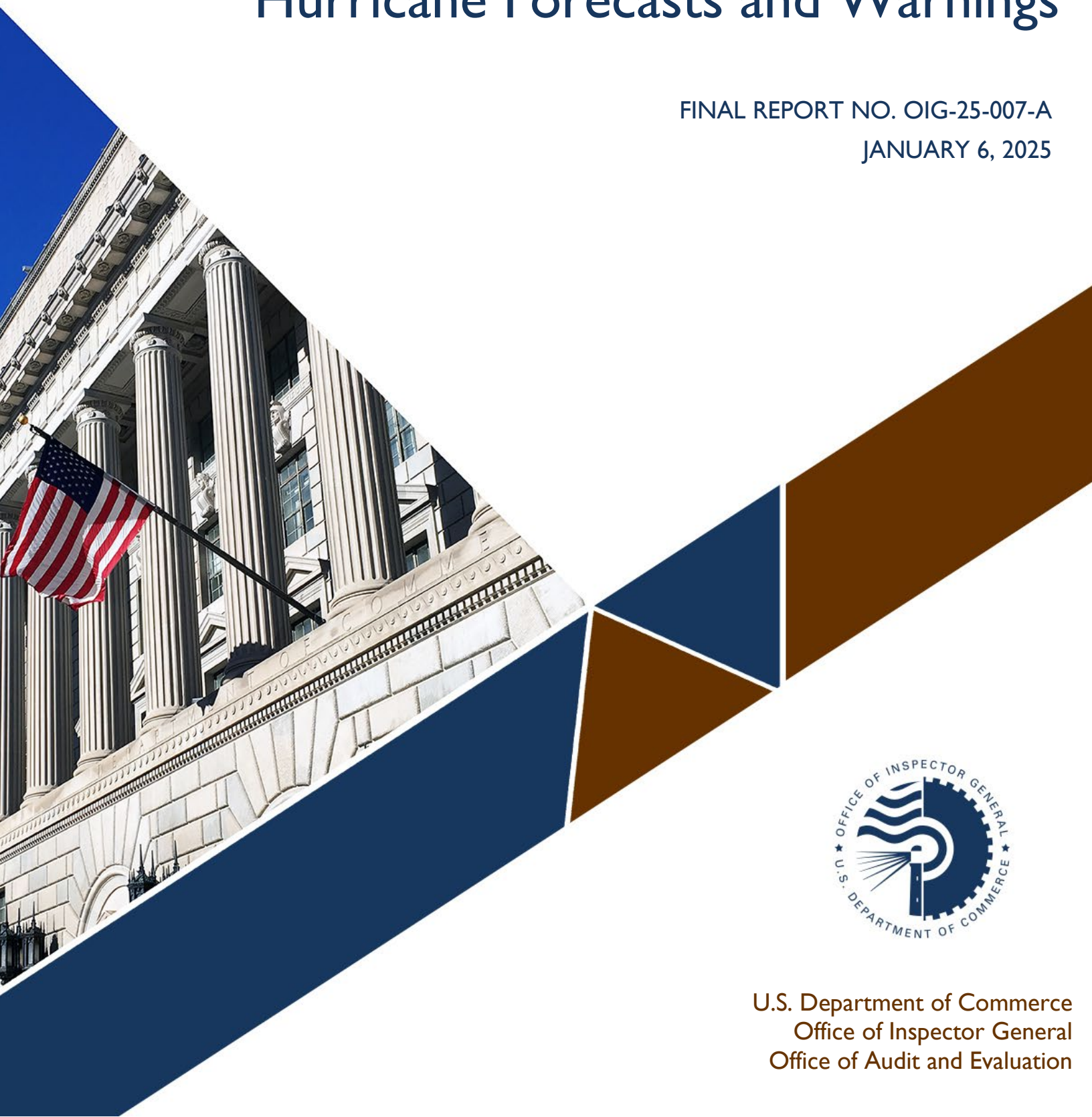


NOAA Should Assess Opportunities to Improve Hurricane Forecasts and Warnings

FINAL REPORT NO. OIG-25-007-A
JANUARY 6, 2025



U.S. Department of Commerce
Office of Inspector General
Office of Audit and Evaluation



January 6, 2025

MEMORANDUM FOR: Richard Spinrad, Ph.D.
Under Secretary of Commerce for Oceans and Atmosphere and
NOAA Administrator
National Oceanic and Atmospheric Administration

A handwritten signature in black ink, appearing to read "F. Meny, Jr.", written over a horizontal line.

FROM: Frederick J. Meny, Jr.
Assistant Inspector General for Audit and Evaluation

SUBJECT: *NOAA Should Assess Opportunities to Improve Hurricane Forecasts and Warnings*
Final Report No. OIG-25-007-A

Attached for your review is our final report on National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) hurricane forecast and warning performance. Our audit objective was to assess NWS progress toward improving hurricane forecasts and warnings.

We found that NWS has made progress improving tropical cyclone track and intensity forecasts since the Weather Act became law in 2017. Notably, NWS also extended its tropical weather outlook product, which provides tropical cyclone formation forecasts, by two days (from 5 to 7 days), made advancements in hurricane modeling, developed new means for communicating storm surge, and has taken early steps to incorporate social and behavioral science into its risk communications. However, we also found:

- I. National Hurricane Center has not extended tropical cyclone warnings and excludes performance measures that could help it better focus improvements on high-impact storms.
- II. National Hurricane Center has not ensured optimal usage of hurricane hunter aircraft.
- III. NOAA's Hurricane Forecast Improvement Program is insufficient to meet the Weather Act's hurricane forecast and warning goal.

In response to our draft report, NOAA concurred with all of our recommendations. NOAA also suggested a modification to recommendation 7 and provided general and technical comments. We considered these comments and revised the report where appropriate. We have summarized NOAA's response and provided our comments in the report. The full text of NOAA's response is included in appendix C of this report.

Pursuant to Department Administrative Order 213-5, please submit to us an action plan that addresses the recommendations in this report within 60 calendar days. This final report will be

posted on our website pursuant to the Inspector General Act of 1978, as amended (5 U.S.C. §§ 404 & 420).

We appreciate the cooperation and courtesies extended to us by your staff during this audit. If you have any questions or concerns about this report, please contact me at (202) 793-2938, Kevin Ryan, Director for Audit and Evaluation, Systems Analysis and NOAA Programs at (202) 750-5190, or Frank Tersigni, Director for Audit and Evaluation, Weather Service Programs, at (202) 793-2939.

Attachment

cc: Jainey Bavishi, Assistant Secretary of Commerce for Oceans and Atmosphere, Deputy NOAA Administrator, NOAA
Michael C. Morgan, Assistant Secretary of Commerce for Environmental Observations and Prediction, NOAA
Vice Admiral Nancy A. Hann, Deputy Undersecretary for Operations, NOAA
Karen Hyun, Chief of Staff, NOAA
Ken Graham, Director, National Weather Service and Assistant Administrator for Weather Services, NOAA
Michelle Mainelli, Deputy Director, National Weather Service, NOAA



Report in Brief

January 6, 2025

Background

The National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) provides weather forecasts, warnings, and impact-based decision support services for the protection of life and property and enhancement of the national economy. Within NWS, the mission of the National Hurricane Center (NHC) is to save lives, mitigate property loss, and improve economic efficiency through the issuance of its watches, warnings, and forecasts.

The Weather Research and Forecasting Innovation Act of 2017 (Weather Act) directed the development and extension of accurate hurricane forecasts and warnings with a goal of reducing loss of life, injury, and economic damage.

The Weather Act mandated a focus on improving hurricane forecasts in terms of track (the path that a storm follows) and intensity (determined by a storm's maximum wind speed), forecasting and communication of storm surge, and creating more effective products (including watches and warnings) by incorporating risk communication research in operations. It also required NOAA to develop a collaborative project plan to achieve the goal and focus areas.

Why We Did This Review

Our audit objective was to assess NWS progress toward improving hurricane forecasts and warnings.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

NOAA Should Assess Opportunities to Improve Hurricane Forecasts and Warnings

OIG-25-007-A

WHAT WE FOUND

NWS has made progress improving tropical cyclone track and intensity forecasts since the Weather Act became law in 2017. However, NWS is only partially meeting the Weather Act's requirements for a hurricane forecast improvement program (HFIP). We found that (1) NHC has not extended tropical cyclone warnings and excludes performance measures that could help it better focus improvements on high-impact storms; (2) NHC has not ensured optimal usage of hurricane hunter aircraft; and (3) NOAA's HFIP is insufficient to meet the Weather Act's hurricane forecast and warning goal.

WHAT WE RECOMMEND

We recommend that the NOAA Administrator ensure that the National Weather Service:

1. Assesses the extent to which tropical cyclone watches and warnings provide adequate advance notice to the public commensurate with NHC capabilities and emergency manager requirements and revises those products as warranted.
2. Assesses its tropical cyclone forecast verification process to (a) determine how best to measure performance excluded by current methodology, (b) determine how best to verify tropical cyclone watches and/or warnings to better understand their effectiveness at protecting life and property, and (c) implement process improvements as warranted.
3. Develops and implements an oversight plan to monitor aircraft scheduling effectiveness, using the initial daily reconnaissance request sent to the Chief, Aerial Reconnaissance Coordination, All Hurricanes as the baseline.
4. Specifies aircraft collection times critical to the forecast and warning production cycle in the National Hurricane Operations Plan.
5. Establishes a process with NOAA/Office of Marine and Aviation Operations and the Air Force Reserve Command to resolve observed aircraft scheduling deficiencies with an emphasis on meeting NHC requirements and documents the outcomes of these engagements.

We recommend that the Under Secretary of Commerce for Oceans and Atmosphere ensures the Deputy Under Secretary for Operations:

6. Implements and maintains an HFIP executive governance agreement to formalize organizational roles, responsibilities, and goals for hurricane forecasting and warning improvement.
7. Establishes clear goals, desired outcomes, and reporting mechanisms for SBES initiatives intended to elicit action to reduce the loss of life and damage to property.
8. Evaluates how to integrate collection of socioeconomic data to align with NOAA's institutional observations requirements process.

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Cover: Herbert C. Hoover Building main entrance at 14th Street Northwest in Washington, DC. Completed in 1932, the building is named after the former Secretary of Commerce and 31st President of the United States.

Introduction

Clear and accurate information about potentially life-threatening tropical hazards is critical to ensure people execute the life-saving actions and economic-sensitive decisions that are intended. The National Oceanic and Atmospheric Administration’s (NOAA’s) National Weather Service (NWS) mission includes providing weather forecasts, warnings, and impact-based decision support services for the protection of life and property and enhancement of the national economy. Within NWS, the National Hurricane Center (NHC) in Miami, Florida, has an aligned mission “to save lives, mitigate property loss, and improve economic efficiency by issuing the best watches, warnings, forecasts, and analyses of hazardous tropical weather, and by increasing understanding of these hazards.”¹

In this report, the term tropical cyclone includes all tropical systems, including tropical storms and hurricanes.² A tropical storm or hurricane watch is an announcement that the specified condition, e.g., hurricane force wind speeds, is *possible* within the specified coastal area. A tropical storm or hurricane warning is an announcement that the specified condition is *expected* within the specified coastal area. NHC issues tropical storm, hurricane, and storm surge watches and warnings for coastal areas as shown in table I.

Table I. NHC Watches and Warnings^a

Condition	Watch	Warning	Description
Tropical storm	✓		Tropical storm conditions (wind speed of 39-73 mph) are possible within the specified coastal area within 48 hours
Tropical storm		✓	Tropical storm conditions (wind speed of 39-73 mph) are expected somewhere within the specified coastal area within 36 hours
Hurricane	✓		Hurricane conditions (wind speed of at least 74 mph) are possible within the specified coastal area; watch is issued within 48 hours of the onset of tropical storm force winds
Hurricane		✓	Hurricane conditions (wind speed of at least 74 mph) are expected somewhere within the specified coastal area; warning is issued within 36 hours of the onset of tropical storm force winds
Storm surge	✓		There is a possibility of life-threatening inundation from rising water moving inland from the shoreline somewhere within the specified area, generally within 48 hours
Storm surge		✓	There is a danger of life-threatening inundation from rising water moving inland from the shoreline somewhere within the specified area, generally within 36 hours

a. We define the advance notice NHC provides prior to the expected conditions occurring as *lead time*.

Source: Office of Inspector General (OIG) representation of NHC definitions.

¹ See <https://www.nhc.noaa.gov/mission.shtml> (accessed July 26, 2024).

² Other examples of tropical systems may include tropical depression, tropical wave, and tropical disturbance. Tropical cyclone characteristics include organized thunderstorm activity and a closed surface wind circulation around a well-defined center.

The Weather Research and Forecasting Innovation Act of 2017, Pub. L. No. 115-25, Section 104 (Weather Act)³ directed the development and extension of accurate hurricane forecasts and warnings with a goal of reducing loss of life, injury, and economic damage. The Weather Act mandated a focus on improving hurricane forecasts in terms of track (the path that a storm follows) and intensity (determined by a storm's maximum wind speed), forecasting and communication of storm surge, and creating more effective products (including watches and warnings) by incorporating risk communication research in operations. It also required NOAA to develop a collaborative project plan within one year of the Weather Act's enactment to achieve the goal and focus areas.

Analyzing and Forecasting Tropical Cyclones

NHC uses a variety of data inputs to create analyses and forecasts.⁴ Forecasters must consider various estimates of a cyclone's position, wind speed intensity, and size and use their experience to make an analysis of the current situation. Aircraft data directly measure weather conditions within the storm, providing the best estimate of storm location and intensity.⁵ NHC forecasters also use predictive guidance from different types of weather models, such as the Hurricane Analysis and Forecasting System (HAFS).⁶ They consider global, regional, ensemble,⁷ and statistical weather models to help construct official NHC forecasts, watches, and warnings.

Forecast Accuracy

NHC verifies the accuracy of some of its forecasts and maintains performance trends on its website.⁸ According to its official metrics, NHC has made substantial improvements to tropical cyclone track and intensity forecasts since 2000. Between 2000 and 2023 for Atlantic storms, NHC reported its 72-hour track forecast errors decreased by 64 percent and 72-hour intensity forecast errors decreased by 50 percent. More recently, NHC experts have written that tropical cyclone track forecasts may be approaching a limit of predictability.⁹ Another prominent NOAA hurricane expert told us that intensity forecast errors are not likely to improve much further. Track and intensity forecast accuracy trends show a slowing of improvement, supporting their hypotheses.

³ The Weather Act was enacted on April 18, 2017.

⁴ NHC hosts active tropical cyclone products at <https://www.nhc.noaa.gov/cyclones/> (accessed July 29, 2024). NWS Weather Forecast Offices (WFOs) issue wind hazard information for inland areas. Additionally, the Central Pacific Hurricane Center and WFOs in Guam and American Samoa issue tropical cyclone hazard products for their respective areas of responsibility.

⁵ This is a concept known as ground-truth data. Measurements made on location can also be used to confirm or calibrate data collected at a distance, such as from satellites. Satellite data provide less certainty of storm position and intensity than aircraft observations.

⁶ NOAA declared HAFS operational June 27, 2023. HAFS is NOAA's new hurricane forecast model.

⁷ An ensemble is a set of computer weather models run with slightly different initial conditions or model versions. Ensembles are meant to improve the accuracy of forecasts by averaging various forecasts and to provide reliable information on forecast uncertainties.

⁸ See <https://www.nhc.noaa.gov/verification/verify5.shtml> (accessed July 30, 2024).

⁹ See Landsea, C. W., and J. P. Cangialosi, 2018: "Have we reached the limits of predictability for tropical cyclone track forecasting?" *Bull. Amer. Meteor. Soc.*, 2237-2243.

Aircraft Reconnaissance Data

The availability of aircraft reconnaissance data prior to a cyclone's landfall has a significant impact on forecast accuracy. NHC relies on two organizations for "hurricane hunter" aircraft reconnaissance missions. NOAA aircraft are flown by personnel from its Office of Marine and Aviation Operations (OMAO). According to the 2023 National Hurricane Operations Plan (NHOP),¹⁰ OMAO flies up to two missions daily from its Aircraft Operations Center, in Lakeland, Florida. In addition, the 53rd Weather Reconnaissance Squadron of the United States Air Force Reserve Command (AFRC) performs this mission.¹¹ Based in Biloxi, Mississippi, this AFRC squadron maintains aircraft to support the Department's requirement to fly up to five missions per day in accordance with the NHOP.¹² As needed, both NOAA and AFRC are authorized to preposition aircraft to forward operating locations to support NHC reconnaissance requests in the Atlantic, Gulf of Mexico, Caribbean, and Central Pacific areas.

NHC requests aircraft reconnaissance missions by stating its observation request in a tropical cyclone plan of the day (TCPOD), which it sends to the AFRC's Chief, Aerial Reconnaissance Coordination, All Hurricanes (CARCAH). CARCAH has an office at the National Hurricane Center in Miami and coordinates NHC flight requests with NOAA and AFRC flying units. CARCAH's mission is to coordinate NHC aircraft data requirements in accordance with the NHOP.

¹⁰ The NHOP describes responsibilities and procedures among responsible federal agencies to address items of mutual concern related to tropical cyclone forecasting and warning services.

¹¹ The AFRC is part of the Department of Defense (DOD). DOD weather reconnaissance support to NOAA is congressionally mandated and funded through the National Defense Appropriations Act.

¹² For aircraft reconnaissance requirements, see Federal Coordinator for Meteorological Services and Supporting Research, May 31, 2023. *National Hurricane Operations Plan*, FCM-P12-2023. Washington, DC: FCM, chapter 5. Available online at https://www.weather.gov/media/tropical/2023_nhop.pdf (accessed August 22, 2024).

Objective, Findings, and Recommendations

Our audit objective was to assess NWS progress toward improving hurricane forecasts and warnings. To satisfy our objective, we reviewed strategies and operational performance data of NOAA, NWS, and NHC as it related to the Weather Act. See appendix A for a full description of our scope and methodology.

We found that NWS has made progress improving tropical cyclone track and intensity forecasts since the Weather Act became law in 2017. Notably, NWS also extended its tropical weather outlook product, which provides tropical cyclone formation forecasts, by two days (from 5 to 7 days), made advancements in hurricane modeling, developed new means for communicating storm surge, and has taken early steps to incorporate social and behavioral science into its risk communications. However, NWS is only partially meeting the Weather Act's requirements for a hurricane forecast improvement program.

Specifically, NHC has not extended tropical cyclone warning lead times since 2010, and its methodology for verifying forecast accuracy excludes performance data that could help it better focus improvements on storm warnings and thereby meet the Weather Act's goal of reducing loss of life, injury, and economic damage. NHC's current measures could also mask performance weaknesses, leading to less effective products. In addition, NHC has not optimized usage of hurricane hunter aircraft, and this has contributed to storm observation gaps that can affect the performance of computer models and NHC forecasters. Finally, we found that NOAA's Hurricane Forecast Improvement Program (HFIP) is insufficient to achieve the Weather Act's hurricane forecast and warning goal, and this has hindered progress transitioning social science research to operations. Social science is the study of people—what they think, how they feel, and how they respond—in a particular context. Understanding societal needs and decision making can help NHC apply risk communication strategies that help determine what types of forecast improvements will provide the greatest societal benefit.

We conclude that, despite progress in multiple areas, NWS' approach to developing and extending accurate hurricane forecasts and warnings has potentially limited further improvements toward reducing loss of life, injury, and economic damage. We have identified recommendations that, if implemented, could improve warning and forecast effectiveness, increase critical data inputs available to the forecast process, and strengthen the HFIP management structure necessary to reduce the impacts of tropical cyclones.

I. National Hurricane Center Has Not Extended Tropical Cyclone Warnings and Excludes Performance Measures That Could Help It Better Focus Improvements on High-Impact Storms

NHC has not extended its lead times for tropical cyclone watches or warnings since 2010, despite significant improvements to the accuracy of its forecasts. Watches and warnings are important products for announcing hazardous weather conditions that can affect life and property. NHC also has not included all available data in its forecast performance statistics.

If more data were included, performance statistics would be more useful for identifying areas that need improvement.

A. NWS should assess whether tropical cyclone watches and warnings provide adequate advanced notice of storm conditions

Watches and warnings are issued to convey risk of weather hazards with enough lead time for emergency managers and the public to complete preparations before the onset of the forecasted storm conditions.

NHC last made changes to tropical cyclone watch and warning lead times in 2010, when watches were extended from 36 to 48 hours and warnings from 24 to 36 hours, due to NHC's improved forecast performance at the time. Based on official NHC metrics, forecast accuracy has further improved since 2010. NHC metrics show that its 72-hour forecast now achieves accuracy comparable to what it was at the 48-hour forecast point in 2010 (see appendix B for more details on these accuracy trends). However, NHC has not extended lead times commensurate with these improvements.

NHC officials told us they have had internal discussions about extending watch lead times beyond 48 hours. However, they had no formal plans to assess or change practices, in part because they stated that it was not clear stakeholders desired longer lead times for watches and warnings and the greater uncertainty of products with longer lead times could degrade their value for decision-making.

Representatives from two southeastern U.S. state emergency management offices, though, commented that NHC standard tropical cyclone watches and warnings generally do not provide enough notice to make evacuation decisions. As a result, they use alternative extended forecast products, such as NHC's 5-day tropical cyclone cone graphic and 72-hour storm surge inundation product, in addition to consulting with local weather forecast offices.

Given that alternative forecast products are being used by emergency managers to make key preparedness decisions, current tropical cyclone watches and warnings may not be optimally serving their intended purpose of conveying risk to inform decision-making. If watch and warning lead times are not providing as much advance notice as effectively possible, NHC may be missing opportunities to reduce loss of life, injury, and damage to the economy as directed by the Weather Act. Moreover, unless NHC assesses how effectively its watches and warnings convey risk for decision-making, it cannot make informed improvements.

B. NHC official metrics could be improved by considering performance data that could help it better focus improvement on weather that affects life and property

An NWS performance and evaluation directive defines *verification* as the "process of matching warnings, watches, and forecasts with corresponding weather observations to

assess the goodness of those products.”¹³ Verification provides answers to questions such as: how closely did a storm’s actual path of travel compare with the forecasted track? We analyzed NHC performance statistics from 2019-2023 and found that NHC does not report performance metrics for watches and warnings. Additionally, NHC’s official metrics have excluded some forecasts that could be valuable for improving performance to reduce loss of life, injury, and damage to the economy.

In coordination with NHC, Weather Forecast Offices (WFOs) issue tropical cyclone products designed to inform media, local decision makers, and the public on present and/or anticipated tropical cyclone conditions in their County Warning Areas (CWAs). WFOs are also responsible for determining if tropical cyclone wind watches and warnings will be issued for the inland portion of their CWAs. However, our analyses were limited to assessing NHC-issued forecasts, watches, and warnings.

NHC issues a tropical cyclone forecast every six hours. Each forecast includes multiple projections of weather conditions extending from the initial time until the end of the forecast period (for example, 12-, 24-, 36-, 48-, 60-, 72-, 96-, and 120-hour projections). At the end of each hurricane season, NHC evaluates its forecasts by comparing the projected positions and intensities to the corresponding “best track”¹⁴ positions and intensities for each cyclone. A forecast is included in the verification only if the system is classified in the final best track analysis as a tropical or subtropical cyclone¹⁵ at both the forecast’s initial time and at the projected time. These systems include tropical or subtropical depressions, tropical or subtropical storms, or hurricanes. NHC uses these criteria because a system with a well-defined closed surface wind circulation is better suited for higher precision forecast verification, compared with a developing or dissipating system that does not have a closed surface wind circulation.

As a result, NHC’s official metrics do not reflect the performance of forecasts issued during the development or dissipation phases of storms, when such forecasts do not meet NHC’s verification criteria. Because these phases of storms can significantly affect people and property, NHC’s methodology may be omitting important aspects of performance as it relates to the Weather Act’s goals for hurricane forecasting.

Furthermore, the extent to which NHC is meeting the Weather Act goal to improve prediction of rapid intensification of hurricanes may be insufficiently understood because a forecast issued (or not issued) when a weather system has non-tropical characteristics but then rapidly intensifies into a tropical storm may be excluded from performance data.

¹³ National Weather Service Instruction 10-1601, Verification, July 7, 2022. Available online at https://www.weather.gov/media/directives/010_pdfs/pd01016001curr.pdf (accessed March 20, 2024).

¹⁴ Best track is a subjectively smoothed representation of a tropical cyclone's location and intensity over its lifetime at 6-hour intervals.

¹⁵ A subtropical cyclone is a weather system that has both tropical and non-tropical characteristics. In comparison to tropical cyclones, such systems have a relatively broad zone of maximum winds that is located farther from the center, and typically have a less symmetric wind field.

A significant example of excluded forecast performance data is a storm that formed off the Texas coast in September 2019 and ultimately developed into Tropical Storm Imelda. NHC issued three official forecasts, but none were issued before Imelda became a tropical system. There were no NHC forecasts predicting the development of the tropical storm. Because its verification methodology does not account for such cases, NHC's performance data does not reflect its failure to issue forecasts predicting the development of Imelda.

The effects of Imelda were extensive, with five deaths, \$5 billion in damage, and significant flooding—it was the seventh-highest rainfall amount recorded for a tropical cyclone ever to impact the U.S. at the time the NHC post-storm report was published in January 2020.¹⁶ Because NHC did not forecast Imelda's development, it issued its sole tropical storm warning only 18 minutes prior to the report of tropical storm conditions on the Texas coast. NHC's official metrics do not include its failure to forecast Tropical Storm Imelda's rapid development prior to becoming a tropical storm, nor the late issuance of the warning. However, based on its methodology, NHC's official performance data indicated the three forecasts' accuracy was better than the 5-year benchmark average even though the formation of the storm was not predicted and the subsequent warning to the Texas coast was late.¹⁷

Excluding storm formation and dissipation data, like the case of Tropical Storm Imelda, risks overstating NHC's performance and missing potential areas for improvement. Including such data in either existing or new performance measures may be challenging but may offer an opportunity for continued improvements to forecasts and warnings.

In addition to the challenges and potential benefits of considering how to incorporate formation and dissipation phase performance data, a lack of observed data in some cases makes tropical cyclone forecasts more difficult to verify than conventional weather forecasts. For example, NHC uses satellite data estimates to fill in the gaps when buoy and aircraft data are unavailable for storms that are far from populated areas. NHC officials told us they are exploring additional hazard-based metrics, but a limited number of storm events and a lack of sufficient ground-truth observational data inhibit their ability to verify such forecasts. For some storms closer to populated areas, there may be more observational data to consider as they approach landfall.

NHC employs a legacy methodology to maintain a long-term track and intensity forecast performance dataset. But by only employing its legacy methodology, NHC may be missing opportunities to identify new performance benchmarks or measures of effectiveness. For instance, NHC currently has no means to assess how effective its forecasts are at reducing loss of life, injury, and property damage, the primary goal of the Weather Act. Because NHC does not track performance differences between storms at sea that do not make landfall (the majority of storms) and storms that do,

¹⁶ In response to our draft report, NOAA stated that WFOs did issue flood watches and warnings associated with rainfall flooding hazard prior to Imelda's landfall. According to NOAA, all the fatalities from Imelda and the vast majority of the damage were due to flooding. Flood forecasting was outside the scope of our analysis.

¹⁷ Compared to the watch and warning timing described in table I.

performance statistics do not focus on storms that affect people and property. Legacy methodologies and metrics may be valuable for long-term comparisons, but NHC is not exploiting all available opportunities to identify improvements.

In short, NHC has not extended tropical cyclone watch and warning lead times, despite improvements since 2010, and has not determined how to incorporate some performance data for developing and dissipating storms that could lead to further improvements. Implementing the following recommendations can help improve warning and forecast effectiveness.

Recommendations

We recommend the NOAA Administrator ensure that the National Weather Service:

1. Assesses the extent to which tropical cyclone watches and warnings provide adequate advance notice to the public commensurate with NHC capabilities and emergency manager requirements and revises those products as warranted.
2. Assesses its tropical cyclone forecast verification process to a) determine how best to measure performance excluded by current methodology, b) determine how best to verify tropical cyclone watches and/or warnings to better understand their effectiveness at protecting life and property, and c) implement process improvements as warranted.

II. National Hurricane Center Has Not Ensured Optimal Usage of Hurricane Hunter Aircraft

Aircraft observations are a key resource to help meet the Weather Act goal to develop and extend accurate hurricane forecasts and warnings.¹⁸ When aircraft data is not available, it can adversely affect the accuracy of hurricane models, forecasts, watches, and warnings. NOAA policy establishes a requirement for *hourly* airborne flight-level observations of tropical cyclones.

The case of Hurricane Otis in October 2023 illustrates the importance of aircraft data in hurricane forecast and warning accuracy. Weather models and NHC did not accurately forecast Otis' track and intensity, and it rapidly intensified over a 21-hour period from a tropical storm with 63-mile-per-hour (mph) winds to a major hurricane with 167-mph winds. The only aircraft reconnaissance flight for Otis occurred after the storm had strengthened into a hurricane. Aircraft observations from the single reconnaissance flight were crucial for forecasters to recognize that none of the models had an accurate representation of Otis' intensity and structure.¹⁹ Numerical forecast models are necessary

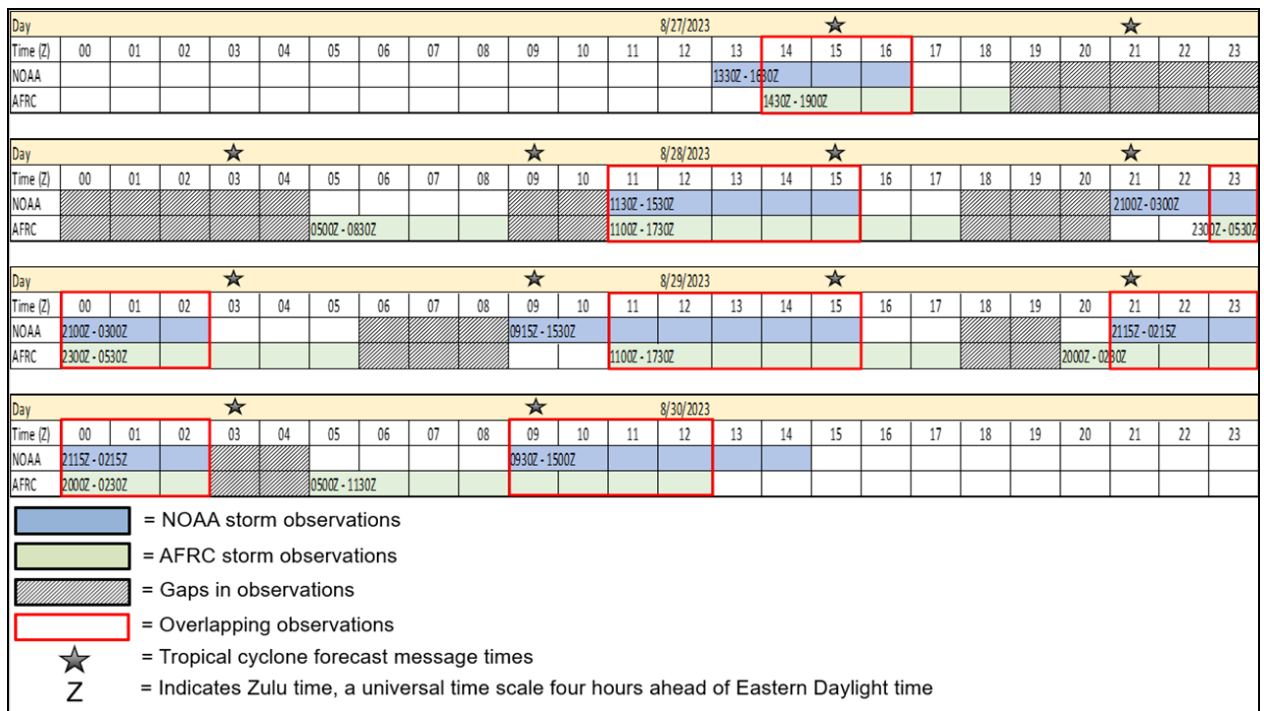
¹⁸ Recent research showed aircraft data can improve weather model track and intensity forecasts by up to 15 percent. See American Meteorological Society (Sippel, et al), September 15, 2022. Weather and Forecasting, "Impacts of Assimilating Additional Reconnaissance Data on Operational GFS Tropical Cyclone Forecasts." Boston, MA: 1615-1639 (volume 37, issue 9). Available online <https://journals.ametsoc.org/view/journals/wefo/37/9/WAF-D-22-0058.1.xml> (accessed April 16, 2024).

¹⁹ This includes the new HAFS model fielded in 2023.

tools, but skilled forecasters and adequate observational data are also required for effective tropical cyclone forecasts.

Despite the important role aircraft observation data plays in forecasting, we found that NHC and CARCAH have not optimized the tasking of NOAA and AFRC aircraft, leading to both storm *observation gaps* (when neither NOAA nor AFRC aircraft are actively collecting data) and *overlapping observations* (when both NOAA and AFRC aircraft fly simultaneously) during tropical cyclones. From 2020 to 2023, we observed 101 instances where CARCAH tasked (based on NHC data requests)²⁰ both NOAA and AFRC to fly in the same storm. Approximately 71 percent of those planned flight taskings included scheduled gaps and overlaps in storm observations: an annual average of 206 hours of gaps in airborne observations of tropical storms. For this same period, we also found there was an average of approximately 75 hours of planned, overlapping observations annually. For an example of this scenario as it related to Hurricane Idalia in 2023, see figure 1.

Figure 1. Aircraft Collection Strategy – Tropical Cyclone Idalia (2023)



Source: OIG analysis of NHC data.

NHC forecasters told us there is no meteorological reason for overlapping observations and that eliminating gaps could improve forecasts and warnings. We determined the storm observation gaps could have been reduced with better scheduling by shifting the times of overlapped flight hours to cover the gaps.

²⁰ CARCAH coordinates NHC’s support requests with the flying units, but it also depends on NHC’s needs. For example, if NHC needs tail doppler radar coverage, only NOAA has such aircraft.

Aircraft data collection can be affected by factors outside of NHC control such as crew or aircraft availability, thus not all overlap hours can be recaptured to fill gaps. NHC informed us that both NOAA and the AFRC flying units have sometimes objected to flying during overnight hours due to crew rest and safety considerations. Such limitations or flying unit preferences are not documented in the NHOP, which refers to daily flight requirements for missions during 24-hour periods (and thus inclusive of nighttime).

According to the NHOP, NHC is granted the authority to define aircraft observation requirements, but the NHOP does not identify the importance of maintaining continuous hourly observations during active storms. The resulting daily flight plans coordinated by CARCAH may not reflect NHC's initial requirements prior to negotiating flying unit preferences or limitations.

Furthermore, NHC does not track the effectiveness of its planned flight schedules in meeting the NOAA hourly aircraft observation requirements. CARCAH began tracking unmet requirements at NHC's request in 2023, but its metrics do not address scheduling optimization with respect to gaps and overlaps. Consequently, without performance measures to assess scheduling effectiveness, unnecessary observation gaps may persist.

Overall, the NHC has not collected the necessary data to measure flying units' effectiveness at meeting its observation requirements and has not included additional guidance in the NHOP to help clarify critical priorities. Without this data, NHC cannot provide feedback to the flying units that may help close observation gaps for its forecasters and numerical models.

Recommendations

We recommend the NOAA Administrator ensure that the National Weather Service:

3. Develops and implements an oversight plan to monitor aircraft scheduling effectiveness, using the initial daily reconnaissance request sent to CARCAH as the baseline.
4. Specifies aircraft collection times critical to the forecast and warning production cycle in the NHOP.
5. Establishes a process with NOAA/OMAO and the AFRC to resolve observed aircraft scheduling deficiencies with an emphasis on meeting NHC requirements and documents the outcomes of these engagements.

III. NOAA's HFIP is Insufficient to Meet the Weather Act's Hurricane Forecast and Warning Goal

To accomplish goals for hurricane forecast improvement, the Weather Act required NOAA to establish an improvement program and develop a project plan. To meet this requirement, NOAA relied on its pre-existing program from 2007 (HFIP) and submitted an updated project plan to address the Weather Act outcomes. We found the program has weaknesses that hindered NWS efforts to transition social science research to operations.

HFIP's focus was on improving weather forecast models, but social science research is important for assessing how people receive, interpret, perceive, and respond to weather information.

Without effective management control,²¹ including establishing the necessary organizational structures, NWS may not achieve its objectives as directed by the Weather Act.

A. *NOAA's HFIP lacks executive oversight and is focused on weather modeling research*

NOAA organized HFIP under the NWS' Office of Science and Technology Integration Modeling division. HFIP performed coordination and advocacy functions for research support, annual meetings, and development of 5-year strategic plans. Multiple other offices²² have had a role in hurricane forecast improvement; however, our review showed HFIP focused on weather model research²³ rather than developing an enterprise-wide program²⁴ to achieve the goals of the Weather Act.

The program lacks executive oversight and is not fully aligned with the Weather Act goal to develop and extend accurate hurricane forecasts and warnings in order to reduce loss of life, injury, and damage to the economy, with a focus on:

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

HFIP's executive governance document,²⁵ which has not been approved nor updated since the Weather Act was signed into law, states that program's focus is improving 3- to 5-day *intensity* forecasts. It does not convey how efforts related to storm track prediction, storm surge forecast and communication, and risk communication/product improvements are encompassed by the program even though this is required by the Weather Act. In particular, roles and responsibilities have not been formally captured to include research implementation activities accomplished by NWS' Analyze Forecast and

²¹ U.S. Government Accountability Office, Sept. 2014. *Standards for Internal Control in the Federal Government*. Washington, DC: GAO, Control Environment, principle 3, 3.02.

²² Some NOAA offices involved in improvement include NWS OSTI-M (HFIP); NOAA Atlantic Oceanographic and Meteorological Laboratory; NOAA Weather Program Office (WPO); NWS NHC Technology and Science Branch; Analyze, Forecast, and Support Office Tropical Program.

²³ NWS was unable to provide a breakout of HFIP activities comparing weather model research funding versus other non-modeling efforts.

²⁴ DOC, March 29, 2023. *DOC Acquisition Program and Project Management Guidebook*. Washington DC: DOC, Version 2.0, 66. Available online at: https://www.commerce.gov/sites/default/files/2023-08/Guidebook%20v.%202.0_2023-03-29%20-%20FINAL%20%287%29.pdf (accessed July 31, 2024). The Department defines a program as a consolidated effort to achieve a specific purpose or outcome of a strategic plan goal or as required by statute or regulation.

²⁵ HFIP executive governance is codified in the program's Terms of Reference documents.

Support Office or the newly established Social, Behavioral and Economic Sciences (SBES) Office.

The role and integration of these offices is a governance challenge that the HFIP Executive Oversight Board acknowledged. NWS leadership told us changes are needed to clarify roles and responsibilities, as well as broaden the program to be less reliant on computer weather modeling research efforts. Currently, however, the lack of coordination has potentially reduced focus on implementing social science research, which is an important link to the Weather Act's goal for achieving improvement in risk communications.

B. The Social, Behavioral, and Economic Sciences office was slow to develop and was disconnected from HFIP risk communication improvement activities

Five years after the Weather Act became law, NWS established the SBES office in 2022. In response to our inquiries, NWS was unable to provide a reason for the delay in standing up the office. NWS created the office to provide a focus for advancing social science research, including evaluating products and services, improving risk communication,²⁶ and understanding social outcomes of weather effects. This focus stands apart from NWS efforts assessing only the technical performance of weather products. Scientific information alone, such as a weather forecast, does not necessarily result in immediate response by the public. Long-term risk communication efforts can influence how people will understand a crisis and how they may adapt and protect themselves.

The focus on such risk communication, however, has been slow to develop. The latest HFIP strategic plan goal 4 is to improve hazard guidance and risk communication for tropical cyclones through the application of social and behavioral sciences, but the performance measures within this goal are predominantly physical science-based modeling measures. The SBES office is currently determining work priorities and how best to integrate within the NWS operational culture, including contributing to HFIP.

As part of identifying work priorities, the SBES team lead told us there is insufficient data collected for social and economic effects of weather partly because it is a challenge to collect quality data. We reviewed NOAA's observing system policy²⁷ and noted that, while the policy refers to physical sensing with sensors such as ground radar or satellite instruments, it also refers to socioeconomic data collection within the definition of an observing system. Thus, a justification for institutionalizing socioeconomic data collection already exists within NOAA policy.

²⁶ NOAA research has identified risk communication as an interactive process about the nature of risk and hazards.

²⁷ NOAA, October 15, 2016. NOAA Administrative Order 212-16: *Policy on NOAA Observing Systems Portfolio Management*. Washington, DC: NOAA, section 3.01, 4. Available online at https://www.noaa.gov/sites/default/files/legacy/document/2020/Jun/NAO_212-16_UNSEC_Signed.pdf (accessed May 20, 2024).

Multiple offices in NWS acknowledged the importance of risk communication to affect positive outcomes and that the SBES office could be an important part of improved technical performance, particularly as it relates to the Weather Act. In addition to the examples discussed in this report, we note that our earlier work has addressed similar issues. For example, in one of our prior reports, we discussed 2022 Hurricane Ian, which caused \$113 billion in damage and 66 deaths. Yet despite these catastrophic effects that the Weather Act sought to reduce, NHC's official 2-day forecast track error was comparable to its average accuracy, suggesting that historic forecast performance benchmarks may not be sufficient measures for the future.²⁸ As discussed in finding I, the metrics may be missing measures of effectiveness for reducing loss of life and property damage.

In summary, NOAA designated the HFIP as the responsive program to meet the Weather Act goal and focus areas, but its scope does not encompass all activities to meet the specified outcomes. Our recommendations provide foundational actions to help NOAA develop and manage a unified effort toward meeting the Act's goal and focus areas.

Recommendations

We recommend the Under Secretary of Commerce for Oceans and Atmosphere ensures the Deputy Under Secretary for Operations:

6. Implements and maintains an HFIP executive governance agreement to formalize organizational roles, responsibilities, and goals for hurricane forecasting and warning improvement.
7. Establishes clear goals, desired outcomes, and reporting mechanisms for SBES initiatives intended to elicit action to reduce the loss of life and damage to property.
8. Evaluates how to integrate collection of socioeconomic data to align with NOAA's institutional observations requirements process.

²⁸ DOC OIG, October 12, 2023. *Top Management and Performance Challenges Facing the Department of Commerce in Fiscal Year 2024*, OIG-24-002. Washington DC: DOC OIG, 21.

Summary of Agency Response and OIG Comments

On November 20, 2024, we received NOAA's response to our draft report. NOAA concurred with all of our recommendations and described actions it has taken, or will take, to address them. NOAA also suggested a modification to recommendation 7 and provided general and technical comments that we considered and revised the report where appropriate. Notable comments are discussed below.

General Comments

NOAA stated NHC does not issue all tropical cyclone-related hazard products for wind and storm surge and that NHC only issues those hazard products for coastal areas. NOAA also stated that the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) should be listed as a partner that NHC relies on for aircraft reconnaissance data.

OIG Comment. We amended the report to clarify the scope of duties among NHC, Central Pacific Hurricane Center, and WFOs where appropriate. We also revised the sentence at page 3 in the "Aircraft Reconnaissance Data" section to clarify that we are referring to NHC's reliance on the two flying organizations for aircraft missions.

Finding I

NOAA noted that the discussion of Tropical Storm Imelda was incomplete because the analysis only addressed tropical storm watches and warnings and did not include flood watches and warnings.

OIG Comment. As described in the report, we limited our scope to official performance metrics associated with NHC-issued forecasts, watches, and warnings. We believe Tropical Storm Imelda provides a pertinent example of how the current performance metrics may not identify areas for forecasting improvements.

Finding II

NOAA stated the finding title should be modified to better reflect the shared responsibility among NHC, NOAA AOC, and the AFRC for tasking and executing aircraft reconnaissance missions. NOAA also stated that NHC does not have the means to perform quality control on data collected from instruments, and that it was not clear if eliminating gaps and/or overlaps in aircraft reconnaissance data would improve tropical cyclone forecasts.

OIG Comment. We acknowledge there is a teamed approach toward meeting NHC requirements; however, based on the NHOP, NHC is responsible for specifying aircraft collection requirements. NHC has not collected data to measure flying units' effectiveness at meeting collection requirements and has not included additional guidance in the NHOP to help

clarify critical priorities. As also discussed in the finding, closing temporal data gaps could be beneficial.

Finding III - Recommendation 7

NOAA concurred but requested a modified recommendation to eliminate the words “that elicit action to reduce the loss of life and damage to property.” NOAA stated that actions taken are the responsibility of groups and individuals external to NWS. They also noted many SBES initiatives will focus on the factors that influence how people make decisions about weather, which are anticipated to improve implementation of actions to reduce the loss of life and damage to property.

OIG Comment. We modified the recommendation to better represent the uncertainty NOAA highlighted in its response. We look forward to the SBES initiatives as described in NOAA’s response and how they may contribute to reducing the loss of life and damage to property, as described in the Weather Act.

NOAA also provided technical comments, which we reviewed and incorporated into the final report where appropriate. NOAA’s full response is included in Appendix C.

We appreciate NOAA’s response to the report and look forward to its action plan for implementing the recommendations.

Appendix A: Objective, Scope, and Methodology

Our audit objective was to assess National Weather Service (NWS) progress toward improving hurricane forecasts and warnings. To meet our objective, we identified relevant criteria for assessing improvement, examined NWS strategies, actions, and results, and assessed the effectiveness of NWS actions to improve hurricane forecasts and warnings.

To identify criteria for assessing improvement, we reviewed the Weather Research and Forecasting Innovation Act of 2017 (Weather Act),²⁹ the National Hurricane Operations Plan,³⁰ and benchmarks associated with the Government Performance and Results Act of 1993, as amended. The Weather Act did not contain objective or quantitative benchmarks, but we identified the legislation's subjective specifications and used them to help refine the scope of our fieldwork.

We determined that our approach would focus on the NWS National Hurricane Center (NHC), which is part of the National Centers for Environmental Prediction and has responsibility to develop and deliver the products and services that are representative of performance, such as forecasts and warnings. To narrow our scope, we focused on NWS improvement in the Atlantic Ocean basin since the 2017 signing of the Weather Act.

We examined NWS strategies, actions, and results by reviewing agency strategic plans, reports, congressional briefings, meeting minutes, and NHC performance data. We also reviewed Hurricane Forecast Improvement Program (HFIP) management activities and oversight of improvement efforts.

To assess the effectiveness of NWS actions, we evaluated official NHC performance metrics, seasonal and individual tropical cyclone storm reports, and aircraft data collection plans. We also spoke with selected key stakeholders such as Federal Emergency Management Administration Region 6, Florida Division of Emergency Management, and the Louisiana Governor's Office of Homeland Security and Emergency Preparedness.

We interviewed NOAA, NWS, and NHC management, staff, and operational personnel involved with hurricane research and products to understand roles, responsibilities, and interactions among key collaborators within hurricane forecast improvement efforts. We also consulted with the Department's Office of Acquisition Management to better understand the weather program enterprise.

In addition, we assessed internal controls significant within the context of our objective. As part of this audit, we reviewed the HFIP Terms of Reference to assess program governance and

²⁹ Pub. L. No. 115-25, § 104 (2017).

³⁰ Federal Coordinator For Meteorological Services And Supporting Research, May 31, 2023. *NHOP*, FCM-P12-2023. Washington DC: FCM. Available online at https://www.weather.gov/media/nws/IHC2023/2023_nhop.pdf (accessed July 19, 2023).

independently analyzed official NHC metrics to determine caveats or exceptions. The findings and recommendations in this report include our assessments of internal control.

To satisfy our objective, we also used computer-processed data with the assistance of OIG Data Analytics. We developed a methodology to estimate the efficiency of NHC's aircraft observation planning during active tropical cyclones. Using all NHC Tropical Cyclone Plans of the Day (TCPODs) issued between 2020 and 2023, we manually reviewed 812 files to identify and select cases where both NOAA and the Air Force Reserve Command (AFRC) were tasked by NHC to fly in the same tropical cyclone. We then categorized the cases as either containing (1) scheduled gaps and overlaps in reconnaissance observations or (2) scheduled gaps, but no overlapping observations of reconnaissance aircraft. Our data analytics staff used the selected subset of cases to sum the gap and overlap hours of reconnaissance aircraft observations. Our analysis only included the overlap hours that could potentially have been recaptured to fill observation gaps. That is, we did not include overlap hours that exceeded the number of gap hours so that our estimates were conservative. Our analysis also did not account for limitations outside NHC's control such as crew or aircraft availability. As such, we would not expect NHC could have filled 100 percent of its observation gaps by rescheduling overlapping missions. We determined the NHC TCPOD data, and our analyses are sufficiently reliable to support our findings.

Although we could not independently verify the reliability of all the information we collected, we tested selected results against a control case, interviewed NWS staff to understand important context, and ensured analyses were the most conservative representation of potential impacts. Based on these efforts, we believe the information we obtained is sufficiently reliable for this report.

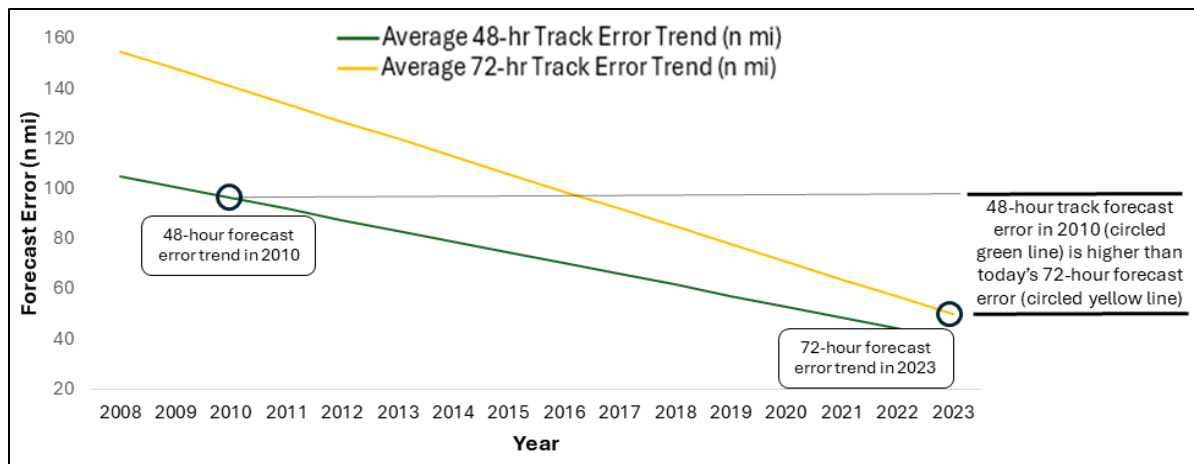
We conducted our review from October 2023 through October 2024 under the authority of the Inspector General Act of 1978, as amended (5 U.S.C. §§401-424), and Department Organization Order 10-13, dated October 21, 2020. We performed our fieldwork remotely and during a site visit to NHC in Miami, Florida.

We conducted this performance audit in accordance with generally accepted government auditing standards. These standards require that we plan and perform the audit to obtain sufficient, appropriate evidence that provides a reasonable basis for our findings and conclusions based on our audit objective. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objective.

Appendix B: Forecast Accuracy Trends

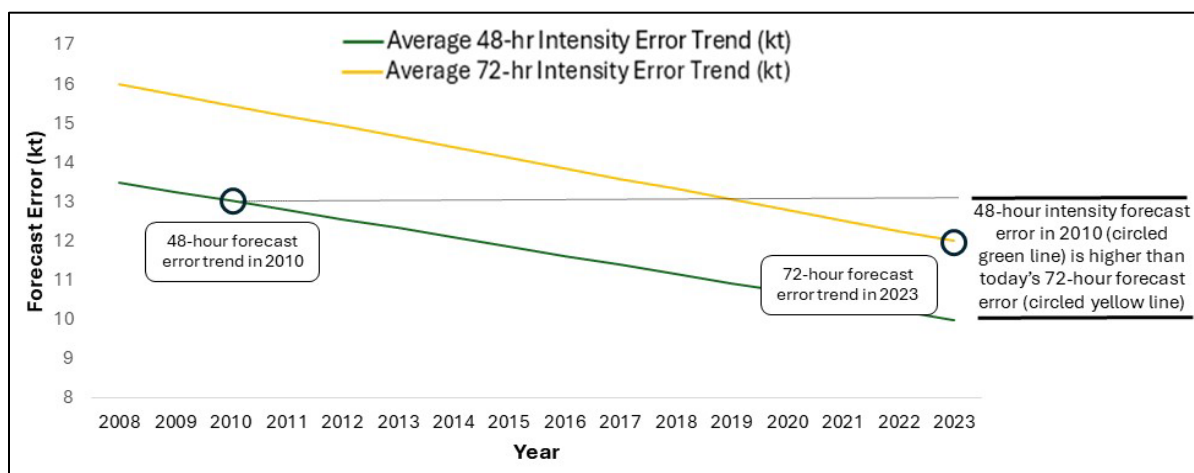
For the Atlantic and Eastern North Pacific Ocean basins, NHC issues forecasts of tropical cyclone position (track) and maximum 1-minute surface wind speed (intensity). After each season, forecasts are compared with NHC's estimates of cyclone track and intensity, as determined by post-storm analyses. Figures B-1 and B-2 show long-term improvement (i.e., lower errors over time) in error trends for the Atlantic Ocean basin.³¹ Based on these trends, today's 72-hour forecasts are as accurate as 48-hour forecasts were in 2010.³²

Figure B-1. NHC Forecast Track Error Trend, Atlantic Basin (nautical miles)



Source: OIG analysis of NHC data.

Figure B-2. NHC Forecast Intensity Error Trend, Atlantic Basin (knots)



Source: OIG analysis of NHC data.

³¹ The lines are best-fit approximations of NHC official annual error trends and do not represent single-year performance metrics. Although not shown, the trends for the Eastern North Pacific Ocean basin are similar.

³² Due to differences in the number of storms each year, it is not valid to directly compare single years.

Appendix C: Agency Response

NOAA's response begins on the following page.



UNITED STATES DEPARTMENT OF COMMERCE
Deputy Under Secretary for Operations
National Oceanic and Atmospheric Administration
Washington, D.C. 20230

MEMORANDUM FOR: Frederick J. Meny, Jr.
Assistant Inspector General for Audit and Evaluation

FROM: VADM Nancy Hann
Deputy Under Secretary for Operations
National Oceanic and Atmospheric Administration

**Nancy
Hann**

Digitally signed by
Nancy Hann
Date: 2024.11.20
08:57:01 -05'00'

SUBJECT: *NOAA Should Assess Opportunities to Improve Hurricane Forecasts
and Warnings*
Draft Report

The Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) is pleased to submit the attached response to the draft report on the NOAA hurricane forecast and warning program. We reviewed the report and concurred with the recommendations.

We appreciate the opportunity to review and respond to your draft report. If you have questions, please contact Lawrence N Burney, Jr, Acting Director, Audit and Information Management Office on (202) 643-6010.

Attachment



Department of Commerce
National Oceanic and Atmospheric Administration
Response to the OIG Draft Report Entitled
NOAA Should Assess Opportunities to Improve Hurricane Forecasts and Warnings
(October 2024)

General Comments

The National Oceanic and Atmospheric Administration (NOAA) appreciates the opportunity to review the Office of Inspector General's (OIG) draft report on hurricane forecast and warning performance. NOAA has reviewed the draft report and concurs with the OIG's recommendations. General comments and responses to the eight recommendations are provided below.

Throughout the document:

It is implied that the National Hurricane Center (NHC) issues all tropical cyclone related hazard products for wind and storm surge. However, NHC only issues those hazards in coastal areas, while the National Weather Service (NWS) Weather Forecast Offices (WFOs) issue wind hazard information for inland areas. Additionally, the Central Pacific Hurricane Center and WFOs in Guam and American Samoa issue tropical cyclone hazard products for their respective areas of responsibility.

The NOAA Atlantic Oceanographic & Meteorological Laboratory (AOML) should be listed as a partner that NHC relies on for quality-controlled aircraft reconnaissance data (e.g., pg 3 in the "Aircraft Reconnaissance Data" section). That is a notable omission since data can not be used with fidelity without AOML at this time.

Pages 6-7, discussion of Imelda:

In the discussion of forecast performance for Imelda, it is worth noting that while Imelda did not develop into a tropical storm until just prior to landfall, NWS WFOs did issue flood watches and warnings about the associated rainfall flooding hazard prior to Imelda's landfall. Tropical storm watches and warnings issued by NHC or WFOs do not address rainfall flooding hazards, only wind hazards. All of the fatalities from Imelda and the vast majority of the \$5 billion in damage were due to flooding, hence the need to include flood watches and warnings in this analysis - not only tropical storm watches and warnings - as they do not reflect rainfall and flooding risk.

Page 8, section II title:

The section title, "National Hurricane Center has not ensured optimal usage of hurricane hunter aircraft" should be modified to read: "Optimal usage of hurricane hunter aircraft has not been ensured". This better reflects the shared responsibility between NHC, the NOAA Aircraft Operations Center (AOC), and the Air Force Reserve Command (AFRC) for tasking and executing aircraft reconnaissance missions, as the National Hurricane Operations Plan spells out the frequency of missions, but there are crew and safety limitations for each flying unit that can prevent optimal usage.

In the "National Hurricane Center Has Not Ensured Optimal Usage of Hurricane Hunter Aircraft" section, the report omits the fact that NHC does not have the means to quality control data collected from operational instruments (e.g., tail Doppler radar, dropsondes) on board

NOAA aircraft. AOML has been fulfilling this need for years and the path to operational QA/QC is still in development.

The "National Hurricane Center Has Not Ensured Optimal Usage of Hurricane Hunter Aircraft" section identifies tasking of NOAA and AFRC aircraft as suboptimal due to observation gaps and overlapping observations. However, the optimal usage of these aircraft has never been studied in detail, so it is unclear if constant observing and/or eliminating overlaps would improve tropical cyclone forecasts. This topic requires significant investment to determine how these aircraft should be used optimally (e.g., through observing system experiments [OSEs] and/or observing system simulation experiments [OSSEs]).

Page 10, section III title:

In the "NOAA's HFIP is Insufficient to Meet the Weather Act's Hurricane Forecast and Warning Goal" section: by prioritizing support of computer modeling efforts, NOAA's Hurricane Forecast Improvement Project (HFIP) directly contributed to the development and operational implementation of HAFS (in record time, no less). However, NOAA AOML agrees with many of the criticisms of HFIP. Future, increased appropriations would allow HFIP to address these criticisms, broaden its portfolio in a useful way, and allow NOAA to fulfill directives as outlined in the Weather Act.

NOAA Response to OIG Recommendations

Recommendation 1: Assesses the extent to which tropical cyclone watches and warnings provide adequate advance notice to the public commensurate with NHC capabilities and emergency manager requirements and revises those products as warranted.

NOAA Response: We concur.

We note that NHC began issuing Potential Tropical Cyclone (PTC) Advisories in 2017, and this has resulted in an average increase of 18-21 h in lead time of the issuance of tropical cyclone watches and warnings for those systems.

The NWS is planning discussions internally and with external users about the feasibility and effectiveness of longer lead time for tropical cyclone wind and storm surge hazard information. NWS is also working toward extending tropical cyclone track and intensity forecasts from 5 days to 7 days.

Recommendation 2: Assesses its tropical cyclone forecast verification process to a) determine how best to measure performance excluded by current methodology, b) determine how best to verify tropical cyclone watches and/or warnings to better understand their effectiveness at protecting life and property, and c) implement process improvements as warranted.

NOAA Response: We concur.

The NWS is working to better understand which outcomes and metrics best align with products and services to support improved decision making. Watches and warnings operate within a continuum of information and messaging, but they are not the only messages that the public receives and there are multiple social, behavioral, and economic factors beyond the scope of

NWS products that can limit protective actions. The NWS is studying individual and group decision making in the context of weather to utilize information beyond the watch and warning time frame.

Recommendation 3: Develops and implements an oversight plan to monitor aircraft scheduling effectiveness, using the initial daily reconnaissance request sent to CARCAH as the baseline.

NOAA Response: We concur.

Recommendation 4: Specifies aircraft collection times critical to the forecast and warning production cycle in the NHOP.

NOAA Response: We concur.

Recommendation 5: Establishes a process with NOAA/OMAO and the AFRC to resolve observed aircraft scheduling deficiencies with an emphasis on meeting NHC requirements and documents the outcomes of these engagements.

NOAA Response: We concur.

Recommendation 6: Implements and maintains an HFIP executive governance agreement to formalize organizational roles, responsibilities, and goals for hurricane forecasting and warning improvement.

NOAA Response: We concur.

The NOAA HFIP was initiated in 2007 and chartered under a Terms of Reference which established a project team, with executive oversight provided by the cross-LO Hurricane Executive Oversight Board (HEOB) chaired by the Oceanic and Atmospheric Research (OAR) and NWS Assistant Administrators (AAs).

The HFIP (Program) is heavily focused on advancing hurricane forecasting through support to data assimilation and model development, historically because the HFIP (Program) resides under the NWS Modeling Program. To more seamlessly align model development with downstream products and services, including integration of social science, NOAA will consider 1) revisiting the HFIP (Project) structure to facilitate improved and more holistic planning and execution, as well as oversight across the enterprise from funding programs within NWS and OAR, and 2) revisit and formalize the HEOB structure to include additional stakeholders across NWS, OAR, and the National Environmental Satellite, Data and Information Service (NESDIS) to fully realize HFIP (Project) objectives across the value chain, including observations, modeling, data assimilation, ensemble prediction, verification, AI applications, social, behavioral, and economic science (SBES), and enhanced products and services.

Recommendation 7: Establishes clear goals, desired outcomes, and reporting mechanisms for SBES initiatives that elicit action to reduce the loss of life and damage to property.

NOAA Response: We concur, but NOAA would prefer a modified recommendation that reads: **“Establishes clear goals, desired outcomes, and reporting mechanisms for SBES**

initiatives”.

Based on the scope of the products and services provided by the NWS, it is unclear if SBES initiatives are designed to will immediately directly increase responsiveness that reduces the loss of life and damage to property, but actions taken are the responsibility of external groups and individuals. However, as stated above in recommendation 2, many SBES initiatives will focus on individual and group decision making and the factors that influence how people make decisions about weather, which are anticipated to have immediate benefits and improve implementation of actions to reduce the loss of life and damage to property.

Recommendation 8: Evaluates how to integrate collection of socioeconomic data to align with NOAA’s institutional observations requirements process.

NOAA Response: We concur.

Recommended Changes for Factual/Technical Information

Page 2, Table 1:

Table 1 should indicate that the definition of all of the watch/warning types include the language “somewhere within the watch or warning area” to indicate that the watches and warnings are not deterministic but rather risk based. This is important to ensure that the full context of the definitions of the watches and warnings is provided.

Page 4, 2nd paragraph, 2nd sentence:

The current text states: “Notably, NWS also extended its tropical outlook product by two days (from 5 to 7 days)...”. It should read: “Notably, NWS also extended its tropical weather outlook product, which provides forecasts of the formation of tropical cyclones, by two days (from 5 to 7 days).”

Editorial Comments

-None