

NOAA includes several disclaimers when issuing its seasonal outlook. For example, NOAA does not make a seasonal hurricane *landfall* forecast, and it does not predict levels of hurricane activity for any particular area within the Atlantic region.[71] Hurricane landfalls are determined largely by weather patterns after the storm has formed, which are predictable only days before the hurricane makes landfall (see "Improvements and Challenges"). NOAA also includes the following with its outlook:

> It only takes one hurricane (or tropical storm) to cause a disaster. Residents, businesses, and government agencies of coastal and near-coastal regions are urged to prepare for every hurricane season regardless of this, or any other, seasonal outlook.[72]

Issues for Congress and the Weather Act

Congress enacted Section 104, Title I, of P.L. 115-25 (the Weather Act) specifically to improve hurricane forecasting with a focus on

- improving the prediction of rapid intensification and track of hurricanes;
- improving the forecast and communication of storm surges from hurricanes; and
- incorporating risk communication research to create more effective watch and warning products.

[71] NOAA, "NOAA 2018 Atlantic Hurricane Season Outlook."

[72] NOAA, "NOAA 2018 Atlantic Hurricane Season Outlook."

Congress has continued to focus on these issues in the second session of the 115th Congress. At an April 12, 2018, hearing before the Senate Committee on Commerce, Science, and Transportation, the acting NOAA Administrator stated that forecasts for the 2017 hurricane season "were the best the NHC [National Hurricane Center] ever produced."[73] However, despite clear improvements in hurricane forecasting, some stakeholders point to the need for even better forecasts. One witness representing the Red Cross at the April 12, 2018, hearing, identified some uncertainties with predicting the track of hurricane Irma that "challenged planners across the state [of Florida]."[74] A witness representing the National Transportation Safety Board noted that the track for Hurricane Joaquin in 2015 was difficult to forecast because of moderate *wind shear* and recommended that NOAA improve the performance of its forecast models in moderate wind-shear environments.[75] In the Weather Act, Congress required a detailed plan for NOAA's hurricane forecast improvement program under Section 104 within a year of enactment; however, the plan was unavailable as of early July 2018.

Other sections of the Weather Act address aspects of the NOAA weather enterprise that also could lead to improvements in hurricane forecasting. For example, Section 107 of Title I requires NOAA to undertake experiments to assess different observing systems and their capabilities to improve hurricane track and intensity forecasting, among other things. Section 413, Title IV, requires NOAA to acquire backup capabilities for Hurricane Hunter aircraft to prevent a single point of failure for that part of the hurricane observing system.

At a July 18, 2018, hearing of the House Transportation and Infrastructure Committee, witnesses focused on recovery activities from the 2017 hurricane season and preparedness for the 2018 season.[76] It is likely that Congress will maintain its interest in federal hurricane forecast abilities every year given the annual threat hurricanes pose to populated coastal regions of the United States.

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[73] Written testimony of Rear Admiral Tim Gallaudet, Senate Committee on Commerce, Science, and Transportation, *Are We Ready for the Next Hurricane Season?*, Status of Preparation and Response Capabilities for 2018, 115th Cong., 2nd sess., April 12, 2018.

[74] Written testimony of Jennifer Pipa, Regional Chief Executive Officer, American Red Cross of Central Florida, in U.S. Congress, Senate Committee on Commerce, Science, and Transportation, *Are We Ready for the Next Hurricane Season?*, Status of Preparation and Response Capabilities for 2018, 115th Cong., 2nd sess., April 12, 2018.

[75] Written testimony of T. Bella Sinh-Zarr, Member, National Transportation Safety Board, in U.S. Congress, Senate Committee on Commerce, Science, and Transportation, *Are We Ready for the Next Hurricane Season?*, Status of Preparation and Response Capabilities for 2018, 115th Cong., 2nd sess., April 12, 2018. *Wind shear* refers to any change in wind speed or direction along a straight line. It is often the most critical factor controlling hurricane formation and destruction. See Weather Underground, "Wind Shear Tutorial," at https://www.wunderground.com/education/shear.asp.

[76] U.S. Congress, House Committee on Transportation and Infrastructure, *Are We Ready? Recovering from 2017 Disasters and Preparing for the 2018 Hurricane Season*, 115th Cong., 2nd sess., July 18, 2018.

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