

**Modernizing the NWS Tropical Cyclone Product Suite by
Evaluating NWS Partner Decisions and Information Needs:
Cross-Method Synthesis of Key Findings and Recommendations**

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REPORT TO NOAA

August 2022

Written with support from NOAA under awards NA19OAR0220121 and NA19OAR0220192.

Suggested citation: Morss, R. E., J. Vickery, A. Bostrom, J. L. Demuth, H. Lazrus, E. K. Laidlaw, and N. Hadjimichael, 2022: *Modernizing the NWS Tropical Cyclone Product Suite by Evaluating NWS Partner Decisions and Information Needs: Cross-Method Synthesis of Key Findings and Recommendations*. Final report to NOAA, 24 pp. <https://doi.org/10.25923/haf7-cb63>

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EXECUTIVE SUMMARY

This report synthesizes priorities for NOAA modernization of Tropical Cyclone (TC) information and services by identifying and proposing strategies to address gaps between the NWS TC Product Suite and its use by NWS partners. The project employed a mixed methods design, combining interviews and surveys of emergency managers and broadcast meteorologists, to integrate deep insights with broader perspectives. The resulting data were analyzed to understand how these NWS partners use TC information and make decisions throughout the lifespan of TC threats, and how well current NWS TC information and services support their decisions. We then built on these findings, in discussion with NOAA collaborators, to analyze unmet information needs, identify opportunities for improvement, and articulate recommendations for accelerating effective TC risk communication.

➤ Findings

1. Broadcast meteorologists and emergency managers find current NWS TC products and services very beneficial in their jobs.
2. NWS partners' TC information needs are interconnected with their job roles and activities, and TC information is most useful when it meshes with their decision timelines.
3. A mix of types of NWS TC products and services is useful to NWS partners, including graphics, data layers, text, and information from human forecasters.
4. Across the TC product suite, key areas for improvement include the usability of graphics and associated data layers, easily understandable text highlights, and consolidated access to relevant up-to-date information for a given TC.
5. At greater than five days of lead time, the highest-priority gap in the TC product suite is improved information about possible TC tracks and threat scenarios
6. At less than five days of lead time, the highest-priority gap in the TC product suite is locally interpretable information about potential TC hazards and impacts.

➤ Recommendations

1. Improve connections between NWS TC products and services and the decision timelines of the audiences they are intended to serve.
2. Continue to provide a mix of complementary types of TC products and services.
3. Improve the understandability and usability of NWS graphics.
4. Explore new ways for conveying locally relevant information about potential TC hazards and impacts, given predictive uncertainties.
5. Expand the use of concise, plain-language text highlights in the NWS TC product suite.
6. Continue to support and strengthen the contributions of NWS forecasters.
7. Develop an improved TC summary product and new ways for NWS partners to access all available NWS products related to a given TC.
8. At more than five days of lead time, develop a new product or service that communicates information about possible TC tracks and scenarios.
9. At less than five days of lead time, enhance the provision and communication of information about potential regional and local TC hazards, TC hazard timing, and coastal flood risks.

Moving forward, we propose that NOAA engage in ongoing modernization of the NWS TC product suite. To do so, we recommend employing an agile, decision-centered strategy for improving how the collection of TC information and services meet a variety of users' needs, as forecast capabilities, technologies, and users' job activities and decision timelines evolve. By deliberately, systematically incorporating a range of perspectives, such an approach can reduce inequities in access to and use of forecast information and the disproportionate impacts on underserved populations.

INTRODUCTION

This report synthesizes key findings and recommendations from a project that aimed to advance NOAA’s mission and service to the Nation by accelerating effective communication of weather forecasts and warnings. The project’s overarching goal was to advise NOAA on priority modernizations to the NWS Tropical Cyclone (TC) product suite, i.e., the collection of products, information, and services that NWS provides during TC threats.

The project was guided by three intersecting objectives:

- OBJECTIVE 1: Evaluate key NWS partners’ TC information needs and the utility of the current TC product suite in supporting decisions;
- OBJECTIVE 2: Analyze NWS partners’ important unmet information needs and associated gaps in the TC product suite; and
- OBJECTIVE 3: Develop research-guided recommendations to NOAA on improving the TC product suite.

To achieve these objectives, our research team employed a user- and decision-centered approach, focusing on two types of NWS partners of interest to NOAA for this work: broadcast meteorologists and emergency managers. We evaluated the TC suite from a forward-looking perspective — asking not only how the collection of current products, information, and services meets these users’ needs, but also what improvements could better support their decisions.

The findings and recommendations are derived from a cross-method analysis of data from interviews and surveys with members of both of these NWS partner groups, combined with results from other relevant research. In analyzing unmet needs and areas for improvement, we considered possible near-term changes to the TC product suite, given current limits in TC forecast skill and anticipated near-term forecast improvements. We also considered longer-term changes that could be realized through investments in social and physical science research, research-to-operations transition, and technological innovations, as well as shifts in thinking that could underlie a broader modernization.

The following sections summarize the project approach and methodology, present highlighted findings from the cross-method analysis, and synthesize recommendations based on the research. This report is intended to provide an accessible, high-level understanding of the project. Details on the methods, findings, and recommendations can be found in two complementary reports: Morss et al. (2022b) for the interviews and Bostrom et al. (2022) for the surveys.

Some of the findings and recommendations in this report are discussed in terms of three phases of broadcast meteorologists’ and emergency managers’ TC decision timelines, shown in Figure 1. These phases were distilled from the interview data and previous relevant literature, as described in Morss et al. (2022b), and incorporated into the surveys.

APPROACH AND METHODOLOGY

The project was conducted by an interdisciplinary team of researchers, in collaboration with NOAA Research and NWS personnel. The research team used a multi-method approach that included a literature review, interviews and surveys with broadcast meteorologists and emergency managers, and a cross-method synthesis.

The interviews were designed to understand (a) NWS partners’ decision timelines, (b) their use of TC information along those timelines, and (c) associated areas for improvement in NWS

products and services. Data were collected from February to March 2020 from 7 broadcast meteorologists and 13 emergency managers in coastal and near-coastal regions of South Carolina, Georgia, and Texas, in a mix of metropolitan and less-populated areas. Additional interviews were planned, but data collection was interrupted in mid-March 2020 by the COVID-19 pandemic. The interview data were thematically analyzed, and the results were used to inform survey development and preliminary recommendations in collaboration with NOAA.

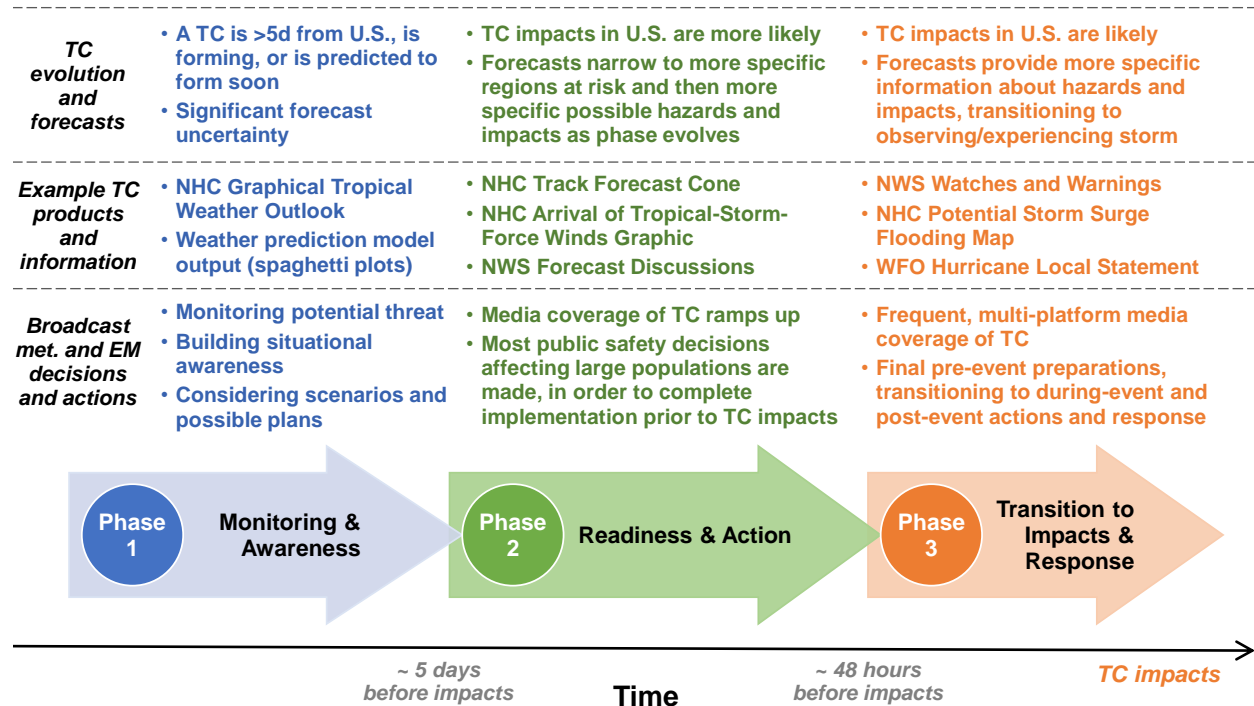


Figure 1. Overview of broadcast meteorologists’ and emergency managers’ decision and action timelines as a TC threat approaches and affects their region and associated forecast information evolves. This graphic was developed based on the interviews and is adapted from Figure 2 in Morss et al. (2022a). Note that the time frames corresponding to these three phases are not absolute; they are related to current predictive capabilities for TCs, and they may vary in timing and length based on the storm.

The surveys were designed to investigate the interview findings and recommendations with a broader, more diverse population of broadcast meteorologists and emergency managers across areas of the conterminous United States (CONUS) affected by Atlantic TCs (Figure 2). Email sampling frames were constructed for broadcast meteorologists based on the George Mason University Center for Climate Change Communication sample of U.S. broadcast meteorologists, and for emergency managers by members of the research team. The surveys were fielded online from March to June 2021, with 87 broadcast meteorologists and 265 emergency managers completing the survey.¹ The surveys included questions on (a) the importance of different types of TC information, (b) NWS effectiveness in supporting respondents’ job activities, (c) the usefulness and usability of NWS TC information and services, and (d) potential changes to the NWS TC product suite. The survey data were analyzed overall and with respondents partitioned

¹ The survey completion rate was 13.0% for broadcast meteorologists and 17.6% for emergency managers.

by the proximity of their area of responsibility to the coast², and the results were used to refine and expand the interview findings and recommendations in collaboration with NOAA. High-priority findings and recommendations from the interviews and surveys were then synthesized, together with other relevant literature, to develop this report.

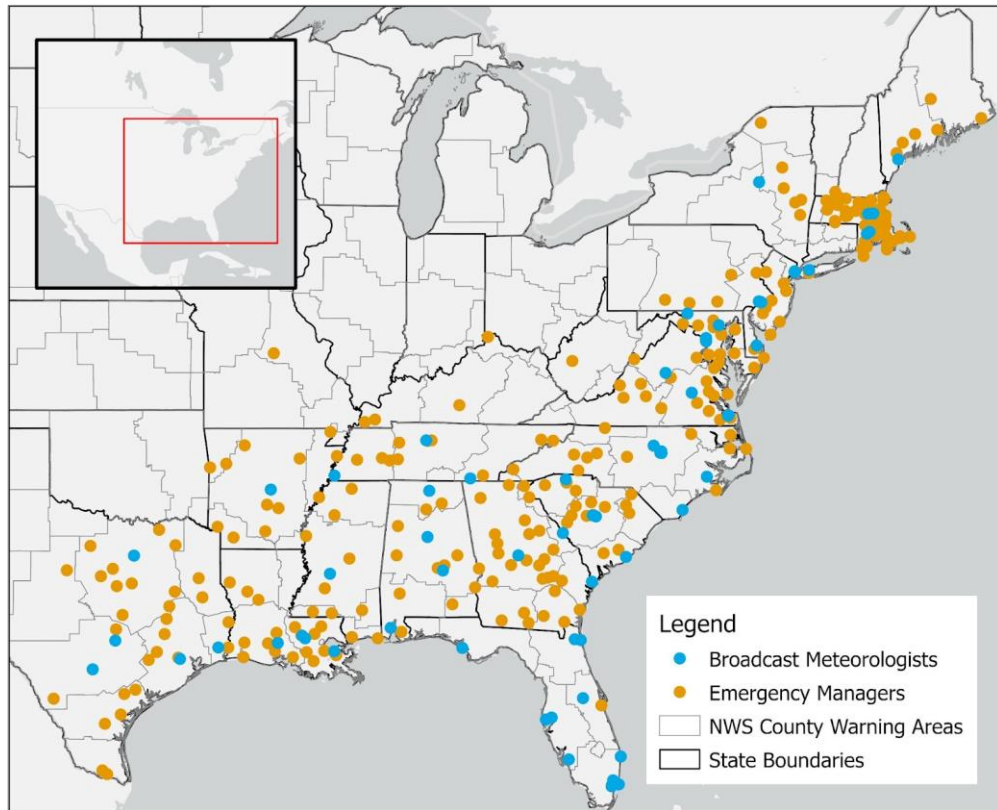


Figure 2. Locations of survey respondents; each circle represents one respondent.

The broadcast meteorologist and emergency manager interviews were guided by a parallel set of questions and were of similar length. The broadcast meteorologist and emergency manager surveys asked questions on similar topics, adapted for their job roles. However, to increase the likelihood of emergency managers responding to the survey (especially given their workload during the pandemic), their survey instrument was shorter than that used for the broadcast meteorologists. Thus, parallel data are not available from the two groups of NWS partners for some survey questions. Where available, comparable data are presented across the two groups.

HIGHLIGHTED RESULTS

This section presents highlighted results synthesized across the project, organized by the three objectives, along with selected supporting data. Additional supporting data and analyses can be found in the interview and survey reports, as indicated in footnotes.

² Broadcast meteorologist survey respondents were partitioned into two groups: coastal (≤ 120 km from coast, a proxy for their media market including coastal locations) and inland (> 120 km from coast). Emergency manager survey respondents were partitioned into three groups: coastal (jurisdiction includes coastal locations), non-coastal (jurisdiction is 1-120 km from coast), and inland (jurisdiction is > 120 km from coast).

OBJECTIVE 1. Evaluate key NWS partners' TC information needs and the utility of the current TC product suite in supporting decisions

➤ FINDING 1: Broadcast meteorologists and emergency managers find current NWS TC products and services very beneficial in their jobs.

Overall, most broadcast meteorologists and emergency managers throughout the study area — coastal, near-coastal, and inland — said that NWS information significantly benefits their job activities during TC threats. For example, when asked to rate the usefulness of approximately 20 types of NWS TC information and services, survey respondents from both groups rated nearly all, on average, Very to Extremely useful.³ Illustrating this finding, Figure 3 shows results for seven example NWS TC products; all were rated Very or Extremely useful by 75% or more of broadcast meteorologists and emergency managers. Figure 4 shows results for four mechanisms for obtaining information, interpretations, and decision support from NWS forecasters, which were again rated highly useful.

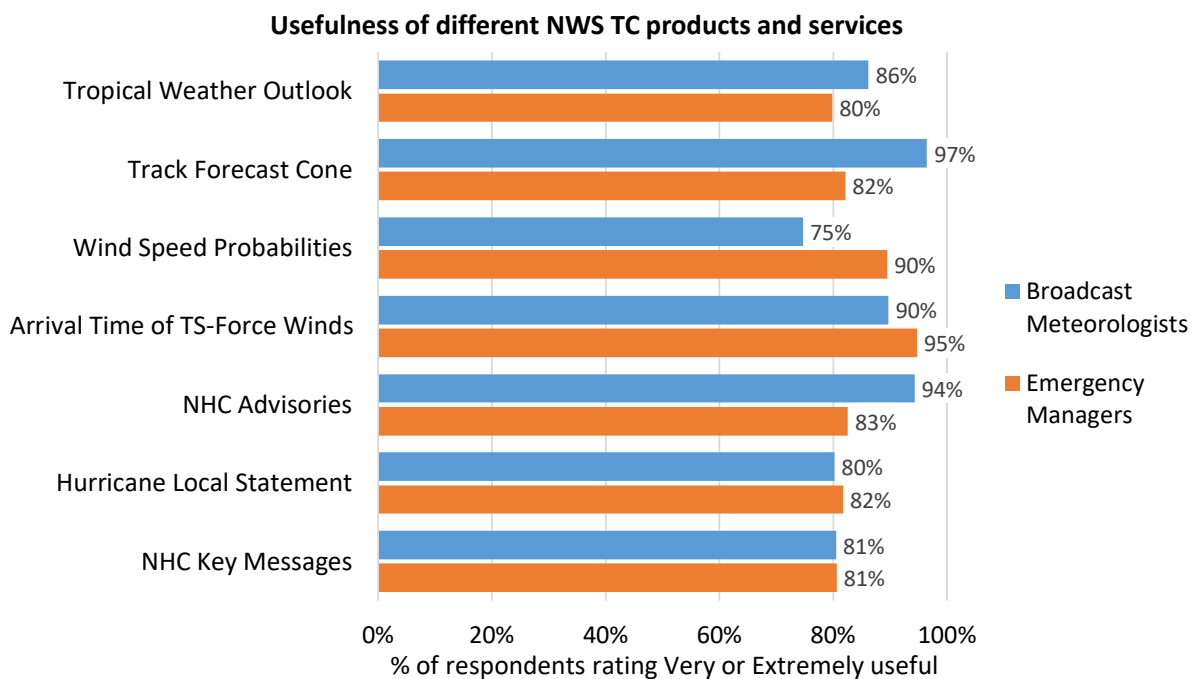


Figure 3. Broadcast meteorologists' and emergency managers' ratings of the usefulness of seven types of NWS information during TC threats. The examples shown represent different TC products provided by NHC and WFOs, conveyed in graphical, text, and hybrid formats. Survey response options: Extremely useful, Very useful, Moderately Useful, Slightly useful, Not at all useful. Data shown are the percentage of survey respondents in each group selecting Very or Extremely useful. Number of respondents: 86 to 87 broadcast meteorologists, 133 to 263 emergency managers, depending on the product.

Further illustrating this finding, more than 75% of broadcast meteorologist survey respondents said that NWS information and services are Very or Extremely helpful to them more than 5 days

³ The only exceptions were storm surge products, which were rated Very to Extremely Useful by coastal emergency managers and broadcast meteorologists, but Moderately to Very Useful by non-coastal respondents. For additional information about the results in this paragraph, see sections 3.5 and 4.4 in the survey report (Bostrom et al. 2022).

before TC impacts.⁴ Five days or less before impacts, the percentage saying that NWS information and services are Very or Extremely helpful increased to 95%. Moreover, all broadcast meteorologist survey respondents rated NWS information and services Very or Extremely helpful during at least one phase of a TC threat.

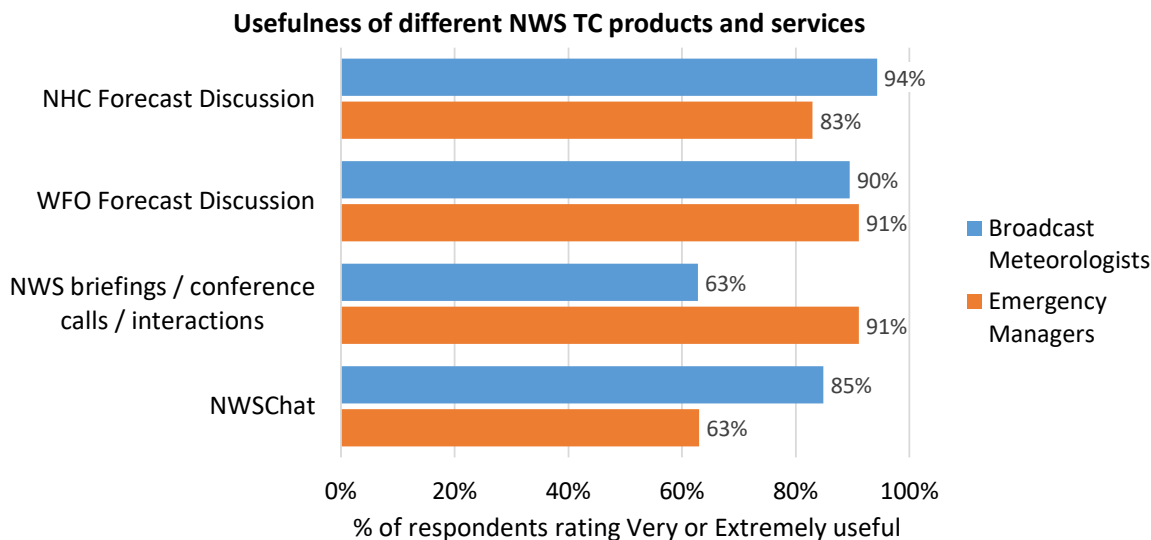


Figure 4. Broadcast meteorologists’ and emergency managers’ ratings of the usefulness of four types of products and services provided by NWS forecasters during TC threats. Survey response options: Extremely useful, Very useful, Moderately Useful, Slightly useful, Not at all useful. Data shown are the percentage of survey respondents in each group selecting Very or Extremely useful. Number of respondents: 86 to 87 broadcast meteorologists, 133 to 135 emergency managers.

➤ **FINDING 2: Broadcast meteorologists’ and emergency managers’ TC information needs are interconnected with their job roles and activities as a TC threat evolves. TC information is most useful to NWS partners when it meshes with their decision timelines, i.e., when it is available before they need to make certain decisions, with sufficient time for assimilation into their job activities.**

NWS partners’ job roles and activities during TC threats provide a foundation for understanding their TC information needs. As shown in Figure 1, broadcast meteorologists’ and emergency managers’ information use, decisions, and actions typically evolve with a TC threat.⁵ During Phase I, TC forecasts are highly uncertain; thus, both groups focus primarily on monitoring the threat, building situational awareness, and considering scenarios. During Phase II, forecasts shift to providing more skillful and specific information. Broadcast meteorologists increase their media coverage of the threat, and emergency managers allocate resources for and begin implementing public safety decisions such as evacuation and sheltering. During Phase III, which transitions from forecast-based to observation-based decisions, broadcast meteorologists provide frequent media coverage, and emergency managers complete preparations.

⁴ For additional information on the results in this paragraph, see section 3.3.1 in the survey report. This set of questions was not asked in the emergency manager survey.

⁵ For additional information on the results in Finding 2, see sections 4, 5, and 6 in the interview report (Morss et al. 2022b) and sections 3.1.2, 3.6.1, 4.1.2, and 4.5.1 in the survey report.

As this description indicates, *broadcast meteorologists' primary job roles during TC threats focus around providing up-to-date media coverage, typically across multiple platforms such as television, websites, and social media.* Therefore, their timelines for TC information use are driven by when different types of information are available, along with timelines for media coverage on platforms with regular schedules, such as television. *Emergency managers' primary job roles during TC threats focus around communicating about and coordinating public safety decisions.* Their TC information needs are therefore driven by both when different information is available and how far in advance different types of public safety decisions must be made.

Analyzing broadcast meteorologists' and emergency managers' job roles and decision timelines enabled us to understand important aspects of their TC information needs. For example, related to their role of providing television coverage, some broadcast meteorologists noted that NWS information is most useful when it is released with sufficient time for them to incorporate it into their regularly scheduled on-air weathercasts. For emergency managers, issues with information alignment arose primarily in terms of needing certain types of information at longer lead times for making public safety decisions (see Finding 6).

➤ **FINDING 3: Broadcast meteorologists and emergency managers find a mix of complementary types of NWS TC products and services useful, including graphics, data layers, textual information, and information from human forecasters.**

The interview and survey analyses demonstrate that a variety of types of NWS TC products and services are useful to NWS partners.⁶ This includes products from different NWS entities that convey different aspects of TC risks in different formats (Figure 3). It includes NWS data layers, numerical model output, and observations. It also includes information, interpretations, and decision support from human forecasters (Figure 4). These different TC products and services provide complementary information. Thus, the value of the TC product suite arises not only from its individual components, but also through how they inform each other and work together.

The value of the TC product suite arises not only from its components, but also through how they work together.

Because visual media are central to broadcast meteorologists' jobs, much of their communication involves graphics. However, in most situations broadcast meteorologists do not communicate using NWS graphics in their NWS format. Instead, NWS graphical products provide a critical foundation that broadcast meteorologists modify for communicating with a broad audience, using the underlying data layers incorporated into their data analysis and display systems. Thus, it is critical that NOAA provide usable data layers and effectively coordinate with the private sector vendors that develop and provide broadcast meteorologists' software systems. Emergency managers often use graphical products as provided by the NWS, although they sometimes revise NWS graphics to improve communication and coordination of decisions or utilize the underlying data layers in analysis systems such as HURREVAC or GIS.

Broadcast meteorologists and emergency managers also noted the value of textual forecast information from the NWS, for example, as a way to quickly discern the most important information and key updates from previous forecasts. This includes textual NWS products, such

⁶ For additional information on the results in Finding 3, see sections 4, 5, and 6 in the interview report and sections 3.4, 3.5, 3.6.2, 4.3, 4.4, and 4.5.2 in the survey report.

as Advisories, Hurricane Local Statements, and Forecast Discussions (Figures 3–4), as well as concise text accompanying graphics that supports interpretation of the often-complex available forecast information. The potential value of this latter type of information is illustrated, for example, by the NHC Key Messages product, which combines graphical products with text highlights. One broadcast meteorologist interviewee explained: “I like that because it’s usually very easy, really quick: one, two, three [bullet points to obtain the] latest information.”

“I don’t see how you could do this job and not be on pretty close terms with your [local] weather service.”

- Emergency manager

Along with products and data, these NWS partners indicated that human forecasters are key components of how NWS supports their work. As shown in Figure 4, most survey respondents rated NHC and WFO forecasters’ interpretations provided asynchronously in written form, through Forecast Discussions, as Very or Extremely useful. Most also rated at least one mechanism for interacting with NWS forecasters in real time to obtain forecast interpretations and decision support (NWSChat or conference calls) Very or Extremely Useful. Further, 86% of broadcast meteorologists and 92% of emergency managers rated their interactions with local WFOs during TC threats as Excellent or Good. Summarizing the value of NWS forecasters, an emergency manager interviewee said: “I don’t see how you could do this job and not be on pretty close terms with your [local] weather service.”

OBJECTIVE 2. Analyze important unmet information needs and associated gaps in the TC product suite

Despite the overall positive assessment above, the interview and survey analyses reveal several important unmet needs and information gaps in the TC product suite. These are related to difficulties that some broadcast meteorologists and emergency managers have using current NWS information and services (Finding 4), as well as information and services that would be useful to broadcast meteorologists and emergency managers but are not currently available from the NWS in the desired time frame (Findings 5 and 6).

➤ **FINDING 4: Across the TC product suite, the usability of some NWS information and services is reduced by:**

- **Graphics that are difficult to edit or do not have readily usable data layers available, do not provide information specific enough to users’ areas, or take too much time to understand;**
- **Text that is lengthy, complex, or uses wording that is difficult to understand; and**
- **Insufficient mechanisms for accessing all relevant TC information available from different NOAA entities and for quickly understanding and communicating the most important highlights and updates for a given storm.**

Each of these are described in more detail in the following paragraphs.

Areas for improvement in NWS graphical products⁷

When asked why they have difficulty using certain NWS graphical products (Figure 5), the most common responses among broadcast meteorologists surveyed were that the product is hard to

⁷ See sections 4, 5, and 6 in the interview report and sections 3.6.4, 3.8.2, 3.8.4, 4.5.4, and 4.7.2 in the survey report.

edit on the devices they use or the data layer is not available. Among emergency managers surveyed, the most common response was that the product does not provide information specific enough to their area. These gaps are related to how each group uses TC information: broadcast meteorologists typically use NWS graphics as a starting point for creating new or revised visuals in their data analysis and display systems, and emergency managers use NWS graphics to assess and communicate TC risks at different locations in their area of responsibility. Therefore, graphical products that are editable or have usable data layers help broadcast meteorologists effectively convey NWS TC information to a broad audience, and graphical products that are locally interpretable help emergency managers effectively coordinate public safety decisions.

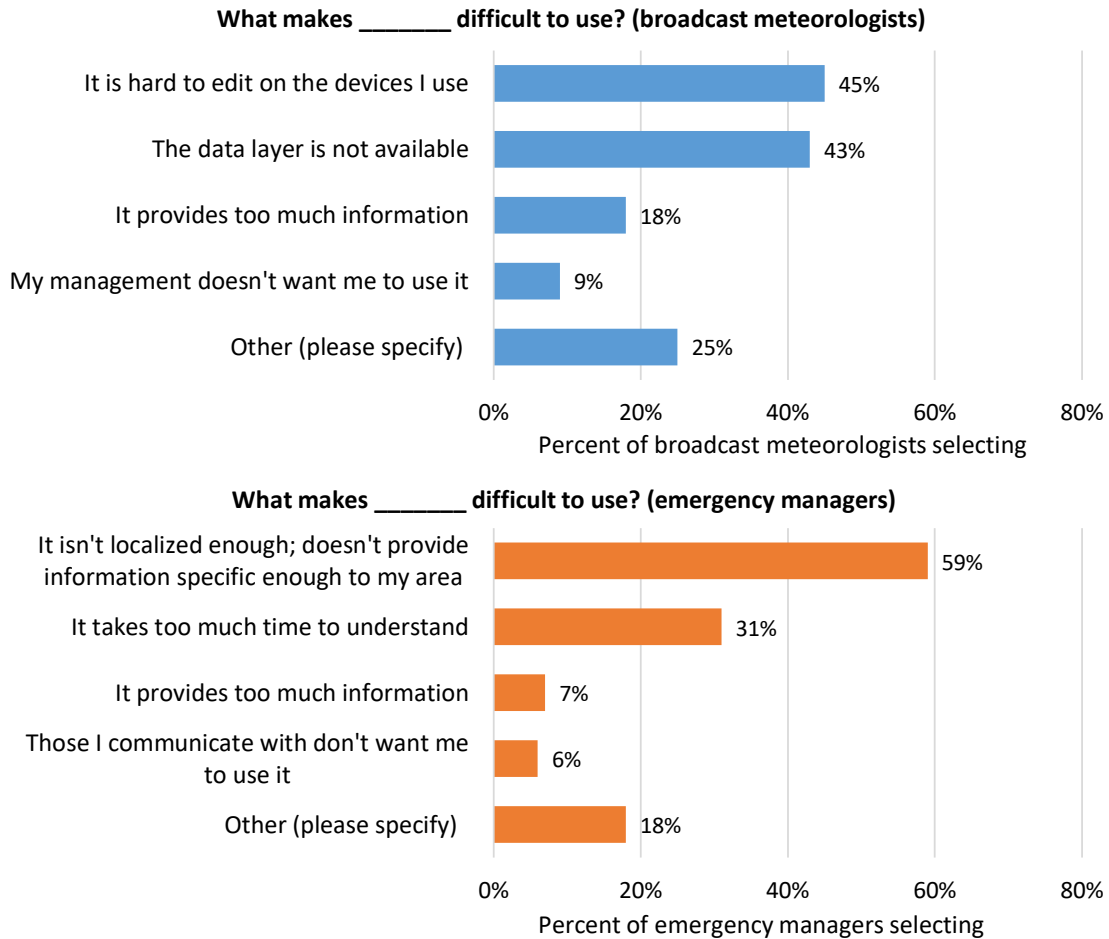


Figure 5. Broadcast meteorologists’ (upper) and emergency managers’ (lower) reasons for difficulty using NWS TC products. As described in Bostrom et al. (2022), each survey respondent was first asked whether they had difficulty using any of several NWS TC products; those who said yes were then asked what makes one of those products difficult to use, with the option to select one or more of the responses shown here. Number of respondents: 44 broadcast meteorologists, 83 emergency managers.

Members of both groups also said that some NWS graphical products are difficult to understand, for themselves or key audiences. Understandability is a multi-faceted topic that arose in a variety of ways, including graphics having too much information, being difficult to explain to others, being commonly misunderstood, and taking too much time to understand. Even if most broadcast meteorologists modify NWS graphics, starting with a more easily understandable format can

support effective communication with a broad audience. It can also enhance their ability to rapidly disseminate the latest NWS information on social media after updates are released. For emergency managers, who often use graphics in the NWS format, products that are more easily understood by non-technical audiences and enable local interpretations can support their own understanding of the risks as well as their communications with others involved in public safety decisions. Importantly, improved graphics can also help reduce misunderstandings of the risks posed by a TC and associated ineffective decision making.

Areas for improvement in NWS textual information⁸

Although NWS has improved text products such as Advisories and Hurricane Local Statements in recent years, some interviewees and survey respondents said that these products can still be long and difficult to use. When using these products, broadcast meteorologists and emergency managers want to be able to quickly find and understand the most critical new information relevant for their job. To help them do so, they requested text products that are as well organized, as consolidated, and as readable as possible — for example, with the newest and most important information at the top, clear headings, minimal redundancy, and as little technical or complex language as possible.

Interviewees and survey respondents also discussed the value of concise, easily understandable text highlights, both within NWS text products and embedded in or alongside graphics. Such text highlights help broadcast meteorologists and emergency managers rapidly make sense of the forecast situation and extract essential elements and updates from the complex collection of TC information available at any given time. Moreover, if the highlights are short and easily understandable to non-meteorologists, they can use the same language in their own communications, helping them rapidly disseminate the latest key information and reduce misunderstandings. As one broadcast meteorologist interviewee said: “If there’s any way to have more of those quick bullet points, I think those really help out a lot.”

Areas for improvement in accessing, synthesizing, and concisely communicating key updated information about a given TC⁹

The interview analysis indicated that, with the volume and complexity of TC information now available from different NOAA sources, it can be challenging for broadcast meteorologists and emergency managers to access, synthesize, and concisely communicate the most updated relevant information as a TC threat evolves. For example, some interviewees discussed using non-NOAA websites to obtain TC information that originated from NOAA. Another example is how some interviewees described using NWS products such as the Track Forecast Cone as a “one-stop shop” for communicating key aspects of a TC threat, even though they noted that the Cone and other products that might serve this purpose have important limitations.

This suggested two possible gaps in the current TC product suite: the need for 1) a summary product that effectively synthesizes and conveys key hazard and risk information for a particular storm (supplementing or replacing the Track Forecast Cone), and 2) a website or other service that compiles available information in one place, making it easier to access all NWS products related to a storm. To assess how important these gaps were across a broader population of broadcast meteorologists and emergency managers, survey respondents were asked to rate the

⁸ See section 6 in the interview report and sections 3.6.4, 3.8.4, and 4.5.4 in the survey report.

⁹ See sections 4, 5, and 6 in the interview report and sections 3.8.3 and 4.7.1 in the survey report.

usefulness of NWS addressing these two gaps (along with six others discussed below). As shown in Figure 6, each of these potential changes to the TC product suite was rated Very or Extremely useful by more than 80% of broadcast meteorologists and 90% of emergency managers. *In other words, modernizing the TC product suite might include providing products or services that help NWS partners and others use all of the information already available from NOAA.*

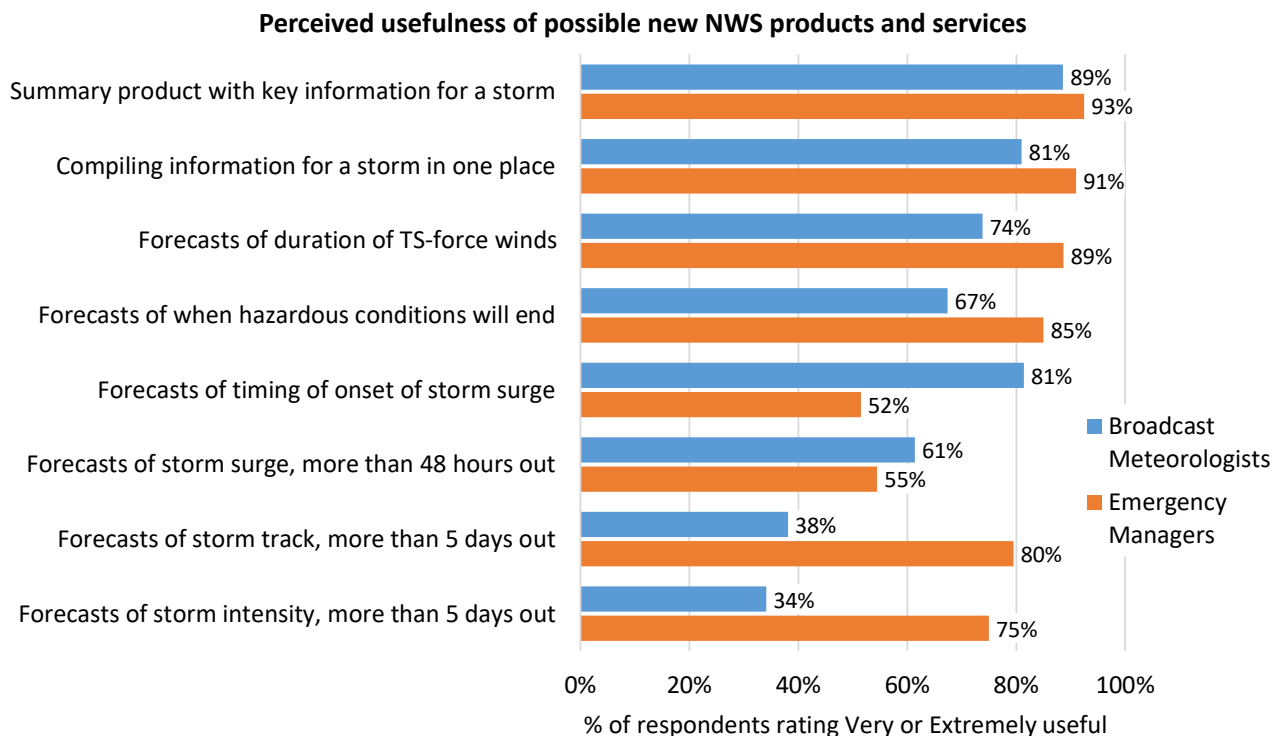


Figure 6. Broadcast meteorologists’ and emergency managers’ ratings of the perceived usefulness of eight possible new NWS TC products or services. Survey response options: Extremely useful, Very useful, Moderately Useful, Slightly useful, Not at all useful. Data shown are the percentage of survey respondents in each group selecting Very or Extremely useful. Ratings of the two storm surge products/services are also shown in Figure 7, partitioned by respondents’ proximity to the coast. Number of respondents: 42 to 44 broadcast meteorologists, 132 to 133 emergency managers.

➤ **FINDING 5: At greater than five days of lead time, the highest-priority gap in the TC product suite is improved information about possible TC tracks and threat scenarios.**

NHC currently only provides TC track and intensity forecasts out to five days. In the absence of an official NWS forecast product, broadcast meteorologist and emergency manager interviewees discussed seeking information about potential TC tracks at longer lead times from other sources, such as extrapolating the Track Forecast Cone or looking at numerical model output.¹⁰ *The fact that NWS partners are seeking out unofficial TC track information at more than five days of lead time suggests that this is an important gap in the TC product suite.*

This gap is further corroborated by the survey data. For example, more than half of broadcast meteorologist respondents said that additional NWS information or tools would be Very or

¹⁰ For additional information on the results in Finding 5, see sections 4, 5, and 6 in the interview report and sections 3.8.1, 3.8.2, 3.8.3, 4.7.1, and 4.7.2 in the survey report.

Extremely useful during this phase of a TC threat. In addition, as shown in Figure 6, 75% of emergency managers said that NWS providing TC track and intensity forecasts more than five days out would be Very or Extremely useful. Broadcast meteorologists, on the other hand, were less positive about extending TC track and intensity forecasts beyond five days. Instead, at these lead times, broadcast meteorologists primarily requested more graphics and additional information from forecast models, about TC scenarios, and about forecast confidence or uncertainty. Some emergency managers requested similar information. Together, *these results suggest that there are additional options for filling this gap in ways that support longer-term situational awareness and decision making, beyond extending current NHC TC track and intensity forecast products out to more than five days.*

- **FINDING 6: At less than five days of lead time, the highest-priority gap in the TC product suite is improved information about potential TC hazards and impacts. This includes more regionally or locally interpretable hazard forecasts, additional information about hazard timing, and TC-specific information about coastal flood risks at more than 48 hours of lead time.**

As a storm approaches, broadcast meteorologists and emergency manager interviewees and survey respondents emphasized the importance of forecasts of TC hazards and impacts, including information that is more specific to their area.¹¹ For broadcast meteorologists, such information helps them communicate about an approaching TC threat in ways that are relevant to their audiences in different locations. For emergency managers, such information supports decisions about evacuation, sheltering, and other protective actions in different parts of their jurisdiction. Although the NWS does provide some of this type of information within 48 hours of impacts, study participants noted some difficulties interpreting such information. Moreover, they noted the need for regionally and locally interpretable TC hazard forecasts at several days (more than 48 hours) of lead time, to support protective decision making during this period. Thus, we identified this as another important gap in the TC product suite.

Another topic that emerged in some of the interviews was desire for additional information about the anticipated onset, cessation, or duration of TC hazards. To explore the importance of this more broadly, survey respondents were asked to rate the usefulness of three different types of hazard timing information, as part of the set of eight possible new NWS products and services shown in Figure 6. Forecasts of duration of tropical-storm-force winds and forecasts of when hazardous conditions will end were each rated Very or Extremely useful by more than 67% of broadcast meteorologists and 85% of emergency managers. Forecasts of timing of storm surge onset were also rated highly useful by broadcast meteorologists, but less so by emergency managers overall. However, Figure 7 shows that this is because forecasts of timing of storm surge onset were rated Very or Extremely useful by 90% of emergency managers in coastal jurisdictions, but less than 25% in non-coastal jurisdictions. These results indicate that information about the timing of TC hazards (beyond arrival of tropical-storm-force and hurricane-force winds) relevant to different regions is another gap in the TC product suite.

¹¹ For additional information on the results in Finding 5, see sections 4, 5, and 6 in the interview report and sections 3.8.2, 3.8.3, 4.2.2, 4.7.1, and 4.7.2 in the survey report.

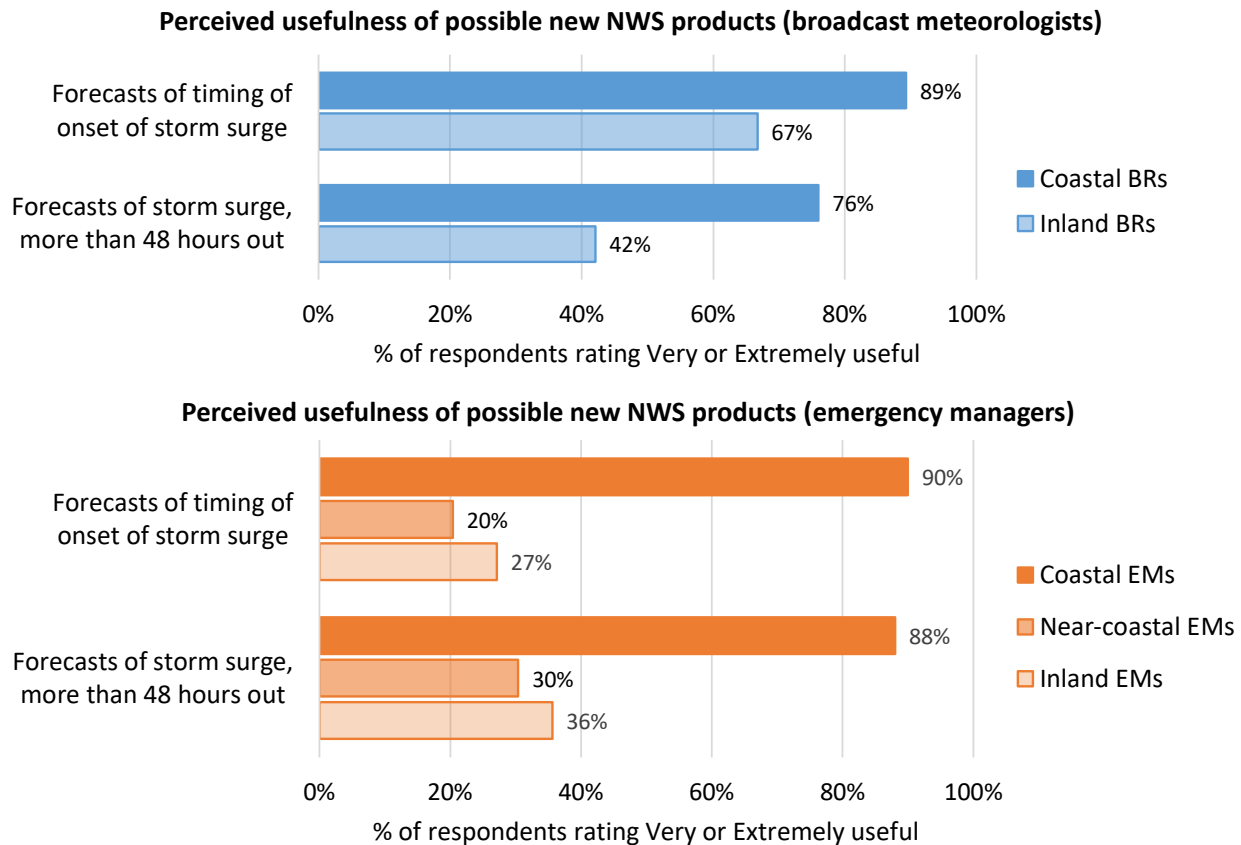


Figure 7. Broadcast meteorologists’ and emergency managers’ ratings of the perceived usefulness of NWS providing two possible new types of TC storm surge information, as in Figure 6, partitioned into coastal and inland broadcast meteorologists (upper) and coastal, near-coastal, and inland emergency managers (lower). Response options: Extremely useful, Very useful, Moderately Useful, Slightly useful, Not at all useful. Data shown are the percentage of survey respondents in each group selecting Very or Extremely useful. Number of respondents: 43 to 44 broadcast meteorologists, 132 emergency managers.

A related topic that emerged in the interviews was the need for TC-specific information about coastal flood risks at several days of lead time. Several emergency management interviewees explained that this information was important for successfully implementing larger scale evacuations, particularly those that involve more vulnerable populations, due to the time required to ramp up communications about the risk and arrange transportation and other resources. As shown in Figure 7, forecasts of storm surge more than 48 hours out were rated Very or Extremely useful by more than 75% of coastal broadcast meteorologists and nearly 90% of coastal emergency managers. These results underscore the importance of this information gap in areas at risk from storm surge inundation.

OBJECTIVE 3. Develop research-guided recommendations to NOAA on improving the TC product suite.

Based on the findings above, we provide nine recommendations for NOAA.

- **RECOMMENDATION 1: To modernize the TC product suite, clarify which audiences different TC products and services are designed to serve, and then identify**

opportunities to improve how products and services fit with those audiences' decision timelines, address their information needs, and leverage their job roles.

Some NWS products and services are very useful for a variety of forecast users across multiple phases of a TC threat, while some are most useful for a subset of forecast users or during certain time frames. Although NWS products are publicly available, clarifying which products and services are designed to serve a broad audience throughout a threat, and which are focused primarily on serving a segment of forecast users or to be useful during certain time periods, can help NOAA target improvements to TC information and services and identify remaining gaps. As discussed in Finding 2, understanding users' job activities and decision timelines provides a starting point for such improvements (Figure 1).

More broadly, although NOAA is the originator of much of the available TC forecast and warning information in the United States, *NWS partners play crucial and indispensable roles in helping NWS achieve its goals when a TC threatens. Thus, when modernizing the TC product suite, we recommend that NOAA seek additional opportunities to leverage partners' roles in the forecast warning system.* This includes leveraging broadcast meteorologists' roles in forecast and risk communication to enhance the reach of NWS-generated information to the public, and leveraging emergency managers' roles in coordinating public safety decisions to help the NWS protect lives and property and enhance economic well-being.

➤ **RECOMMENDATION 2: Continue to emphasize providing a mix of types of TC products and services, recognizing their complementarity and the different ways they can be valuable.**

Given how beneficial currently available TC information and services are for most broadcast meteorologists and emergency managers (Finding 1), NOAA can and should build on its successes. These successes arise, in part, from the mix of information types that NWS provides, including graphics, data layers, text, and information from human forecasters (Finding 3). These different types of products and services are complementary, and each would likely be less useful if the others were not available. Collectively, they support a wide range of users' needs.

The findings also illustrate the multiple ways that NWS information and services can be useful. For example, NWS graphics provide value as is, as a starting point for revising for further dissemination, and as data layers that can be used to create revised visuals or be integrated with other data to generate new information. Text can be useful for communicating with audiences that require text, conveying information that is not easily communicated in graphical form, and providing concise written or oral information that helps people interpret graphics and rapidly understand key aspects of the forecast situation. Understanding the different pathways for NWS information to create value can help NOAA identify areas for improvement and support synergies across products and services.

Understanding the different pathways for NWS information to create value can help NOAA identify areas for improvement and support synergies.

➤ **RECOMMENDATION 3: Improve the understandability and usability of NWS graphics.**

As discussed in Findings 3 and 4 and Recommendation 2, graphics are a core component of how broadcast meteorologists, emergency managers, and others interpret and communicate about TC

forecast situations. Thus, ensuring that NWS graphics are as usable and useful as possible is a critical component of modernizing the TC product suite. *Because broadcast meteorologists and emergency managers typically tailor messages to their audiences, one way to maximize the usability and reach of NWS graphics is to facilitate partners' ability to make modifications.* This can be accomplished by providing NWS graphics in editable formats, and by providing the underlying data in ways that are usable in NWS partners' software systems. Both facilitate NWS partners using NWS graphics as a foundation and making minor changes to improve communication, for example, by simplifying titles and legends or adding annotations to highlight key information. In addition, the second enables NWS partners combining data from different NWS products or combining NWS data with data from other sources in order to synthesize data or create new visuals. Each has value in different situations.

Another way to enhance the usability of NWS graphics is to provide the information in ways that support regionally and locally relevant interpretations. For map-based graphics, this could be accomplished, for example, by making national or state-level NWS graphics “zoomable” with additional regional reference points, or by providing NWS geospatial data as part of interactive tools that facilitate interpreting regional or local risks. For location-specific NWS graphics such as hydrographs, users would benefit from tools that support interpretations at other locations. However, as discussed further in Recommendation 4, this can be challenging to implement in some situations without implying unrealistic spatial resolution or specificity.

A third way to enhance the usability of NWS graphics is to make them more accessible to and easily understood by non-meteorologists — and less commonly misunderstood. Developing more “user friendly” NWS graphics will require working closely with a product's target audiences to develop readily interpretable, usable content and design, without altering important information. *Thus, where possible, users' perspectives and interpretations should be integrated into research and development beginning early in a product's conceptualization.*

➤ **RECOMMENDATION 4: Explore new ways for conveying locally relevant TC hazard forecast information for decisions, given predictive uncertainties.**

Building on Recommendation 3, broadcast meteorologists and emergency managers value TC forecasts that provide regionally and locally interpretable information, especially about potential TC hazards and impacts. However, predictability limits currently constrain meteorologists' ability to provide geographically specific forecasts of TC hazards several days in advance. To help address this, research is ongoing to improve TC forecast skill. Nevertheless, given the unavoidable uncertainties in such forecasts, complementary efforts are needed.

Thus, we recommend research and development to design new ways of conveying forecasts of TC hazards that are usable in local decisions, at lead times when geographically specific forecast information is highly uncertain. This may involve complementing or moving beyond and current approaches, such as probabilistic forecasts of hydrometeorological parameters, maps depicting the likelihood of exceeding a specified threshold at different locations, or lengthy text products such as the Hurricane Local Statement. Such information formats are useful to some forecast users in some situations, and NOAA has made valuable investments in improving them. However, interviewees and survey respondents noted that these formats continue to raise some challenges, and so important gaps remain. New designs could graphically convey regional risks or, given study participants' discussions of using scenarios for communication and decision making, they could take a scenario-based approach.

➤ **RECOMMENDATION 5: Expand the use of concise, plain-language text highlights in the NWS TC product suite.**

As discussed in Findings 3 and 4, concise, easily understandable text highlights help people quickly comprehend the most important elements of the forecast situation and the latest updates. Thus, one broadcast meteorologist survey respondent recommended: “Simplify, with bullet points, the most important information, in addition to the in depth.” Text highlights provided by NWS also help broadcast meteorologists and emergency managers craft messages for their own audiences. Thus, we recommend that NWS expand the use of such text highlights, in three ways:

- increase the use of easily understandable, prominent text highlights within NWS text products and forecaster services;
- consider adding plain language text highlights to NWS graphical products that are widely used by non-meteorologists, to emphasize key information and support effective interpretation and use of more complex or more technical information; and
- extend the “key messages” concept to all TC-affected WFOs so that, collectively, NWS is providing all potentially affected regions with readily accessible, locally relevant messaging beginning several days or more prior to anticipated impacts.

“Simplify, with bullet points, the most important information.”

- Broadcast meteorologist

Regarding extending the “key messages” concept to WFOs, such a product might not have the same name or format as the current NHC Key Messages. Rather, we recommend extending the *concept*: a widely recognizable, quickly understandable, and easily disseminated product that provides key graphical information accompanied by easily understandable text highlights conveying forecasters’ interpretations of the most important information for the region.

➤ **RECOMMENDATION 6: Continue to support and strengthen the contributions of NWS forecasters’ expertise, interpretations, and relationships with NWS partners.**

As discussed in Finding 3 and shown in Figure 4, *the interview and survey analyses demonstrate the multi-faceted value of the human dimension of NWS information and services, i.e., of NWS forecasters*. Consequently, we recommend that efforts to modernize the TC product suite continue to capitalize on NWS forecasters’ expertise and interactions with partners along with providing improved products and data. This means recognizing and valuing forecasters’ ability to distill complex, uncertain data into situationally relevant, readily interpretable information. It means valuing and enhancing forecasters’ ability to craft this information into concise, plain language text highlights and to communicate it effectively in conversations and digital interactions with NWS partners and members of the public. And, it means recognizing the potential of human relationships to augment and amplify the impacts of data and information, and to provide a trusted source for addressing potential misunderstandings.

The importance of NWS forecasters providing information and interpretations for emergency managers is already widely appreciated and a core component of NOAA’s transition to impact-based decisions support services. Nevertheless, some emergency managers indicated that there are areas for improvement; for example, one emergency manager survey respondent wrote: “We, both sides of this, need to find a way to walk a few miles in the other's shoes so we better understand how your information can flow into my actions.” Since broadcast meteorologists are also key NWS partners, NWS might consider how to improve decision support for this group, in

the context of their roles in accessibly communicating forecast and warning information with a broad audience.

➤ **RECOMMENDATION 7: Develop an improved TC summary product and new ways for people to access all available NWS products related to a given TC.**

As discussed in Finding 4, this research identified two distinct issues with the usability of the current NWS TC product suite: easily finding and accessing available information, and quickly synthesizing and communicating it. Thus, as shown in Figure 6, broadcast meteorologists and emergency managers were overwhelmingly positive about two possible changes to help them understand and convey the most up-to-date, relevant information about a TC threat. The first is a new or improved summary product that compiles key hazard and risk information about a storm. This would likely take the form of an NWS graphic that updates or replaces other products that are currently used for this purpose, such as the NHC Track Forecast Cone, NHC Key Messages, and the WFO Hurricane Local Statement. Such a graphic could be national, or it could have several regional versions providing a situational overview along with key hazard information for different areas (consistent with Recommendation 9). The second change is an interactive website, easy-to-navigate central location, or other tool or service where people can easily obtain all relevant NWS information related to a storm. These improvements are complementary, with each fulfilling different aspects of NWS partners' needs.

Developing such products and services effectively is challenging, because it requires balancing different audiences' needs for different types of information. It also requires balancing audiences' desire for simplicity and understandability with the complexity and diversity of TC forecast and warning information. Nevertheless, the interview and survey data suggest that incorporating these developments into modernization of the TC product suite could help accelerate the value of a wide range of NOAA-generated TC products and data.

➤ **RECOMMENDATION 8: At greater than 5 days of lead time, develop a new product or service that communicates information about possible TC tracks and scenarios using curated, interpreted ensemble numerical model output.**

A key gap that we identified in the TC product suite was improved information about possible TC tracks and threat scenarios at more than five days of lead time (Finding 5). Given the uncertainty in TC track and intensity forecasts at these lead times and the misunderstandings associated with the Track Forecast Cone, we do not recommend extending current TC track forecasts and their depiction in the Track Forecast Cone to longer lead times, at least with current forecast skill. Instead, *we recommend developing a new graphical product or interactive service that complements the already-popular NHC Tropical Weather Outlook and Track Forecast Cone products by leveraging a type of information and graphical format that broadcast meteorologists, emergency managers, and the public are already familiar with: ensemble numerical model output in the form of spaghetti plots.*

One concern among meteorologists is that people can use model output without knowing that some model solutions are unrealistic, contributing to misinterpretations or unnecessary alarm when TC forecasts are still highly uncertain. However, spaghetti plots are now commonly shown in the media, and so having forecasters with deep expertise about TCs create them could be a beneficial addition to this space. This could take the form, for example, of visuals that depict

multiple potential TC evolutions using curated model output, accompanied by forecaster annotation or interpretations indicating scenarios and uncertainties.

- **RECOMMENDATION 9: At less than 5 days of lead time, enhance the provision and communication of regional and local information about potential TC hazards, information about TC hazard timing, and TC-specific information about coastal flood risks at 48-120 hours of lead time.**

As articulated in Finding 6, another key need is improved information about potential TC hazards and impacts at less than five days of lead time. Our analysis identified three more specific areas for improvement. One is *developing improved graphical products or interactive services that provide regionally and locally interpretable TC hazard forecasts*. NWS already has products that convey the risk of TC hazards at different locations, such as WFO Hurricane Threat and Impact Graphics, Potential Storm Surge Flooding Maps, Wind Speed Probabilities, SPC and WPC graphics, and Hurricane Local Statements. However, some interviewees and survey respondents noted issues with these products, including difficulty understanding which hazards and impacts might occur in different areas and not having the information at the lead times needed for decision making. Thus, this gap in the TC product suite remains important to fill.

Second, many broadcast meteorologists and emergency managers indicated interest in additional information about anticipated hazard timing. This suggests that expansion of TC hazard timing forecasts beyond the current Arrival Time of Tropical Storm Force Winds products would be beneficial. However, some study participants said that they experience difficulties using the current Arrival Time products, which should be considered prior to expanding the concept. In addition, study participants expressed interest in multiple types of timing information, including onset, cessation, and duration of different types of hazards. Although emergency managers can currently access some of this information in HURREVAC/HVX, this does not meet the needs of emergency managers who prefer not to or are unable to use this service. Therefore, *additional research and development is needed to understand what timing information is the most useful to different audiences and how to most effectively convey it*.

A third needed improvement, which is especially important in coastal regions at risk from storm surge, is TC-specific coastal flood risk information at greater than 48 hours of lead time. As part of efforts to address this issue, NHC provides storm surge hazard maps for use in longer-lead-time planning and operations, and NOAA is working on reducing uncertainty in storm surge forecasts and extending existing TC-specific surge forecasting capabilities to 72 hours. However, when asked when during a TC threat forecasts of storm surge or coastal flooding are most important for their emergency management decisions, the most commonly selected time frames among coastal emergency managers surveyed were 120–72 and 72–48 hours prior to impacts¹². This suggests that, at least for some emergency managers, information even earlier than 72 hours is needed. As one emergency manager interviewee said, it is at “120 hours that we have to start making real decisions that cost real money, that affect real people.” Moreover, the inherent uncertainties in location-specific storm surge predictions and the feedback provided by

It is at “120 hours that we have to start making real decisions that cost real money, that affect real people.”

- Emergency manager

¹² See section 4.2.2 (Figure 4.4 and Table 4.1) in the survey report.

our interviewees indicate that additional storm surge risk communication strategies are needed. Consequently, in addition to continuing to pursue these efforts, *we recommend that NOAA and the research community develop alternative product formats for conveying storm surge risks at longer lead times, with an emphasis on providing the best possible information for supporting the public safety decisions made as a TC threat evolves.*

STRATEGIC MODERNIZATION OF THE TC PRODUCT SUITE

The methodology used in this project highlights the potential benefits of a strategic, decision-focused approach to modernizing NOAA forecast information and services. To support NOAA in moving forward, we conclude this report by recommending several principles that provide the foundation for such a strategy. Additional valuable guidance for such efforts can be found in recent community-developed reports, including the National Academies report on *Integrating Social and Behavioral Sciences in the Weather Enterprise* (NASEM 2018) and the NOAA Science Advisory Board report on *Priorities for Weather Research* (NOAA SAB 2021).¹³

Principles for ongoing strategic modernization include:

1. Identify the types of users and decision makers that different components of the NWS product suite are intended to support, and engage them to understand their decision timelines, information use processes, opportunities, and constraints.
2. Utilizing this understanding, regularly examine opportunities to improve how the collection of NOAA information and services meets key users' decision timelines and information needs, as these evolve alongside predictive capabilities and technology.
3. Co-design new and updated NWS products and services with users and with predictive and technological experts, employing interdisciplinary methods that integrate meteorology, social and behavioral sciences, and other relevant expertise. Doing so will help ensure that new products and services not only are meteorologically sound and technologically feasible, but also are applicable to users' decision contexts and can be integrated into their job activities.
4. Before operationalizing new or revised products and services, evaluate them with the users they are intended to serve, employing robust assessment methods that are consistent with basic tenets of risk communication. Incorporate relevant intermediaries, such as private sector vendors of broadcast meteorologists' software systems, into such efforts so that the resulting information is not only potentially useful and usable but also used.
5. Consider investments in improving TC information and services with the aim of enhancing the value for users' decisions and improving broad societal outcomes. When doing so, take into account how information use and decision making vary across locations and time relative to storm progression and among users, including underserved populations. This is critical for increasing accessibility and usability of information for populations with different needs and capacities, enhancing equity and information reach.
6. When developing and evaluating proposed changes, draw on, connect, and triangulate

¹³ See chapter 5 (p. 95–107) in NASEM (2018) and the Mission Critical Mile theme (p. 20–21) and Priority Area 2 (p. 61–66) in NOAA SAB (2021).

findings across research studies that explore a variety of NOAA products and services. This enables identification of synergies and ensures that changes are based on the best available knowledge and a range of relevant perspectives.

These principles are consistent with the recommendations in NOAA SAB (2021), which articulates the importance of (a) a paradigm shift to a more agile, user-centered approach to development and provision of weather information and (b) iterative collection and analysis of the data required to inform this approach and to formulate improvements that meet users' needs. To achieve its goals, NOAA must continue to evaluate how well the collection of NWS information and services is supporting a variety of users and integrate across relevant knowledge and perspectives to prioritize investments over the near- and longer-term.

Acknowledgments

The authors thank the interviewees and survey respondents for contributing their time and knowledge, along with our NOAA colleagues and project advisors. We are especially grateful to Robbie Berg, Gina Eosco, Jessica Schauer, Jennifer Sprague-Hilderbrand, Castle Williams, Michael Brennan, Frank Marks, Shirley Murillo, Micki Olson, Valerie Were, Nate Johnson, Rebecca Moulton, Andrea Schumacher, Alyssa Cannistraci, Robert Prestley, and the NEMA Hurricane Subcommittee. We also thank Jennifer Boehnert for creating Figure 2.

This study was funded by NOAA awards NA19OAR0220121 and NA19OAR0220192. This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977. Views and opinions in this document are those of the authors.

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