# Improving Tropical Cyclone Forecast Communication by Understanding NWS Partners' Decision Timelines and Forecast Information Needs

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ABSTRACT: As tropical cyclone threats evolve, broadcast meteorologists and emergency managers rely on timely forecast information to help them communicate risk with the public and protect public safety. This study aims to improve the usability and applicability of National Weather Service (NWS) forecast information in the context of these NWS core partners' decisions during tropical cyclone threats. The research collected and analyzed data from in-depth interviews with broadcast meteorologists and emergency managers in three coastal U.S. states. These data were used to analyze broadcast meteorologists' and emergency managers' tropical cyclone decision and action timelines, their use of tropical cyclone information during different phases of threats, and gaps in forecast information for decision-making. Based on these findings, several opportunities for improving tropical cyclone risk communication were identified. Recommendations to address gaps in the NWS tropical cyclone product suite include designing improved ways to communicate storm-specific storm surge risk at greater than 48 h of lead time, expanding the use of concise highlights that help people quickly extract and understand key information, and improving product understandability and usability by more comprehensively integrating users' perspectives into product research and development. Broader strategic recommendations include developing new approaches for informing broadcast meteorologists about major forecast updates, presenting forecast information in ways that enable locally relevant interpretation, and supporting human forecasters' contributions to the effectiveness of NWS products and services. These findings and recommendations can help NOAA prioritize ways to modernize the current NWS tropical cyclone product suite as well as motivate research to enable longer-term high-priority improvements.

SIGNIFICANCE STATEMENT: Tropical cyclones pose significant risks to coastal and inland U.S. populations. This project aims to improve creation, communication, and use of tropical cyclone forecast and warning information by studying broadcast meteorologists' and emergency managers' information needs for decision-making during different phases of tropical cyclone threats. We identify several priority areas for improvement, including advancing longer-lead-time storm surge forecast communication, enhancing dissemination of forecast updates, and increasing use of concise text highlights. Additional findings include the importance of locally interpretable forecast information, the value of human forecasters in weather risk communication, and the need for iterative, user-informed forecast product development. These findings can help NOAA and the research community improve forecast communication and invest in research that facilitates continued improvements.

KEYWORDS: Social Science; Hurricanes/typhoons; Tropical cyclones; Forecasting; Broadcasting; Communications/decision making; Emergency preparedness

## 1. Introduction

When a tropical cyclone[1] (TC) threatens the United States, broadcast meteorology and emergency management professionals act as key partners to NOAA's National Weather Service (NWS) in communicating the complex forecast information available and translating that information into protective actions. Although the NWS originates much of the weather forecast and warning information available in the United States, most members of the public see and hear TC and other weather forecast information from non-NWS sources, including broadcast meteorologists (Lazo et al. 2009; Milch et al. 2018; Sherman-Morris et al. 2020). Using information from the NWS and other sources, emergency managers play critical roles in informing people about approaching TC risks and making community preparation and response decisions (Demuth et al. 2012; Bostrom et al. 2016). Together, these groups provide a foundation for the TC forecast and warning system, whose broader common goals include saving lives and reducing property loss and other harm (Mileti and Sorensen 1990; Gladwin et al. 2007; Lindell et al. 2007; Demuth et al. 2012; Bostrom et al. 2016).

This study aims to enhance the effectiveness of the forecast and warning system by helping NOAA improve its TC risk communication with these key partners. In particular, we investigate how, over the shorter and longer term, NOAA

[1] We use the term "tropical cyclone" to include a variety of types of tropical cyclones that may pose threats to the United States, including hurricanes.

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can improve the collection of TC forecast and warning products, information, and services provided by the NWS,[2] referred to by NOAA as the *TC product suite* (NOAA 2019). To do so, we take a forward-looking perspective on the TC product suite as a whole, using a decision- and user-centered approach (Argyle et al. 2017; Demuth et al. 2020). Using data collected from semi-structured interviews with broadcast meteorologists and emergency managers in TC-affected areas of the contiguous United States, this article addresses three research questions:

1) What are broadcast meteorologists' and emergency managers' primary decisions and actions during different phases of TC threats?
2) What NWS TC products and other TC information do broadcast meteorologists and emergency managers use in different phases of threats?
3) What are broadcast meteorologists' and emergency managers' key unmet needs related to TC forecast and warning information?

We then use the in-depth knowledge gained to identify key information gaps and develop research-guided recommendations. This includes recommended priorities for modernizing the TC product suite over the next few years, as well as strategic recommendations for long-term investments in TC forecasting and risk communication. Our research team collaborated with a core team of NOAA research and NWS personnel[3] to develop the study approach, design the methods, and translate the findings into usable recommendations. An additional goal of the interviews was to build foundational knowledge for designing and implementing surveys with broader populations of broadcast meteorologists and emergency managers, which will be reported on in future work (Vickery et al. 2022).

By investigating these questions, this study advances the body of knowledge in hazard risk communication, decision-making, and warning systems in several ways. Although the literature on how members of the public interpret and respond to TC forecasts and warnings has grown rapidly over the last decade, fewer studies have focused on NWS partners in the TC warning system. Much of the previous research on U.S. emergency management decision-making during TCs focuses around evacuation order decisions (e.g., Lindell and Prater 2007; Dye et al. 2014; Gudishala and Wilmot 2017; Hoekstra and Montz 2017a,b). Evacuation orders are important because, for some members of the public, they are a major motivator for taking protective action when a TC approaches (e.g., Gladwin et al. 2001; Demuth et al. 2018). Emergency managers may make evacuation order decisions or provide advice to elected officials making those decisions. One particular emphasis of prior research is the timing of general population evacuation orders, because it is challenging to issue evacuation orders for as few areas as possible, but far enough in advance to enable everyone at risk to get to safety, given clearance times[4] and forecast uncertainties. Complementing prior research focused on evacuation order decisions, it is also important to develop process-oriented understandings of a broader range of emergency managers' decisions and actions. This includes investigating the decisions that lead up to and follow evacuation orders and the information used to inform those decisions, across a variety of jurisdictions and TC situations. Here, we do so by investigating how emergency managers working in different types of jurisdictions assess risks and coordinate public safety throughout the life of TC threats, in the context of evolving forecast information and decision-making (Wolshon et al. 2005; Morss and Ralph 2007; Bostrom et al. 2016; Morss et al. 2017; Hoekstra and Montz 2017b).

Many state and local emergency plans contain recommended guidelines and schedules for emergency management decisions during TC threats (Urbina and Wolshon 2003; Wolshon et al. 2005; FEMA 2013; Gudishala and Wilmot 2017; National Hurricane Program 2017), and these inform our work. However, such decisions require managing complex, intersecting uncertainties and thus involve significant judgment within general established procedures (Wolshon et al. 2005; Hoekstra and Montz 2017a). Moreover, emergency managers update their decision processes as forecasts improve, enabling longer-lead-time decisions, and as other influencing factors change. Consequently, another way in which our study contributes to the literature is by seeking to understand emergency managers' current perspectives on their actual decision timelines and priority forecast information needs, complementary to written emergency plans.

In comparison with emergency managers, there have been fewer studies of broadcast meteorologists during TCs. Daniels and Loggins (2007) and Prestley et al. (2020) investigated how television meteorologists communicate with the public during TC threats, but they did not examine the research questions of interest here, and they focused primarily on high-impact periods near landfall. Other research has examined broadcast meteorologists together with emergency managers and NWS forecasters in the context of their roles and interactions within the TC warning system (Demuth et al. 2012; Anthony et al. 2014; Bostrom et al. 2016). This research noted the importance of effective coordination among these groups and the NWS, as well as the tensions and tradeoffs of managing uncertainties. It therefore recommended further efforts to

[2] This article focuses on TC information for the Atlantic Basin provided by several groups within the NWS structure, including three national centers within the NWS National Centers for Environmental Prediction—the NHC, WPC, and SPC—as well as River Forecast Centers and local NWS WFOs. WFOs are organized within NWS regional headquarters (e.g., Eastern Region, Southern Region) and focus on a multicounty warning area of responsibility (see, e.g., https://www.weather.gov/about/nws). Collectively, we refer to these groups as NWS.

[3] This core NOAA team included the NWS tropical services program leader, an NHC hurricane specialist, and additional NWS staff, as well as staff in the Weather Program Office's Social Science Program and the Atlantic Oceanographic and Meteorological Laboratory within NOAA's OAR.

[4] Clearance time is the expected number of hours required to move the at-risk population in a geographic area to safety.

"evaluate, test, and improve the NWS product suite through collaborations among warning system partners and with social scientists" (Demuth et al. 2012, p. 1142), which the study discussed in this article helps to fulfill.

Our study also builds on prior work to understand and improve how NWS partners interpret and use specific NWS TC forecast and warning products. Findings from this prior work include the importance of developing NWS products that are more easily understood, visually appealing, and locally relevant, as well as emergency managers' interest in receiving TC storm surge and flood forecast information earlier (Safford et al. 2006; Losego et al. 2012; Morrow and Lazo 2014; Morrow et al. 2015; Hogan Carr et al. 2016; Hoekstra and Montz 2017b; Munroe et al. 2018). Here we examine whether these product improvements are still priorities given recent changes to the NWS product suite. We also expand this work beyond modifying specific TC product types to investigating priority needs for modernizing the TC product suite as a whole.

Section 2 describes the study methods, and sections 3 and 4 present findings pertaining to research questions 1 and 2 above. Section 5 addresses research question 3, highlighting key information gaps identified by our analysis and associated recommendations, followed by conclusions in section 6.

## 2. Methods

Our study focused on broadcast meteorologists and emergency managers because of their essential, sustained roles in fulfilling the NOAA and NWS missions when a TC threatens the United States. As depicted in Fig. 3 of Uccellini and Ten Hoeve (2019), broadcast meteorologists are *core partners* to the NWS, that is, "government and non-government entities who are directly involved in the preparation, dissemination, and discussions involving National Weather Service information that supports decision making," and emergency managers are *deep relationship core partners*, that is, a subset of core partners that includes "government officials responsible for public safety" (p. 1931; see also NWS 2018). Within the broader weather enterprise, which also includes academia and others in private industry, government, and nongovernmental organizations (NWS 2019, p. 6), broadcast meteorologists and emergency managers serve as vital conduits between the NWS and other core partners, general partners, and members of the public, helping "amplify NWS's message" and its influence on decision-making (Uccellini and Ten Hoeve 2019, p. 1931). Thus, from the perspective of our NOAA collaborators, input from these groups was critical for making decisions about modernizing the TC product suite, complementing other recent and ongoing social and behavioral science research.

### a. *Interview sample and implementation*

Data were collected from 17 in-depth interviews with 20 participants[5] in coastal and inland communities in two TC-prone regions of the United States, the Gulf Coast, and the southeastern U.S. Atlantic Coast, as shown in Table 1. We selected these two regions and the states within them, in collaboration with NOAA, for their variability in terms of TC risks and vulnerabilities, recent TC experiences, social and cultural factors, and governmental structures for evacuation order decision-making. Interviews were conducted in a mix of metropolitan and less-populated areas, along the coast and inland, consistent with our goal of developing foundational knowledge that could be used to design surveys relevant to broader samples of broadcast meteorologists and emergency managers in the Atlantic TC basin. Our initial study plan included interviews in a third region, the New York/New Jersey area, but we were unable to conduct these interviews because of the COVID-19 pandemic as explained below.

TABLE 1. Number of broadcast meteorologist and emergency manager interviewees by state.

| State | Broadcast meteorologists ($n$ = 7) | Emergency managers ($n$ = 13) |
|---|---|---|
| Georgia | $n$ = 3 | $n$ = 5 |
| South Carolina | $n$ = 2 | $n$ = 2 |
| Texas | $n$ = 2 | $n$ = 6 |

The broadcast meteorologist interviewees worked at local television stations in either a chief meteorologist or morning meteorologist role. Their experience in this type of job ranged from 10 to more than 30 years. Emergency manager interviewees worked in job roles such as public safety director, emergency management coordinator, or district coordinator, with jurisdictions at the city, county, regional (within state), or state level. Their experience in this type of job ranged from 6 to 50 years.

The interviews were conducted in person and by phone in February–March 2020. Several additional interviews in the two sampled regions were planned, as well as interviews in a third region as noted above. However, the rapidly evolving COVID-19 pandemic created difficulties for recruiting additional interviewees and scheduling interviews, forcing us to stop interview data collection in mid-March 2020. The interviews lasted 45–120 min (median of 66 min). Each interview was audio recorded and professionally transcribed for analysis.

### b. *Interview guide*

The interview guide included questions adapted from previous work to understand professionals' weather-related decisions and information use (Demuth et al. 2012; Morss et al. 2015, 2022; Bostrom et al. 2016), as well as new questions for this study developed in discussion with our core team of NOAA collaborators, based on NOAA research and NWS interests related to the study. A draft version of the interview guide was pretested with one broadcast meteorologist and one emergency management professional prior to conducting the interviews used in the analysis. Interviewees were asked to talk about a variety of types of TC threats or events, ranging from a tropical depression or tropical storm to a category-5

[5] Fourteen interviews had one interviewee, and three interviews had two interviewees.

| TC product | Product source | Product description |
|---|---|---|
| **Graphical Tropical Weather Outlook** | NWS National Hurricane Center | Map depicting the TC formation potential of current and future tropical disturbances during the next 2 or 5 days. |
| **Track Forecast Cone** ("Cone of Uncertainty") | NWS National Hurricane Center | Map depicting the probable track of the center of a TC during the next 5 days, along with its forecasted intensity, watches/warnings, and other information. |
| **Tropical Cyclone Wind Speed Probabilities Graphic** | NWS National Hurricane Center | Map depicting the probability of sustained surface winds of at least 39 mph (tropical storm), 58 mph, or 74 mph (hurricane) at different locations during the next 5 days. |
| **Arrival of Tropical-Storm-Force Winds Graphic** | NWS National Hurricane Center | Map depicting the forecasted Earliest Reasonable or Most Likely time of onset of sustained 39 mph winds at different locations during the next 5 days. |
| **Key Messages Graphic** | NWS National Hurricane Center | Graphic with text highlights about a TC's forecast and hazards, along with relevant NWS graphical TC products. |
| **Tropical Cyclone Public Advisory** | NWS National Hurricane Center | Text product containing a list of all current watches and warnings for a TC, along with the storm's position, current motion, intensity, and other information. |
| **Potential Storm Surge Flooding Map** | NWS National Hurricane Center | Map depicting the risk of coastal flooding from storm surge at different land locations, issued within 48 hours of anticipated impacts along the U.S. coast. |
| **Storm Surge Watch/ Warning Graphic** | NWS National Hurricane Center | Map depicting areas where there is a possibility (watch) or danger (warning) of life-threatening storm surge in the next 48 or 36 hours, respectively. |
| **Excessive Rainfall Outlook Graphic** | NWS Weather Prediction Center | National map depicting the risk of potentially flooding rainfall at different locations during the time indicated (e.g., Day 1, Day 2, Day 3). |
| **Convective Outlook Graphic** | NWS Storm Prediction Center | National map depicting the risk of severe convective weather at different locations during the time indicated (e.g., Day 1, Day 2, Day 3). |
| **Hurricane Local Statement** | NWS Weather Forecast Offices | Text product containing a list of watches/warnings, potential hazardous conditions and impacts, and other information about a TC for a local area. |
| **Hurricane Threats and Impacts Graphics** | NWS Weather Forecast Offices | Set of regional maps depicting the risk of TC-related hazardous wind, storm surge, flooding rain, and tornadoes at different locations, issued within 48 hours of anticipated impacts in the region. |

FIG. 1. NWS TC-related products presented to interviewees, as described in section 2b. Product descriptions were obtained online from NOAA (noaa.gov and weather.gov). A version of the figure with examples of the products is available in the online supplemental material.

hurricane, along with different types of associated hazards (e.g., strong winds, storm surge, heavy rainfall, tornadoes).

After questions about their job roles and experience, interviewees were asked a series of questions about their decisions and actions, forecast information use and sources, and recommendations for improved forecast information during each of three phases of TC threats: 1) from when they first become aware of a threat until about 5 days out from when a storm is expected to affect their area, 2) from about 5 days to 48 h out, and 3) from about 48 h out until landfall or impacts. These time frames were selected based on the literature review and pretests; we invited interviewees to adjust the time frames based on what made sense in their job context, but none did so. We then asked interviewees about exceptions to their typical TC timeline, information they use about specific TC hazards, individuals or communities in their region that are particularly vulnerable to TCs, and management of uncertainties and inconsistencies in forecast information and decision-making.

Next, interviewees were presented with a set of 12 NWS TC product examples (Fig. 1) and asked which they use, which they find most useful, and why. We selected this set of products, with guidance from our NOAA collaborators, to represent different types of key forecast and warning information within the NWS TC product suite. It includes TC-related products issued by the National Hurricane Center (NHC), the Weather Prediction Center (WPC), the Storm Prediction Center (SPC), and local weather forecast offices (WFOs) across the lifetime of a TC threat.[6] Last, we asked interviewees about possible improvements to the product

[6] NHC focuses on hazardous tropical weather, including TCs; its TC track, intensity, and size forecasts underpin most TC hazard forecast and warning information generated by NHC itself (e.g., the Storm Surge Unit), other NWS national prediction centers, and WFOs. In the context of TCs, WPC and SPC provide information focused on TC-related hydrometeorological (e.g., heavy rainfall) and convective (e.g., tornado) hazards, respectively. WFOs provide more localized weather products and information focused on their area of responsibility.

suite and additional TC forecast information they would like to have.

### c. Interview data coding and analysis

The qualitative coding and analysis were performed in NVivo, with the goal of integrating project-driven objectives with data-driven insights. First, two members of the research team read through all 17 interview transcripts and designed an initial hierarchical coding scheme that combined key concepts in the interview questions and project goals with those mentioned by interviewees. The two researchers then went through two stages of testing and refining the coding scheme, with each stage consisting of independently coding two transcripts (one broadcast meteorologist and one emergency manager), comparing the coded transcripts, discussing discrepancies, and revising the coding scheme. The two transcripts independently coded in the second stage were used to evaluate intercoder reliability.

The coding scheme included 67 codes: 59 subcodes within four high-level codes (decisions and actions,[7] forecast and other meteorological information, TC hazards and characteristics, and TC time frame) and four additional codes (at-risk populations, public messaging and decision making, job roles, and miscellaneous). Eleven of these 67 were either inferential codes designed to mark excerpts for later analysis of latent constructs (Miles and Huberman 1994) or codes used for marking miscellaneous content not listed in the coding scheme; the remaining 56 codes were used to evaluate intercoder reliability at the paragraph level, with sub codes aggregated to higher-level codes. Cohen's kappa was 0.8 or higher for 34 (61%) of these codes and was between 0.65 and 0.8 for an additional 9 codes (16%). The only codes with kappa $\leq$ 0.5 were used five or fewer times by the two coders. The full coding scheme and intercoder reliability results are provided in the online supplemental material.

After assessing intercoder reliability, the researchers discussed and addressed discrepancies, with a focus on clarifying the definitions of codes that had lower intercoder reliability or had been used few times. Next, the final coding scheme was used by one researcher to adjudicate the four cross-coded transcripts and code the remaining 13 transcripts. We then systematically analyzed the interview data by compiling excerpts associated with different codes and synthesizing findings. To illustrate key points, we use anonymized quotes[8] accompanied by an identifier indicating the interviewees' job type [emergency manager (EM)/broadcast meteorologist (BR)], location [Texas (TX)/South Carolina (SC)/Georgia (GA)], and interview order (e.g., BRTX1, or EMTX4&5 for an interview with two participants).

Although sometimes interviewees specified from which NWS entity they were obtaining information, often they discussed NWS more generally. They also sometimes referred to obtaining information or products generated by one NWS entity in the context of another NWS entity, for example, by discussing information that is typically originated by a national center in the context of communication with a local office. For these reasons as well as our focus on the NWS TC product suite as a whole, much of the paper refers to NWS forecast information and products more generally rather than information from specific groups within the NWS. Our approach is consistent with the NWS's emphasis in recent years on improving coordination and consistency of forecast and warning messaging across the organization (NWS 2019; Uccellini and Ten Hoeve 2019).

## 3. NWS partner decision and action timelines

This section analyzes broadcast meteorologists' and emergency managers' decisions and actions during three phases of TC threats: 1) monitoring and awareness, 2) readiness and action, and 3) transition to impacts and response. These phases, summarized in Fig. 2, were distilled from the interview data, emergency management planning materials, and previous literature (e.g., Morss and Ralph 2007; Gudishala and Wilmot 2017; Hoekstra and Montz 2017b). They mirror the three time frames used in the interview guide, but we discuss them in terms of decision and action themes to provide a more general framework that accounts for a wider range of TC situations.

With different TC situations in mind, the timing of the three phases in Fig. 2 is not absolute but relative to anticipated TC impacts in a decision-maker's jurisdiction.[9] Depending on the storm, the first phase can be short or last for many days. With current forecast skill, the second phase typically begins about 5 days before TC impacts, and the third phase about 48 h before impacts. However, these phases can begin earlier or later depending on the forecast uncertainty and how close to the United States a TC forms or significantly intensifies. The time frames corresponding to the three phases are also determined in part by current predictive capabilities for TCs and the associated availability of different NWS TC products at different times; consequently, the time frames for decision-making have shifted as forecasts have improved.

These timelines and associated descriptions are for those in regions that continue to be at risk as a TC approaches. Others may start in phase 1 of the timeline but then shift to other activities as the area at risk narrows and no longer includes their region. Unless otherwise noted, findings presented throughout the article reflect key themes in the interview data, across multiple interviewees.

[7] We phrased the interview questions in terms of decisions and actions and kept these together in the coding scheme because in some cases interview pretesters and interviewees discussed the actions they take at different times corresponding to their decisions, rather than explicitly referencing the decisions they make that lead up to those actions.

[8] Quotes are verbatim, except for removal of filler words.

[9] Some emergency manager interviewees discussed their decision timelines using reference points in their emergency plans, such as operating conditions (OPCONs), which correspond to different levels of readiness and alert, or time to evacuation (E-hours) or TC impacts (H-hours). However, all emergency managers said that a key driver of their timelines was completing evacuations and preparations prior to the arrival of TC conditions that will threaten the safety of their own personnel and others outside or in vehicles. Thus, to provide a common framework across emergency managers, we discuss timelines relative to arrival of TC impacts.

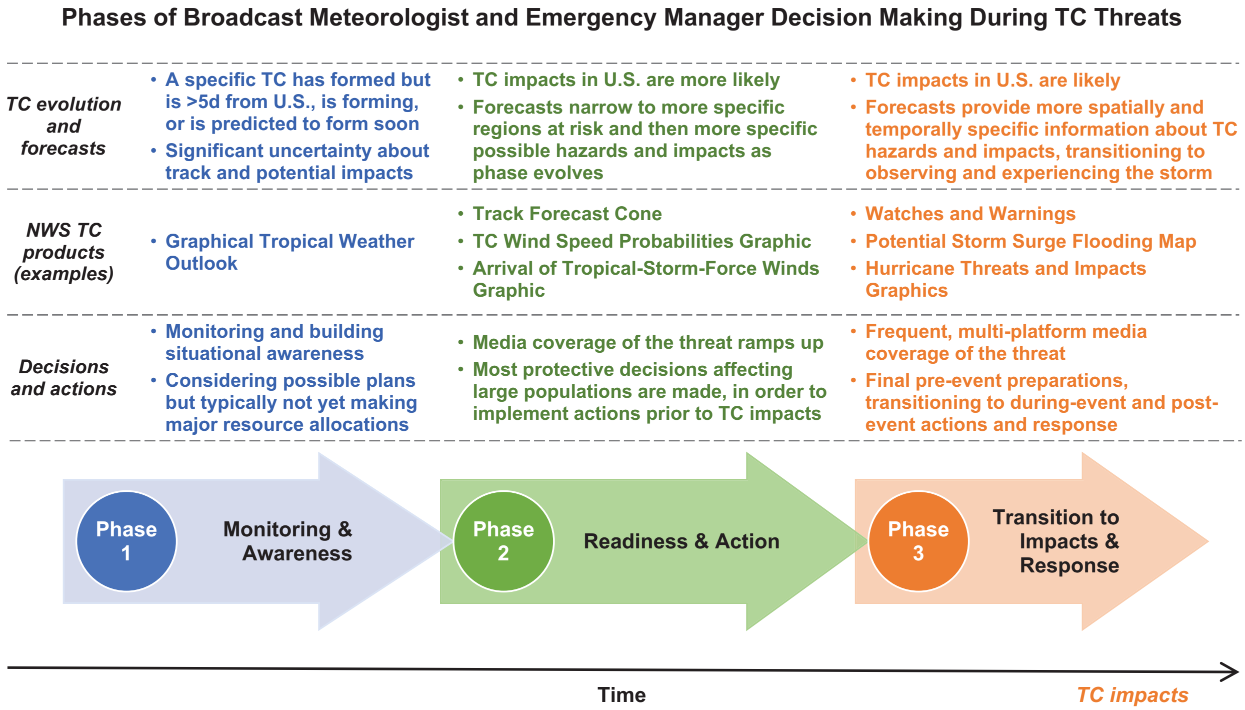


FIG. 2. Overview of the three phases in the NWS partner decision and action timelines, including the characteristics of TCs and their forecasts, example NWS TC products, and a synthesis of decisions and actions that are typical within each phase, as described in section 3. Examples of the TC products listed are shown in Fig. 1.

### *a. Broadcast meteorologist decision and action timeline*

Broadcast meteorologists discussed three intersecting types of activities that they engage in during TC threats: information gathering and interpretation, communication and engagement with public audiences, and communication and preparation within their station. An overview of these activities in different phases of TC threats is provided in Fig. 3, and illustrative quotes are presented in Fig. 4.

Across the timeline, broadcast meteorologists' information-gathering and interpretation activities focused on receiving and seeking TC-related information from the NWS and other sources, and comparing and interpreting the information to synthesize key aspects of TC threats. They do so by using software from private sector vendors that enables them to access and process NWS data, as well as in other ways for information accessed outside their vendor platforms. Broadcast meteorologists use this information to provide media coverage of evolving threats, in other words, to communicate about TC threats with viewers and other audiences through multiple media platforms, including television, station websites and apps, and social media. Because in most situations they convey information visually as well as verbally, much of their communication involves graphics, especially graphics adapted from NWS products or designed in house using NWS and other data. Internally, they communicate and collaborate with staff and management to decide how to cover the situation and prepare their station.

Other than emergency preparation to keep station staff safe, broadcast meteorologists' TC-related activities focus around providing up-to-date media coverage of evolving TC threats. Therefore, their TC timelines are driven primarily by when, during the lifetime of a storm, different TC information (e.g., different types of NWS products, forecast model output, and observations) is typically available (Figs. 1 and 2).

Broadcast meteorologist interviewees explained that their primary goals are to provide audiences with clear, accurate, credible information that is consistent across shifts and station personnel, and to tell people to remain aware and prepared. Within the weather community, concerns have been raised about broadcast meteorologists conveying information differently for marketing and branding reasons (Williams and Eosco 2021). However, many interviewees said that they aim to provide forecast information that is consistent with official NWS sources so as not to create divergent or inconsistent messaging that may cause confusion. For example, one described how they look at NWS briefings and other information and consult with the local NWS office to "try to relay a similar message" (BRSC1); another explained that although they "assess the situation from our own perspective . . . we always show the Hurricane Center's forecast; we don't deviate from that" (BRTX1).

#### 1) PHASE 1

During the first phase of their timeline, broadcast meteorologists described their primary decisions and actions as watching

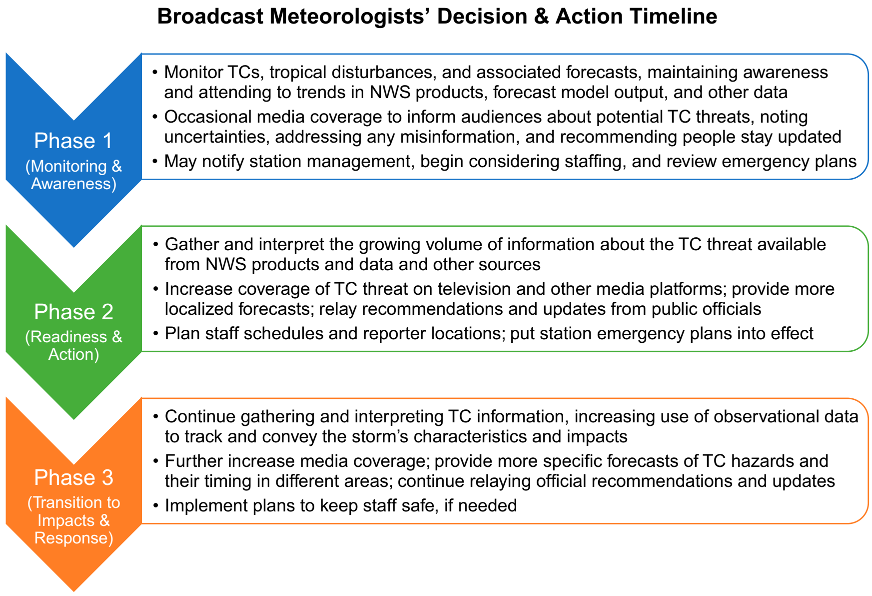


FIG. 3. Overview of broadcast meteorologists' major decisions and actions during TC threats, for each of the three phases in the timeline depicted in Fig. 2. Additional information about each of the activities shown is provided in section 3a, and illustrative quotes for each phase are provided in Fig. 4, below.

storms and forecasts to maintain awareness for themselves, their station, and their audiences, while communicating externally and internally in ways that "try not to get people too anxious" (BMGA1&2) because of the inherent uncertainty with storm development and track at this stage. Their information gathering and interpretation activities focused on tracking tropical disturbances, including current and potential TCs, and assessing their possible future evolution. This includes monitoring trends as well as comparing interpretations among meteorologists within the station and across information sources.

When engaging with the public during this phase, broadcast meteorologists said that they notify their audiences about potential TC threats and recommend that people stay aware because the threats can and will change (Fig. 4). In addition, several interviewees noted that during this phase, they may see or receive questions from members of the public based on what they believe to be misinformation posted on social media, for example, overstatements of the risk that a TC poses to their region based on a model simulation that is highly unlikely or "has known biases in this range" (BRTX1).

**Broadcast Meteorologist Timeline: Illustrative quotes**

***Phase 1: Monitoring and Awareness***

"We'll kind of put a feeler out if it's more than five days out. Say: Hey, it's possible that next week there could be a tropical something coming to the Gulf of Mexico. We're not too concerned about it right now, but we'll keep you informed. … We will use broad strokes to talk about it … and try to give some early guidance or general feel for which direction it may trend. Like right now we don't think it's going to be a threat to the Gulf, or we think this will come to the Gulf and it's too soon to say exactly where." (BRTX1)

***Phase 2: Readiness & Action***

"The closer that it gets to the event, it gets a bit wild at times because you're constantly updating, you're constantly on the air, you're trying to make sure you have the web stuff and your apps updated and fresh … it can get very, very busy." (BRSC1)

***Phase 3: Transition to Impacts and Response***

"When it gets 48 hours to impact, it's what's happening in the state, what's happening in our viewing area, how will it impact us?" (BRSC1)

"A lot of it, within 48 hours, is breaking it down by specific areas. The impacts, whether it's storm surge, wind or rain." (BRGA1&2)

FIG. 4. Illustrative quotes for the three phases in broadcast meteorologists' decision and action timeline (discussed in section 3a and summarized in Fig. 3).

When this occurs, they "spend time batting down rumors" (BRTX1) to reassure people (Bica et al. 2020).

Internally, during this phase broadcast meteorologists may initiate discussions beyond their meteorology team, including station management. They may also "start to meet as a station" (BRSC2) to discuss the forecast situation, review station emergency plans, and consider staffing schedules.

#### 2) Phase 2

Broadcast meteorologists described the second phase as a critical time period during which their TC-related activities ramp up significantly. In particular, if the TC poses a risk to their region, they transition from monitoring into increased action.

As in the first phase, they continue to gather, compare, and interpret TC forecast information from the NWS and other sources, but with growing volume, specificity, and localization of information (Fig. 2). They increase television coverage, for example, through longer weather segments on the news and added cut-ins during programming. They also increase communication on other media platforms, such as sending out app alerts, livestreaming on social media, and posting more updates to their station website and social media (Fig. 4). In addition, as the available forecast information evolves during this phase, broadcast meteorologists shift to communicating more specific information. This includes using more localized reference points for explaining potential tracks and talking through more localized potential hazards and impacts. They described conveying forecast uncertainty by presenting viewers with possible storm scenarios, as well as explaining the "why" behind the forecasts and scenarios. They also relay preparation recommendations, evacuation updates, and other information from emergency managers, law enforcement, and elected officials through the communication mechanisms above as well as broadcasting storm-related press conferences.

Internally, during this phase, broadcast meteorologists discussed having more meetings with management and their weather teams and "starting to get into the nitty gritty of [media] coverage plans" (BRSC1). This includes deciding about staffing schedules and reporter deployment, in coordination with partner stations if additional staff or resources are needed. As the storm gets closer, their station puts its hurricane plans into action to ensure that staff have safe shelter, food, and water during the storm.

#### 3) Phase 3

This phase, as BRSC1 described, "is our Super Bowl." Broadcast meteorologists continue to gather and provide updated forecast, warning, and other official information as it is issued. Their communication and engagement with audiences continues to increase through more frequent or even wall-to-wall (24 h) television coverage, as well as on-screen crawlers, "app" pushes, and website and social media updates. Their emphasis shifts to "giving people much more specific information, with more certainty on where landfall will occur, about the time that it will occur," (BRTX1) as well as forecasts of when hazards and impacts are expected in different areas within their viewer region (Fig. 4). As the storm nears and then begins to affect their area, they also increasingly use observational data (including radar, live news coverage from reporters, and images from members of the public) to track the storm and its impacts and to show viewers what is happening and how it may affect them.

Within their organization, they increase the number of meteorologists on shift to manage their increased media coverage of the storm, and they finalize field reporter deployment. They also continue to implement emergency plans and prioritize the safety of staff, including deciding when to pull reporters out of certain areas or move station staff to safety if needed.

### b. *Emergency manager decision and action timeline*

Emergency managers discussed four intersecting types of activities they engage in during TC threats: information gathering and interpretation; communication, coordination, and advisement within their agency, with elected officials, and with local, regional, state, and federal partners; communication with the public; and evacuation and resource staging. An overview of these activities in different phases of TC threats is provided in Fig. 5, and illustrative quotes are presented in Fig. 6.

Across the timeline, emergency managers' information-gathering and interpretation activities focused on maintaining awareness and obtaining up-to-date forecasts about the storm's track and potential hazards and impacts in their region. Although several interviewees noted that they may look at forecasts from other sources for situational awareness, they reported making most of their decisions using forecast information from the NWS rather than other sources. They interpret and use forecast information on its own and sometimes integrate information into decision-support tools such as the National Hurricane Program's hurricane evacuation system (HURREVAC) and HURREVAC-eXtended (HVX).[10] Emergency managers use this information to communicate about the TC and coordinate evacuations, resource staging, and other preparedness activities across the organizations that provide emergency support functions (ESFs),[11] such as transportation, public works, search and rescue, mass care, and health services. They also communicate with and advise agency leadership, elected officials, and others making decisions that influence public safety, such as educational institutions and businesses. In addition, they may coordinate or

[10] HURREVAC, recently updated to HVX, is a decision-support tool for government emergency managers developed and supported by the U.S. National Hurricane Program. It enables combining TC scenarios and NHC forecasts with emergency management decision timelines, e.g., for evacuation. Although many interviewees discussed using HURREVAC/HVX, two working in a smaller emergency management agency noted that they do not, because they lacked sufficient staff to allocate time for training on the system or for using it during TC threats.

[11] ESFs provide an organizational structure for grouping and coordinating the different types of resources, support, and services that are likely to be needed to prepare for, manage, respond to, and recover from disasters and other emergency incidents.

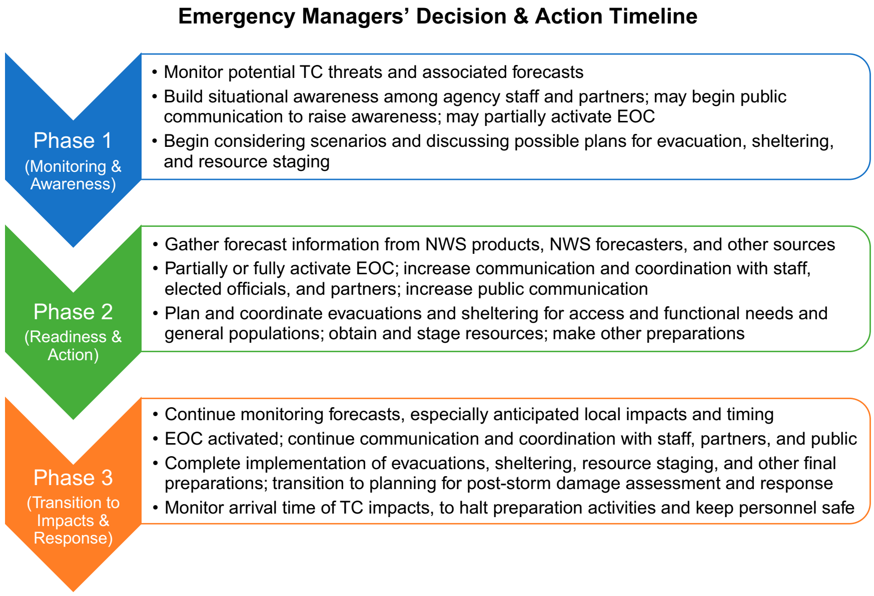


FIG. 5. Overview of emergency managers' major decisions and actions during TC threats, for each of the three phases in the timeline depicted in Fig. 2. Additional information about each of the activities shown is provided in section 3b, and illustrative quotes for each phase are provided in Fig. 6, below.

participate in communication with the public about the risks and recommended actions, for example, through press conferences, social media, and emergency notification systems. Although emergency managers' specific roles in evacuations and other decisions vary based on their level of governance, state, jurisdiction, and job characteristics, this set of activities was relevant across the emergency managers interviewed.

These activities focus around informing and protecting the public. Emergency managers' information use timeline is therefore driven by both when different types of information are available and how far in advance different types of public safety decisions must be made. If decisions must be made before desired forecast information is received, they discussed seeking out additional information, if possible, and then making the decision using the information available, along with experiential and other forms of knowledge.

During TC threats, emergency managers described their goals as ensuring public safety and well-being. They aim to do so by maintaining sound situational awareness for themselves and others making decisions, coordinating decisions and actions across public safety functions, and clearly communicating with partners and the public about impending storm threats, public safety measures, and recommended protective actions. This includes a focus on planning and helping implement evacuation and sheltering of at-risk members of the public, if needed, and obtaining and positioning resources for prestorm protective actions and poststorm response and recovery.

#### 1) PHASE 1

During the first phase, emergency managers described their primary activities as monitoring potential threats, building situational awareness, and, if a TC might threaten their region, beginning to consider scenarios and discuss possible plans. Some said that they begin daily monitoring of potential TCs in the Atlantic Ocean at the start of hurricane season; another described starting to look at forecasts "anytime a potential system pops up" (EMGA4).

If a TC might approach their region, emergency managers begin notifying their agency staff, leadership, and partners, to build situational awareness (Fig. 6). Because effectively implementing prestorm evacuations and poststorm response requires taking a number of earlier actions, they may begin to consider options for decisions such as evacuation areas and routes, bussing, and medical transport, sheltering, and staging resources. They may also begin to coordinate staffing for the event, partially activate their emergency operations center (EOC) to support enhanced monitoring and logistical discussions, and start communicating with the public about the TC.

Emergency managers noted that this far in advance, much can change with TC-related forecasts. Therefore, they are paying attention to forecast information and considering future actions but typically not yet committing to major decisions or resource allocations (Fig. 6).

#### 2) PHASE 2

Similar to broadcast meteorologists, emergency managers described the next phase as a critical time period, during which their roles transition from building situational awareness and considering plans to taking actions. As EMTX4&5 explained, it is at "120 hours that we have to start making real decisions that cost real money, that affect real people." In gathering and

**Emergency Manager Timeline: Illustrative quotes**

***Phase 1: Monitoring and Awareness***

"If it's quite a distance away out in the Atlantic, I usually wait until it becomes a tropical depression or tropical storm to send out emails to all our partners … and make everyone aware. … That's really to get everybody primed for okay, we may see something. Try to give an idea of: especially this timeframe, keep an eye on it." (EMSC2)

"A lot of awareness, lot of looking forward to the next four to five days." (EMGA1)

***Phase 2: Readiness & Action***

"Once we get inside 96 hours … we have probably 300 items that we have to take care of. Those items are starting to be clicked off. We've ordered buses. We're doing evacuations. We've ordered commodities … Hospitals are being evacuated. All these things are all starting to take place based on the impacts. If we're expecting surge … we might not have issued [an evacuation order] at 120 hours, but we're at least talking to the public about it, that we might have to do these evacuations. So, we're working to soften the public up for this message to come in, probably tomorrow at this time, we'll probably be issuing a mandatory for such and such. All those things have to take place." (EMTX4&5)

"In order to call up all of the resources that the local jurisdictions will need to help them and evacuate a populace, we have to have the time to identify those resources and where they are, mobilize them … The decision to evacuate becomes a very difficult decision because that takes time, but it also takes a lot of money. We're talking about multimillion dollar [transportation] contracts that have to be activated … and you're asking [industry and the port] to shut down … So there's going to be a tremendous economic loss to call an evacuation. Also, you're looking at the human factor. If you call for an evacuation, you're going to ask nursing homes, assisted living facilities, that may have patients that are medically critical, that may have to evacuate. So they have to weigh that risk against the potential that the storm is going to make a landfall here and it will be devastating." (EMTX1)

***Phase 3: Transition to Impacts and Response***

"It's over at 48 [hours]. Things have to be completed or rapidly coming to closure as far as timing on all the lists and things that we have to do." (EMTX4&5)

"If we're 12 hours away from [onset of tropical storm force winds] and there's something we haven't done, then we've got a problem. … We call this phase OPCON 1. We call it final staging … within 24 hours … it's more like details at that point." (EMGA3)

FIG. 6. Illustrative quotes for the three phases in emergency managers' decision and action timeline (discussed in section 3b and summarized in Fig. 5).

interpreting forecast information, they are especially interested in assessing the storm's potential hazards and impacts in their area of responsibility, including storm surge, strong winds, and flood-inducing rainfall. They also monitor television and social media to maintain awareness of what others are communicating and doing. If impacts are anticipated in their region, emergency managers activate or ramp up their EOC and staffing during this phase, and they increase communication and coordination within their agency and with elected officials and partners so that everyone involved in making public safety decisions has "the best information available at the time to make whatever decision needs to be made" (EMSC2).

One major set of decisions that typically needs to be made during this phase relates to public evacuations. The timing of evacuation order decisions may appear straightforward, working backwards from the anticipated arrival of TC impacts using an area's clearance time. However, interviewees emphasized that hurricane evacuations are complex processes that involve multiple intersecting considerations and decisions.

One complexity is the different timelines involved in successfully evacuating the general population versus access and functional needs populations, in other words, people who may need assistance evacuating. For the general population, emergency managers plan to initiate evacuations with sufficient time for people to finish moving to safety prior to arrival of impacts, which involves considering clearance times. Safely moving access and functional needs populations, including those with disabilities, who are at hospitals or long-term care facilities, or who lack transportation or other means to evacuate, requires additional time and resources. In addition, evacuations can be initiated for different populations due to different risks; for example, people in coastal evacuation zones are typically evacuated due to risk of inundation from storm surge, while hospitals and long-term care facilities may also be evacuated due to the risk of strong winds and associated power outages. Mobile-home residents are also more susceptible to TC winds, even inland. To manage evacuation traffic, recommended and mandatory evacuations for different populations can be sequenced.

Moreover, successfully implementing evacuations requires emergency management organizations and their partners to plan logistics and expend significant resources earlier in their timeline. Time, personnel, equipment, and funds are needed to notify affected populations, manage traffic, identify public shelter locations and set up shelters, arrange bussing and medical transportation, and so on. These actions must be coordinated across multiple public, nonprofit, and private sector organizations, often starting 96 or 120 h before arrival of TC impacts (Fig. 6). Thus, forecast information during this phase is critical for setting up successful public safety decisions and actions as the storm approaches.

Along with evacuations, emergency managers described many other preparation activities that take place during this phase. Examples include issuing emergency declarations; closing schools and other facilities; allocating and positioning additional resources that may be needed for preparedness and poststorm response (such as sandbags, rescue equipment, fuel for generators, food, and water); and requesting additional resources from other jurisdictions if they may be needed. They also significantly ramp up public communication (Fig. 6).

Emergency managers noted that although forecasts are uncertain during this phase, they still have major, expensive decisions to make that are difficult or impossible to implement effectively beyond a certain point. One way that they manage this uncertainty is to consider scenarios for their area, for example, a storm that makes landfall a category higher than predicted or shifts track and generates greater impacts. Nevertheless, it is often challenging to make costly, critical decisions given the uncertainty in TC forecasts and local impacts when decisions need to be made (Fig. 6).

#### 3) PHASE 3

Within 48 h prior to TC impacts, emergency managers shared that they have shifted to final readiness and staging (Fig. 6). Depending on the region and scale of evacuation, evacuations have already been determined and are being implemented, or final evacuation decisions are made during the beginning of this phase. In high-risk areas, emergency managers are continuing to facilitate evacuation or safe local sheltering for those remaining. Inland and outside the highest-risk areas, they are managing traffic from evacuees and helping those who need gas, supplies, or shelter. They also make other final preparations, such as planning for continuity of government, shutting down transportation and other public services, and issuing curfews to clear roads.

Although major prestorm decisions have usually already been made, during this phase emergency managers continue to access forecast information. They use this information to make final decisions such as where to open shelters of last resort, position supplies and poststorm response crews, and house their critical workforce during the storm. They also monitor forecasts for any major changes that may affect plans in progress. As the storm approaches, they continue to monitor updated forecasts as well as storm observations, to ensure that preparations have been completed and that staff and first responders are in safe locations by the time hazardous conditions begin.

During this phase, emergency managers will have a fully activated EOC, and they will continue to communicate frequently with partners and members of the public. As the storm nears, they shift from prestorm preparations to planning for during-storm operations and poststorm response. This includes monitoring when hazardous conditions are expected to end, using forecasts and observations, to anticipate when they can initiate poststorm damage assessment and response.

## 4. Forecast information use

Building on the decision and action timelines above, next we examine what NWS TC products and other forecast information these NWS partners use in different phases of TC threats. As in section 3, we present findings for broadcast meteorologists and then for emergency managers, summarized in Figs. 7 and 8, respectively.[12]

### *a. Broadcast meteorologist information use*

During the first phase, the primary visual TC product generated by the NWS is the NHC Graphical Tropical Weather Outlook (Figs. 1 and 2). All of the broadcast meteorologists interviewed shared that they use this product for monitoring, tracking, and communicating the locations of current and potential future TCs during this phase. Because the NWS typically does not provide official forecasts of TC track and intensity during this phase, broadcast meteorologists obtain such information primarily from numerical weather prediction model output. Models mentioned include the GFS (United States), Canadian, and European global models as well as "spaghetti plots" depicting multiple possible TC tracks.

During the second phase, as forecast skill increases, NHC and other NWS entities begin providing a number of additional forecast products that broadcast meteorologists use. This includes the NHC Track Forecast Cone, which all of the broadcast meteorologists referenced. As BRSC2 explained, once the cone product becomes available, it provides "a one-stop shop that gives our viewers and our consumers a chance to get [key] information on one graphic," including a TC's position, current wind field, and forecasted track and intensity. Interviewees noted, however, that it is also important to understand and communicate the potential for impacts outside the cone.

To understand and convey more specific forecasts of TC hazards and impacts during the second and third phases, broadcast meteorologists discussed using NHC wind graphics, as well as WPC and SPC products if the TC may generate heavy rainfall, inland flooding, and/or tornadoes in their region. As a TC approaches, they discussed using additional WFO products, NHC storm surge and watch/warning

[12] This section and Figs. 7 and 8 are designed to examine broad patterns of information use across the interview data. As discussed in the text, some types of information were mentioned more commonly than others; however, given the limited number of interviewees and the varying ways in which they discussed using information, we have decided not to present quantitative results. We anticipate that more generalizable, quantitative data on the use of different types of information will be available from the follow-on surveys. Note also that information not listed in a given time frame may still be used by some broadcast meteorologists or emergency managers, but it was not a prominent theme in the interviews.

**Broadcast Meteorologist Timeline: Major Types of TC Information Used**

| Phase 1: Monitoring & Awareness | Phase 2: Readiness & Action | Phase 3: Transition to Impacts & Response |
|---|---|---|
| *NWS TC Products* | | |
| ▪ NHC Graphical Tropical Weather Outlook<br>▪ Forecast Discussions | ▪ NHC Track Forecast Cone<br>▪ TC hazard forecasts: NHC TC Wind Speed Probabilities; NHC Arrival of Tropical-Storm-Force Winds; WPC and SPC products<br>▪ NHC Key Messages<br>▪ NHC Public or Forecast Advisories<br>▪ Forecast Discussions | Same NWS TC products as Phase 2 and<br>▪ Watches and Warnings: Hurricane / Tropical Storm; Storm Surge<br>▪ TC hazard forecasts: NHC Potential Storm Surge Flooding; WFO Hurricane Threats and Impacts graphics<br>▪ WFO Hurricane Local Statement |
| *Other Information from NWS* | | |
| ▪ Interpretations and updates from NWS forecasters, e.g., through webinars / conference calls, NWSChat | ▪ Interpretations and updates from NWS forecasters, e.g., through webinars / conference calls, NWSChat | ▪ Interpretations and updates from NWS forecasters, e.g., through webinars / conference calls, NWSChat |
| *Modeling and Analysis Tools* | | |
| ▪ Weather prediction models: global; spaghetti plots<br>▪ Vendor data analysis and display system | ▪ Weather prediction models: global; spaghetti plots<br>▪ Vendor data analysis and display system | ▪ Weather prediction models: global; regional; in-house; spaghetti plots<br>▪ Vendor data analysis and display system |
| *Other* | | |
| ▪ Observational data: satellite<br>▪ Weather information from private companies, web sites, social media | ▪ Observational data: satellite; Hurricane Hunter aircraft; buoys<br>▪ Weather information from private companies, web sites, social media<br>▪ Information from public officials, e.g., preparedness, evacuation, closures | ▪ Observational data: satellite; radar; Hurricane Hunter aircraft; buoys; river and tide gauges; reporter and public reports, pictures, and videos<br>▪ Weather information from private companies, web sites, social media<br>▪ Information from public officials, e.g., preparedness, evacuation, closures |

FIG. 7. Overview of the major types of TC information used by broadcast meteorologists during each of the three phases in the TC threat timeline depicted in Fig. 2. Further discussion can be found in section 4a.

products, and evacuation and preparedness information from public officials, as those become available. As their timeline progresses, they also described using more observational data, and a few discussed transitioning from using global to regional weather prediction model output.

Throughout their timeline, broadcast meteorologists noted the importance of data analysis and display systems provided by private sector vendors for their use of TC information (section 3a). Although they occasionally mentioned disseminating NWS products in the NWS format, for example, on social media, more frequently they use the data underlying NWS products to create revised or new graphics, including new combinations of information. Along with NWS products and data layers, many broadcast meteorologist interviewees discussed accessing information from NWS forecasters, to obtain additional interpretations and insights. Mechanisms for obtaining this information varied across individuals but included Forecast Discussion products; online interactions via NWSChat; WFO briefing packages, webinars, and conference calls; and one-on-one interactions through telephone calls. Interviewees also noted the value of being able to obtain forecast highlights through NWS products such as NHC Key Messages graphics, NHC Advisories, and, as a storm approaches, WFO Hurricane Local Statements.

### b. *Emergency manager information use*

In the first phase of TC threats, emergency managers discussed accessing forecast information from the NHC Graphical Tropical Weather Outlook and weather prediction model output, especially in the form of spaghetti plots. As discussed in section 3b, they use this information to monitor potential threats, build situational awareness, and, depending on the likelihood of a TC entering their region, begin considering possible plans for different scenarios.

Beginning in the second phase, as multiple NWS entities start to issue more types of TC products, emergency managers discussed using many of the same types of information as broadcast meteorologists to assess, communicate, and prepare for different aspects of TC risks. Similar to broadcast meteorologists, emergency managers described the NHC Track

**Emergency Manager Timeline: Major Types of TC Information Used**

| Phase 1: Monitoring & Awareness | Phase 2: Readiness & Action | Phase 3: Transition to Impacts & Response |
|---|---|---|
| *NWS TC Products* | | |
| ▪ NHC Graphical Tropical Weather Outlook<br>▪ Forecast Discussions | ▪ NHC Track Forecast Cone<br>▪ TC hazard forecasts: NHC TC Wind Speed Probabilities; NHC Arrival of Tropical-Storm-Force Winds; WPC and SPC products<br>▪ NHC Key Messages<br>▪ NHC Public or Forecast Advisories<br>▪ Forecast Discussions | Same NWS TC products as Phase 2 and<br>▪ Watches and Warnings: Hurricane / Tropical Storm; Storm Surge<br>▪ TC hazard forecasts: NHC Potential Storm Surge Flooding; RFC products<br>▪ WFO Hurricane Local Statement |
| *Other Information from NWS* | | |
| ▪ Interpretations and decision support from NWS forecasters, e.g., through webinars / conference calls, one-on-one conversations, other interactions | ▪ Interpretations and decision support from NWS forecasters, e.g., through webinars / conference calls, one-on-one conversations, other interactions | ▪ Interpretations and decision support from NWS forecasters, e.g., through webinars / conference calls, one-on-one conversations, other interactions |
| *Modeling and Analysis Tools* | | |
| ▪ Weather prediction models and spaghetti plots<br>▪ HURREVAC/HVX | ▪ Weather prediction models and spaghetti plots<br>▪ HURREVAC/HVX | ▪ HURREVAC/HVX |
| *Other* | | |
| ▪ Observational data: satellite<br>▪ Weather information from television, web sites, social media | ▪ Observational data: satellite; buoys<br>▪ Weather information from television, web sites, social media | ▪ Observational data: buoys; river and tide gauges; radar<br>▪ Weather information from television, web sites, social media |

FIG. 8. Overview of the major types of TC information used by emergency managers during each of the three phases in the TC threat timeline depicted in Fig. 2. Further discussion can be found in section 4b.

Forecast Cone as providing a useful high-level overview of a TC's potential track, timing, and intensity, although again some discussed challenges with people misunderstanding it (including the potential for TC impacts outside the cone). In addition, during the second phase, many emergency managers described using spaghetti plots from non-NWS sources to assess possible TC tracks and situation-specific track uncertainties.

For information about potential TC hazards and impacts during the second and third phases, many interviewees discussed using NHC Wind Speed Probabilities and Arrival of Tropical-Storm-Force Winds graphics. Depending on the situation, they also noted using products from WPC, SPC, RFCs, and their local WFOs. In addition, emergency managers in coastal areas discussed the importance of storm surge risk information, as well as the intersection between the timing of TC-induced flooding and tides. Several described storm surge forecasts as especially important during the second phase, when critical and expensive decisions leading up to evacuations often need to be made, even though this is before the NWS currently issues storm-specific storm surge inundation products.

One major group of NWS products provided during the third phase is tropical storm, hurricane, and storm surge watches and warnings; these are not issued until 48 and 36 h prior to anticipated impacts, respectively. Given the evacuation decision timelines discussed in section 3b, several emergency managers explained that they do not use these products to inform decisions about evacuation orders. Rather, they typically use watches and warnings as justification for evacuation orders that have already been decided on, or to provide an additional inducement for people to evacuate or make other preparations. This does not mean, however, that watches, warnings, and forecasts provided within 48 h of impacts are not useful; evacuations are being implemented, and emergency managers and others are still making additional protective decisions. As the storm nears and arrives, emergency managers continue to use forecasts and observational information to make final preparations and then shift to planning poststorm response.

Throughout their timeline, emergency managers discussed using TC forecast information on its own as well as in HURREVAC/HVX or GIS to enable overlaying the forecasted TC hazards with other geospatial data, such as the locations of evacuation zones or critical infrastructure in their jurisdiction. Similar to broadcast meteorologists, they discussed the value of quickly understandable forecast highlights provided in products such as the NHC Key Messages graphic. However, some explained that due to NHC's national and

**Information gaps and recommendations: Illustrative quotes #1**

***Timing of NWS product issuance and availability***

"During a tropical situation, you're sitting there on pins and needles because an [NWS] update's supposed to come out at 02:00, 05:00, 08:00, 11:00 and sometimes they get it out 15 minutes ahead, sometimes it's 2 minutes behind. And the problem is we're on the air at 11:00 PM, and, of course, they're going to want weather first.... And then we'd have to build the graphics … It will update on its own to a degree, but you still have to tweak it, which even if it only takes 45 seconds, that's 45 seconds. And it's critical in TV broadcasting." (BRGA3)

"We would need to begin a vulnerable population evacuation no later than about 72 hours from landfall, which is a long time. But in order for us to start that evacuation three days out, we have to activate contracts and sign contracts with bus companies, ambulance companies, different things like that either four or five days from landfall. So … we have some pretty big questions with a lot of money attached to it that we have to start asking ourselves about five days out. Because if we wait until three days out or, you know, two and a half days out to start that vulnerable population evacuation, it's going to bleed over into the general population evacuation. And it's going to create kind of a chaotic situation." (EMGA3)

***Product understandability and usability***

"These two next pages [NWS products], I'll be honest with you … I find myself having a difficult time understanding it myself, much less trying to explain it to our viewers." (BRSC2)

"We take what the National Weather Service puts out and, I'll say, craft it. We put it in a format we can use and get it to our folks in a fairly understandable manner." (EMGA5)

FIG. 9. Illustrative quotes for key information gaps and recommendations, part 1.

international focus, the Key Messages product typically provides coarser-scale information that emergency managers must narrow down to their jurisdiction. In addition, a few noted that the national or multistate geographic scale of most NWS graphical TC products can make it difficult to extract locally relevant information that they can use in making the decisions discussed in section 3b. Thus, many emergency managers shared that they look to their local WFOs for information about the "particulars about our area and how it's going to impact us" (EMTX1). They obtain this information through WFO-generated graphics and briefing packages as well as through webinars, conference calls, and conversations with NWS forecasters. A few interviewees also discussed accessing forecasters' interpretations through Forecast Discussion products or the FEMA Hurricane Liaison Team located at NHC. Summarizing the value to emergency managers of information and decision-support services from NWS forecasters, EMTX2&3 said, "I don't see how you could do this job and not be on pretty close terms with your [local] weather service."

## 5. Key information gaps and recommendations

Although interviewees noted the usefulness of a variety of NWS information and products for informing decision-making, they also discussed unmet information needs and recommended improvements. In this section, we synthesize key information gaps and propose associated recommendations. Illustrative quotes are presented in Figs. 9 and 10. As described above, our project included collaboration with a core team of NOAA Research and NWS personnel, who helped us interpret our research findings in the context of NOAA policies, practices, and planning, and they provided feedback as we began formulating and then refined recommendations. This enabled us to coproduce research-guided recommendations that are usable by NOAA in a variety of ways. For example, although some aspects of the recommendations can be implemented by NHC or WFO forecasters as part of their current products and services, many were designed to help NOAA prioritize modernizations to the TC product suite and support longer-term NOAA OAR and NWS planning.

One theme that emerged across our data was the *timing of NWS product releases*. For broadcast meteorologists, the primary issue noted was the timing of major NWS TC product releases relative to the timing of television newscasts. Although broadcasters can ad lib on television when necessary, a few minutes to digest forecast updates and prepare new visuals can help them more effectively convey the latest information from NWS to the public (Fig. 9). This issue has been identified in prior work (e.g., Demuth et al. 2012), but it is difficult to solve, because NWS forecasters must themselves wait for the latest observations and model output and engage in their own activities in order to generate TC product packages. Nevertheless, considering new ways to address this issue can help broadcast meteorologists fulfill their role as partners with the NWS in communicating with members of the public. Thus, *we recommend that NOAA collaborate with broadcast meteorologists to develop strategies for informing them about key TC forecast and warning updates prior to standard television broadcast times—especially when there are delays in releasing the full product package*. Based on our interviews, key updates are those that may affect major television visuals or communication approaches; examples include upgrading or downgrading a storm between a tropical storm and hurricane, significant changes in track or intensity forecasts, and issuance of new watches or warnings. Possible strategies to consider further include early release of selected products or data within the existing TC

**Information gaps and recommendations: Illustrative quotes #2**

***Locally relevant forecast information***

"We'll usually start off with the broad view showing the current storm's location, the expected path it is projected to take … And then, we would zoom down to our local region and populate on a few of our well-known cities the probability of receiving the hurricane force winds or the tropical storm force winds, or the general range of rainfall." (BRTX1)

"Not zoomed this far out. We'll want one much more local from the Weather Service…. zoomed in where we can see our county or at least our region." (EMTX2&3)

***Concise, easily understandable highlights to help extract key information***

"If there's any way to have more of those quick bullet points, I think those really help out a lot." (BRSC1)

"We'll work to see what are those key things that the products are indicating that are critical, whether it be wind, rainfall, flooding, tornado chance, whatever those things are. And then we make sure that we're really highlighting that stuff out to our partners, as well as within our own graphics that we're creating to message to the public." (EMGA4)

***Value of human forecasters***

"Our forecast office here in [location] is amazing. They have constant conference calls. They have webinars. … they are constantly feeding us one-sheeters leading up to a potential threat" (BRSC2)

"If there's things that I'm not clearly understanding, then that's when I reach out to [names of people at local WFO], and they always put it in terms that I can understand and what it means for us here locally." (EMTX1)

FIG. 10. Illustrative quotes for key information gaps and recommendations, part 2.

package, when needed; an additional (potentially embargoed) product informing broadcasters of updates in progress; or a national-level NWS broadcaster liaison position to coordinate providing this information and other decision support for broadcasters.

For emergency managers, the primary timing issue was when, leading up to TC impacts, certain types of NWS forecast information were unavailable when decisions needed to be made. Coastal emergency managers, in particular, discussed the importance of TC-specific storm surge forecast information at greater than 48 h of lead time, even though they are aware of the challenges in providing that information. Thus, *we recommend that NOAA improve communication of TC-specific storm surge risk at greater than 48 h of lead time*. As part of addressing this issue, NHC provides storm surge hazard maps for use in longer-lead-time planning and operations (Zachry et al. 2015), and NOAA is working on reducing uncertainty in storm surge forecasts and extending TC-specific surge forecasting capabilities to 72 h (NOAA 2019). However, the inherent uncertainties in location-specific storm surge predictions (Fossell et al. 2017) and the feedback provided by our interviewees suggest that additional strategies are needed. Consequently, in addition to ongoing efforts, *we recommend that NOAA and the research community develop alternative product formats for conveying storm surge risks at greater than 48 h of lead time, with an emphasis on providing the best possible information for supporting the public safety decisions made in this time frame*.

A second theme was the *understandability and usability of NWS TC products*. Members of both groups talked about the difficulties that they and others have in effectively interpreting and using certain NWS products (Fig. 9). Broadcast meteorologists, in particular, reported that whenever possible, they use the data layers underlying NWS products to create modified graphics that are more intuitive and visually appealing, with more accessible language. Moreover, the popularity and widespread usage of the NHC Track Forecast Cone, despite issues with its interpretation, demonstrates the challenges of changing a product's format once it is familiar. Thus, *we recommend that NOAA and the research community continue to invest in designing more readily usable product formats and data layers, by integrating users' perspectives into research and development beginning early in a product's formulation*. In doing so, it is important to recognize that NWS products have several major pathways for use: in their original format, as a starting point for revision prior to further dissemination, and as data layers that can be used to create new visuals or be integrated with other data to generate new information.

Many of the decisions that emergency managers and others make during TC threats depend on the anticipated TC hazards and impacts in their area. Thus, a third theme from our analysis was *interest in locally relevant forecast information whenever possible* (Fig. 10). In some situations, the primary need expressed by emergency managers was being able to zoom in or otherwise obtain local (e.g., county-level) information from larger-scale graphical products; therefore, *we recommend that NOAA explore options for interactive product formats and delivery, working closely with forecasters and key partners throughout the development cycle to ensure appropriate content and design*. In other situations, emergency managers are seeking more localized information than current TC forecast products provide. To help to address this, research is ongoing to improve TC forecast skill, including geographically specific predictions of TC hazards and impacts. However, given the unavoidable uncertainties in TC forecasts, complementary efforts are needed. Thus, *we recommend research and development to codesign and coevaluate new ways of communicating forecasts of TC hazards that are usable in local decisions, at lead times when geographically specific forecast information is highly uncertain*. Such products might convey regional risks, or, given interviewees' discussions of using scenarios for communication and decision-making, they might take a scenario-based approach.

Another key theme was the *importance of concise, easily understandable highlights that help people quickly extract key information from the NWS TC product suite* (Fig. 10). In particular, interviewees noted the value of high-level takeaways such as those in the NHC Key Messages graphic. Several suggested using easily accessible, synthesized key points on other TC products. Similar key points can also be found in other NWS products, such as NHC Advisories and WFO Hurricane Local Statements; however, interviewees said that these textual products provide a lot of information to sift through, can be difficult to find, and may not be available at the lead times when key decisions need to be made. Moreover, interviewees said that the key points currently provided by NWS are sometimes wordy, and some emergency managers noted that NHC's Key Messages are often not specific or localized enough to be useful for their decisions. Therefore, *we recommend that NWS expand the use of "plain language" highlights to additional graphical products*. Individual WFOs are best suited to provide specific, local information, and although some WFOs do provide locally relevant graphical summaries with text highlights, they are not always easily accessible or widely disseminated. Thus, *we also recommend extending 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 in advance of impacts*. Being able to quickly find and understand up-to-date information from the NWS through these types of products is especially important when risks are changing quickly, such as when a forecast track shifts or a TC rapidly intensifies.

A final theme that emerged was *the value to NWS partners of human forecasters' interpretations and decision support* (Fig. 10). Broadcast meteorologists discussed obtaining from NWS forecasters the most up-to-date forecast information and interpretations. Emergency managers emphasized the value not only of hearing NWS forecasters' updates and interpretations, but also of having conversations with forecasters for decision support. This indicates that while timely, clear, and applicable TC forecast products and data are undoubtedly critical for NWS partners, the human dimension accompanying products and data is also critical (Fig. 10). Consequently, *we recommend that efforts to modernize the TC product suite continue to support and emphasize the contributions of NWS forecasters' expertise and interactions with partners along with providing improved data*. This means recognizing and valuing forecasters' ability to distill complex, uncertain data into situationally relevant, readily interpretable information, which they can communicate (i) via plain language highlights and the key messages concept, as suggested in the above recommendations, and (ii) directly with partners per their decision-support needs. This also means more fully realizing the potential of human relationships and trust to act as "force multipliers" in effective NWS decision support and product creation (Uccellini and Ten Hoeve 2019). Actualizing these recommendations will involve ensuring that forecasters have the time, training, support, and other resources needed to engage in such activities, as well as regularly incorporating the perspectives of forecasters into product and service development and testing. It may also involve thinking more intentionally about NWS partnerships, in ways that evolve one-way or back-and-forth communication of information into strategic collaborations aimed at achieving common goals.

## 6. Conclusions

This study aimed to understand key NWS partners' information needs for decision-making during TC threats and to prioritize areas for improving NWS TC risk communication. To do so, we used in-depth interviews with broadcast meteorologists and emergency managers, interpreted in the context of other literature, to investigate the types of decisions these NWS partners make, the actions they take, and the information they use during different phases of TC threats. We then analyzed key information gaps and potential opportunities for improvement. This approach was designed to help NOAA improve the current TC product suite, promote longer-term improvements by informing investments in TC research and research-to-operations, and guide future related research.

TC forecasts and their communication have changed significantly in recent years, and they will continue to evolve. Thus, it is important for NOAA to find ways to be agile and adaptive, while also continuing to provide products and services that support the agency's mission. In addition to addressing gaps in the TC product suite, doing so may involve rethinking larger aspects of NWS strategy. For example, given today's rapid, multi-actor communication of weather information across multiple channels, would it be beneficial for NWS to modify its current approach to releasing regularly scheduled TC product packages? Given the growing volume and complexity of TC forecast and warning information, how can NOAA integrate the provision of products, data, and human forecaster interpretations and decision support to best serve its audiences' different needs? Navigating these types of questions is interlinked with NWS's ongoing evolution toward a next-generation forecast and warning framework and impact-based decision-support services (Rothfusz et al. 2018; Uccellini and Ten Hoeve 2019). More broadly, we recommend that NOAA approach improvements to TC products as part of a broader risk communication strategy that involves effectively partnering with broadcast meteorologists, emergency managers, and others to communicate the latest TC forecast and warning information widely and translate this information into public safety decisions.

The results presented synthesize themes that emerged across interviewees. However, for some topics (such as preferences for specific products and interest in forecasts of storm surge versus other TC hazards), NWS partners' perspectives varied based on geography, resources, experience, and other factors associated with their decision-making contexts. Thus, additional exploration is needed of emergency managers' and broadcast meteorologists' decision timelines, TC information use, and unmet TC information needs across a wider range of jurisdictions and media markets. To extend our understanding in these ways and enhance the generalizability of these findings and recommendations, we followed these interviews with online surveys of broadcast meteorologists and emergency managers throughout TC-affected regions of the contiguous United States (Vickery et al. 2022). Through this multimethod investigation, we aim to improve how NOAA, broadcast meteorologists, emergency managers, and others work together to benefit the U.S. public when TCs threaten.

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