Creating a Communication Framework for FACETs: How Probabilistic Hazard Information Affected Warning Operations in NOAA’s Hazardous Weather Testbed

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ABSTRACT: Scientists at NOAA are testing a new tool that allows forecasters to communicate estimated probabilities of severe hazards (tornadoes, severe wind, and hail) as part of the Forecasting a Continuum of Environmental Threats (FACETs) framework. In this study, we employ the embedded systems theory (EST)—a communication framework that analyzes small group workplace practices as products of group, organizational, and local dynamics—to understand how probabilistic hazard information (PHI) is produced and negotiated among multiple NWS weather forecast offices in an experimental setting. Gathering feedback from NWS meteorologists who participated in the 2020 Hazard Services (HS)-PHI Interoffice Collaboration experiment, we explored implications of local and interoffice collaboration while using this experimental tool. By using a qualitative thematic analysis, it was found that differing probability thresholds, forecasting styles, social dynamics, and workload will be social factors that developers should consider as they bring PHI toward operational readiness. Warning operations in this new paradigm were also implemented into the EST model to create a communication ecosystem for future weather hazard communication research.

SIGNIFICANCE STATEMENT: Meteorologists are currently exploring how to use probabilities to communicate life-saving information. From tornadoes to hail, a new type of probabilistic hazard information could fundamentally change the way that NWS meteorologists collaborate with one another when issuing weather products, especially near and along the boundaries of County Warning Areas. To explore potential collaboration challenges and solutions, we applied a communication framework and explored perceptions of NWS meteorologists who had used this new tool in an experimental setting. NWS meteorologists expressed that differing ways of communicating hazard information between each office, along with forecasting styles and workload, would change the way they go about producing critical hazard information to the public.

KEYWORDS: Communications/decision-making; Decision-making; Forecasting; Probability forecasts/models/distribution; Societal impacts

1. Introduction

The NWS has 122 weather forecast offices (WFOs) tasked with communicating life-saving information for their jurisdictions, known as County Warning Areas (CWAs). WFOs issue hazardous convective weather warnings for their own CWAs, unless providing backup to another office. WFOs are encouraged to collaborate with neighboring offices when a storm crosses from one CWA to another to provide consistent service. Despite this long-standing policy, WFOs have expressed difficulties negotiating tasks and corresponding with one another during warning operations, limiting warning consistency across CWA lines (Daipha 2007).

In addition to collaboration challenges, inconsistencies of service can arise simply through the way warnings are issued today. The NWS’s present watch and warning system has largely been text-based and binary (i.e., an area is either inside the warning or not) (Rothfusz et al. 2018). If new warnings are not issued, end users and the public experience information “gaps,” where no updates are provided (Galluppi et al. 2015). End users have different needs and risk perceptions, and discontinuous information can leave these audiences with ambiguity with regard to their present and future weather risk, hampering their ability to make optimal decisions for themselves (Mors and Senkbeil et al. 2014).

The Forecasting a Continuum of Environmental Threats (FACETs) program aims to address this issue with the provision of rapidly updating probabilistic hazard information (PHI) from days before to within minutes of a hazardous weather event (Rothfusz et al. 2018). Since 2008, researchers have tested and evaluated convective warning-scale PHI for severe wind/hail, tornadoes, and lightning in NOAA’s Hazardous Weather Testbed (HWT; Kuhlman et al. 2008;
The experiments conducted in the HWT have involved object-based probabilistic guidance (Cintineo et al. 2014; Meyer et al. 2019; Calhoun et al. 2018). From this guidance, NWS forecasters created and modified grid-based probabilistic information (i.e., PHI plumes) using an experimental version of Hazard Services (HS), called HS-PHI (Fig. 1; Hansen et al. 2018). The PHI plumes move with the storm and automatically update every minute, with storm motions and probability controls that can be adjusted by forecasters any time after they are initially issued. The color-shaded probabilistic plumes highlight the threat area and introduce more components to evaluate during the forecaster’s operations process (Fig. 2).

In addition to exploring scientific components of PHI, FACETs has prioritized social and behavioral sciences research in order to ensure that innovations will meet the needs of forecasters and end users (Rothfusz et al. 2018). As a result, the National Severe Storms Laboratory (NSSL) is exploring how PHI would affect communication and collaboration within the public, stakeholders, and within WFOs through experiments at the NOAA HWT. Preliminary studies have noted that interoffice collaboration between WFOs may look somewhat different in a possible FACETs system than in the current NWS operational paradigm (Klockow-McClain et al. 2020). Current NWS policy and software prohibits WFOs from issuing warnings beyond their CWA boundaries. The HS-PHI software was designed to allow the PHI probability plumes to cross CWA boundaries. A need noted by Karstens et al. (2015) and discussed in detail by James et al. (2022, manuscript submitted to Wea. Forecasting), collaboration tools were developed and tested with handoff procedures in this HS-PHI Interoffice Collaboration experiment.

This paper proposes the use of embedded systems theory (EST; Gastil 2010) to better understand the challenges and potential solutions for operationalizing PHI. EST focuses on how small groups (e.g., WFOs) are shaped both by their own characteristics and interactions, as well as by the organizations (e.g., NOAA) and society (e.g., local community language and social norms) to which they belong. In other words, WFOs are interconnected within broader contexts that can have powerful effects on individual and group-level decision-making. Applying the concept to the hazards warning system, we considered the implications of small group teamwork of NWS WFOs in the emerging FACETs paradigm. Using qualitative thematic analysis and data from the 2020 HS-PHI Interoffice Collaboration experiment at the HWT, we analyzed perceptions of how NWS forecaster workplace practices could evolve when introduced to PHI. First, we examined the role of the NWS forecaster in the local context, such as within their WFO and in interactions with their community. Exploring how forecasters perceive potential conflicts and challenges beyond the office level, we also contextualized the perceived role of a WFO within the larger meteorological community and how decision-making was affected by these factors. The paper concludes by introducing a communication framework for social scientists, developers, and forecasters to consider in a possible FACETs future.
2. Creating a communication framework for FACETs operations

a. Systems theory: How small groups operate

Small groups, generally defined as units from 3 to no more than 20–30 individuals that strive to accomplish a common goal or resolve an issue, can enhance collaboration and production while considering the task in hand (Wilson and Hanna 1990). When examining how small groups operate, the most fundamental model involves an input, which, through internal processes (meetings, delegation of work, etc.), produces an output (McGrath 1964; Pavitt 1999). Although this framework helps to visualize the core day-to-day practices of small groups, the process needs to be expanded further to explain the complexity of these entities.

Systems theory (Arrow et al. 2000) visualizes small group processes as integral components of an entire system, where inputs, processes, and outputs have the ability to influence one another. In this perspective, small groups develop structural properties as they adapt to changing circumstances over time. This model 1) focuses on elements of small groups (e.g., individual members), 2) visualizes small groups as part of a bigger system, and 3) analyzes the social contexts in which small groups place themselves.

Although this model expands on initial perspectives, systems theory does not provide insights on organizational contexts (i.e., how a small group influences or is influenced by broader, institutional practices) (Putnam and Stohl 1990; Stohl and Putnam 2003; Gastil 2010). With small groups comprising at least three individuals, an improved perspective would consider that all members of a small group come from other groups and organizations, thus making the process of working together more complex. Visualizing this concept in a weather context, NWS forecasters are assigned to smaller groups (i.e., WFOs) to provide warning information for a specific region, despite being part of a larger organization. In instances where storms cross CWAs, these small groups now have to collaborate with their neighboring WFO to create effective warning communication. Considering organizational contexts, along with interconnected small groups, is of utmost importance to analyze how a certain WFO would go about warning their communities.

b. Organizational implications of small group work

Structuration theory (Giddens 1984) provides valuable information about how individuals act, from the scale of minuscule settings to large organizations. According to the theory, structures are defined as rules (i.e., propositions that suggest how something should be done) and resources (i.e., relevant personal traits, abilities, knowledge, and possessions people bring to an interaction). As members of the group begin to interact, they draw on these rules and resources to come up with social actions. If the rules and resources are met with positivity within the group, the social setting will reinforce these qualities into future interactions. On the other hand, if members express dissatisfaction with social actions, the social setting implicitly removes certain rules and resources from future interactions. Depending on power imbalances, some members of the group may have a greater say in what rules and resources are adopted across their entities (e.g., a supervisor’s opinion carries more weight than one of a new employee). Structuration theory considers how interactions within social settings create (and recreate) the blueprints of small groups.
c. Embedded systems theory

Stemming from systems theory (Arrow et al. 2000) and structuration theory (Giddens 1984), the EST framework considers the rules and resources of the group, its members, the organization that the entity belongs in, along with societal-level factors, to analyze how internal and external factors affect small group operations and functions (Fig. 3; Gastil 2010). In other words, small groups are “embedded” within larger entities, such as organizations, communities, cultures, and countries. In this scenario, both the large and small systems depend on one another to shape the structure and practices of one another. Each of these sets of individual, group, organizational, and societal variables (i.e., the boxes in Fig. 3 below) potentially affects the group in some way. In addition, these sets of variables may interact with each other during the lifespan of a group and may also connect back into the societal/organizational context in which the group operates (i.e., the purple, blue, and brown arrows connecting the boxes in Fig. 3 below). Within the EST framework, groups act as more than simple linear models that would move from an input to an output; rather, groups may iteratively change the organization to which they belong, or the group itself, as it develops over time. For example, a high-performing work group that develops some novel techniques for building team cohesion and accomplishing their goals (blue and purple boxes) could lead the group to adopting that as a formal practice as new team members join (as illustrated by the blue and purple arrows leading from “group interaction” and “group decisions” back to the “local context” and “tasks and/or purpose” boxes). It might also lead to the larger organization adopting those practices for other work teams to try to replicate this success (as illustrated by the purple line leading to the “social system” box). The EST perspective, then, “zooms out” from fundamental small group communication theory that focuses solely on inputs, processes, and outputs and visualizes broad relationships between small groups, organizations, and social systems.

NWS WFOs comprise several forecasters (NWS 2016) and are considered small groups by definition. Operating in a societal and organizational context, WFO practices are affected by a myriad of partners and institutions (Golden and Adams 2000; Daipha 2007; Demuth et al. 2012; Uccellini and Ten Hoeve 2019). At the most basic level, NWS meteorologists are enabled or constrained by expectations of their corresponding WFO staff and of management, usually the meteorologist in charge, science and operations officer, and warning coordination meteorologist. Within the NWS organization, WFOs are also dependent on their neighboring office’s rules and resources, as they collaborate to provide consistent information during hazardous weather. NWS national and regional headquarters offices introduce policy directives and other guidance that each WFO must follow, along with broader mission statements that create institution-wide culture and practices (NWS 2018, 2020, 2021). While intraorganizational structure has the potential to affect operations, so do outside forces. Local communities and end users also influence the way WFOs go about communicating critical life-saving information. For example, some end users may prefer a more conservative forecast to reduce false alarms, while others appreciate wanting to know all risks at stake. Last, mediums of communication can vary by preference of the end user and community: some WFOs use NWSChat (https://nwschat.weather.gov), while others depend on social media or other means to communicate across various institutions and people. The EST framework, then, can help visualize the entire
decision-making process that forecasters must undergo during their everyday operations.

d. Embedded systems theory in a FACETs paradigm

Emphasizing the importance of social science, FACETs has categorized social, behavioral, and economic science as a component that is incorporated at each step of the forecasting process, from development to external communication (Rothfusz et al. 2018). To facilitate this process, the EST framework can serve the FACETs mission in various ways. First, the versatility of the EST framework provides a resourceful lens to analyze data at each step of the operations process, from research to operations. Second, the EST framework provides a unique opportunity to analyze internal and external forces that influence how meteorologists create life-saving products and messages through the various relationships and feedback loops in the EST framework (Fig. 3). For example, one forecasting group’s experiences with the more continuous, complex information generated by FACETs can help inform other groups within NWS and with partner organizations as they begin using FACETs. The direct and indirect relationships that the EST framework illustrates provides an analysis of relationships between variables and entities that are usually not associated with one another. By engaging in this practice, future research could consider both scientific and social factors of the forecasting process. For example, the EST framework could help explain how forecasters’ community partners’ information needs and risk tolerances might affect decision-making on communicating probabilities of potential hazards during a storm event. In addition, the EST framework could be useful for understanding new forms of collaboration that may occur in the FACETs paradigm, such as interoffice collaboration over convective warnings, which do not extend across CWA boundaries under current NWS practices but could under FACETs.

This study employed the EST framework to analyze perceptions of forecasters participating in the HS-PHI Interoffice Collaboration experiment in the HWT and demonstrated how operations and partnerships would evolve with the introduction of PHI. We explored two specific research questions (RQ) that explore intraorganizational and interoffice structures in a WFO office through a possible FACETs paradigm:

1) RQ1—How do forecasters perceive that local and intraorganizational factors may affect their office operations if HS-PHI becomes operational within the NWS?
2) RQ2—How do forecasters perceive that organizational and interoffice factors may affect their office operations if HS-PHI becomes operational within the NWS?

3. Methods

a. Experiment design

A necessity identified by Karstens et al. (2015), the 2020 HS-PHI experiment focused on collaboration between NWS WFOs using newly developed HS-PHI collaboration tools during severe weather warning operations (James et al. 2022, manuscript submitted to Wea. Forecasting.). Split into two 1-week blocks, forecasters used the HS-PHI software to issue warnings in a simulated operational environment, divided into two teams to create simulated WFOs, and worked together while handling storms near the boundaries of their adjacent CWAs. This was accomplished by separating the two teams of forecasters in two separate locations: 1) the HWT operations area and 2) the NSSL Development Laboratory (Fig. 4). Communication media, such as a forecaster discussion box included in the HS-PHI software, landline telephone, and Slack chat servers (to simulate NWSChat), were made available to the participants so that they could collaborate throughout the week.

Five archived severe weather cases were selected to explore outcomes for an array of situations in which challenging circumstances would promote interoffice collaboration (James et al. 2022, manuscript submitted to Wea. Forecasting). Using existing and modified CWA borders, the scenarios presented cases in which storms could 1) move from one jurisdiction to another, 2) straddle CWAs, and 3) be so large in spatial size that they cover both boundaries at the same time (squall lines, mesoscale convective systems, etc.). The scenarios also included fictitious Impact-Based Decision Support Services...
(IDSS) events, in which forecasters were asked to provide spot forecasts for emergency manager–supported events that were strategically placed along CWA borders. Directives were also included in some scenarios to emulate differing warning philosophies between the two simulated WFOs. To familiarize the participants with the technology and expectations of the experiment, they underwent an orientation and hands-on training prior to using PHI in a simulated environment.

The collaboration software allowed for two new processes in warning operations: the first was an “ownership transfer” function that allowed participants to transfer the rights of a storm object (i.e., PHI and warning information) to their neighboring WFO as the storm approached their respective boundaries. The second was a “domain permission” capability that allowed one WFO to create a storm object within the domain of their neighbor’s CWA when granted permission. Pairs of forecasters from both offices were also given a live view of the storm objects that were being edited by the other WFO.

b. Participants

Eight NWS forecasters were invited to the 2020 HS-PHI experiment to simulate WFO operations. Forecasters were selected in part on their office and personal warning philosophies; a diversity of philosophies were sought to simulate realistic tension between neighboring offices. In the first week of the experiment, each of the two forecast pairs were from the same WFO. This way each team was already familiar with working together and likely shared similar or at least familiar warning philosophies. In the second week, one forecast pair had forecasters from two different WFOs, while the other team came from the same workplace. The NWS forecasters participating in the experiment had warning operations experience ranging from 2 to 16 years (overall mean warning operations experience was 4 years). Of the four forecaster pairs, only one had a disparity in warning experience (16 years and 3 years). Each forecaster had their sectorized area of responsibility, and no significant power imbalances were noted throughout the experiment. Using the lens of EST, we analyzed interactions between the two forecast teams.

c. Data collection

Throughout the HS-PHI experiment, we gathered both quantitative and qualitative data. After each scenario and at the end of the weeklong experiment, participants were given collaboration surveys to complete and underwent focus group debriefs to reflect on the case. At the end of each workday, participants reunited at the HWT to discuss how PHI changed their workplace operations and collaborations with neighboring WFOs. In these group debriefs, we challenged participants to think critically about how PHI could change their everyday operations. Topics that were covered included technological challenges, collaboration philosophies, risk communication preferences, among others. On the last day of the experiment, the participants met one last time and recapped their overall perceptions of PHI. All conversations were recorded.

d. Thematic analysis

Transcripts of 1) debriefings conducted at the end of each workday and 2) postexperiment interviews underwent a qualitative thematic analysis (Lindlof and Taylor 2011). To increase familiarity with the data, we first transcribed the data from all relevant audio files from the experiment. The data included 83 pages of transcriptions from days 2, 3, 4, and 5 (excluding the training sessions on day 1). We then established corresponding codes using the EST framework keeping the two research questions in mind (i.e., local/intraorganizational and interoffice collaboration, respectively). We identified common themes, or descriptive labels, among the codes using well-validated procedures for qualitative analysis of social data (Lindlof and Taylor 2011). We individually outlined initial themes, then met multiple times to develop final themes. We matched each theme with examples from the transcripts to highlight how operations would look like in a FACETs paradigm.

4. Local office operations in a FACETs paradigm

Using the experimental HS-PHI software, NWS participants evaluated how the PHI paradigm could change their WFO operations in local contexts and within their offices (Table 1).

First, all participants noted that PHI made storm-scale tasks more complex and time-consuming. Highlighting that NWS forecasters had enough responsibilities as it is, the practice of implementing probabilities into warning-scale forecasts raised concerns about this new product inhibiting the time they dedicate to diagnostic analysis. Questions were also raised about how work would be distributed during severe weather events (i.e., would they sectorize warnings/PHI by geography, hazard, etc.), and how this would affect the other responsibilities that forecasters already have.

Second, participants in both weeks of the experiment discussed how precise and/or accurate PHI would be in the future. As scenarios involved events ranging from discrete supercells to squall lines, participants speculated how precisely their probabilistic estimates should be constructed, especially in the event that storms began to merge with one another. When contextualized in an interoffice collaboration perspective, participants suggested that an agreement between two WFOs needed to happen before the trade-off occurred so that both offices can coordinate effectively.

Third, forecaster participants always kept their local jurisdiction in mind. All NWS participants stressed the importance of partnerships with local entities in a FACETs paradigm during the debrief section. The majority of participants argued that partnerships would become even more prominent in a FACETs era, and it was even suggested that local partnerships could be used to dictate which WFO is the rightful owner of a storm object (Table 2). According to participants, geopolitical boundaries, then, should be only one of many factors to consider for determining ownership of warning responsibilities.
Increased workload
Forecasters worried that, by adding PHI, their work responsibilities would become more complex and time consuming.

"[PHI is] adding an extra step in the process of a binary warning decision that we don’t do now. And we can use that extra time to stay situationally aware of the environment."

Precision vs accuracy
Forecasters were unsure of how specific their warnings should be as a result of PHI.

"It’s easy to build a big polygon. You can obviously split it up, but initially, as you’re dealing with storms that are growing upscale, you’re just kind of like, ‘Oh, well I can just make this bigger.’ But then there’s going to be areas inside of that getting 70 or 80 mph winds versus other areas that maybe aren’t getting that same kind of threat or hail or whatever the case is."

Importance of local partnership
Forecasters considered end users when producing PHI nowcasts.

"Whoever, the person that they normally deal with, like the EM . . ., station or the incident commander that’s there . . . Whoever they feel comfortable calling is who’s going to have to own the event because that’s their core partner. And hopefully that relationship was built before they decide to straddle a border [with a large outdoor event]."

Focus on quick, reliable information
Forecasters measured success by how much time they provided their communities to prepare; although PHI provides more lead time for populations, it may also add operational workload.

"The drafting process [of PHI] is really where we lose [operational] lead time . . . Here now, you must draw the object, draw the plumes, put the threats in there, put some discussion in there, work it out with your neighbors . . ."

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Last, a substantial theme found in the study concerned how NWS forecasters measured success. Ultimately, all eight participants agreed that their end goal is to provide ample amounts of time for communities to prepare regardless of PHI. This perception of success is important to note, as lead time influenced how NWS forecasters perceived the efficacy of the PHI product overall. For example, participants contemplated the additional steps that PHI would introduce to a typical NWS forecaster, because it would decrease the amount of time during which they could go about warning their communities during a rapidly evolving severe weather event.

5. Interoffice collaboration in a FACETs paradigm

Forecasters also considered the implications of PHI when collaborating with neighboring WFOs and external organizations (Table 2).

Hazard probability tolerances of participants were frequently discussed throughout all postcase debriefing sessions. In our analysis, hazard probability tolerance relates to the differing PHI probability thresholds that prompted participants to issue severe thunderstorm or tornado warnings. NWS participants debated if probability thresholds should be established if PHI were transitioned to NWS operations. The theme of standardizing probability criteria for tornado warnings and severe thunderstorm warnings became a popular topic, as participants speculated whether a certain percentage should be associated with a warning. It should be noted that past PHI experiments in the HWT tested multiple probability thresholds (Obermeier et al. 2022). Each threshold approach tested created significant communication problems for broadcast and emergency management participants. As a result, warnings in HS-PHI (i.e., “Threats-in-Motion”; Stumpf and Gerard 2021) are not tied to a probability threshold and are a warning forecaster decision. Keeping in mind their end users, participants noted that interoffice collaboration would affect the process of transferring warnings from one WFO to another. For example, when storms crossed jurisdictions, participants brainstormed the best possible resolution to make sure both WFOs’ risk thresholds were respected. Acknowledging that hazard probability thresholds would be different for each forecaster, they suggested that local WFOs should have a say in deciding the probability of a given PHI product before the storm even arrived in their jurisdiction.

As warnings were being transferred from one CWA to another, all participants in the experiment worried about keeping accountability with their end users. Concerned that conflicting probability thresholds between neighboring WFOs would complicate local and external partnerships near the CWA border, participants imagined scenarios in which a local partner would be paying attention to an incoming storm from an adjacent CWA and had questions about it. Would the local WFO answer it? Should they contact the neighboring WFO for more information? After discussions, the pairs of forecasters set boundaries and were territorial with their end users overall. For example, during an experimental scenario in which a
local partner within the border of two WFOs requested assistance, forecasters suggested that the WFO with the established relationship should take ownership of the storm to help guide the entity that requested help. If there were ever to be a scenario in which a local partner would reach out to the wrong WFO, they would speak on behalf of them and respect their forecast.

Human behavior and social dynamics were brought up in postcase discussions during both weeks of the experiment. NWS participants perceived the potential for PHI to induce future conflicts between offices due to forecaster personalities and warning styles at different WFOs. Although participants in the 2020 experiment worked very cordially with their counterparts at the neighboring “office” during the operations process, they foresaw the potential for heated conversations with their real-life collaborators as possible under PHI. Forecasters also discussed how personal warning styles at their WFO might get in the way of effective interoffice collaboration, with some offices warning more permissively while others are more conservative (Table 2).

Despite possible disagreement on probability thresholds, all participants in the experiment stressed solidarity among collaborators. Even in instances in which two offices heavily disagreed with one another (e.g., one office issues a 70% chance of a tornado whereas the other office believes it is 40%), NWS participants emphasized that they are “one” organization, stressing the importance of consistency among CWAs. Participants preferred to resolve any disagreements before issuing warnings and transferring them from one office to another, but in instances in which a solution could not be agreed upon, all participants were ready to support one another and go with the warning decision of the neighboring office, if necessary.

All NWS forecasters suggested increased collaboration during the warning transfer process. While all participants noted that conflict in warning products is inevitable, they agreed that conflict would be substantially lower if they had the chance to communicate with one another before transferring warning information to the other CWA. Participants felt the need to increase collaboration prior to the moment when they would need to make warning decisions for their own populations. This process represents a communication process known as sensemaking, or the process by which people attribute meaning to events and experiences (Weick et al. 2005).
Forecasters acknowledge that, if they collectively assign meaning and analysis to a given storm, their resulting action will enhance warning operations and effective collaboration.

While all forecasters unanimously agreed it would be optimal to tackle problems directly through collaboration, they did not all agree on what communication medium would best help to facilitate communication between offices. Today, NWS offices use NWSChat and landline phones to collaborate with neighboring offices when they have occasion to do so. Many participants saw the use of video chatting and/or telephone as impractical, because it adds an extra platform to monitor during the warning process. Participants advocated that a visual collaboration tool be built into the HS-PHI software to make it easier to convey more complex information. With this tool, NWS forecasters would be able to communicate with their neighboring WFO in the same platform that they use to issue warnings. The latter proposal was unanimously supported by all participants in both weeks.

Forecasters also offered timeliness and reliability as measures of success for interoffice collaboration with HS-PHI. In scenarios where ownership conflicts arose, NWS participants made it clear that, at the end of the day, the main priority is to keep their communities safe. When asked if they would impose warnings if another office was not being responsive to collaboration requests, for example, all participants agreed that they would for the sake of providing their communities ample amounts of time to prepare and make life-saving decisions.

6. Discussion

a. Contributions to communication theory

The EST framework expands the application of small groups and integrates them into a much broader community of interconnected groups, institutions, and societies (Gastil 2010). Results from this study illustrated the complexity of small groups and the various influences that shape the way they produce the eventual, desired output. Instead of a singular, linear model, weather forecasters decision-making strategies were influenced heavily by their local communities and organizations they belong to. With limited applied research in the context of weather forecasting operations (e.g., Daipha 2007; Roeder et al. 2021), this study supplements existing research and provides a glimpse into how future technology could affect the way weather forecasters engage in collective sensemaking about emergent hazardous weather events and produce life-saving information for the public.

In addition, this study provides a unique glimpse as to how hazard thresholds and perceptions play a role in the EST framework. Given the type of decisions that weather forecasters make, our study illustrates that small groups in disaster environments must also consider factors that are not usually considered in traditional small group contexts. Though this concept is beyond the scope of this paper, future studies should consider how risk and crisis communication concepts interact with small group communication theory.

b. Practical implications: Creating a communication framework for FACETs

By viewing warning operations as a series of intertwined systems working toward the goal of keeping communities safe, the EST framework provides a unique opportunity to visualize how intraorganizational, interoffice, and external collaboration could evolve in a FACETs paradigm. Participants in the 2020 HS-PHI Collaboration experiment considered both scientific and human factors when issuing alerts and making life-saving decisions, thus reinforcing the value of creating a warning system that revolves around both concepts. To expand social science efforts within FACETs, we examined responses from participants in the 2020 HS-PHI experiment, along with knowledge of EST theory, to develop a communication ecosystem for studying potential future warning operations in a probabilistic world (Fig. 5).

Beginning with the “local context” (the light-green box in Fig. 5), NWS participants noted that they would continue to
consider 1) neighboring WFOs, 2) local partners (i.e., end users in their CWA), and 3) their surrounding community when issuing warnings alongside PHI. Communication within CWAs can become challenging, especially since most CWAs do not line up with broadcast and emergency management jurisdictions. These setbacks need to be addressed in a probabilistic world, as results stressed the increased importance of partnership. The EST suggests the embedded system, in this case forecast collaboration using PHI, would ultimately fail if NWS forecasters and other partners do not work together to achieve the ultimate goal: effective risk communication. Outreach to neighboring offices and having points of contact with local partners, then, is critical for WFOs to consider in a FACETs environment.

Within NWS WFOs, workplace practices would have to adapt to new responsibilities with the introduction of PHI, as visualized in “intra-organizational inputs” (the dark-green box in Fig. 5). As participants described in the experiment, workload and delegation raised concern for forecasters, as these factors proved to be the difference between a calm and chaotic shift at the simulated WFOs. In the 2020 HS-PHI experiment, participant pairs, often colleagues that previously worked together, experienced trouble agreeing on what warning style best supports a FACETs environment. As probabilities open the chance for more disagreement, our study stressed the concept that interoffice collaboration ultimately relies on social dynamics, such as personalities and warning styles. This finding echoes many issues about individual office warning philosophies in the present day (Stumpf and Gerard 2021). It is important to note that, while many forecasters in our study expressed negative thoughts on increased workload presented by PHI, previous studies show that forecasters begin to worry less about workload when they become familiar with the tool, and techniques and software are under development to address feedback provided by forecasters in prior experiments (see Karstens et al. 2015, 2018; James et al. 2022, manuscript submitted to Wea. Forecasting).

When collaborating with one another, NWS meteorologists would have to pursue new strategies to guarantee effective intra/interoffice collaboration in a possible FACETs world (the blue box in Fig. 5). First, a reconsideration of current communication mediums would need to be addressed. PHI participants were not fond of traditional telephone and Internet chat features, because they introduced another platform to monitor during rapidly evolving weather events. Alongside probabilities, an increase of platforms to monitor served as impractical. Participants instead advocated for a visual collaboration tool to be implemented into existing forecasting software. Whether or not this proposed software is added into future PHI technology, developers should support next-generation communication mediums to keep collaborations efficient.

One of the characteristics that would change the least under a FACETs paradigm revolves around the group outputs that NWS WFOs produce on an everyday basis (the purple box in Fig. 5). Sticking to the mission of delivering effective risk communication, participants in the HS-PHI experiment vowed to work together, even in times of major disagreement. To ensure a successful rollout, PHI needs to be able to deliver rapid and reliable information. Finding a balance between accessibility and timeliness, PHI developers should keep in mind that, in both intraorganizational and interoffice collaboration, forecast participants measure their success on these two factors.

7. Limitations
Each week, two pairs of forecasters used the HS-PHI software to create storm-scale PHI and issue severe convective warnings in the NOAA HWT. Each forecast pair emulated a forecast team that would normally constitute a small group, defined earlier as a group of no fewer than three individuals. We acknowledge that this limits our ability to explore intraorganizational components of the EST model (RQ1), since there are more than two forecasters on shift at any time within a WFO. While we were able to explore interoffice collaboration in a small group setting (RQ2) since four people in total worked together, we recognize that having a larger forecast team would lessen the workload of the forecasters so that they can focus on more specialized roles in the decision-making process. Next, we acknowledge that we only conducted qualitative focus groups with eight forecasters. A bigger sample would provide more diverse perspectives and help to balance any individual voices that could dominate the overall feedback in group discussions. In addition, this experiment did not consider updated communication technology: we only focused on landlines and computer-based chat software. The Internet-based AWIPS system allows for hands-on collaboration, and forecasters can see the same screen and take control of the warning process from different locations. Future testing of PHI collaboration should implement this feature and explore whether it affects the decision-making process. Last, the HWT experiment did not test NWS National Center policies to explore whether they played a role on the broader WFO (the brown box in Fig. 5). In the future, PHI experiments should consider all of these factors to analyze how varying policies enhance or limit overall forecaster performance.

8. Conclusions
Considered to be a small group, NWS WFOs are part of an embedded system of groups and organizations. During severe weather events, NWS meteorologists work as small groups as they delegate tasks and warn communities to advise precautionary measures within their own jurisdiction. In times that storms approach CWA boundaries, the small group expands, as now several meteorologists work to negotiate and trade off critical life-saving information. This research demonstrates the important insights that can be gained by applying the EST framework to NWS operations, including local contexts, intraorganizational inputs, intra/interoffice collaboration, group outputs, and the social system that oversees them. To support a proposed, next-generation warning system, WFO internal and external partnerships, forecasting practices, and communication mediums must also be modernized alongside the new technology. In addition, finding a proper balance between
accuracy and timeliness is critical for forecasters in charge of developing life-saving information. When considering a FACETs future, social science researchers can utilize the EST framework showcased in this article to visualize and improve the way probabilistic information is delivered.

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Data availability statement. The nonidentifiable data collected in this study (i.e., HS-PHI Interoffice Collaboration) will be made available upon request and free of charge following a reasonable period of time for data analysis and publishing (approximately 2 yr).

REFERENCES


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