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Tropical Cyclone Forecasting in the United States

An Information Statement of the American Meteorological Society

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The devastating hurricane seasons of 2017 to 2021 have highlighted the importance of hurricane observations, forecasts, preparedness, resilience, communications, and societal response for protection of life and property. Advances in all of these areas will help mitigate damage, improve emergency response, enable communities to recover more quickly and completely, and lessen impacts on government budgets. The collaborative shared mission of America's Weather Enterprise, which is comprised of government agencies, academic and university research institutions, and representative companies from America's Weather and Climate Industry, is to reduce the loss of life and vulnerability to hurricane-related hazards through improved observations, forecasting of storms, and broad-based communications that provide a wide dissemination of official government hurricane watches and warnings, and forecasts and commentary from experts in the other sectors. We acknowledge that the social sciences play a critical role in saving lives and property, but such important work is beyond the scope of this statement.

Hurricanes belong to a class of storms referred to generically as tropical cyclones. Tropical cyclones are warm-core, non-frontal, synoptic scale cyclones, originating over tropical or subtropical waters, with organized deep convection (thunderstorm activity) and a closed surface wind circulation about a well-defined center. The term hurricane is applied to tropical cyclones in the central and eastern North Pacific and Atlantic Oceans, signifying when their maximum sustained surface wind (the 1-min mean wind at a height of 33 ft or 10 m) is at least 64 kt (74 mph or 33 m s^{-1}). In the remainder of this statement, the term tropical cyclone is generally used, recognizing that even tropical cyclones that are not as strong as hurricanes – tropical storms and even tropical depressions - can cause substantial damage and fatalities, primarily due to water. When referring specifically to storms with winds exceeding 64 kt, the term hurricane will be used.

Tropical-cyclone-related hazards

The extensive damage and loss of life caused by tropical cyclones result from five primary hazards: storm surge (a local abnormal rise in coastal water levels), heavy rains and their associated freshwater flooding, strong winds, rainband-spawned tornadoes, and rip currents. While tropical cyclones are most hazardous in coastal regions, their weakening, moisture-laden circulations can produce extensive, damaging floods and tornadoes hundreds of miles inland for days after landfall. In addition, during the past several decades, tropical cyclones have indirectly caused almost as many fatalities as the direct forces of the storms, further emphasizing the public need for forecast and preparedness information to keep them safe before, during and after the storm.

In general, the rapid growth of U. S. coastal populations and related infrastructure, and the increasing complexity of evacuation, have led to increased vulnerability of coastal communities. The largest losses of life and property in tropical cyclones during the past several decades have resulted from the storm surge, which is a rapid rise of sea water and associated flooding of normally dry ground that occurs up to several miles inland when tropical cyclones make landfall. Storm surge flooding can in some cases locally exceed 20 ft (6 m) above normally dry ground when strong and/or large tropical cyclones strike a coastline with shallow water offshore. The vulnerability to storm surge was tragically illustrated by 2005's Hurricane Katrina, which directly and indirectly killed well over 1500 people in Louisiana and Mississippi. In recent years, large losses of life due to storm surge have become less frequent and rainfall/flooding related deaths have become more prominent. Harvey in 2017 caused catastrophic and deadly flooding in Houston and other portions of southeast Texas, mostly while it was a tropical storm, with many areas receiving more than 40 inches (1000 mm) of rainfall, and causing damage estimated at $131 billion (in 2020 USD). While improved building codes in some tropical cyclone-prone regions have reduced fatalities from wind damage, fatalities continue to result from both the wind and water of major storms. In 2017, Hurricane Maria's strong winds devastated Dominica and Puerto Rico, destroying buildings ($95 billion in damage in 2020 USD), causing widespread power outages in Puerto Rico, and leading directly and indirectly to the deaths of thousands of people.

Tropical cyclone-caused damage in the continental United States averages $28 billion (in 2021 USD) annually according to the National Center for Environmental Information (https://www.ncdc.noaa.gov/billions/summary-stats), representing about 52% of the cost of all billion dollar disasters (including other severe storms, droughts, and wildfires). This cost is very likely increasing due to growing population, wealth, and development in the vulnerable coastal zones.

Tropical cyclone observations

A key factor limiting TC forecasts is insufficient sampling of appropriate observations of the storm environment and inner-core region. Because tropical cyclones spend much of their existence over remote oceanic areas, they are predominantly observed using remote-sensing instruments such as visible and infrared imagers, radars, and passive microwave systems on both satellites and aircraft. The advent of operationally available geostationary satellite surveillance in 1970 greatly improved our ability to detect tropical cyclones over the open ocean, some of which – especially short-lived and relatively weak tropical cyclones - would inevitably have otherwise escaped detection. The GOES-R generation of geostationary operational environmental satellites provides significantly improved spatial, spectral, and temporal resolution measurements critical to monitoring tropical cyclones. However, traditional geostationary satellite-derived position estimates may have errors of tens of miles when the circulation center is obscured by clouds, and satellite-derived intensity estimates may have errors of tens of knots. Passive microwave imagery on Low-Earth Orbiting (LEO) satellites can provide radar-like depictions of storm precipitation structure to aid in the analysis of tropical cyclones, including information on the occurrence of convective bursts, changes in eyewall or overall storm size, and the onset and evolution of eyewall replacement cycles. However, these data are neither as timely nor as frequent as they need to be for optimum coverage of individual tropical cyclones. Microwave imagers with frequencies near 10 GHz have also provided valuable information on sea surface temperatures beneath the tropical cyclone upper-cloud deck. Scatterometers such as the Advanced Scatterometer (ASCAT) provide surface wind measurements over large oceanic swaths, but these measurements are significantly degraded by rain and generally cannot resolve the maximum winds in moderate-to-strong hurricanes. Spaceborne Synthetic Aperture Radar (SAR) and the Soil Moisture and Ocean Stability (SMOS) and Soil Moisture Active Passive (SMAP) missions also show promise for estimating tropical cyclone surface winds, but with similar temporal limitations as other instruments on LEO satellites.

While there has been a tremendous increase in the quality and quantity of remotely sensed wind and thermodynamic data over the formerly data-sparse oceans, the tropical cyclone and its environment are still severely under-sampled. As discussed in the 2017 report of the National Academies *Thriving on Our Changing Planet: A [NASA] Decadal Survey for Earth Observation From Space*, (available online at https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth), some of the progress in remote sensing of tropical cyclones from space may not be adequately maintained, particularly in terms of the number of passive microwave imagers. Unfettered access to relevant U.S. and international satellite data sets is critical to maintaining capabilities to monitor storms. Technologies exist to more accurately and completely capture the entire surface wind field of a tropical cyclone, including the inner core, from a near polar orbiting satellite platform, but funding has not to date been available for launching such capabilities. Commercial weather satellite GNSS-Radio Occultation data provides three-dimensional water vapor measurements over the tropics, which can be valuable for tropical cyclone genesis, intensity and track forecasts.

In addition to satellite observations, reconnaissance aircraft such as the Air Force Reserve C-130J and National Oceanic and Atmospheric Administration (NOAA) P-3 are used to gather in-situ observations of storm location, central pressure, and winds when tropical cyclones threaten land areas. This information is invaluable to operational centers because it provides greater certainty of the estimates of tropical cyclone position and intensity. This point is especially true for weaker tropical cyclones, but satellite position and especially intensity estimates even for major storm can sometimes be greatly inferior to what aircraft reconnaissance can measure. Surface winds are generally estimated from the stepped-frequency microwave radiometer (SFMR) data, estimated by reducing flight-level winds to values representative of the surface, or determined from direct measurement by GPS dropwindsondes. Aircraft reconnaissance data do have substantial sampling limitations, however, since SFMR and flight-level data are only collected along the line of the aircraft flight path, and dropsondes are point observations. These limitations highlight why developing the capability to measure the entire surface wind field of a hurricane from a satellite platform would be advantageous. Storm structure and steering currents surrounding the storm can be measured by dropwindsondes released from the NOAA Gulfstream-IV jet or other aircraft, resulting in track forecast improvements in some models of up to 15%. Doppler radar data from the P-3 aircraft provide information on the three-dimensional structure of the inner-core wind field. This information is assimilated into high-resolution hurricane modeling systems to further improve hurricane track and intensity forecasts.

Airborne observing technologies are being developed to provide greater situational awareness of tropical cyclone position, structure, and intensity. Several field experiments have demonstrated advances in these technologies and their application to tropical cyclone science and operations. The Tropical Cyclone Intensity (TCI, 2015) experiment used large numbers of rapidly released mini dropsondes to provide high vertical and horizontal resolution profiling of Hurricane Patricia (2015). The Hurricane and Severe Storm Sentinel (HS3, 2012-2014) and Sensing Hazards with Operational Unmanned Technologies (SHOUT, 2015-2016) campaigns used the high-altitude, long-endurance Global Hawk unmanned airborne system (UAS) to map the storm environment and inner core using full-tropospheric dropsonde soundings and Doppler radars, with the aircraft capable of overflying storms almost anywhere over the Atlantic Ocean. The Coyote, a small UAS released from the NOAA P-3 as a part of the ongoing Intensity Forecasting Experiment (IFEX, 2005-present), enabled in-situ measurements of the eyewall within and just above the tropical cyclone boundary layer. Real-time testing of small UAS aircraft to replace the Coyote began in 2022 . While experimental in nature, such experiments push the boundaries of observing systems and provide potential paths forward for future reconnaissance.

Tropical cyclone forecasting

The AMS recognizes that the private weather enterprise is playing an increasing role in many facets of the tropical cyclone forecasting problem, including the development and provision of new satellite observations such as radio occultation measurements that can be used to improve numerical weather prediction, seasonal projections of tropical cyclone activity, and short-term forecasts tailored to the public (e.g., cable channels such as The Weather Company and AccuWeather) and commercial clients. A discussion of both the public and private weather enterprise is beyond the scope of this statement. This section focuses on federal forecasting responsibilities, but many of the issues and challenges faced by federal forecasters also apply to their private sector counterparts.

a. Forecast responsibility within the National Weather Service

The National Hurricane Center (NHC) has overall responsibility for issuing track and intensity forecasts for North Atlantic and eastern North Pacific tropical cyclones, while the Central Pacific Hurricane Center is responsible for central North Pacific cyclones. However, the Nation’s tropical cyclone warning program is a collaborative one in which other national and local National Weather Service (NWS) offices, other federal, state, and local government agencies, and private sector companies all play an important role. Forecasters at local NWS offices use their knowledge of the regional and local meteorology, oceanography, topography, and population demographics to provide specific information about the expected wind speed and direction, rainfall, storm surge, and rainband-spawned tornadoes to local and state emergency management offices and the general public. Broadcast meteorology outlets on cable, radio and television, as well as their dissemination partner-companies from America's Weather and Climate Industry that have extensive social media platform outlets, also play a key role in communications of hazards. In addition, the Weather Prediction Center (WPC) provides heavy rainfall and flash flooding guidance both to the local NWS offices and directly to emergency management agencies, while forecasts of severe local weather, such as tornadoes, are provided by the Storm Prediction Center (SPC). NHC's Tropical Analysis and Forecast Branch (TAFB) and the Ocean Prediction Center (OPC) provide guidance on marine hazards for areas south and north of 30^{o}N, respectively. River Forecast Centers (RFCs) across the United States use the hurricane rainfall predictions within the context of their hydrodynamical models to forecast river heights and the possibility of flooding. Finally, the NHC collaborates with and advises other nations across the North Atlantic and eastern North Pacific basins, as part of its role as a Regional Specialized Meteorological Center (RSMC) for World Meteorological Organization (WMO) Regional Association IV. While NHC has the sole operational responsibility for official tropical cyclone forecasts for the North Atlantic and eastern North Pacific basins and provides watch and warning guidance to other countries in these basins, each nation maintains watch and warning responsibility for their country.

The Department of Defense Joint Typhoon Warning Center (JTWC) provides track, intensity and wind structure forecasts similar to those from NHC and CPHC for all areas outside of the Atlantic and eastern Pacific basins. The JTWC forecasts are used by the NWS Pacific Region to create hazard graphics for use in the areas of responsibility of the NWS local forecast offices in Guam and American Samoa.

b. Track forecasting

The tropical cyclone track forecast is the foundation of the forecast and warning process; accurate prediction of other storm parameters is of little value if the track forecast is greatly in error. Fortunately, track forecasts have significantly improved over the past few decades. For the 5-year period 2016-2020, NHC Atlantic Basin track forecast errors averaged 36 nautical miles (67 km) for the 24-hour forecast and 63 nautical miles (117 km) for the 48-hour forecast. During the active Atlantic hurricane season of 2017, NHC 12–72 h forecast accuracy was at or near record levels. In fact, track errors in 2017 reached all-time lows in records going back to 1970. As a result of these improvements, the 2018 average 5-day track forecast error is similar to the 2-day forecast error of 1995. Much of this progress is attributable to improvements in global and regional numerical models, the explosion in the amount of remotely sensed data over the oceans, and advances in the assimilation of all data types. There is some evidence, however, that the rate of track forecast improvement is slowing in the past few years, with no new records set at any forecast period through 5 days since 2019.

Forecast uncertainty still necessitates the issuance of tropical cyclone warnings for relatively large coastal areas. The continuing increase in coastal population and development, without concurrent expansion of evacuation routes, has resulted in longer evacuation clearance times. As a result, the NHC has put greater emphasis on enhancing the lead time of warnings, increasing average lead time from about 18 h in the 1960s to over 40 h during 2015-2019. This lead-time increase has occurred with no increase in the size of the warnings, which have remained fairly constant between 2000 and 2019. Even so, about one-quarter to one-third of an average hurricane warning area experiences hurricane conditions and this number has only slightly increased during 2010-2019. Continued improvements in track forecast accuracy should decrease the amount of "over warning," but this must be carefully balanced with the priority to safeguard lives and property. However, Hurricanes Maria (2017), Michael (2018), Dorian (2019), and Zeta (2020) remind us that even with excellent track forecasts, intensity forecasts remain a significant challenge, especially for such rapid intensifiers, and the United States and other areas in the Atlantic remain vulnerable to large losses of life and property from both wind and water of tropical cyclones.

c. Intensity, size, and structure forecasting

Intensity forecasts have been much slower to improve than track forecasts. However, with advancements in data assimilation, including improved methodologies and an in increase in the number and types of observations ingested, and the advent of higher-skill models such as the Hurricane Weather Research and Forecasting model (HWRF), Logistic Growth Equation Model (LGEM), and Coupled Ocean/Atmosphere Mesoscale Prediction System - Tropical Cyclones (COAMPS-TC) models, and more skillful global model forecasts from the Global Forecast System (GFS), these intensity forecast errors have decreased between 2010 and 2021. For the 5-year period 2001-2005, NHC intensity forecast errors averaged 10 kt (5 m s^{-1}) for the 24-h forecast and 14 kt (7 m s^{-1}) for the 48-h forecast. For the 5-year period from 2017-2021, NHC Atlantic basin intensity errors averaged about 8 knots (4 m s^{-1}) for the 24-h forecast and 11 knots (6 m s^{-1}) for the 48-h forecast. These average statistics obscure the large errors that typically occur when storms strengthen (or weaken) rapidly. These rapid intensity changes, particularly rapid intensification, can have significant impacts on preparedness, especially when these changes occur near landfall. As a result, improving the understanding and prediction of rapid intensification is a high priority of the TC operational and research communities.

From 2015-2021, operational capabilities to estimate the distribution of gale force winds (the 34-kt wind radii or R34) have been improved through better use of the available satellite data and initial conditions from numerical models [e.g., GFS, HWRF, and European Centre for Medium-Range Forecasts (ECMWF)]. Model forecasts of R34 have become skillful. Consensus methods that combine forecasts from regional, statistical, and global models have further improved forecast skill and can now provide forecast confidence, along with location-specific wind speed probabilities to account for the uncertainties in forecasts of track, and intensity and size/wind radii.

Analysis and forecasts of inner-core winds (e.g., the radius of maximum winds and radii of the 50- and 64-knot winds) has proven to be more challenging. Measurements, though improved, are still more sparse and less accurate for the inner core than they are for R34, and forecast models require these measurements for both development and real-time forecasts. Changes in the distribution of inner-core winds, particularly those that result from eyewall replacement cycles or extratropical transition, are extremely difficult to anticipate. These inner-core changes can significantly affect storm impacts such as wind damage and storm surge, and so forecasts of these fields are of utmost importance.

d. Storm surge hazard

NOAA and the NWS have made an extensive effort to enhance storm surge predictability and improve communication of hazards by working closely with its dissemination partner companies from America's Weather and Climate Industry. In addition to distributing these NWS forecasts, some private sector forecasters issue their own surge forecasts and their own communications around the impacts. The NWS in particular has developed a probabilistic storm surge modeling system (P-Surge) to quantify the risk in real time. In this model, a statistically based ensemble is generated to account for forecast uncertainty in tropical cyclone size, intensity, and track since these specific factors, along with timing relative to astronomical tides, and local differences in coastline shape and bathymetry, influence the overall predictability of storm surge at any specific location. The risk of any storm surge inundation, not just along the coast but extending as far inland as the hazard could reasonably occur, is then illustrated by a potential storm surge flooding map, and life-threatening storm surge (i.e., greater than 3 feet above normally dry ground) is communicated via a NWS storm surge watch/warning. The potential storm surge flooding map highlights geographical areas where storm surge could occur and the heights at which the water could reach above ground and is primarily used by evacuation decision makers but is also used by the media and other private companies, whereas the storm surge watch/warning highlights areas that are at a significant risk to life-threatening storm surge and is primarily used by the NWS and the private sector to urge the public to follow evacuation and other instructions from local officials.

In addition to real-time storm surge forecasts, products, warnings, and guidance, the NWS generates storm surge risk guidance for evacuation planning by emergency management agencies and for public awareness and preparedness, to be used well in advance of hurricane season. These products depict storm surge flooding vulnerability for U.S. communities along and near the coast in terms of the worst-case scenario for each tropical cyclone scenario, considering a wide variety of tracks, forward speeds, intensities, and storm sizes. These are intended to be analyzed far ahead of a real-time event and to help localities and states to construct and publicly communicate the nation's hurricane evacuation zones. Specifically, these NWS products include the Maximum Envelope of Water (MEOW), and the Maximum of MEOWs (MOM) and are generated by computing the maximum storm surge that results from a representative sample of hypothetical storms based on climatology and what is physically possible. More recently, NHC has produced a national storm surge risk map, similarly based on these hypothetical scenarios, but conveying the risk at each location in terms of storm surge inundation.

e. Rainfall forecasting

The prediction accuracy of rainfall from landfalling tropical cyclones is improving as predictability of convective rainfall increases and uncertainties in the track and structure forecasts decrease, with numerical models providing improved guidance. Accurately forecasting when a tropical cyclone will slow down or even stall is often key to predicting the most excessive, damaging, and deadly rain-induced flooding events, as exemplified by Harvey, Florence, and Imelda. Since significant forecast uncertainties remain, and since rain-induced flooding remains a frequent cause of loss of life in tropical cyclones and other events, the NWS Weather Prediction Center (WPC) produces a probabilistic Excessive Rainfall Outlook that is heavily used by the media to communicate flood risk out to three days in advance. Satellite-based quantitative precipitation estimation techniques using blends of infrared and microwave imagery have been developed and applied to make short-term (~12 h) predictions of TC rainfall, while parametric models incorporating information on TC track, intensity, environmental influences, and topographic interactions, have also shown some promise. Mesoscale and neural network statistical forecast models have improved precipitation forecasts with operational objective techniques playing a role in the forecast process.

f. Seasonal to sub-seasonal hurricane forecasting

Predictions of seasonal hurricane activity, released by both public and private organizations, in the Atlantic basin have demonstrated forecast skill since the mid-1980s; however, as of 2022, it is not yet possible to confidently predict seasonal landfall number or distribution, or activity for smaller regions. Forecasts of seasonal hurricane activity issued at the start of the tropical cyclone season have been able to anticipate a substantial amount of the variance of hurricane frequencies, durations, and intensities. However, these forecasts have diminished skill when issued several months before the beginning of the season, primarily because of the low amount of skill in predicting the El Niño–Southern Oscillation and the associated changes in the atmosphere and ocean at long lead times. Communicating to the public the need for individuals, families, businesses, and communities to prepare in advance of hurricane season the same way every year (since it only takes one tropical cyclone to make it a disastrous year in any location even in a below-average year) remains a shared responsibility between NOAA/NWS, media and other private companies, and emergency management agencies.

The Climate Prediction Center (CPC) has been issuing tropical cyclone genesis forecasts for week 1 and week 2 for about 15 years. These forecasts have been based on global model output, primarily from the GFS, Climate Forecast System (CFS), and ECMWF; the phase of the Madden-Julian Oscillation; and any other significant features (e.g. convectively coupled Kelvin waves). The highest skill has been in the NW Pacific Ocean, partially due to the strength of the Madden Julian Oscillation influencing those predictions and in the eastern North Pacific basin. Forecast skill is gradually increasing for the Atlantic basin, although this is an ongoing challenge since the basin has inherently lower average forecast skill due to the climatological weakening of the Madden-Julian Oscillation (MJO) over the western Hemisphere. Future plans are to start forecasting for weeks 3 and 4 within the next few years, which should be aided by a scheduled upgrade to the CFS in 2023, and new 31-day Global Ensemble Forecast System (GEFS) forecasts implemented in 2020. The global ensemble systems from other agencies such as the ECMWF and United Kingdom Meteorological Office also continued to be upgraded. Government agencies are not alone in longer-range forecasting and prediction of tropical cyclones, as private sector forecasters also provide advance warning. These companies issue forecasts days, weeks and months ahead as well, communicating the threats for development and potential impacts and areas to be affected.

g. Climate change and tropical cyclones

For the topic of climate change and tropical cyclones, publications from the World Meteorological Organization (WMO) and Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) have concluded at least a medium-to-high confidence that the global average of TC intensity will increase, with more rainfall, and a higher proportion of very intense TCs. The highest confidence was that sea-level rise will lead to greater storm inundation. Further information is available in three AMS journal articles *(https://journals.ametsoc.org/doi/full/10.1175/BAMS-D-18-0189.1 , https://journals.ametsoc.org/doi/abs/10.1175/BAMS-D-18-0194.1 and https://doi.org/10.1175/JCLI-D-21-0071.1).* Effectively communicating to the public the facts about what is known and what is not known about tropical cyclones and climate change depends in large part on media and other private sector companies collaborating with various government and academic organizations regarding what the latest science is revealing.

Challenges for the next decade

A number of factors are presently limiting the accuracy or utility of tropical cyclone forecasts. Intensity forecasts would benefit from observational systems that can effectively observe the details of the inner region of storms, and from improved data assimilation techniques, modeling capabilities on both the global and regional scale, and prediction of ocean–atmosphere interactions. While track forecasts have steadily improved over the years with global model improvements, difficult cases still remain such as incipient tropical cyclones with poorly defined low-level circulations and/or misaligned low and mid-level circulations, sudden track changes, and synoptic-scale steering flow collapses. The use of targeted observations has the potential to improve both track and intensity forecasts when tropical cyclones are threatening landfall. Theoretical and modeling advances show promise for future advances in genesis forecasting. More effective remote sensing of ocean surface and tropospheric winds is essential to improving the analysis, forecasting, and initial detection of incipient tropical cyclones. Before 2017, official tropical cyclone forecasts of track, intensity, and structure were not issued until a tropical cyclone existed, thus providing little advance notice for tropical cyclones that form near the coast and quickly head toward land. However, NHC addressed this problem in 2017 by issuing forecasts for Potential Tropical Cyclones, or tropical cyclones that have not yet formed but pose a threat of bringing tropical storm or hurricane conditions to land within 48 hours. Finally, better quantification of forecast uncertainty would enable users to make more informed decisions. Ensemble forecasts (multiple simulations with different forecast models and/or a model with slightly different starting conditions) provide a starting point for quantifying forecast uncertainty. The NHC wind speed probability and potential storm surge flooding products are significant recent steps in that direction.

Improving forecasts of rapid intensification (RI) remains a key challenge. As recommended at the Ninth International Workshop on Tropical Cyclones (IWTC-9) in 2018, further research is needed on improving understanding of the environmental and internal conditions and precursors to RI and the associated symmetric and asymmetric inner-core dynamics. A holistic approach should be used, pulling together satellite and airborne observations and results from high-resolution numerical models to disentangle the multiple internal and external factors that act in concert during RI. Improved understanding of RI will likely lead to improvements in dynamical and statistical forecast models.

The National Academies 2017 National Aeronautics and Space Administration (NASA) Decadal Survey Report referred to above indicates significant challenges associated with the nation's Earth satellite systems, particularly in terms of satellites carrying high-quality passive microwave imagers. A gradual decline in the number of imagers will make it much more difficult to track changes in storm precipitation structure. Advances in miniaturization of passive microwave sensors may provide relatively inexpensive solutions for filling gaps or even providing constellations for rapid-revisit observations, but also present issues associated with larger footprint sizes and higher measurement uncertainties. A significant part of the improvement in tropical cyclone track forecasts since 2000 had been the greater availability of satellite observations and their effective use in numerical models. It is critical to continue and improve (in terms of both temporal coverage and spatial resolution) satellite observations of winds, temperature, water vapor, rainfall, sea surface temperature, and other variables in the vicinity of tropical cyclones.

New initiatives began in 2019 to expand planning, mitigation, and operational forecasting capability for the storm surge hazard to the Caribbean and Pacific Islands. Doing so, however, requires explicit modeling of the wave dynamics that occur within these steeply sloped island environments. It is well understood that waves contribute significantly to the total water level; thus, modeling of the storm surge hazard in these regions requires a coupled surge-wave model. Fortunately, advances in modeling architecture in the past several years have made this possible so that storm surge risk analysis maps (MOMs and MEOWs) are available for Puerto Rico, U.S. Virgin Islands, Hispaniola, Hawaii, American Samoa, Guam, southern California, the Yucatan Peninsula and Belize. Looking toward the future, the NHC in collaboration with other Federal partners will continue to expand this capability across the Pacific and Caribbean region, as well as develop and operationally produce real-time combined probabilistic surge and wave guidance to U.S. island states and territories.

The ultimate goal of tropical cyclone monitoring and forecasting is to prevent loss of life and to reduce vulnerability to storm-related hazards. The 2017 (Harvey, Irma, Maria), 2018 (Florence, Michael), 2019 (Dorian), 2020 (Laura, Sally, Delta, Zeta etc.), and 2021 (Ida) Atlantic seasons were powerful reminders of that vulnerability. Evacuation times for some communities exceed expectations for present and projected forecast accuracy, and some of the potentially most difficult evacuation problems have not been tested for generations. Thus, while the primary focus of the meteorological community must always be on a concerted scientific effort to improve forecasts, greater resilience to tropical cyclones requires effective engagement of other disciplines including engineering, ecology, biology; the social, behavioral, and economic sciences; and public policy. Further development of community awareness and preparedness programs through a comprehensive framework is also essential for ensuring public understanding of tropical cyclone threats and the ability to take appropriate action to mitigate the loss of life and property that links the entire process — from data collection to forecast to communication of the societal impact.

It is important to note that preventing loss of life and reducing individuals' and society's vulnerability to tropical cyclone-related hazards cannot be accomplished through improved tropical cyclone monitoring and forecasting alone. Perfect forecasts of a storm's track, intensity, and associated hazards are not sufficient — people need to actually receive the forecast, they need to be able to understand the forecast, and they need to be able to take appropriate action on the forecast and any recommended actions. These particular challenges can be tackled through the infusion of social sciences, a set of distinct disciplines that includes, but is not limited to anthropology, communication science, economics, geography, political science, psychology, and sociology, reflecting a range of inquiry into the diversity and complexity of human life. The AMS Statement on Strengthening Social Sciences in the Weather-Climate Enterprise (https://www.ametsoc.org/ams/index.cfm/about-ams/ams-statements/statements-of-the-ams-in-force/strengthening-social-sciences-in-the-weather-climate-enterprise/) advocates for regular and sustained funding opportunities that promote research agendas in the social sciences to meet demands for more accurate, timely, and relevant weather and climate information.

Tropical cyclone-related social science research and its subsequent infusion into forecasting and communication is expanding within the weather enterprise. Since 2010, tropical cyclone forecast products have been developed within the NWS (including the NHC and Central Pacific Hurricane Center), universities, and the private sector using iterative social science techniques in order to meet specific decision-support requirements with customers and partners. Other research is investigating how people consume and interpret tropical cyclone-related information, how they react to changing forecasts over time, how they access forecast information, and how, if at all, the tropical cyclone product suite should be modernized to meet the evolving needs of customers and partners. A better understanding of human behavior, risk perception, and communication dynamics before, during, and after tropical cyclone events will only help to amplify simultaneous advances in our capacity to observe and forecast storm impacts. The more that people prepare well in advance of the next tropical cyclone, including devising their storm evacuation plan, having supplies, getting an insurance checkup, strengthening their homes, and helping the less fortunate in their communities, the more we will all be able in real-time tropical cyclone events to respond to forecasts and warnings to stay safe before, during, and after the storm.

[This statement is considered in force until August 2027 unless superseded by a new statement issued by the AMS Council before this date.]