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I will end my acknowledgments with one of my favorite quotes:

> When it rains, most birds head for shelter; the eagle is the only bird that,
> in order to avoid the rain, starts flying above the clouds.

As an Eagle Scout, this quote has resonated with me for years. To all of my fellow colleagues, remember never to give up, and when it is raining in life, keep going until you are past the rain. I thank you, the reader, for taking the time to read my thesis and, as Larry Cohen always ends his talks: "Keep Smiling."

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Abstract

The CopterSonde is a state of the art sampling platform that can be used to advance the field of meteorology in operational forecasting and data collection. One capability of the CopterSonde is that it can collect high-resolution observations in the lowest levels of the atmosphere, including in the atmospheric boundary layer, which traditionally is not well sampled. CopterSonde data were collected during a mixed-phase precipitation event in central Oklahoma in February 2019 and during a quasi-linear convective system event in the Mississippi Delta in March 2022. The primary goal of this study was to determine the operational benefits of CopterSonde data when used by National Weather Service forecasters. Specifically, a virtual post-event forecast experiment investigated the impacts on forecasters' operational processes, decisions, and communication of hazards.

Volunteers from four National Weather Service Weather Forecast Offices in the Southern Region initially participated in a background survey during the winter of 2021. This survey investigated the current suite of boundary layer observations available and introduced the CopterSonde platform to them. The survey results suggested that the most anticipated benefits from incorporating CopterSonde data in NWS operational forecasting were: improved understanding of numerous weather phenomena (severe and winter weather were highlighted), increased forecaster confidence and situational awareness, and enhanced communication of hazard expectations to core partners and the public. These findings guided the goals and creation of a forecast experiment that followed.

In the fall of 2022, 16 total forecasters from the 4 Weather Forecast Offices completed 2 case studies over the course of 4 days. The goals were to investigate the impact of the CopterSonde data focusing on their situational awareness, hazard identification, and communications. For each case, CopterSonde data were only provided to half of the forecasters, and focus groups were held at the end of each day. These meetings allowed forecasters to discuss the impacts of the CopterSonde data for both cases.

A situational awareness framework was used to guide the thematic coding of data collected during the case studies. Forecasters with the CopterSonde data reported greater levels of situational awareness and higher confidence in their environmental analysis and decisions. One key finding between the two cases was that the CopterSonde data had a demonstrably more significant impact on the winter weather case versus the severe weather case. This difference in impact is due to the greater uncertainty regarding expected outcomes for the winter weather case. When using the CopterSonde data to identify precipitation types, the probability of detection for forecasters, during the winter weather case, was 0.50. This exceeded that of the group without the CopterSonde data by 0.12. During the severe weather case, an outflow boundary and its impacts were identified in the CopterSonde data. This feature went unnoticed by participants that did not have CopterSonde data available. Overall, forecasters were very enthusiastic about the potential to include CopterSonde data in their day-to-day operations when making decisions and communicating expected weather impacts to their audiences.

Chapter 1

Introduction

1.1 Background Science

National Weather Service (NWS) forecasters are responsible “for the protection of life and property (National Weather Service 2020).” Forecasters interpret atmospheric data and quality control numerical weather prediction (NWP) models in order to develop forecast products, briefings, and warnings for their core partners and the public (Stuart et al. 2022). For short-term forecasting or nowcasting, forecasters primarily use observations to analyze the environment. In contrast, they rely upon NWP guidance when forecasting on the timescale of days. As technological advances continue to push the field of meteorology forward it is necessary to ensure that the technologies developed are beneficial to NWS forecasters. Murphy (1993) found that a good forecast is only a good forecast if it impacts a decision made by the user. In order to achieve “good” forecasts, NWS products and warnings must be accurate, timely, and communicated in plain language (Rothfusz et al. 2018; National Weather Service 2020).

The atmospheric boundary layer is an active area of research. The boundary layer is the lowest layer in Earth’s atmosphere extending from the surface to approximately two kilometers. The depth of this layer can fluctuate with time and space depending on kinematic and thermodynamic interactions (e.g., Stull 1988; Lappin et al. 2022). Field campaigns have targeted understanding the boundary layer’s diurnal transition (Angevine et al. 2001; Lapworth 2006). These campaigns used tall towers and surface stations that collected observations over several months (Angevine et al. 2001) and several years (Lapworth 2006).

While the boundary layer has been studied over long periods of time at stationary sites, specific boundary layer features have been studied during mobile field campaigns. The Plains Elevated Convection at Night (PECAN) was one of the first field campaigns to specifically target observing bores and was successful in sampling several bores during this project (Geerts et al. 2017). In association with observing bores, PECAN focused on the nocturnal low-level jet and the initiation and evolution of nocturnal mesoscale convective systems. Additionally, differences in the internal dynamics for mesoscale convective systems were observed, especially when externally (e.g., frontal forcing) and internally (e.g., cold pool forcing) driven systems were sampled. Beyond field campaigns using specialized instruments, radiosondes collect boundary layer observations daily and globally.

Radiosondes are currently one of the primary sources of reliable boundary layer and upper air observations. Radiosondes are launched daily at 0000 and 1200 UTC at Weather Forecast Offices (WFO) in the United States and elsewhere globally. Due to their sampling frequency, the boundary layer remains largely unsampled. Additionally, WFOs are located several hundred miles apart, creating a sparse horizontal dataset (Reeves et al. 2014; Pinto et al. 2021). Furthermore, the balloons carrying the radiosondes drift as they ascend through the atmosphere resulting in quasi-vertical profiles. Most radiosondes ascend at approximately 5 ms^{-1} and sample on the order of seconds, collecting observations on the order of tens of meters (Ko et al. 2019). Radiosondes are plotted on skew-T log-P charts (skew-T). Due to this display choice, the boundary layer is not displayed on the order of meters, but rather hundreds of meters due to the full depth of the boundary layer encompassing the lowest few hundred hectopascals. Small-scale features that are observed can be missed or difficult to see and interpret on the diagrams. These display-driven data gaps can impact forecasters' ability to forecast and communicate the expected impacts.

Improvements to weather observing technologies have benefited NWS forecasters' situational awareness and communication. An example of one benefit was the upgrade of the operational radar network in the United States to Weather-Surveillance Radar-1988 Doppler. These upgrades formed the Next-Generation radar network that NWS forecasters use today (Friday Jr. 1994). LaDue et al. (2010) found that forecasters felt Doppler radars significantly improved their abilities to do their job due to the data being more reliable and easily viewable. Overall, the percentage of tornado warnings issued before a tornado formation increased from 35% to 75%. The lead time associated with these warnings also increased from 5 minutes to 18 minutes (Bieringer and Ray 1996; Simmons and Sutter 2005; Erickson and Brooks 2006).

Similar to radars, satellites use remote sensing techniques to provide meteorologists with real-time data of the atmosphere. Satellites increased the real-time availability of worldwide observations from sporadic to near constant (Hanson et al. 2013). Land and ship-based observations were the only means of forecasting immediate weather during the pre-satellite era. The 1925 tri-state tornado and the 1900 Galveston hurricane are two notable examples of storms that “hit without warning” due to poor observing techniques (Brodt 1986; Burnett 2017).

A limitation of satellites observations for forecasting and NWP is that the vertical profiles of infrared radiance, which are a key component of satellite observing strategies are generally not useful within and below clouds. Thus, the utility of satellite observations to short-term forecasting of convective systems and weather associated with fronts and cyclones is limited (e.g., McNally 2002; Errico et al. 2007; Prates et al. 2013; Geer et al. 2019). Satellite's temporal resolution is on the order of minutes. Their horizontal resolution is on the order of kilometers and their vertical resolution is on the order of meters (Balsamo et al. 2018; Leuenberger et al. 2020). Both satellites and radiosondes can leave microscale and mesoscale features unsampled in the boundary layer due to their vertical sampling resolution. Meteorological features can exist on the order of meters or hundreds of centimeters in the boundary layer (Stull 1988). In the upper atmosphere, radiosondes and satellites have the ability to better sample mesoscale and synoptic scale features.

New and emerging technology, like uncrewed aerial systems (UAS), have been identified as a possible solution to fill some observing gaps, particularly in the boundary layer (National Research Council 2009; National Academies of Sciences, Engineering and Medicine 2018). Sampling with UASs has previously been limited due to costs and restrictions by the Federal Aviation Administration. The cost of purchasing a UAS has significantly reduced in price recently. A fully autonomous weather sensing UAS costs approximately $100,000 (Pinto et al. 2021). This cost is considerably less than the cost of satellites or radiosondes. Radiosondes cost approximately $300 per launch per site. With a minimum of two daily launches, radiosondes cost roughly $220,000 per site annually. The intention of UASs is not to replace but rather to complement the current radiosonde network (McFarquhar et al. 2020).

The CopterSonde is a UAS that was developed by the University of Oklahoma Center for Autonomous Sensing and Sampling, now the Cooperative Institute for Severe and High-Impact Weather Research and Operations, as an inexpensive solution to sampling the boundary layer in high resolution (Segales et al. 2020). Leveraging novel approaches in observational technology, the CopterSonde improves spatiotemporal resolution compared to other instruments commonly used to observe the boundary layer, such as radiosondes. Currently, the CopterSonde samples at 10 Hz, and the samples are averaged to provide measurements every second. With an approximate ascent rate of 3 ms^{-1}, the CopterSonde collects observations every 3 m or 1 s as it ascends through the boundary layer. This fine scale of observations can be used to understand boundary layer processes not sampled by radiosondes or satellites. Currently, the Federal Aviation Administration requires a pilot and visual observer to be present for all flights, which limits the ability of UASs to be autonomous. Once UASs can be fully autonomous and operational, they can be regularly integrated into the routine workflow of a forecaster and increase the number of observations they have at their disposal. Section 1.2 provides a more complete technical description.

In addition to observations, forecasters heavily rely upon NWP guidance when forecasting. The skill of NWP models has been advancing at a rate of one day per decade, and a noticeable increase in skill was observed after the inclusion of satellite observations (Bauer et al. 2015). On the order of 10^7 observations are assimilated into NWP daily. Satellites account for approximately 85% of the these observations and approximately 75% of the overall observational impact on NWP from observations (Candy et al. 2021). The improvement in observational capabilities from satellites has a high economic cost. The Geostationary Operational Environmental Satellite Network (GOES) latest initiative (GOES-R) is estimated to cost 10 billion dollars for the 30 year lifespan of the project (National Oceanic and Atmospheric Administration 2019). Observations from radiosondes rank the next most impactful within NWP.

Across Europe, the European Cooperation in Science and Technology (COST) initiative has allowed for the inclusion of boundary layer observations into NWP (Cimini et al. 2020). Microwave radiometers are an example of one source of boundary layer observations. They also use remote sensing techniques to sample the boundary layer and have a resolution on the order of tens of meters (Illingworth et al. 2019). Some examples of active areas of research within the COST initiative are air quality, severe weather, fog, urban meteorology, renewable energy, and aviation (Illingworth et al. 2019; Cimini et al. 2020). Additional studies have also examined the inclusion of UAS data in NWP models (e.g., Flagg et al. 2018; Cione et al. 2020; Leuenberger et al. 2020; Jensen et al. 2021; Tripp et al. 2022). An overall observation from these studies is that the inclusion of high-resolution UAS observations from the boundary layer reduced model bias and error of the thermodynamic profiles. Additionally, these reductions in biases improved the forecast of high-impact weather events.

Forecasters' forecast and decision-making processes could potentially be improved by increasing the skill in models. Still, there may be a direct benefit from providing them with the observational data collected. In meteorology, the benefits of having boundary layer datasets are vast, from improving day-to-day weather prediction to real-time monitoring of developing impactful situations and modeling for future weather. The benefits of improved observations extend beyond meteorology, including public health, aerosol and atmospheric chemistry, agriculture, wildfire management, and renewable energy production (Fiebrich et al. 2021). The structure of the boundary layer can dictate the dispersion of chemicals within it. With improved measurements in the boundary layer, the risks to both people and agriculture associated with pollution and other hazardous chemical exposures can be better modeled and communicated.

One important note is that all the recent benefits to forecasters cannot be credited to technological improvements. Meteorologists' understanding and training have improved (National Research Council 2012). Social science research can highlight the improvements from technology versus the collective improvements. Houston et al. (2020, 2021) led focus groups followed by a national survey to collect opinions about UASs in the weather enterprise. The focus groups revealed NWS forecasters anticipated benefits from including UAS data in their workflow. Forecasters identified 25 meteorological features ranging from deep convection, wildfires, ice jams, and cloud fields as challenging to diagnose or predict with the current data during the focus groups. Houston et al. (2020) found that 96% of these features would require the lowest one kilometer of the atmosphere to be sampled, at a minimum. Houston et al. (2021) presented these features in a nationwide survey to assess the impact UAS data could have on the forecast process of each feature. Forecasters highlighted mixed-phase precipitation events and the pre-convective environment as two areas where UAS data collection should be prioritized in the survey.

In addition to investigating forecasters' opinions about specific features, Houston et al. (2021) queried the implementation of UASs. Forecasters rated the operationalization of UASs as the highest priority since they offer a feasible solution to filling current data gaps. Another high priority was receiving the data within 30 minutes of it being collected. Though Houston et al. (2020, 2021) found these potential benefits of UASs, these studies have not been followed up in an experiment where data is provided to forecasters. Pinto et al. (2021) expressed the need for more testbed experiments to determine the operational benefits of UAS data. This study aimed to deepen the understanding of the operational benefits of UAS data, specifically focusing on situational awareness by conducting a forecast experiment.

The first phase of research in this study was a background survey with the goal of collecting information about the current use and understanding of boundary layer observations. Additionally, ideas were solicited regarding the potential benefit of using CopterSonde data in operations. The specific research questions were:

1. What boundary layer observations are currently used in short-term NWS operations (nowcasting), and how are they used?
2. Is the current set of observations sufficient?
3. What is the difference in observations used for calm versus impactful weather days?
4. How could CopterSonde data be used in NWS operations?
5. What would be the ideal ways to display CopterSonde data?

The second phase of this study was a forecast experiment with the goal of determining the impacts of CopterSonde data on forecasters' forecast and decision-making processes. The results of the background survey guided the development of the forecast experiment. The specific research questions were to investigate the impacts of CopterSonde data on forecasters':

1. Situational awareness
2. Precipitation type classification
3. Hazard identification
4. Confidence
5. Communication of threats

Additionally, forecasters' level of trust and comfort in using the data were investigated. This study will build upon the background information learned from Houston et al. (2020, 2021) and fulfill the goal set by Pinto et al. (2021) by gathering background information and anticipated benefits from a sample population and then evaluating potential solutions in a forecast experiment.

Testbed experiments are needed to demonstrate the value of novel technology in operational settings. During the Environmental Profiling and Initiation of Convection campaign (EPIC; Koch et al. 2018), CopterSondes were deployed to sample the prestorm convective environment. During the five campaign deployments, the data were provided to local NWS offices in real-time. The amount of information forecasters had at their disposal was increased, but the usefulness of the data was rated low. In Koch et al. (2018), forecasters addressed that they rely on familiar data types, such as satellites and radiosondes. The EPIC campaign focused on data collection and distribution rather than the use of the data. This study, presented here, focused on the use of the data by NWS forecasters rather than collection and distribution.

This thesis will be structured in the following manner: in Section 1.2, a description of the development and testing of the CopterSonde will be provided. Section 2 will detail the methods used in the background study, followed by a presentation of the results. Section 3 will describe the development of the forecast experiment, a description of each case, and the results from the two case studies. Section 4 will provide a discussion on the anticipated benefits identified in the background survey and the observed impact of the CopterSonde data during the two case studies. Finally, Section 5 will provide a summary and conclusion.

1.2 CopterSonde Technical Description

Figure 1.1: CopterSonde in flight next to an Oklahoma Mesonet tower with a three-dimensional model (inset) of the CopterSonde. Image from Greene et al. (2019).

The CopterSonde (Fig. 1.1) is a rotary-wing UAS and consists of an instrument package that collects thermodynamic and kinematic measurements. This package is enclosed within a shell atop a rotary-wing uncrewed aerial vehicle. Efforts led by Greene (2018); Greene et al. (2019); Bell et al. (2020); and Segales et al. (2020) have calibrated the sensors on the CopterSonde to collect measurements within the acceptable ranges defined by the UAS and meteorological community (Argrow et al. 2017). The CopterSondes temperature measurements are within 0.5° C and wind speed calculations are within 0.6 ms^{-1} (Bell et al. 2020). Extensive testing and redundant sensor placement have reduced the error and bias associated with CopterSonde measurements from external sources, such as solar radiation, and ensures the effects of the craft, such as heating from the motors, will also have minimal influence on the atmospheric measurements collected (Greene 2018; Greene et al. 2019; Bell et al. 2020).

The CopterSonde uses onboard inertial measurements to continuously rotate the craft into the wind, enabling the calculation of wind speed and direction (Segales et al. 2020). This design omits the need for onboard wind sensors, which enables longer flight times and greater maneuverability. The CopterSonde can fly vertically through the boundary layer and sample at 10 Hz. The samples are averaged to provide measurements every second or approximately every three meters, which is the approximate ascent rate of the craft (Bell et al. 2020; Segales et al. 2020). The reader is directed to Greene (2018); Greene et al. (2019); Segales et al. (2020); and Bell et al. (2021) for further details on CopterSonde instrumentation and testing.

The CopterSonde has been used in field campaigns to gain new insight into the sampling frequency and versatility of the CopterSonde. One such campaign was the Innovative Strategies for Observations in the Arctic Atmospheric Boundary Layer campaign (ISOBAR; Kral et al. 2018), where the stable boundary layer was investigated at high resolutions. Typically, tall towers or other inflexible observation systems take observations in the stable boundary layer. ISOBAR aimed at developing an approach to combine these inflexible observation platforms with UASs since they have been found to be a flexible platform for observation collections. During the Flux Capacitor campaign, CopterSondes and a Doppler lidar sampled sub-hourly periods of downward mixing of warm air and momentum (Segales et al. 2020). Standard radiosonde observations would have missed these phenomena due to their limited vertical sampling in the boundary layer. The International Society for Atmospheric

Research using Remotely piloted Aircraft deployed ground-based observation systems and UASs, including the CopterSondes, to sample the boundary layer in Colorado's San Luis Valley during the Lower Atmospheric Profiling Studies at Elevation-a Remotely-piloted Aircraft Team Experiment (LAPSE-RATE; de Boer et al. 2020). Due to this location's unique geography, being situated between the San Juan Mountain Range to the west and the Sangre de Cristo Mountain Range to the east, datasets were collected to research valley drainage flows, convection initiation, aerosol properties, turbulence, transitions of the boundary layer and comparisons between UAS and ground observing systems (de Boer et al. 2020; Pillar-Little et al. 2021). In 2022, CopterSondes were deployed to investigate sea breeze convection and aerosol interactions along the Gulf Coast near Houston, Texas, as part of the Tracking Aerosol Convection Interactions ExpeRiment (TRACER; Jensen 2019). The CopterSonde is currently being deployed during the Propagation, Evolution, and Rotation in Linear Storms field campaign to investigate the pre-storm environment of tornadic quasi-linear convective system (QLCS) events (PERiLS; Koshiba et al. 2022).

Beyond individual field campaigns, CopterSondes could be deployed to monitor the boundary layer in real-time. Chilson et al. (2019) presented the idea of a three-dimensional Mesonet with UASs stationed at Oklahoma Mesonet sites. Fiebrich et al. (2021) expanded on this concept by proposing that CopterSondes could be spaced approximately 100 km apart within the Oklahoma Mesonet to provide a dataset with a sufficient horizontal resolution dataset to augment the current radiosonde sites. Stationing UASs at Oklahoma Mesonet sites to vertically sample the boundary layer would transform the two-dimensional surface mesonet into a three-dimensional mesonet. These improvements in observational networks can increase forecasters' ability to diagnose the current state of the boundary layer and better forecast the development of impactful weather (Kral et al. 2018; Fiebrich et al. 2021).

Chapter 2

Background Survey

2.1 Survey Design

A long-term goal of UAS weather research is to provide real-time high-resolution boundary layer data to NWS forecasters for their use in operations. A short-term goal for this project was to assess the potential utility of experimental CopterSonde data via a post-event experiment. It was necessary for this initial phase of the research project to gain information about forecaster knowledge of and comfort using these experimental high-resolution data. To accomplish this goal, two methods were considered: a survey and focus groups.

Surveys are more economical in terms of cost and time but have the potential downside of providing simple and short answers without carefully crafting questions (Kelley et al. 2003). Focus groups can provide more in-depth information, but the data collection and analysis is much more time and labor-intensive (Guest et al. 2017). A combination of methods is common, with small focus groups being held first to guide survey question creation (Ponto 2015).

We consulted two of the four Science and Operations Officers from WFOs participating in this study to inform our method choice. Questions regarding the use of boundary layer observations within their offices were asked to determine a high level of understanding of concepts planned to be explored in either a survey or focus groups. Due to the limited use and knowledge of high-resolution boundary layer observations, it was determined that there was not a wide breadth of knowledge about the topics of interest. A survey was chosen since the depth of information collected in a survey would likely be similar to that collected in a focus group. Also, with more in-depth interactions planned in the subsequent experimental part of the research project, the survey was used as a recruiting tool for participants.

The survey design was informed by methods used in the meteorology and education communities. Examples from both fields were reviewed to understand diverse ways to phrase and organize questions. Valli (2017) found that the organization of a survey is critically important to the results. Background questions should be used to warm up the respondents, and key questions should be asked near the middle of the survey. DeCarlo (2018) found that surveys are reliable due to the questions and order of questions remaining the same for all participants. In researching question design, it was found that questions need to be generated that directly relate to the research questions. With specific questions relating to specific research questions, a more robust analysis can be performed.

Open-ended and closed-ended questions are two ways to ask the same question that could provide different responses. Open-ended questions require a respondent to write out an answer and give them a choice to include as much or as little depth as they choose. Closed-ended questions ask the respondent to select one or multiple answers. Despite the differences in question style, the depth of information provided in open-ended questions does not always outweigh the depth of information provided in closed-ended questions (Valli 2017).

The choice to use open-ended or closed-ended questions was guided by the desired responses to a question. For example, asking about forecasters' comfortability of using high-resolution data could have been asked with a fill in the blank, but this would have generated a list of answers without any baseline to compare and measure them. Asking this question using a predetermined scale allowed for a more in-depth comparison between participants since their level of comfort would be selected from the same list.

Five-point Likert scales were used for closed-ended questions because they provide a rating tool that can effectively reveal respondents' attitudes to different topics (Likert 1932; Gall et al. 2006). Likert scales provide five possible answers to indicate the respondents' level of agreement with the question. A benefit of Likert scales is they tend to mitigate the neutrality problem found in number-only scales, where responses can trend toward neutral versus towards extreme ends of the scale (DeCarlo 2018). Another benefit of closed-ended questions is they tend to lower the workload and strain on the participants since a selection is required versus writing out a response.

Questions were grouped into subsections by their topic. Grouping the questions allowed a topic to be introduced, discussed, and closed before moving on to the next topic. The order of questions within subsections was carefully chosen not to lead responses. Generally, broader questions were asked first to introduce a topic, and then more specific questions were asked. This process also mitigated respondents from believing a specific answer was desired and potentially introducing bias. Taking into consideration how to best solicit information to answer the research questions, the survey was constructed as a blend of both open-ended and closed-ended questions (see Appendix 1).

After the survey was created, it was piloted with four graduate students recruited from the University of Oklahoma School of Meteorology through purposive sampling (Patton 2002). All pilot participants held bachelor's degrees, enabling a fair assessment of the survey content. After the pilot study, some of the questions were reworded to reduce confusion in their interpretation. For example, question 25 initially read as follows:

> If temperature, relative humidity, pressure, wind velocity, and wind direction measurements from CopterSondes were made available, how would you prefer them to be displayed?

The goal of this question was to solicit ideas from forecasters about the best way to display data; there was no correct answer. Feedback from the pilot study revealed that the word "prefer" was perceived as potentially misleading. Participants felt that there was a correct answer or that they should be choosing from a set of answers instead of giving their opinion. The question was rephrased to ask for ideas as follows:

> If temperature, relative humidity, pressure, wind velocity, and wind direction measurements from the CopterSondes were made available, what ideas do you have for displaying these data?

The Science and Operations Officers facilitated the distribution of the voluntary survey at the four WFOs. The Science and Operations Officers used internal distribution techniques to share the survey with their entire staff, and 12 weeks were allowed to complete the survey. Total population sampling was attempted in this study as the size of the workforce in each office is relatively small. Forty two forecasters answered the survey, but 13 surveys were disqualified due to being incomplete. The participation from the offices ranged from 3–12 participants. Given that only 4 of 122 WFOs participated, the resulting dataset does not provide a sufficient sample size to generalize the results. However, the dataset enabled themes and ideas to be identified and was used to guide the experiment design.

The responses from open-ended questions were analyzed thematically using a framework described in Braun and Clarke (2006). Qualitative research involves making meaning from the data collected (Pauly 1991). Rather than looking for commonalities between data, as narrative analysis often does (Joffee and Yardley 2003), a deeper level of understanding of forecaster preferences and use of CopterSonde data was necessary. This involved generating codes and themes that reflected the ideas and opinions of the respondents. The survey responses to questions were initially analyzed per question, but the final set of codes and themes reflect all the responses from all the questions. The Likert scale questions were analyzed by calculating the median responses for each question. This allowed attitudes from individual offices, as well as the sample population, to be compared.

The selected quotes throughout this thesis were chosen due to their relation to specific research questions. Qualitative expression are used to represent the proportion of forecasters who had shared opinions. In thematic analysis, using qualitative expressions like "some," "most," and "a few" is common (Braun and Clarke 2022). These terms will be used throughout the analysis and generally relate to the following percentages. "A few" will be used when less than 25% of forecasters were included, "some" will be included when 25–50% of forecasters were included, and "most" will be used when greater than 50% of forecasters were included.

Forecasters were provided the definitions for the boundary layer and surface layer. The definition can be found in the National Oceanic and Atmospheric Administration Glossary. In addition to these terms, forecasts, products, messaging, and core partners will be used in the analysis. In this study, these terms are defined as follows:

1. The atmospheric boundary layer is considered to be roughly the lowest one or two kilometers of the atmosphere.
2. The surface boundary layer is a thin layer roughly 10 meters thick (from the surface up to 10 m above the ground) immediately above the earth's surface.
3. Forecasts are predictions of the future state of the atmosphere produced by forecasters.
4. Products are graphics and tweets used to communicate the forecasts and other relevant information by the forecasters.
5. Messaging refers to the use of NWSChat to communicate threats to the appropriate audiences.
6. Core partners are emergency managers, the media, government, and public partners.

2.2 Background Survey Results

Responses from the background survey revealed forecasters' ideas and opinions about boundary layer observations and CopterSonde data. Thematic codes were developed around two prominent themes: *improved meteorological understanding* and *impacts on forecasters*. The boundary layer data gap and specific weather scenarios where high-resolution data could benefit operational forecasting were prominent codes supporting the *improved meteorological understanding* theme. Impacts to situational awareness and forecaster confidence were codes supporting the *impacts on forecasters* theme. Overall, forecasters emphasized the importance of the boundary layer in their forecast processes and the need for real-time observations in their responses to the survey questions. Quotes from forecaster responses will be denoted using "R#."

2.2.1 The Boundary Layer Data Gap

Forecasters expressed that "there is a critical need for more data" when describing the current suite of boundary layer observations and how these observations are used every day in all weather scenarios. For example, R17 described that boundary layer observations are used "for everything from tracking fronts, drylines, outflow boundaries, to monitoring areas for convection initiation, fog & stratus development and dissipation, precipitation type, breaking of inversions, mixing of winds, low-level wind shear, icing, etc." Some forecasters explicitly stated that they wanted more data or that data was missing. In operations, a lack of updated observations leaves critical variables only available by estimation. R9 discussed how forecasters must infer many boundary layer characteristics due to either lack of or sporadic data. "There are so many unknowns above the surface that can have profound effects on the weather."

Without a complete suite of boundary layer observations, NWP models are a widely used tool. R28 discussed that the CopterSonde data would be beneficial because "there is a dearth of information still which has created an over-reliance on model trends." A limitation of NWP models is their data output are not ground truth observations. R9 discussed how they like to have observations "to confirm what the models 'think' is ongoing so that I can adapt these nuances into what they are saying." The availability of observations has been increasing. R19 provided a history of surface observations available during their career. Prior to the creation of the Oklahoma and Texas Tech (West Texas Mesonet) Mesonets, there used to be 6 observations spaced approximately 120 miles apart that reported hourly in their county warning area (CWA). R19 went on to discuss how the new networks of observations have been a "game changer" for them in forecasting.

The Oklahoma Mesonet is statewide with 120 stations, and the West Texas Mesonet is primarily located in the panhandle and western part of the state with 146 stations (Brock et al. 1995; Schroeder et al. 2005; McPherson et al. 2007). While both mesonets provide high-resolution and real-time observations, they are primarily limited to surface observations. A few West Texas Mesonet sites have a sodar or lidar to collect observations. In a few forecasters' opinions, the data collected by these instruments are unusable due to the display techniques. The data is plotted in the form of highly spatially dense wind barbs, which makes it difficult to be easily read or widely used. This was an interesting point raised by a few forecasters that they have access to potentially valuable data, but due to display techniques, it is unusable and not widely used in forecasting operations.

R8 and R20 discussed how new tools and observations become routinely used in operations. For them, the first criterion is trust in the data. Once forecasters have confidence in the data collection and display data, they can begin to rely on the new data. R20 explained that for data sources to be relied upon, the data must be there regularly and consistently. "If only there occasionally, then it does not become ingrained within the forecast process." In order for new data to become routine within NWS offices, it needs to be collected consistently and available in easy to interpret formats.

Data quality and reliability were discussed regarding the process of new observations becoming part of forecasters' workflow. R4 remarked, "more data is always better, especially if we know that it's high quality." Some other forecasters used the terms "reliable" and "accurate" in their responses about new datasets. Data provided by the CopterSonde could solve the reliability and availability concern noted by forecasters with high-resolution and consistent data collection. R19 connected forecasters' opinions about the data gap and the CopterSondes by stating, "this exact information is usually what we are lacking and have to really estimate."

When envisioning the potential impact of CopterSonde data on their forecasting process, forecasters used powerful and enthusiastic words and sentiments. Across all four WFOs, statements like "They are integral," "Extremely enthused," "Exceptionally beneficial," or "Such data could revolutionize forecast and warning practices" were mentioned when the CopterSonde data was introduced as a new potential data source. A total of 18 different sentiments were recorded that showed excitement or positivity towards the CopterSonde data and boundary layer observations in general. R26 eloquently described the use of boundary layer observations, "these items are used in just about all aspects of the forecast, from aviation weather to fire weather to severe weather forecast. They are all an integral part of the process, especially in the short term." R23 discussed how these data would help when needed the most. Both these statements demonstrate a need and desire for the data and, specifically, how CopterSonde data could fill a critical gap and improve weather forecasts.

2.2.2 Improved Meteorological Understanding

In order for forecasters to be able to conduct their jobs to the best of their abilities, they need to understand the processes that are being forecast. R28 voiced that, "literally any meteorological phenomena that have a sensible effect on people and their lives on earth's surface needs to be understood." R16 echoed how the use of boundary layer data ”depends entirely on what the forecast problem is that particular day.” In general, this forecaster noted that “boundary layer thermodynamic and moisture data is essential on basically a daily basis for any application.” One area that R20 introduced was low-level wind shear. They explained how it is a boundary layer process that is not well understood or forecast. Additionally, R20 described that high-resolution boundary layer data “could be helpful for forecasters to first understand and ultimately better forecast it.” Forecasters introduced specific areas and phenomena that could be better understood and forecast with CopterSonde data.

Question 23 presented the forecasters with nine weather scenarios and asked them to rank how useful CopterSonde data would be in them using a five-point Likert scale (Fig. 2.1). The scenarios presented were: severe weather events, winter weather events, fire weather events, aviation weather events, flooding events, air quality events, high-wind events, temperature-related events, (frost, freezing temperature, excessive heat), and visibility events. There was strong agreement in the forecasters’ rating of the value of CopterSonde data for all the scenarios except air quality. Due to the forecasters all being from the Southern Region, the most common and impactful weather scenarios at the offices are similar. This may have influenced the higher rating of severe and winter weather and low rating or air quality. In general, forecasters in the Southern Region do not make air quality forecast and a few forecasters referenced this in their explanations.

In eight of the scenarios (all except air quality), the median rating was at least *Useful Sometimes*, with the rating reaching *Useful Every Time* for severe weather. Four areas that received extensive attention in forecasters’ responses and had a median of at least *Useful Most of the Time* were: Severe, Winter, Fire, and Aviation weather. These scenarios had no outliers, and the interquartile range (IQR) was one, demonstrating a consensus of forecasters’ opinions. R18 generalized the scenarios into a succinct statement about the potential benefit. “The scenarios described above all rely on boundary layer conditions to either develop or propagate. Having a knowledge-based approach to forecasting can help forecast these occurrences better and push that information to our partners." A summary of forecasters' responses for severe, winter, fire, and aviation weather forecasting are provided in sections 2.2.2.1, 2.2.2.2, 2.2.2.3, 2.2.2.4.

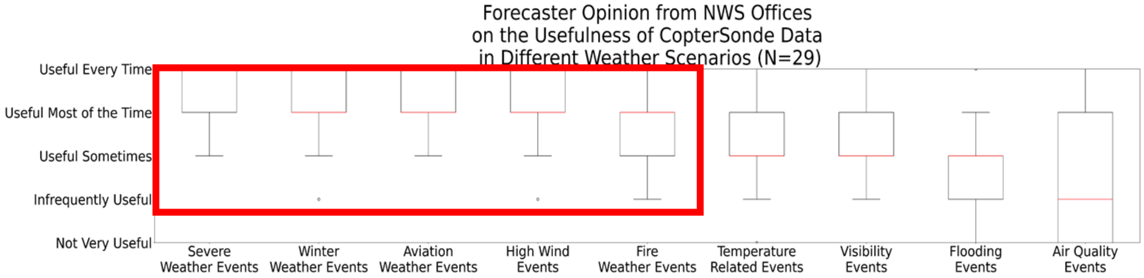


Figure 2.1: Box and whisker plots of forecasters' rating of the usefulness of the CopterSonde data in different weather scenarios from the background survey. The boxes represent the 25th to 75th percentile, with the median as the red center line. The whiskers are the minimum and maximum values. The circles are outliers. The red box is highlighting responses where the median response was at least *Useful Most of the Time*.

2.2.2.1 Severe Weather Forecasting

In the Southern Region, severe weather is common in the spring. All four WFOs surveyed are included in the classic definition of Tornado Alley (Dixon et al. 2011). Therefore, it is not surprising that half of the 58 coded responses and 21 out of 29 respondents included discussions about severe weather in their responses. One struggle that forecasters discussed was convection initiation, as it is derived primarily from model data. R1 noted, "access to such high-resolution data would be transformative, especially for winter weather scenarios and for convection initiation." High-resolution temporal measurements can be used to characterize the current state of the environment and then project it forward. In doing so, the areas most likely for storm formation can be identified.

In addition to convection initiation, responses ranged from descriptions of atmospheric layers that would need to be sampled to assist tornadogenesis forecasting to simply having accurate and current surface measurements. Low-level layers in the boundary layer can be used to assess the strength of temperature inversions, wind shear, moisture profiles, and instability. In addition to these variables, forecasters identified the lifted condensation level, convective available potential energy (CAPE), and convective inhibition as essential quantities. Currently, either radiosondes or model data are required to calculate these quantities. Subtle variability within the boundary layer can vary the depth of the boundary layer or the above-listed quantities influencing whether convection will form at all or become severe.

2.2.2.2 Winter Weather Forecasting

A variety of winter weather occurs within each of the CWAs. In more than half of the winter weather related responses, precipitation type was discussed. Winter weather precipitation can take the form of rain, sleet, ice, or snow, depending on the thermodynamic profile. R12 and R29 described how the low-level thermal profile is critical in forecasting the correct initial precipitation type and determining the crossover from one precipitation type to another. Identifying melting and freezing layers is essential to assess how much of the boundary layer is above or below 32° F. In addition to temperature, the moisture content in the boundary layer can aid in forecasting how much precipitation will evaporate before saturating the boundary layer, leading to surface-observed precipitation. Having an increased understanding of the boundary layer can lead to better precipitation type classifications.

The precipitation type changes the hazards and mitigation efforts that can occur. Forecasters work with emergency managers, the media, and municipalities to help them prepare for impending weather. It is more difficult to pre-treat roads with salt or sand for winter weather if the upcoming event begins as rain. If there is going to be a transition to freezing rain, there may be an increase in the number of power outages. Forecasters' responses indicated that better forecasts could lead to more timely and appropriate responses to impactful weather events.

2.2.2.3 Fire Weather Forecasting

The NWS has incident meteorologists who respond to wildfires. These specialized forecasters forecast the ingredients that lead to favorable or unfavorable fire weather conditions and the progression of a fire if one occurs (National Oceanic and Atmospheric Administration 2020). Storm Prediction Center (SPC) and NWS forecasters also issue fire weather outlooks and warnings. Similar to severe weather, the conditions of the pre-fire environment were highlighted. R3 described how "analysis of the low-level wind and temperature profiles could also potentially help in diagnosing low-level patterns conducive to fire development." Depending on frontal passages, fires could be initiated or extinguished with rainfall. R5 detailed another scenario where boundary layer data would be necessary, "fire managers need to know how deep the mixing will occur for smoke dispersion. Shallow mixing usually inhibits their ability to do a control burn if near a populated area, and the smoke could move into the populated region." Forecasting the smoke, progression of a fire, or potential for fires was discussed as areas CopterSonde data could support.

2.2.2.4 Aviation Weather Forecasting

The major airports in these four CWAs are Dallas Fort Worth International, Will Rogers World, and Dallas Love Field. Forecasters create terminal aerodrome forecasts for airports and pilots detailing the weather over the next 24 hours. Air traffic control uses these to direct aircraft activity at and around airports. R16 discussed how knowing the moisture content of the boundary layer can aid in forecasting radiation fog. Some forecasters discussed how the wind shear and gust potential near the surface could be assessed using the boundary layer and layers above it. Wind shear and gusts can cause runway changes or even ground aircraft. Forecasting these conditions correctly can have life or death consequences for pilots, and having these data could allow for more accurate forecasts.

2.2.3 Improved Forecaster Abilities

Within forecasters' responses about each weather scenario, they included areas where the CopterSonde data could benefit their ability to do their job. Forecasters develop forecasts and determine the most probable outcome using their understanding of the environment and pattern recognition, alongside deterministic and probabilistic NWP model guidance. R16 described clear and calm days as one in a million and noted that there is impactful weather every day. Forecasting boundary layer processes better can lead to more accurate and timely forecasts. Numerous responses from the background survey addressed how CopterSonde data could benefit their forecast process. Forecasters explained how this data could increase their situational awareness, confidence, and messaging.

2.2.3.1 Situational Awareness

Situational awareness is described as "knowing what is going" on in a rapidly changing environment with respect to space and time (Endsley 1995). More specifically, in meteorology, situational awareness involves analyzing all the available data to forecast the possible future state of the environment. R19 discussed how boundary layer data, in general, is used to form "as a complete picture of the atmosphere that we can." Conditional setups present the challenge of the potential for several drastically different outcomes to occur. Regarding the potential benefit of CopterSonde data, R22 and R25 commented on how CopterSonde data could influence the forecast for conditional setups. R22 felt "it would greatly increase SA [Situational Awareness] leading up to and during severe and winter weather. I can see it being particularly useful during highly conditional setups and when precipitation type is in question." R25 explained, "they would likely help a great deal, especially when conditions for a specific event or threshold are borderline marginal and significant."

Maintaining situational awareness may be the most important during impactful weather. Having a greater number of observations can lead to forecasters having more accurate conceptual models. R7 added that the CopterSonde data "... would allow us to better determine what the threat would actually be and to re-shape our mental picture of how the event should unfold." The nowcasting time frame is where people and property are affected by impactful weather. R14 discussed how CopterSonde data could enhance short-term forecasting by better knowing "... what to expect, how things are changing, what new or current concerns are, where, etc." All these factors describe a forecaster's situational awareness. A few forecasters discussed how real-time data could be used to update short-term forecasts. These forecasters described that having a better understanding of what is occurring in the boundary layer allows them to make real-time adjustments to their forecast and conceptual models. These adjustments influence their forecasts, messaging, and warnings.

In addition to providing a better real-time understanding of the environment, CopterSonde data was discussed as being able to validate current model initializations. R6 discussed how data like these could allow them to get a better handle on which computer forecast model is accurately forecasting the situation, allowing them to understand better and anticipate changes in the forecast. R3's response added to this idea by stating that the CopterSonde data could help forecasters "better assess CAMs [convection allowing models] and more quickly deviate from them when needed." If a model poorly forecasts an event, forecasters can adapt their forecast process accordingly. Increasing confidence in NWP models would increase forecasters' situational awareness.

2.2.3.2 Confidence and Messaging

When forecasters have increased situational awareness of an ongoing event, their confidence and ability to communicate effectively about that event may be positively impacted. Relating back to the boundary layer data gap discussed previously, R9 described how having observations of the unknowns aloft can significantly reduce the stress of forecasting them. Some forecasters addressed hazard expectations and how boundary layer data influences them. R15 addressed how a stable environment would have less threat potential than an unstable atmosphere, which CopterSonde data can be used to diagnose. R23 enthusiastically added, “I think this data could significantly benefit my ability to own the mesoscale and provide more accurate forecasting data when it’s needed the most.”

Issuing forecast products and messages is one way that forecasters accomplish their mission of protecting life and property. R9 discussed when they understand a forecast better, they can communicate better. “The better handle we have on what’s going on, the better we can refine the forecast. This is often manifested by more wording to handle ambiguities.” This statement was not unique to R9; three other forecasters (R8, R14, and R16) directly addressed how they would likely be able to add in more detail and be timelier with messaging when using CopterSonde data.

2.2.4 Preferences on the CopterSonde Data

In addition to asking forecasters about their use of current boundary layer observations and how the CopterSonde could be used, specifics about the raw data were queried. Forecasters were asked to provide desired vertical and temporal resolutions and general suggestions for display techniques. These opinions from the forecasters will be shared with the CopterSonde development team to improve the system’s design before more widespread deployments and are summarized below.

2.2.4.1 Vertical and Temporal Resolution

After the CopterSonde had been introduced within the survey, several multiple-choice questions were asked to gauge the preferences of the forecasters on vertical and temporal resolution. The vertical resolution refers to the increments between data points collected by the CopterSonde. Figures 2.2a and 2.2b show the preferences of the vertical resolution for impactful weather and calm weather days per each WFO. A few responses indicated potential confusion in the question, with preferences of higher-resolution data on calm weather days versus impactful. Since this response was not expected (as typically, during severe and impactful weather, more data is desired), these answers were excluded. Overall, interquartile range values were similar for both scenarios: 40 m for impactful weather and 50 m for calm weather. One possible explanation for the IQR values being close together is the influence of the extreme values. The range of values is from 5–1000 m. To account for this, the median was calculated due to it being unaffected by extreme values.

The overall median vertical resolution values for severe and calm weather were 25 m and 100 m, respectively. Between offices, the respective median vertical resolution values for calm and severe weather decreased from 75–25 m for Norman, 100–10 m for Amarillo, 100–37.5 m for Fort Worth, and 50–10 m for Lubbock. All four WFOs showed the same pattern as the overall median. This result indicates that the trend for higher-resolution data during impactful weather was not specific to one office.

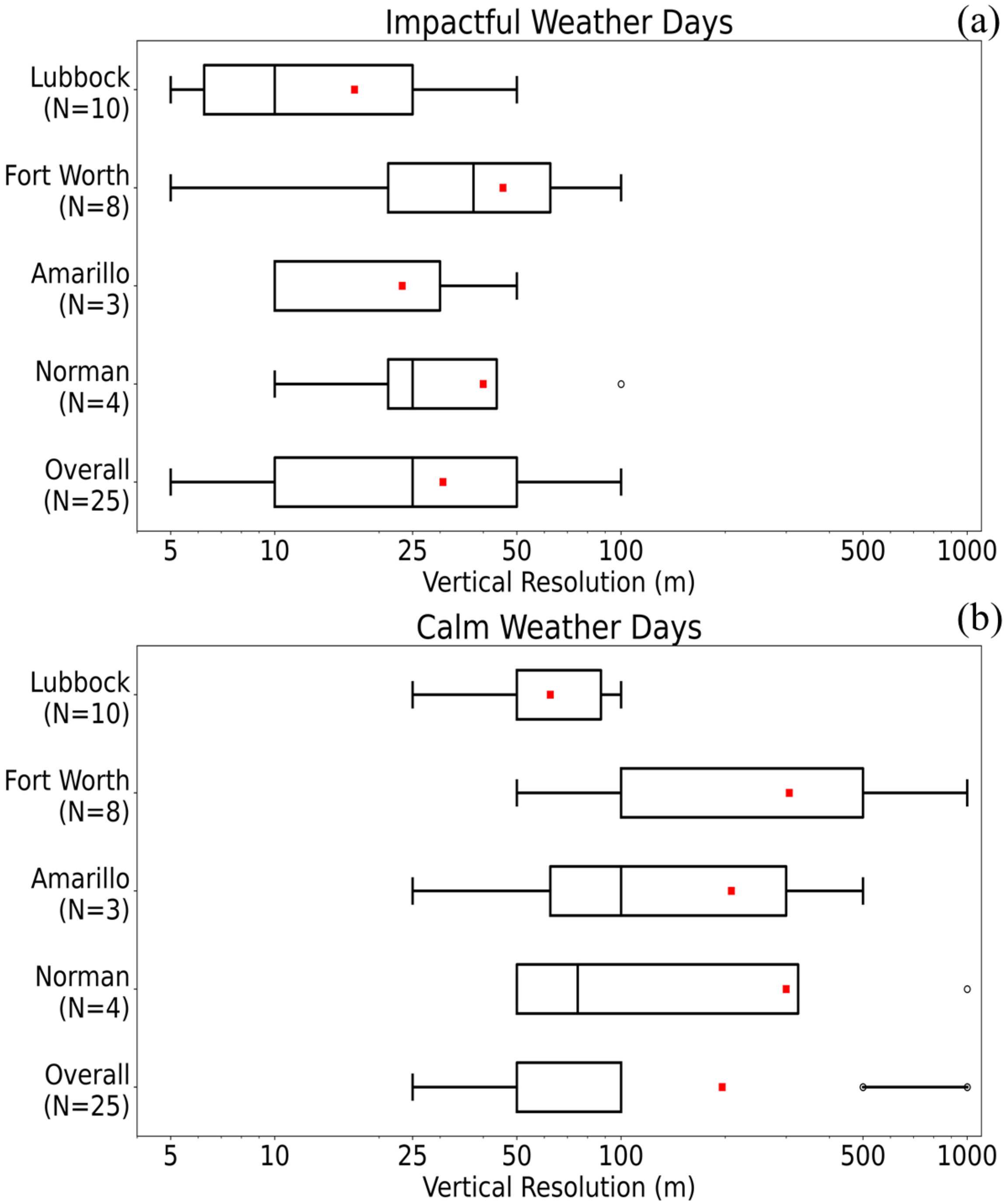


Figure 2.2: Box and whisker plots for forecaster's preferred vertical resolution of the CopterSonde data during (a) impactful weather and (b) calm weather stratified by WFO. The red square is the mean. The boxes represent the 25th to 75th percentile, with the median as the red center line. The whiskers are the minimum and maximum values. The circles are outliers.

Forecasters also provided preferences on the temporal resolution of the data. Choices for this question ranged from data every second to every thirty minutes. Some forecasters preferred data on the order of seconds, and a few forecasters identified every 15 minutes would be sufficient during impactful weather. Overall, there was a decrease in the median and IQR temporal resolution values chosen for calm weather days compared to impactful weather days. For calm weather, the median temporal resolution was 30 minutes with an IQR of 25 minutes. For severe weather, the median decreased to one minute with an IQR of four minutes. This overall decrease in the spread between forecasters' answers demonstrates that data is desired at a much higher temporal resolution during impactful weather.

In addition to providing preferred vertical and temporal resolutions, a few forecasters added other specifics about CopterSonde data that they would like to see. R1 noted that it would be "transformative" if the drone could sample the full depth of the boundary layer and mixed layers aloft. Due to Federal Aviation Administration rules, the maximum sampled height is currently restricted to 5000 ft above ground level. Future waivers and permissions could be obtained through continued interactions with the Federal Aviation Administration to expand the CopterSondes vertical sampling range, as well as grant beyond visual line of sight waivers.

2.2.4.2 Operational Ideas

One of the closing questions asked, *If temperature, relative humidity, pressure, wind velocity, and wind direction measurements from the CopterSondes were made available, what ideas do you have for displaying these data?* This question was used to design the modified soundings and time-height plots. A common theme throughout the answers about displaying the data was to display it in a familiar format. The ability to seamlessly integrate these data into the current operational workflow was paramount.

A reported challenge with using some currently available boundary layer data is their data displays. Part of this survey was explicitly geared at soliciting ideas on how the individual forecasters would want this data displayed. R16 discussed how the best way to display the CopterSonde data would be on a skew-T. “These would be helpful if displayed in the format of a ‘truncated’ sounding so that I could see how the boundary layer was evolving in a faster time scale and to fill in gaps between full soundings.” The gaps between soundings are typically twelve hours unless a special sounding is launched. When forecasting events between this time frame, estimations must be made based on existing data and past experiences. If these data were readily available, low-level data would be available to update the 0000 UTC and 1200 UTC soundings. R3 similarly offered, “with the skew-T or hodographs, it would be nice to be able to overlay the closest or most recent upper air sounding (or a model sounding) to help give the boundary layer data some context.” R3 added that they would like to be able to recalculate the derived quantities of the soundings, CAPE, convective inhibition, shear, etc., with the addition of the CopterSonde data. This idea was not unique to R3, as R16 mentioned overlaying RAP soundings onto the data. Other ideas about displaying the data were to display the data as time-height plots or single isobaric surface maps and to potentially integrate the data into the Advanced Weather Interactive Processing System-2.

The Advanced Weather Interactive Processing System-2 is a primary tool NWS forecasters (Andra Jr. et al. 2002) use. A few forecasters discussed how it would be best to include these data directly into the Advanced Weather Interactive Processing System-2 to interrogate. Another idea suggested by R14 and R23 was data collection sites could be plotted spatially on a map or an ArcGIS dashboard. This viewer would enable quick access to and interrogation of boundary layer data where forecasters expect it to be most useful. R5 and R18 thought that by displaying the data in this way, the soundings could also be animated. This display type would be similar to how the Oklahoma Mesonet displays their data.

Chapter 3

Forecast Experiment

3.1 Experiment Design

The forecast experiment research questions and experiment design were guided by what was learned in the background survey. Analysis of the background survey found that forecasters considered winter weather and severe weather as two forecast areas that could benefit most from CopterSonde observations (Fig. 2.1). This finding, in addition to having a limited dataset, led to the decision to focus the forecast experiment on cases presenting winter and severe weather events. The winter weather case occurred on 19 February 2019 and the severe weather case occurred on 22 March 2022. Situational awareness was also identified throughout the background survey as an area where CopterSonde data could benefit forecasters and therefore was a concept targeted in the case study questions.

The design of the case studies followed many concepts that were used in the background survey. Considerations for order of question, type of question (open or closed), and wording were all carefully considered and followed the guidance detailed above (Section 2.1). The winter weather case had a total of eight time steps, and the severe weather case had a total of five time steps. The questions asked were the same for each time step and varied slightly between cases to adjust for different hazards and locations. See Appendix 2 for a list of questions asked in both case study surveys.

A pilot study was also conducted for the forecast experiment. Two individuals from NWS WFOs that were not involved in the study, and an individual familiar with the CopterSonde platform, participated in a pilot study of the winter weather case study. The experiment protocol was run as it would have been during the case studies to reveal areas for improvement. Comments from the pilot study helped to revise (1) the locations where threat identifications were to be made, (2) the length of the case, and (3) the specific wording of some of the questions.

The experiment was conducted across four days, with a total of four participants each day from the four WFOs that participated in the background survey. Each experiment day included two case studies that were completed in displaced time to enable the forecasters to progress through the case at their own rate. By conducting the case studies in displaced time versus in simulated real-time as in Wilson et al. (2017), forecasters had the ability to progress through the cases faster since they did not have to wait for data to come in. This can be a limiting factor to case studies that occur in "real-time."

The CopterSonde data were displayed in two ways, and at some time steps in the case, multiple sets of CopterSonde data were provided. The Science and Operations Officers from the WFOs were asked to schedule volunteer forecasters from their offices to participate on each of the days. Participating forecasters ranged in terms of their interest in the CopterSonde, including those who had expressed excitement about this technology in the background survey and those who did not participate in the background survey.

Two forecasters from each day were randomly assigned to the control group (C), and the remaining two were assigned to the experimental group (EX) to work the first case of the day. The group assignment reversed between cases, allowing all forecasters access to CopterSonde data during one of the cases. In addition, the order of the cases worked was reversed for the second two experiment days to reduce ordering effects (Koppell and Steen 2004). The control group had access to observations and RAP point soundings, whereas the experimental group had the addition of the CopterSonde data. Neither group had access to NWP guidance for the event. This mitigated the impact on their decisions that model guidance could have had. Table 3.1 displays the distribution of participants from the WFOs and their assigned groups for the first case of the day.

Table 3.1: Forecaster groups for the first case of each experiment day. Participants switched groups between the two cases. C denotes the Control group, and EX denotes the Experimental group.

Day 1	Day 2	Day 3	Day 4
P1 (WFO 2) (C)	P3 (WFO 4) (C)	P5 (WFO 2) (C)	P7 (WFO 1) (C)
P2 (WFO 1) (C)	P4 (WFO 3) (C)	P6 (WFO 3) (C)	P8 (WFO 4) (C)
P9 (WFO 2) (EX)	P11 (WFO 3) (EX)	P13 (WFO 4) (EX)	P15 (WFO 2) (EX)
P10 (WFO 1) (EX)	P12 (WFO 4) (EX)	P14 (WFO 3) (EX)	P16 (WFO 1) (EX)

To determine what data were operationally important, a Science and Operations Officer from a participating WFO was asked to explain the typical forecast process within their office for winter and severe weather. Using this feedback, the following data were provided during the case studies (data examples are available in Appendix 3).

- Upper Air Data collected from the SPC
- Surface Data collected from the Weather Prediction Center
- Oklahoma Mesonet Data collected from the Oklahoma Mesonet (Brock et al. 1995; McPherson et al. 2007)
- Radar data collected from National Centers for Environmental Information (Vose et al. 2014) and displayed using GR2Analyst
- RAP soundings collected from National Centers for Environmental Information (Vose et al. 2014), formatted using the python package siphon (May et al. 2017) and displayed using the python packages MetPY (May et al. 2022)
- mPING and local storm reports from the National Severe Storms Laboratory and StormData and formatted using ArcGIS software by Esri

- Experimental CopterSonde data collected by the Boundary Layer Integrated Sensing and Simulation group at the University of Oklahoma during February 2019 and March 2022 and displayed using the python packages MetPY (May et al. 2022) and cmocean (Thyng et al. 2016)

Each experiment day began with an introductory meeting. Following a short meet and greet, the forecasting task was explained to the participants, and a short presentation on the CopterSonde was shared. Additionally, time was provided for participants' questions, and all were invited to a debrief meeting scheduled near the end of each day. For both cases, a forecast briefing video was prepared leading up to the start of the case. The briefing allowed forecasters to gain situational awareness leading up to the case. A synoptic overview of the environment and then an analysis of ongoing precipitation were included in the briefing. Links to these briefings are provided in Sections 3.3 and 3.5. PDF documents and ArcGIS maps were available at each time step to display the available data.

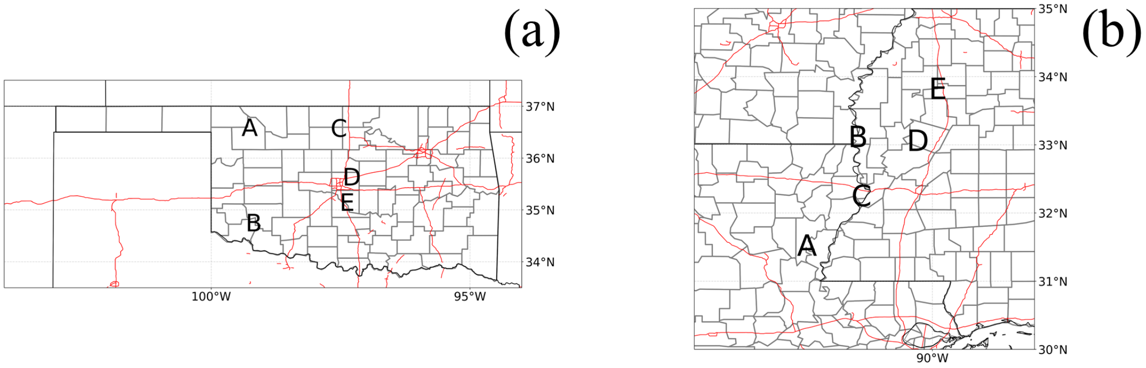


Figure 3.1: Maps of the area of interest for the (a) winter weather case and (b) severe weather case. Locations A-E represent the locations that forecasters were asked to make precipitation classifications and hazard identifications.

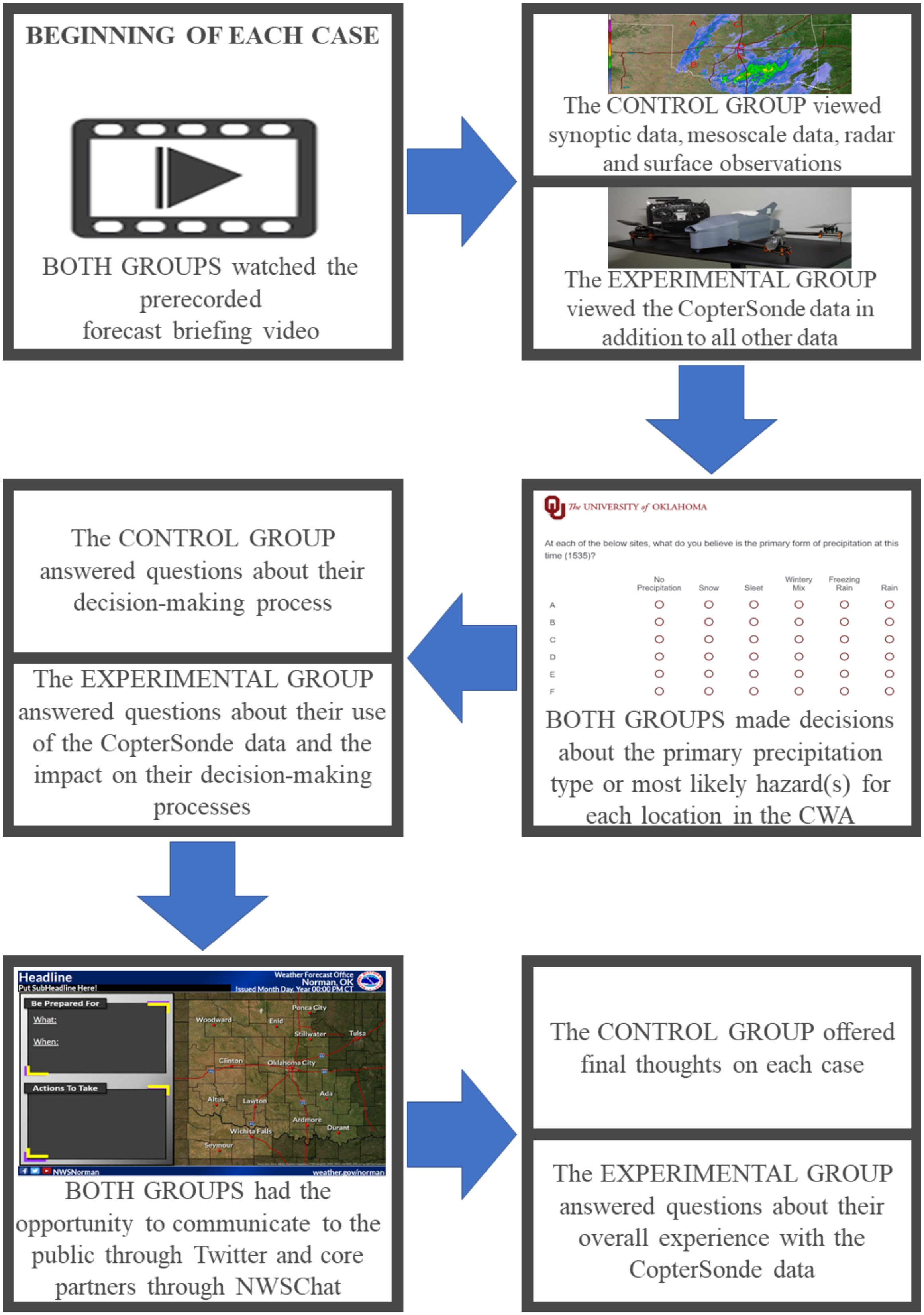
At the start of each time step, the forecasters were asked to assess the meteorological data available. During the winter weather case, they were asked to classify the most likely precipitation that was occurring at multiple locations across the Norman CWA (OUN) (Fig. 3.1a). For the severe weather case, the forecasters were asked to identify the most likely weather hazard(s) across the Jackson CWA (JAN) (Fig. 3.1b). The participants were then asked the following questions:

- Did the addition of the CopterSonde data influence your decision, leading to a change in precipitation type (hazard expectation) or an increase in confidence in your original decision? (Experimental group only)
- Please detail what led to any change or reinforcement in your decision (Experimental group only).
- Please describe the (1) information used and (2) how it was used to assess the changes in the environment and associated precipitation types.
- With the information available about the past and current weather, what areas are of the most concern for impacts within the next hour and why?

If forecasters felt that their concerns should be communicated to their core partners or the public, they were directed to a Google Slides slide deck containing templates for Twitter graphics and a simulated NWSChat to communicate those concerns. This was repeated eight times in the winter weather case and five times in the severe weather case, approximately 30 minutes apart. At the conclusion of each case, forecasters were asked to summarize the event, and the experimental group was asked to express their opinions about using the CopterSonde data. Figure 3.2 displays the steps forecasters followed in both cases.

During the afternoon meeting, a semi-structured focus group interview was used to target specific research goals (see Appendix 4). Conducting the focus groups this way allowed for forecasters' opinions to be investigated in greater detail than the survey would have allowed. Follow-up questions and discussion further revealed the impact of the CopterSonde data, forecasters' level of trust in the CopterSonde data, and ideas about integrating CopterSonde data into NWS forecasters' workflows. During the focus group, a figure was shown that displayed the precipitation type or hazard classifications by each forecaster and the verification. This allowed discussion about the impact of the CopterSonde data on the experimental group.

Following each case's discussion, topics not presented in the survey were introduced. For example, forecasters were asked to describe their level of trust in the CopterSonde data. Trust was part of the research questions, but instead of having forecasters select their level of trust off of an arbitrary scale in the Qualtrics surveys, their explanations were desired. A discussion about the best way to visualize the CopterSonde in operations was held, using the two ways CopterSonde data were displayed during the case and a third option presented in the focus group.



BEGINNING OF EACH CASE

BOTH GROUPS watched the prerecorded forecast briefing video

The CONTROL GROUP viewed synoptic data, mesoscale data, radar and surface observations

The EXPERIMENTAL GROUP viewed the CopterSonde data in addition to all other data

The UNIVERSITY of OKLAHOMA

At each of the below sites, what do you believe is the primary form of precipitation at this time (1535)?

	No Precipitation	Snow	Sleet	Wintery Mix	Freezing Rain	Rain
A	○	○	○	○	○	○
B	○	○	○	○	○	○
C	○	○	○	○	○	○
D	○	○	○	○	○	○
E	○	○	○	○	○	○
F	○	○	○	○	○	○

BOTH GROUPS made decisions about the primary precipitation type or most likely hazard(s) for each location in the CWA

The CONTROL GROUP answered questions about their decision-making process

The EXPERIMENTAL GROUP answered questions about their use of the CopterSonde data and the impact on their decision-making processes

BOTH GROUPS had the opportunity to communicate to the public through Twitter and core partners through NWSChat

The CONTROL GROUP offered final thoughts on each case

The EXPERIMENTAL GROUP answered questions about their overall experience with the CopterSonde data

Figure 3.2: Diagram showing the workflow of the case studies for each group.

3.2 Analysis Protocols

During each time step of the cases, forecasters provided narrative responses. These responses included explanations of their forecast processes and their use of the CopterSonde data. Additionally, forecasters sent NWSChat messages and constructed graphics and tweets regarding the threats and hazards of each case. The narrative responses were analyzed qualitatively. Thematic analysis was chosen, as it is accepted for being a flexible method in conducting qualitative analysis and can reveal deeper answers related to open research questions (Braun and Clarke 2006). Taylor and Ussher (2001) and Braun and Clarke (2006) postulated that themes do not emerge and rather are selected from the data. Thematic analysis protocol adapted from Braun and Clarke (2006) has been used in Bowden and Heinselman (2016); Houston et al. (2020); Tripp et al. (2022); and Obermeier et al. (2022). A thematic analysis protocol adapted from Braun and Clarke (2006) was used to analyze the open-ended questions from the background survey and case studies, graphics, tweets, NWSChat messages, and focus group transcriptions. The protocol for this study included the following:

1. The author immersed themself in the data by transcribing recorded focus group interviews and repeatedly reading through all elements of the dataset (surveys, communications, and focus groups).

2. The author generated initial questions, ideas, and codes about the data in the form of statements.

3. The codes were grouped into broad and general themes or categories revolving around the research questions.

4. The themes and codes were refined to revolve around Endsley's 1995 situational awareness framework to ensure they represent the dataset well.

5. The themes and codes were finalized and defined.

The process of discovering themes is iterative. The choice to stop is one of the many choices made by a qualitative researcher. Once the coded excerpts sufficiently represented the data and answered the research questions, the coding process concluded (Tuckett 2005). The conclusion of the coding process traditionally occurs when meaning saturation has been achieved and the thematic codes represent the perspectives of the sample (Pauly 1991; Hennink et al. 2017). Meaning saturation is defined as the point where 80–90% of new information has been extracted, and further iterations of the coding process would reveal minimal new information or codes (Morse et al. 2014; Hennink et al. 2017).

One of the study's goals was to understand the impact of CopterSonde data on forecasters' situational awareness. Endsley's 1995 hierarchical framework for situational awareness was applied to the study. The first level of situational awareness is perception, followed by comprehension (level 2), and the highest level (3) projection. McGuiness and Foy (2000) expanded upon this framework to add a fourth level (resolution). Viewing all the data used by the forecasters to make decisions (e.g., soundings, radar, local storm reports) represents the first level of situational awareness (projection). The ability to make connections between these data and form a better interpretation of the atmosphere represents the second level of situational awareness (comprehension). The ability to determine the likelihood of each precipitation type and identify the most likely precipitation type classification represents the third level of situational awareness (projection). Forecasters' decision to communicate (or not communicate) their interpretation of the atmosphere and associated threats to core partners and the public represent the fourth level of situational awareness (resolution).

Forecasters' communication slides and the transcribed focus groups were also thematically analyzed. At each time step, forecasters could edit their communication slides. The graphics created, and NWSChat messages sent were analyzed per forecaster and between groups to determine how the CopterSonde data impacted communications. After assigning codes to the survey responses, communication graphics, and NWSChat messages, the focus group text was analyzed. The overall themes and codes generated from the experiment were from the survey responses, communication graphics, messages, and focus group text.

In addition to analyzing forecasters' narrative responses, their classifications of precipitation type and hazards at each time step, and their overall comfort level using the CopterSonde data were analyzed. The precipitation and threat classifications, and level of comfort questions, were the only closed-ended questions analyzed. The forecasters' classifications were compared, and the probability of detection (PoD) was calculated for individual forecasters as well as groups. PoD is a statistic that quantifies the fraction of correctly forecast events compared to the total number of events that occurred (Wilks 2011). PoD allowed forecasters' decision accuracy to be compared between the control and experimental groups. Statistical analysis using a Wilcoxon Rank Sum Non-Parametric Test was done since this test does not require the sample to be normally distributed or information about the sample size to be known (Wilks 2011). The verification statistics were computed using CopterSonde pilot reports, mPING reports, local storm reports, and Twitter reports.

3.3 19 February 2019 Description

The winter weather case chosen occurred between 1500–2000 UTC on 19 February 2019. A link to the weather briefing provided to the forecasters participating in this study can be found here (`https://youtu.be/2ClF8zrWbww`). During mixed-phase events, the difference between rain, freezing rain, sleet, and snow can be determined by surface and melting layer characteristics (Hux et al. 2001). Forecasters currently rely on radiosonde observations and high-resolution surface data to make their precipitation classifications, but this resolution is not always sufficient to get an accurate depiction of the state of the boundary layer across CWA (Reeves et al. 2014). In this case, half of the forecasters (P9–16) were provided CopterSonde data at roughly 30 minute increments to evaluate the impact of higher resolution data on precipitation type classifications and the communication of associated threats.

In the lead-up to 19 February 2019, a closed 500 mb low was broadening and digging along the West Coast of the United States. By the morning of 19 February, a negatively tilted open trough was positioned over the Rocky Mountains (Fig. 3.3a-b). Central Oklahoma was positioned in the right entrance region of a 150-kt jet streak at 250 mb (Fig. 3.3c). Southerly isentropic lift developed east of the wave at 850 mb and was also present over central Oklahoma at 500 mb (Fig. 3.3d). These combined factors led to strong ascent in central Oklahoma.

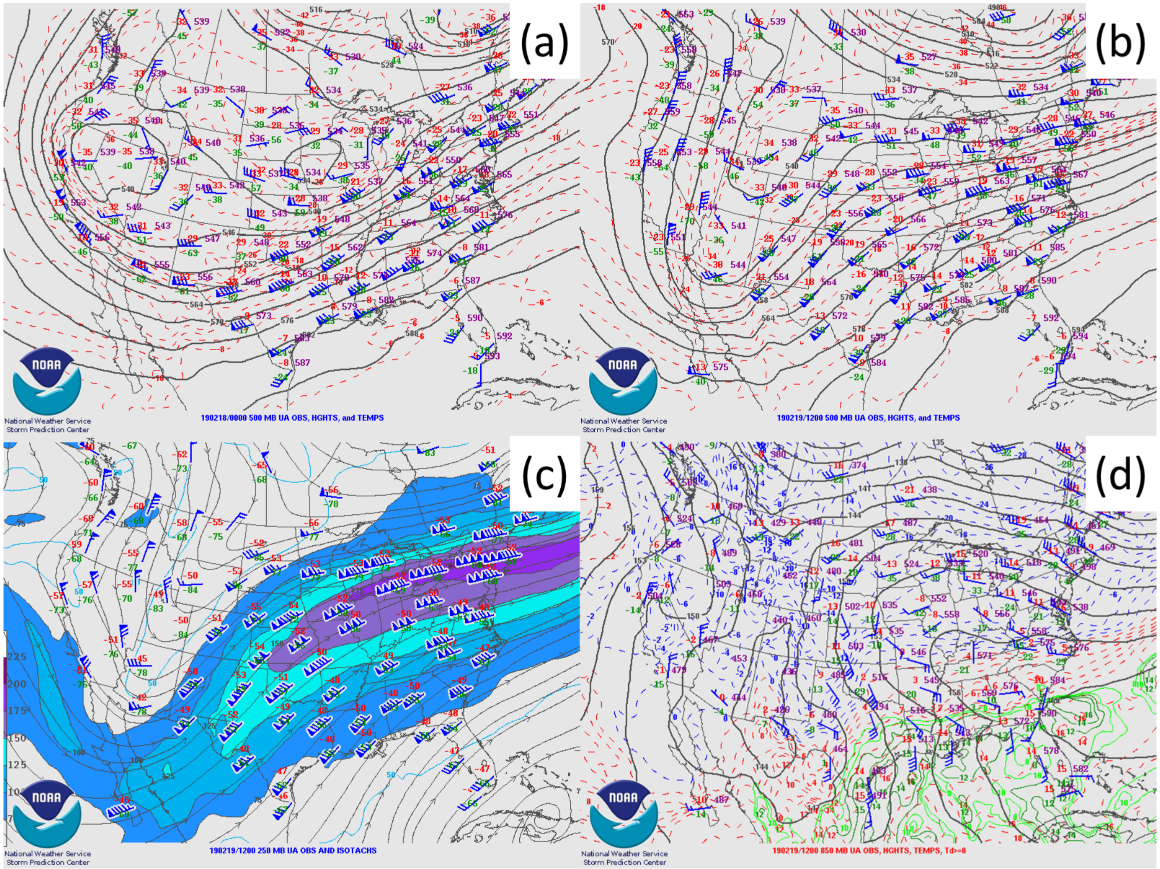
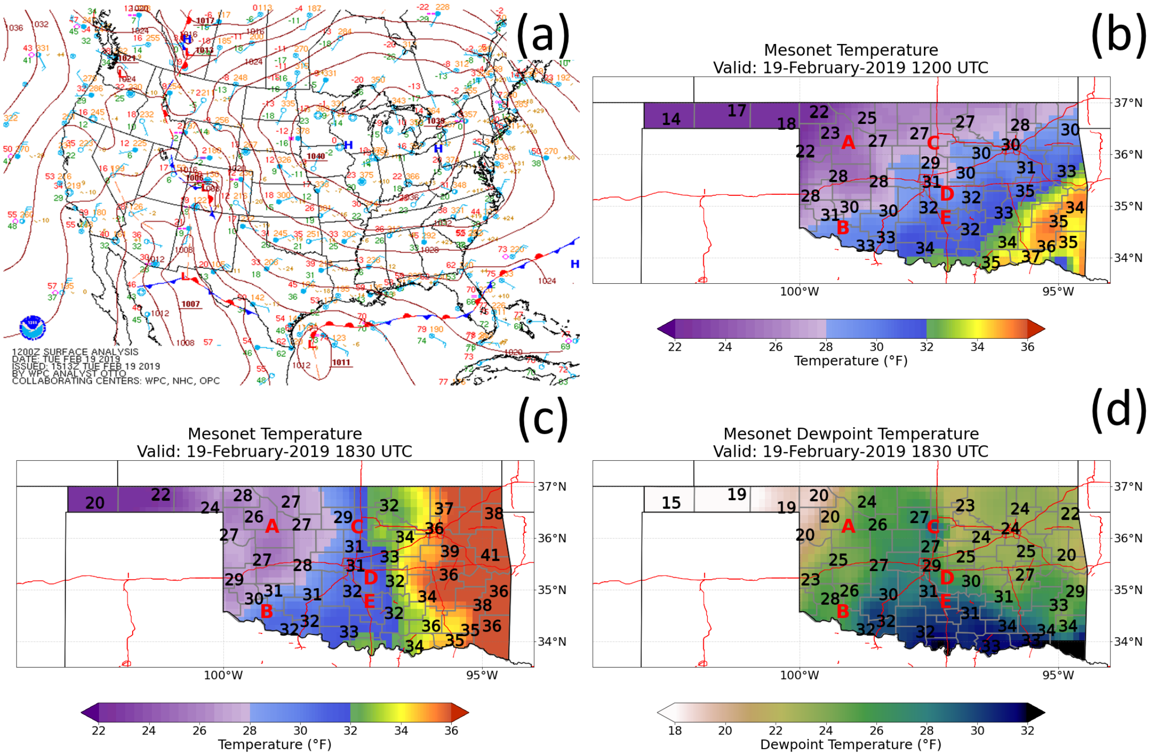


Figure 3.3: SPC upper air analysis at (a) 500 mb from 0000 UTC 18 February 2019, (b) 500 mb from 1200 UTC 19 February 2019, (c) 250 mb from 1200 UTC 19 February 2019, and (d) 850 mb from 1200 UTC 19 February 2019.

At the surface, central Oklahoma was under the influence of a high-pressure system situated over the Great Lakes region (Fig. 3.4a). During the morning of 19 February, the surface 32° F isotherm advanced to the southeast. As diurnal heating resumed in the morning, this line retreated towards central Oklahoma (Fig. 3.4b). As the day progressed, the I-35 corridor was aligned with the 32° F isotherm (Fig. 3.4c). Surface moisture steadily increased throughout the day, reaching 25–30° F north of the I-40 Corridor and 30–34° F south of I-40 (Fig. 3.4d).



Mesonet Temperature
Valid: 19-February-2019 1200 UTC

Mesonet Temperature
Valid: 19-February-2019 1830 UTC

Mesonet Dewpoint Temperature
Valid: 19-February-2019 1830 UTC

Figure 3.4: (a) Weather Prediction Center surface analysis from 1200 UTC 19 February 2019, Oklahoma Mesonet recorded (b) temperature from 1200 UTC 19 February 2019, (c) temperature from 1830 UTC 19 February 2019, and (d) dewpoint temperature from 1830 UTC 19 February 2019.

The surface was unsaturated and near freezing for the majority of the CWA for this case. Using the 1200 UTC sounding from OUN, a melting layer can be seen roughly one kilometer above the surface, extending 640 m in depth (Fig. 3.5a). The entire tropospheric column was below freezing further north and west in the state, as determined from RAP point soundings (not shown). At 1800 UTC, an OUN special sounding showed a deepening melting layer beginning 1.5 km above the surface and extending roughly 1.25 km in depth (Fig. 3.5b). Between the 1200 UTC and 1800 UTC soundings, cooling occurred in the lower part of the atmospheric column (<850 mb), and warming occurred above this column (850–500 mb). The thermodynamic change led to a deeper refreezing level over central Oklahoma, leading to more favorable mechanisms for winter weather precipitation.

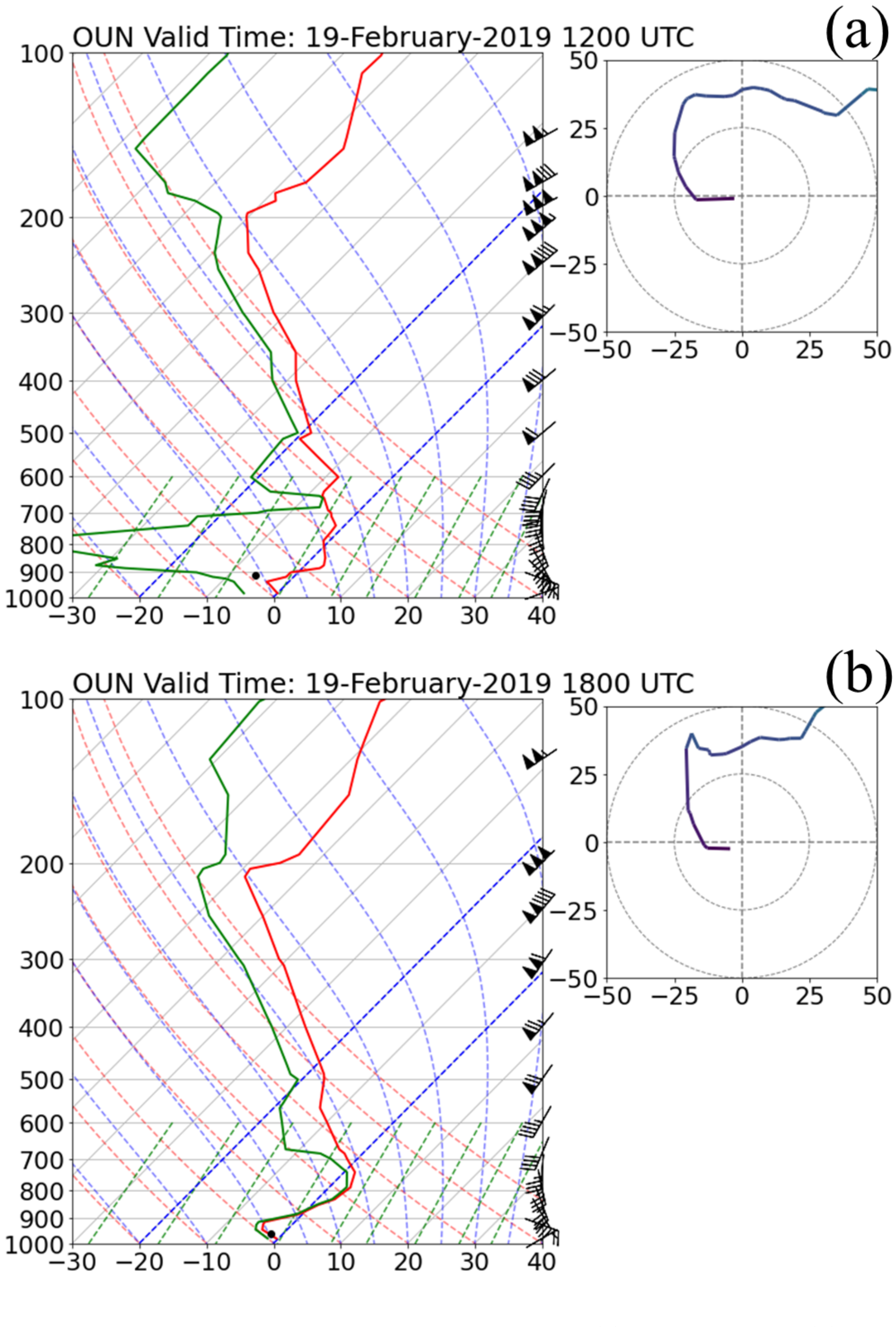


Figure 3.5: OUN sounding from 19 February 2019 at (a) 1200 UTC and (b) 1800 UTC.

Associated with the sub-freezing profiles in the western part of the state, a band of wintry precipitation developed and increased in intensity throughout the day (Fig. 3.6a-b). This band produced a combination of freezing rain, sleet, and snow. An area of heavier precipitation was moving northward from the Red River, impacting the Oklahoma City metropolitan area (OKC metro) at 1800 UTC (Fig. 3.6c-d). Initially, in northern Texas and southern Oklahoma, where surface temperatures were above freezing, rain was the only type of precipitation observed. As the precipitation moved into Oklahoma, a mixed-phase precipitation event began.

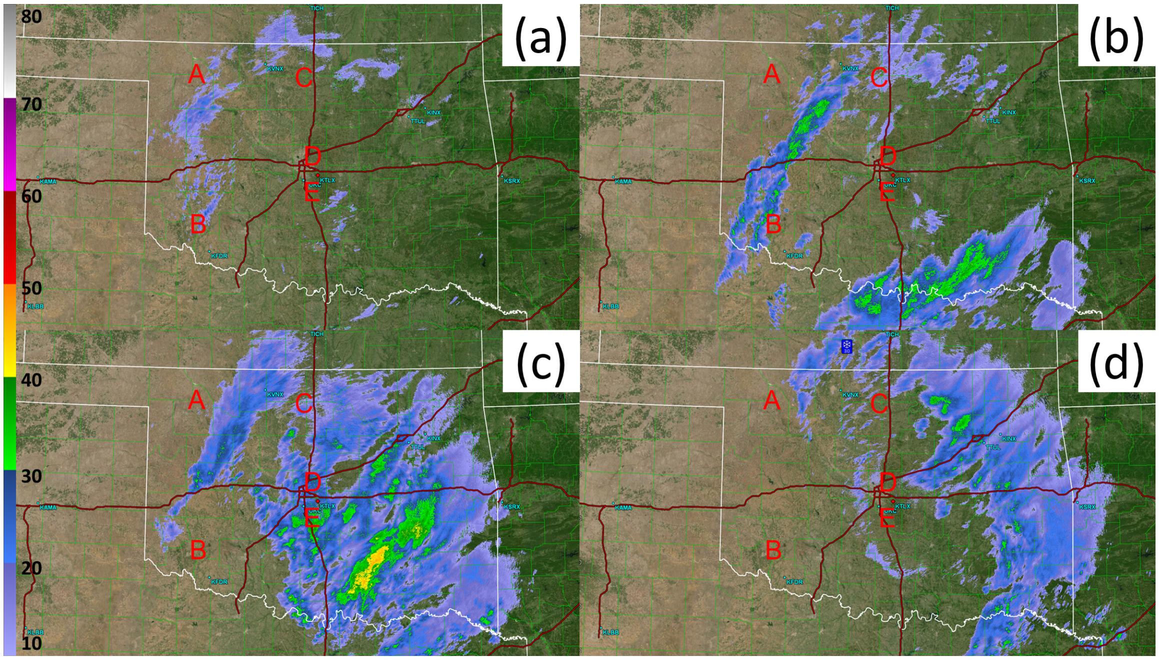


Figure 3.6: GR2Analyst displaying 0.4° reflectivity from 19 February 2019 at (a) 1533 UTC, (b) 1738 UTC, (c) 1946 UTC, and (d) 2147 UTC.

Specifically, at Location E, where the CopterSonde sampled the boundary layer, the precipitation type changed five different times, as determined by reports from the CopterSonde crew, mPING, and Twitter. No precipitation was observed at the start of the case (1535 UTC). By 1600 UTC, precipitation had begun and was classified as freezing rain. Within the next hour, the precipitation transitioned to sleet (1645 UTC). By 1745 UTC, the precipitation had transitioned to all rain. Between 1815 UTC and 1910 UTC, the rain transitioned to freezing rain. Finally, at 1930 UTC, a wintry mix was observed. These changes in precipitation occurred on sub-hourly time frames. Current radiosondes would not observe the changes in the boundary layer leading to these. UASs have the capability to sample at this increased frequency.

3.4 Winter Weather Case Study Results

The winter weather case study focused on forecasters' identification of precipitation types across the CWA at sub-hourly timescales. At the beginning of this case, the mixed-phase precipitation event had already begun in the western portion of the CWA but not over the OKC metro. Beyond directly classifying the precipitation types, forecasters were asked to communicate their concerns and calls to action with the public and their core partners. Access to Coptersonde data by half of the forecasters (P9–16) enabled the analysis of any differences in decision processes between the experimental and control groups. Quotes from forecasters will be denoted using "P#."

3.4.1 Precipitation Type Identification

During each time step of the winter weather case study, the first question asked forecasters to classify the primary precipitation type at five locations across the state (Fig. 3.1a). Figure 3.7 shows the point classifications made by all forecasters, each group's most common precipitation choice, and the report used for verification. There were two noticeable differences between the classifications the control and experimental group made. The first was an increase in overall PoD for the experimental group at the location where the CopterSonde data were collected (Fig. 3.1a Location E). The PoD was calculated by taking the number of correct precipitation classifications over the total number of possible decisions. The median PoD for the experimental group was 0.50, whereas, without the CopterSonde data, it was 0.38, demonstrating an improvement in classification accuracy using the CopterSonde data. Statistical significance could not be established for the improvement in overall PoD due to the small sample size. Figure 3.8 shows the distribution of PoD for the two groups.

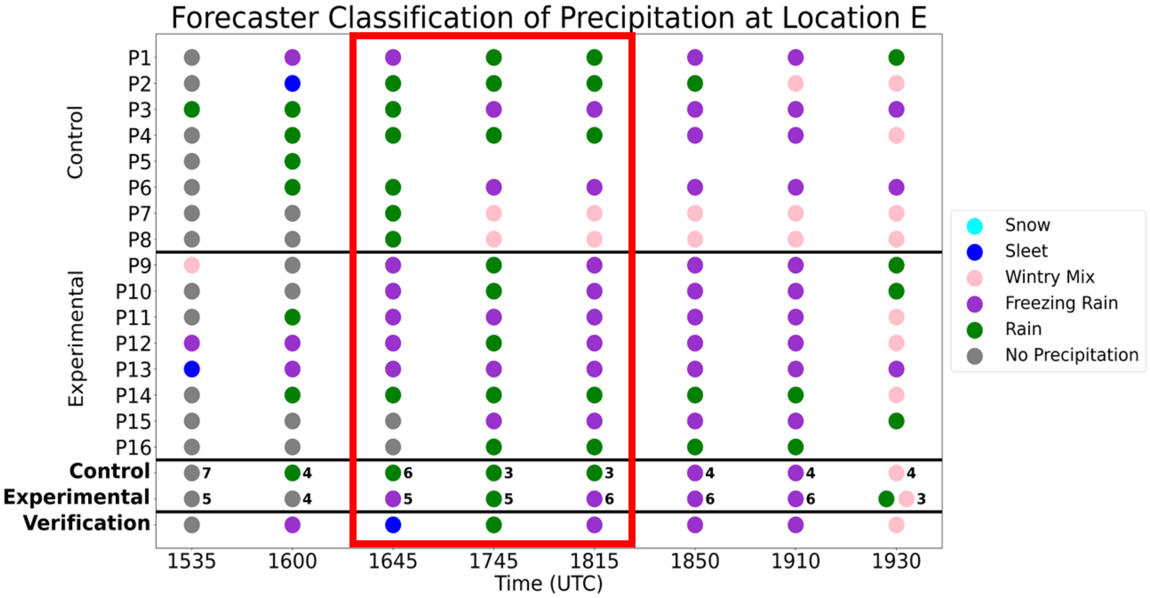


Figure 3.7: Classification of precipitation type selected by all forecasters at Location E. The two rows near the bottom labeled as *Control* and *Experimental* represent the majority decision by each group; the response totals are plotted next to the classifications (dots). The bottom line is the verification of precipitation as determined by field observations. The red box highlights a portion of the case when the precipitation type rapidly changed.

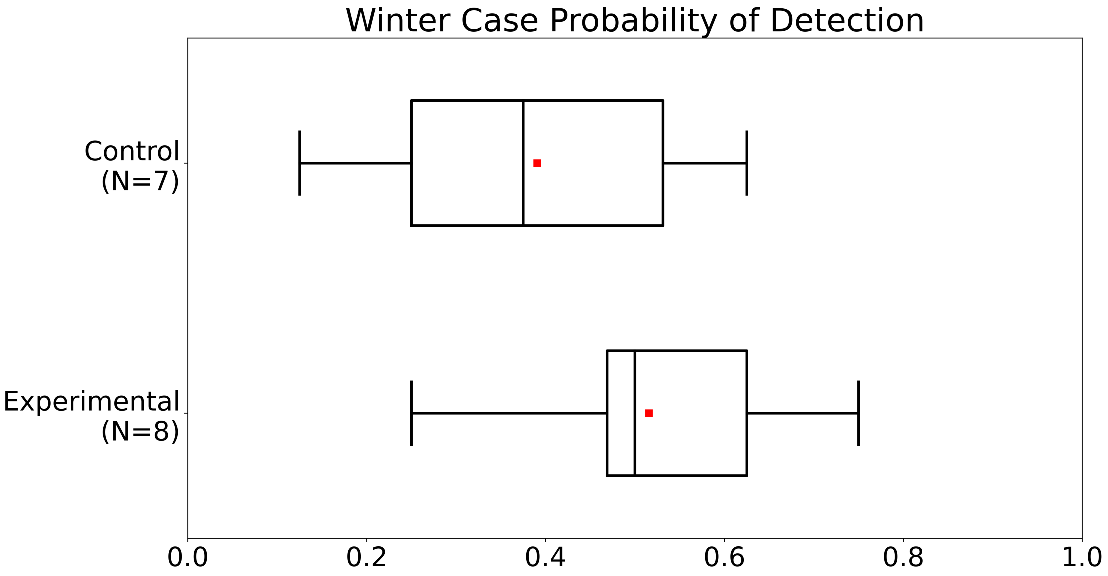


Figure 3.8: Distribution of PoD for the classification of precipitation at Location E.

The second improvement resulting from accessibility to CopterSonde data was forecasters' ability to differentiate between wintry precipitation (snow, sleet, and freezing rain) and rain or drizzle. Snow, sleet, and freezing rain are wintry precipitation types common when the surface temperature is at or below 32° F. In contrast, rain or drizzle are non-wintry precipitation types (surface temperatures above 32° F). This improved ability was measured by the overall higher median and mean PoD values for classifications made by the experimental group. Analysis of the subset of data from 1645–1910 UTC yielded a p-value of 0.07 using a Wilcoxon Rank Sum Non-Parametric Test, estimating this difference as statistically significant at the 90% confidence level (Fig. 3.7). This statistic was confirmed by conducting a bootstrap resampling with replacement of 1000 iterations producing a p-value of 0.05. The mean (median) PoD for the experimental group during this period was 0.70 (0.80), whereas the mean (median) POD for the control group was 0.40 (0.60). During this period, at Location E, the primary precipitation type transitioned from wintry to liquid and back to wintry.

At 1645 UTC, *sleet* was the primary precipitation type as determined by field observations. Five of eight forecasters with CopterSonde data identified it as *freezing rain/drizzle*, with one classifying it as *rain/drizzle* and two as *no precipitation*. Six out of seven forecasters in the control group classified it as *rain/drizzle* and the remaining one as *freezing rain/drizzle*. Although no forecaster correctly identified *sleet*, most of the experimental group was able to identify it as wintry precipitation. Without the addition of the CopterSonde data, most forecasters classified the precipitation as *rain/drizzle*, demonstrating an improvement in recognizing locations where rain and drizzle were transitioning to wintry precipitation types.

Observing the next time step, 1745 UTC, the precipitation type transitioned to *rain/drizzle*. The experimental group correctly identified the environmental changes leading to *rain/drizzle* versus wintry precipitation and made the appropriate adjustments. Three of the five forecasters in the experimental group (P9, P10, P12) who had *freezing rain/drizzle* at the prior time step correctly switched to *rain/drizzle*. In the control group, the only forecaster who had *freezing rain/drizzle* did correctly switch to *rain/drizzle* (P3). Still, four forecasters from the control group changed from *rain/drizzle* to wintry precipitation types (*wintry mix*) or (*freezing rain/drizzle*). These changes were the opposite of what was observed physically and demonstrated a decreased ability to correctly identify the precipitation type without the CopterSonde data. Finally, at 1815 UTC, the primary precipitation type changed to *freezing rain/drizzle*. All three forecasters with CopterSonde data who switched to *rain/drizzle* returned to *freezing rain/drizzle*, whereas none of the control group participants changed their classification.

One of the reasons the delineation between *freezing rain/drizzle* and *rain/drizzle* was able to be made at 1745 and 1815 UTC was due to subtle near-ground warm and cool layers that evolved during the case. Most of the experimental group referenced seeing slight warming or cooling and moistening in the CopterSonde data that led to their decision changes. Figure 3.9 shows the temperature profile displayed as a time series with the CopterSonde flights plotted in dotted lines. Between the 1645 UTC and 1745 UTC time steps, the melting layer (layer with temperatures above freezing) can be seen to increase from near 0–70 m in depth. This subtle warm layer was referenced directly as the reason for changing the primary precipitation type from wintry precipitation to rain/drizzle. At 1815 UTC this warm layer was weakening. Without the finer resolution CopterSonde data, the control group could not identify these layers, leading to incorrect classifications of precipitation type. The addition of the CopterSonde data positively impacted the precipitation classifications throughout the case, with significant impacts when the precipitation type was rapidly changing. The small sample size limits the generalizability of these improvements, though it demonstrates encouraging results for this case study.

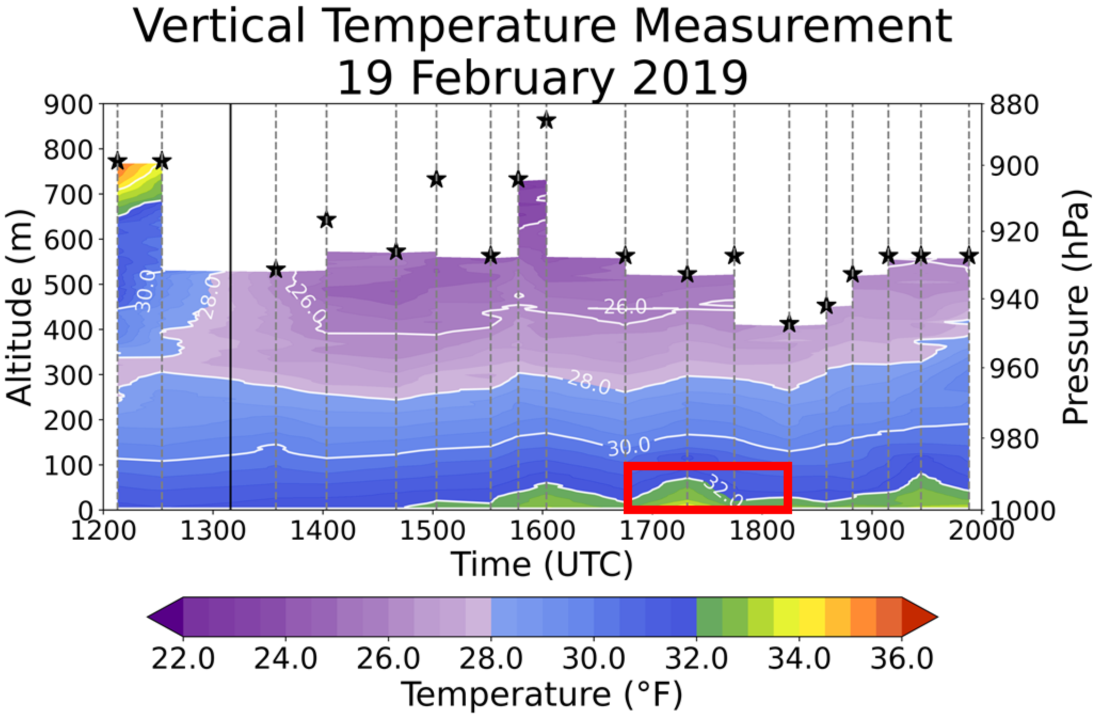


Figure 3.9: Time-height temperature plot measured by the CopterSonde at Location E. The solid black line denotes sunrise. The dashed gray lines denote the times of each CopterSonde profile. The black stars mark the maximum height reached for each flight. The red box is highlighting a melting layer.

3.4.2 Differences in Decision-Making Processes

The decision-making process in which forecasters classified the precipitation was analyzed to investigate differences in situational awareness due to the addition of CopterSonde data. In general, forecasters used thermodynamic and kinematic observations to analyze the environment. They used radar data to build their conceptual models, which led to them classifying different precipitation types across the state. The specific use and value of different data types differed with the introduction of the CopterSonde data.

3.4.2.1 Use of Radar

Both groups used radar imagery to determine where it was precipitating. The reliance on radar data differed between the control and experimental group. Control group participants primarily classified precipitation type at locations containing radar echoes at or above 10 dBz (minimum threshold set in GR2Analyst). After determining where it was precipitating, the forecasters conducted an environmental analysis to classify the specific precipitation type. In contrast, the experimental group conducted their environmental analysis in tandem with viewing the radar data. This approach led them to classify precipitation across the state, even without radar echoes present. The more frequently sampled CopterSonde data were directly cited as the information used to identify precipitation before it was observed on radar. P14 noted, "I mean if we look at the case closely, I felt like the CopterSonde data was really useful and actually like before the drizzle bloomed on the radar."

Being able to see the rapid development of saturation in the CopterSonde data was one of the reasons the forecasters cited in their ability to anticipate precipitation. Figure 3.10 shows a time evolution of the CopterSonde data (dashed) overlaid with the 1200 UTC OUN sounding (solid). During the focus group, P10 gestured two lines converging, referencing the temperature and dewpoint temperature line converging on a sounding, and discussed how they were able to "... see the thermodynamic environment change" and that it was a "... confidence booster in the low-level thermo environment at OUN." P9 discussed their experience seeing the CopterSonde data. "It's almost like it portrays the image at which I'm thinking is going on out my window." This led to them trusting the data and having confidence in their decisions, even when no echoes were on the radar imagery.

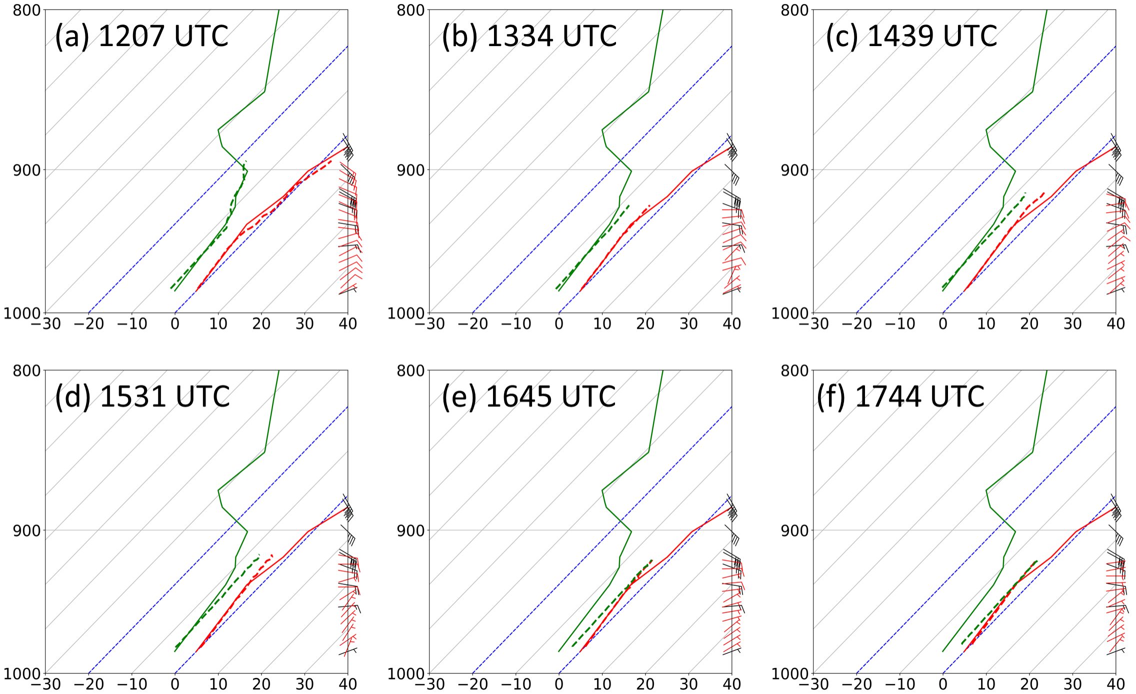


Figure 3.10: Zoomed in soundings showing the 1200 UTC OUN sounding in solid lines (not changing between plots) and the CopterSonde measurements of temperature and dewpoint temperature (dashed lines) between 1200 and 1800 UTC. Black wind barbs are from the OUN sounding, and red barbs are from the CopterSonde.

3.4.2.2 Validation of the RAP Model

Forecasters in the experimental group also found CopterSonde data useful for validating model soundings. Without the CopterSonde data, the 1200 UTC sounding was the control group's only set of boundary layer observations. Both groups had access to hourly RAP soundings, but forecasters discussed that observations are preferred to model data when conducting a fine-scale environmental analysis. P10 explained this preference.

> "I think maybe even sometimes we over-rely on stuff like RAP soundings and call it truth... There's a lot of uncertainty with that, and the models get it wrong a lot, and when you're talking about a winter weather case, where the difference of a degree or two degrees can make a total difference in the precip type."

The quote above shows how there is uncertainty in model analyses, and forecasters do not place complete trust in them when making decisions. P10 built upon their discussion of how the CopterSonde data benefited them.

> “Being able to see, almost in real-time, the change in the thermodynamic profile and know that it’s good data, it’s observational, you can trust it. It does so much for your confidence level when you do have to go ahead and try and message that or try and forecast over the next one, two, three hours. You know what’s going to be occurring.”

All the experimental group participants discussed how the ability to see and trust the observations in the lowest part of the atmosphere allowed them to identify and understand the biases in the RAP model. Forecasters were able to identify the subtle temperature and moisture biases in the model and then augment them in their conceptual model. By increasing their confidence in the initialization of the RAP and recognizing its biases, forecasters could project their conceptual model across the rest of the forecast area. This expedited analysis at all locations due to the reduced time spent questioning the RAP and trying to assess if it was accurate for this event. P14 added to this discussion by saying, “if you have something to look at to confirm that everything’s on track, then you’re in and out of the forecast process faster. So, I think that’s the key there is that this can be used to speed up the forecast interrogation.”

Figure 3.11 is an example of how the RAP and CopterSonde data were provided to the forecasters. P9 discussed how they try to overlay observations over model soundings in their WFO currently and that being able to do it with the CopterSonde data allowed them to more efficiently and accurately correct for model biases.

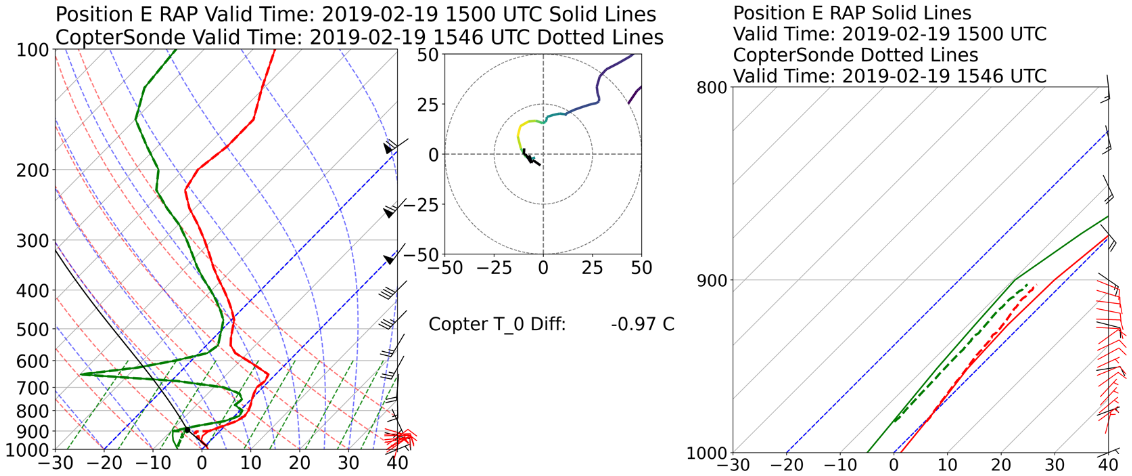


Figure 3.11: 1200 UTC OUN sounding in solid lines with CopterSonde measurements from 1546 UTC of temperature and dewpoint temperature in dashed lines. Black wind barbs are from the OUN sounding, and red barbs are from the CopterSonde. The OUN hodograph is colored, and the CopterSonde hodograph is black.

3.4.2.3 Use of mPING Reports

A majority of the control group cited mPING reports as the primary reason for their final precipitation classifications. In one example, P7 noted, “choices this time were made chiefly based on ground truth mPING data.” This decision-making process was not unique to P7. Throughout the case, P3 cited that the resulting precipitation classifications were ”largely due to mPING” or ”surface temps and mPING reports.” Interestingly, the control group relied on mPING reports to guide their classifications, even though they noted distrust of mPING reports. In the focus groups, forecasters from both groups discussed their perception that the public gets wintry precipitation classifications wrong all the time, resulting in a lack of trust in the reports.

In the experimental group, mPING reports were used in the final steps of their forecast process as only a confirmation of their decisions. Even when mPING reports did not align with the precipitation type classifications, forecasters explained that they trusted their decisions and did not change their decisions because of mPING reports. An example of this was at 1745 UTC, P13 added into their discussion of their decision-making process, “no major changes here, but I have been expecting to see the switch over to freezing rain/drizzle but haven’t seen it yet in the LSRs [local storm reports].” Though incorrect, their decision to stick to *freezing rain/drizzle* was not impacted by the mPING reports majorly showing mostly *rain/drizzle*. Overall, the experimental group’s decisions were more meteorologically driven than the control group, who primarily relied upon radar and mPING reports.

3.4.2.4 Consistency-based Forecasts

Without high-resolution boundary layer observations, forecasters from the control group discussed how they analyzed conflicting information from different data types during certain case periods. As discussed above, observations are preferred to NWP models or other data types. Without observations, the conflicting analysis led to a more conservative forecast approach and the use of consistency-based forecasts. P4 explained in the focus group:

> “Yeah, I think I was pretty conservative on, you know, my decisions on the precip types, especially in the Norman and Oklahoma City area. You know, sometimes you question, maybe not the Mesonet data as much, but like the RAP analysis and what’s going on in the lower level. So, you look back at your conceptual models... I was pretty conservative on how quickly I transitioned to a winter precip versus the all liquid.”

P3 built on the comment.

> “Similar to P4, you know, without more real-time data in the lower levels, you’re kind of a little more conservative, you’re a little more going to stick on your assumptions based on your initial analysis... So, you’re kind of less apt to jump on some new thing that’s going on. It’ll just take you a bit longer to recognize it usually.”

P3 added that without more observations, even seeing changes in the RAP, for example, they are less inclined to change their forecast (i.e., a consistent forecast). Observing P7 and P8's decisions from Figure 3.7, they chose *wintry mix* from 1745 UTC onward. These forecasters could not determine a specific precipitation type. They discussed how mPING reports showed one precipitation type, but their individual analyses suggested something different. These different conclusions led them to choose the *wintry mix* option. After 1745 UTC (Fig. 3.7), there were very few changes in precipitation classifications from all forecasters in the control group, even with the addition of updating surface information, RAP soundings, and an 1800 UTC sounding. This behavior further demonstrated the control groups' tendency to make consistency-based decisions.

3.4.2.5 Impact of Societal Factors

Between 1815–1910 UTC, no forecaster in the experimental group changed their classifications, and only two of the eight forecasters made incorrect precipitation classifications. The primary reason these two forecasters (P14 and P16) classifications differed from the rest of the experimental group was due to their consideration of societal factors. These forecasters discussed how borderline the event was, and P14 added, "I think it's so close that it's not really impactful." P15 discussed the philosophical question that offices and forecasters face with low-impact events.

> "... but we do know that the impacts are going to be minimal. So, that's a little tricky. Do you play the forecast as freezing drizzle, but minimal impacts, or... do you just leave it as drizzle, so it doesn't alert people."

Despite P15 discussion, they still classified the primary precipitation as *freezing rain/drizzle.* P16 used the CopterSonde data to characterize the near-surface boundary conditions. Throughout the case, P16 concluded that the environment would not produce impactful freezing drizzle for Location E. The precipitation type classification question asked the participants to identify the primary form of precipitation. However, P15 and P16 interpreted the question differently to classify the primary precipitation type they would communicate about. P2 discussed something similar: they explained in an operational scenario they would have had *wintry mix* in the forecast grids to make it easy.

3.4.3 Impacts to Communication

After the meteorological decisions were made at each time step, the forecasters were given the opportunity to communicate to the public and their core partners about the threats by creating graphics, using a mock Twitter account, and sending out messages in a mock NWSChat. The question did not specifically ask them to focus on any area of the forecast or CWA. The influence of the CopterSonde was apparent in the different approaches to communication.

3.4.3.1 Location Focus of Communications

A comparison of the first time step that forecasters communicated threats about the OKC metro revealed on average, the experimental group communicated two time steps or approximately one hour earlier. This earlier messaging is statistically significant at the 95% confidence level based on the results of a Wilcoxon Rank Sum Non-Parametric Test (p-value = 0.015). This result of a statistically significant difference in the issuance of first communication (at the 95% confidence level) was also found by applying a bootstrap resampling with replacement of 1000 replacements (p-value of 0.006). Figure 3.12 displays the distribution of time steps that forecasters issued their first communication to the OKC metro.

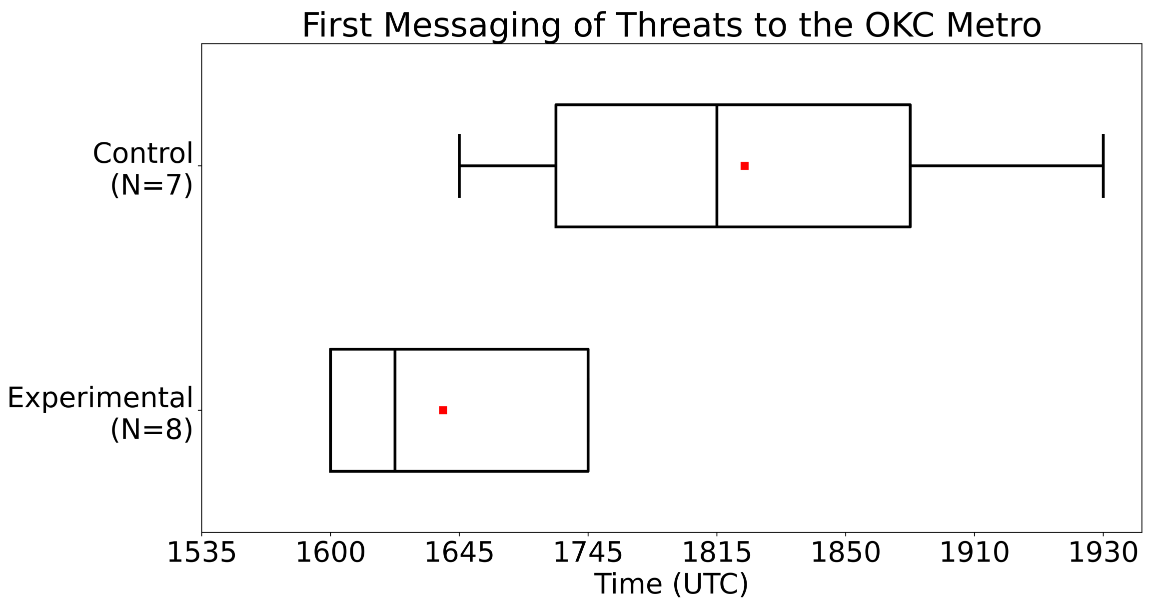
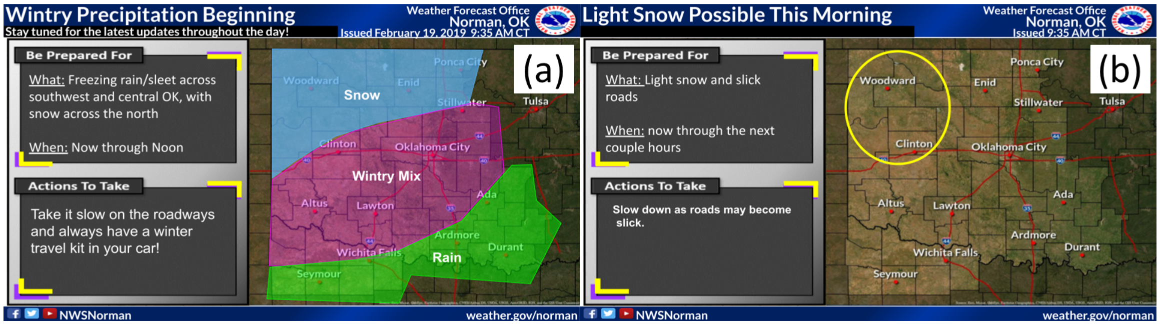


Figure 3.12: Distribution of time of forecasters' first communication issued that included threats to the OKC metro. The red square is the mean. The boxes represent the 25th to 75th percentile, with the median as the middle line. The whiskers are the minimum and maximum values. The numerical time steps have been replaced with the time of the case.

P10 cited the CopterSonde data as the most important piece of information that led to their early communication. Their first identification of precipitation for the OKC metro was at 1645 UTC, but their communication began a time step before at 1605 UTC. P10 referenced the cooling and moistening in the CopterSonde data and that freezing drizzle in the OKC metro is becoming more concerning. Following their NWSChat message, they issued a graphic highlighting the OKC metro.

P8 and P12 began their cases by issuing the graphics in Figure 3.13. There were differences in the location focus of the two forecasters' graphics. P12's graphic (Experimental group Fig. 3.13a) is detailed about the impending winter weather across the whole state, whereas P8's graphic (Control group Fig. 3.13b) was confined to the northwest part of the state, where it was currently precipitating. P12 referenced trends in temperature and moisture and how freezing rain and sleet were likely over the OKC metro. P8's decision was determined from two radars and the RAP soundings from each location.



Wintry Precipitation Beginning

Stay tuned for the latest updates throughout the day!

Weather Forecast Office Norman, OK

Issued February 19, 2019 9:35 AM CT

Be Prepared For

What: Freezing rain/sleet across southwest and central OK, with snow across the north

When: Now through Noon

Actions To Take

Take it slow on the roadways and always have a winter travel kit in your car!

NWSNorman

weather.gov/norman

Light Snow Possible This Morning

Weather Forecast Office Norman, OK

Issued 9:35 AM CT

Be Prepared For

What: Light snow and slick roads

When: now through the next couple hours

Actions To Take

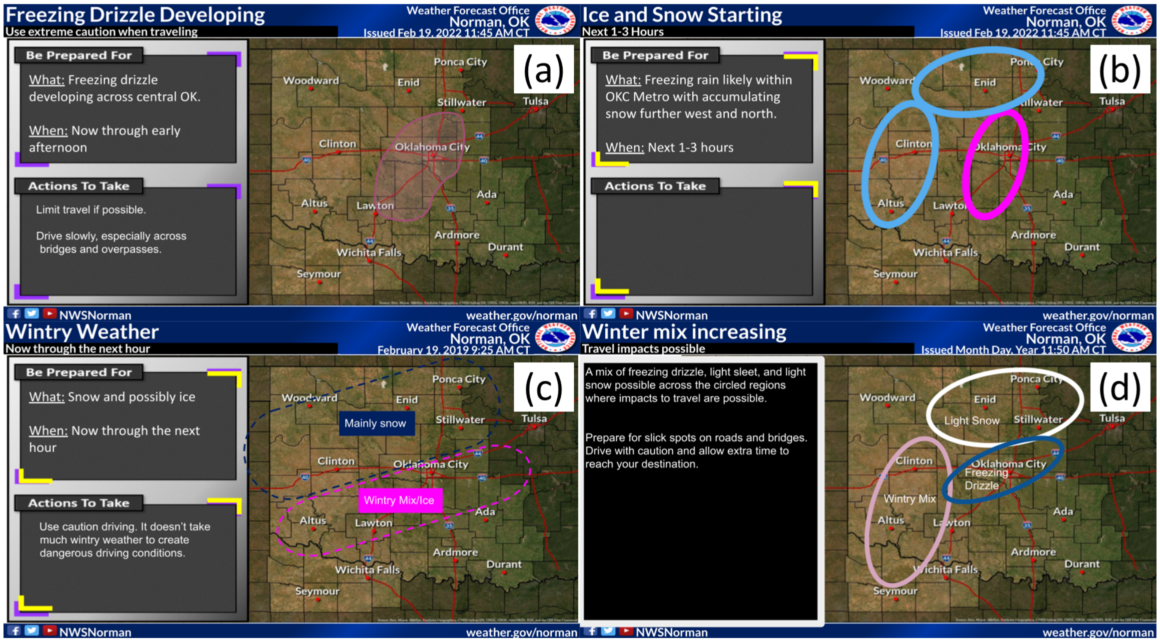
Slow down as roads may become slick.

NWSNorman

weather.gov/norman

Figure 3.13: Graphics issued at 1535 UTC by (a) P12 and (b) P8.

In addition to the experimental group communicating earlier about the OKC metro, the primary focus of their NWSChat messages was also about the OKC metro. The areas experiencing precipitation at each time step were included in the experimental groups graphics as well as the OKC metro (Fig. 3.14). By comparison, the primary focus of the graphics and NWSChat messages from the control group was on areas currently receiving precipitation (Fig. 3.15). Initially, the OKC metro had no radar-observed precipitation, but western and northern Oklahoma were receiving snow and sleet. The control group focused their communications on these areas. Throughout the case, a few of the control group forecasters included in their survey responses and NWSChat messages that the OKC metro had lower threats and there was less concern for the OKC metro. In contrast, the experimental group was able to have a bimodal focus of communication.



Freezing Drizzle Developing
Use extreme caution when traveling
Issued Feb 19, 2022 11:45 AM CT

Be Prepared For
What: Freezing drizzle developing across central OK.
When: Now through early afternoon

Actions To Take
Limit travel if possible.
Drive slowly, especially across bridges and overpasses.

Ice and Snow Starting
Next 1-3 Hours
Issued Feb 19, 2022 11:45 AM CT

Be Prepared For
What: Freezing rain likely within OKC Metro with accumulating snow further west and north.
When: Next 1-3 hours

Actions To Take

Wintry Weather
Now through the next hour
February 19, 2019 9:25 AM CT

Be Prepared For
What: Snow and possibly ice
When: Now through the next hour

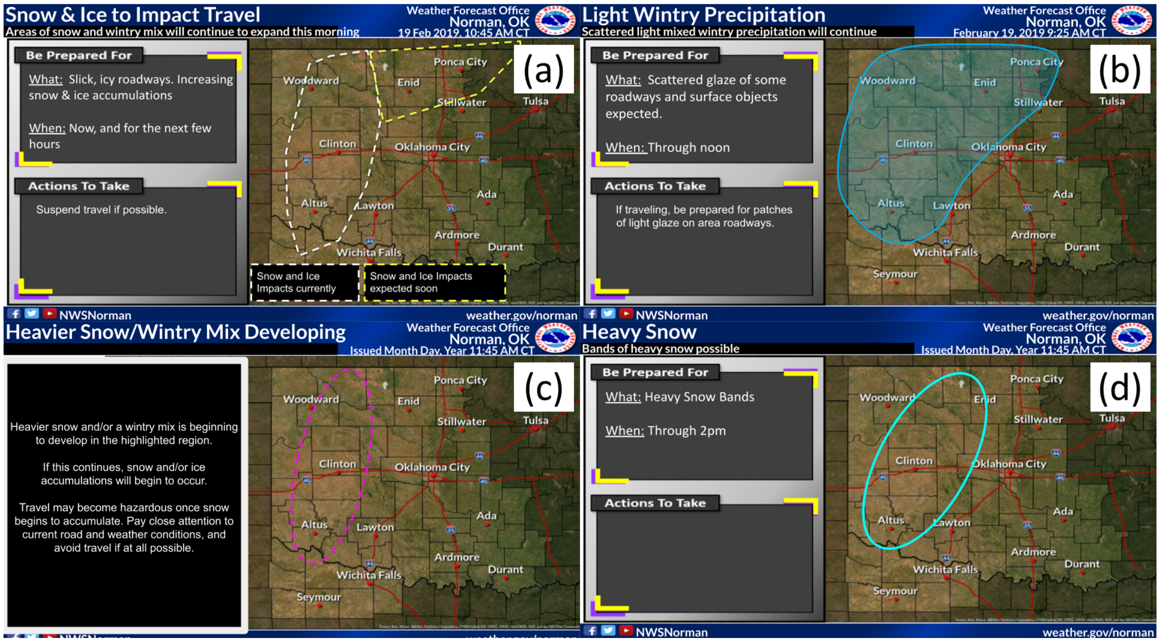
Actions To Take
Use caution driving. It doesn't take much wintry weather to create dangerous driving conditions.

Winter mix increasing
Travel impacts possible
Issued Month Day, Year 11:50 AM CT

A mix of freezing drizzle, light sleet, and light snow possible across the circled regions where impacts to travel are possible.

Prepare for slick spots on roads and bridges. Drive with caution and allow extra time to reach your destination.

Figure 3.14: Graphics issued by (a) P10 at 1645 UTC, (b) P11 at 1645 UTC, (c) P13 at 1545 UTC, and (d) P14 at 1745 UTC.



Snow & Ice to Impact Travel
Areas of snow and wintry mix will continue to expand this morning
19 Feb 2019, 10:45 AM CT

Be Prepared For
What: Slick, icy roadways. Increasing snow & ice accumulations
When: Now, and for the next few hours

Actions To Take
Suspend travel if possible.

Light Wintry Precipitation
Scattered light mixed wintry precipitation will continue
February 19, 2019 9:25 AM CT

Be Prepared For
What: Scattered glaze of some roadways and surface objects expected.
When: Through noon

Actions To Take
If traveling, be prepared for patches of light glaze on area roadways.

Heavier Snow/Wintry Mix Developing
Issued Month Day, Year 11:45 AM CT

Heavier snow and/or a wintry mix is beginning to develop in the highlighted region.

If this continues, snow and/or ice accumulations will begin to occur.

Travel may become hazardous once snow begins to accumulate. Pay close attention to current road and weather conditions, and avoid travel if at all possible.

Heavy Snow
Bands of heavy snow possible
Issued Month Day, Year 11:45 AM CT

Be Prepared For
What: Heavy Snow Bands
When: Through 2pm

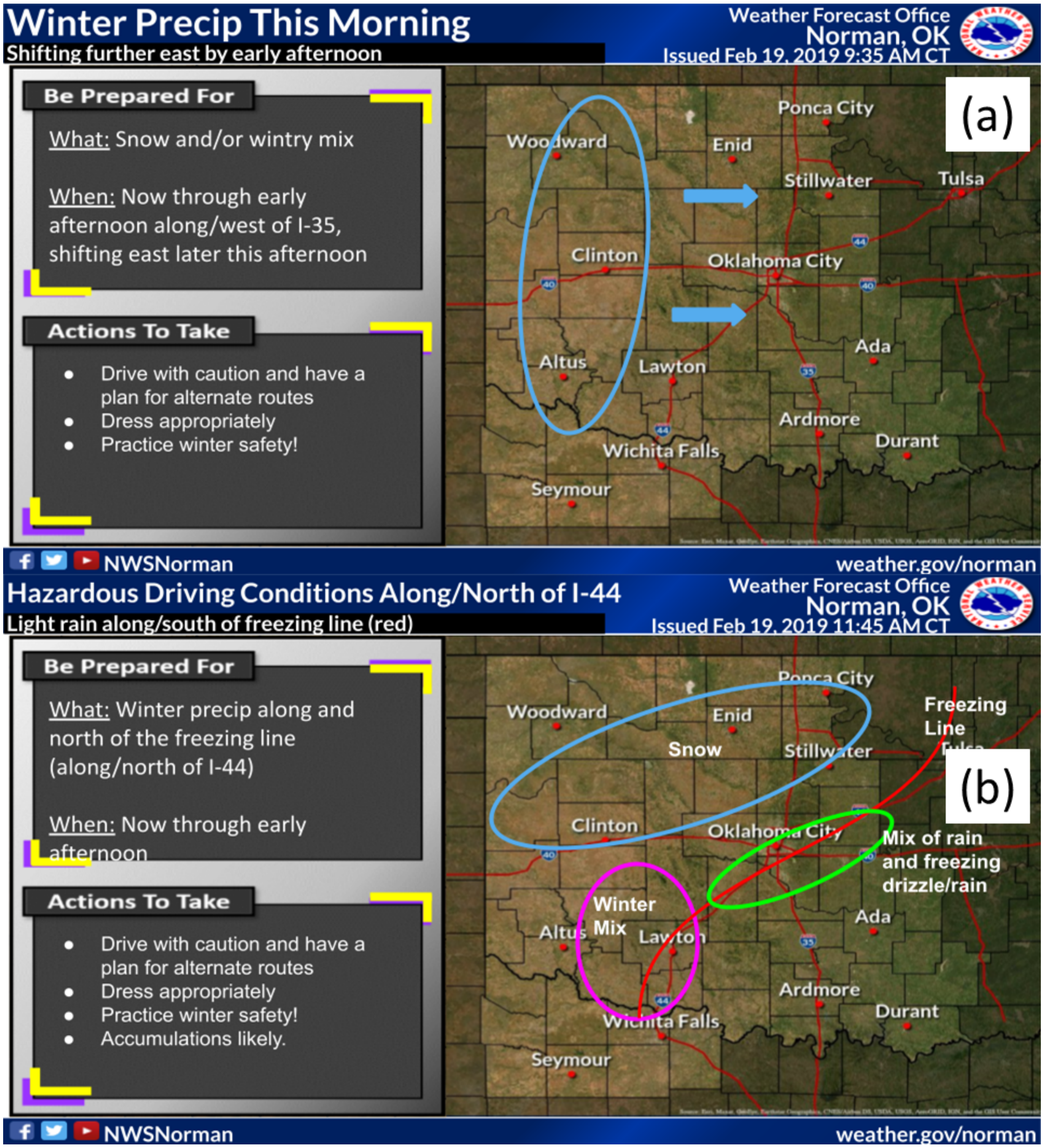
Actions To Take

Figure 3.15: Graphics issued by (a) P1 at 1645 UTC, (b) P2 at 1535 UTC, (c) P6 at 1700 UTC, and (d) P7 at 1645 UTC.

P3 justified focusing on western Oklahoma due to "... actually getting radar returns there." P1 messaged in NWSChat that OKC should "be on our guard," but the

OKC metro was excluded from their graphics (Fig. 3.15a) At 1910 UTC, P1 became “slightly concerned” about the metro but continued to concentrate their messaging elsewhere. At this point, the OKC metro had been receiving wintry precipitation for three hours. P6 included in their messaging that the OKC metro was likely seeing freezing rain, but the focus of their messaging was to the west (Fig. 3.15c).

After radar echoes began appearing over the OKC metro (after 1745 UTC), most of the forecasters in the control group began to expand their messaging from one area to multiple regions of the CWA. P4’s first graphic, issued at 1535 UTC, highlighted the western part of the state with arrows signifying the wintry precipitation would proceed eastward (Fig 3.16a). Their graphics evolved at every time step to highlight the areas of heaviest precipitation. By 1745 UTC, the fourth time step, P4 included OKC in their graphics, indicating a mix of rain and freezing rain/drizzle (Fig. 3.16b). Associated with the graphics, their NWSChat messages and Twitter messages evolved. Initially, at 1535 UTC, P4 discussed how a dry layer over OKC needed to be overcome for impacts. They messaged increasing impacts to western and northern Oklahoma throughout the next few steps. By 1745 UTC, this forecaster began to message about mPING reports in the OKC metro and how freezing rain was becoming the predominant precipitation type. From this point on, they messaged about the entire CWA.



Winter Precip This Morning

Shifting further east by early afternoon

Weather Forecast Office
Norman, OK
Issued Feb 19, 2019 9:35 AM CT

Be Prepared For

What: Snow and/or wintry mix

When: Now through early afternoon along/west of I-35, shifting east later this afternoon

Actions To Take

- Drive with caution and have a plan for alternate routes
- Dress appropriately
- Practice winter safety!

NWSNorman

weather.gov/norman

Hazardous Driving Conditions Along/North of I-44

Light rain along/south of freezing line (red)

Weather Forecast Office
Norman, OK
Issued Feb 19, 2019 11:45 AM CT

Be Prepared For

What: Winter precip along and north of the freezing line (along/north of I-44)

When: Now through early afternoon

Actions To Take

- Drive with caution and have a plan for alternate routes
- Dress appropriately
- Practice winter safety!
- Accumulations likely.

NWSNorman

weather.gov/norman

Figure 3.16: Graphics issued by P4 at (a) 1535 UTC and (b) 1745 UTC.

3.4.3.2 Communicating Trends of Decreasing Impacts

A final aspect of the communication products issued that differed between the groups was the ability to communicate trends of decreasing impacts to areas across the CWA. In P16's discussions at 1815 UTC, they first referenced lower threats to OKC. At 1850 UTC, P16 messaged in NWSChat that "there continues to be moderate confidence that impactful freezing drizzle will not occur across the OKC metro with temperatures near to slightly above freezing." Similarly, P10 and P11 discussed how the threats for OKC would be lower after the thermodynamic profile over OKC was saturated. The threats were still being communicated, but the shifting magnitude was able to be discussed. This communication style was not seen in any of the communications from the control group.

Part of the reason for the difference in messaging was the impact on situational awareness that the CopterSonde data had. The forecasters with CopterSonde data had increased situational awareness, which increased their confidence leading to more refined and earlier threat communication. At 1605 UTC, Oklahoma Mesonet stations observed increasing surface and dewpoint temperatures. P3 observed this and discussed that "the OKC metro appears to be at less potential risk than before as warm advection keeps precip liquid there." By 1645 UTC, the increase in moisture at the surface continued, but there was no observed increase in surface temperature. With the CopterSonde data, forecasters were able to confirm the moistening but noticed that the air directly above the surface was cooling, leading to the *freezing rain/drizzle* and *sleet*. Multiple forecasters explained they messaged about the OKC metro due to favorable precipitation mechanisms and imminent threats. P10 discussed how communicating threats with good observational data drastically increased confidence because there is no longer a need to assess the uncertainty in NWP models.

3.5 22 March 2022 Description

The severe weather case chosen occurred between 1400–1700 UTC on 22 March 2022. A link to the weather briefing provided to the forecasters participating in this study can be found here (`https://youtu.be/cwfbyShKlgg`). This case involved a QLCS event during the early morning hours. During QLCS events, the entire line may be severe, or pockets of severe convective cells can quickly form and dissipate (Walker et al. 2019). In this case, half of the forecasters (P1–8) were provided CopterSonde data at roughly 30-minute increments to evaluate the impact of higher resolution data on severe hazard identification and the communication of associated threats.

On 21 March 2022, a 500 mb low began to accelerate and lift through west Texas and the Oklahoma panhandle after translating eastward near the southern United States border. By the morning of 22 March, the upper-level low was located in eastern Kansas (Fig. 3.17a). There was relatively weak forcing aloft with less than 100 kts of flow at 250 mb in the Arkansas, Louisiana, and Mississippi vicinity (Fig. 3.17b). Nearly 50 kts of flow at 850 mb from the south was advecting warm and moist air into the Mississippi Delta (Fig. 3.17c). At the surface, a low developed in western Oklahoma and tracked to the northeast. The warm and cold fronts associated with the surface low were translating eastward. By the morning of 22 March, the Mississippi Delta was in the warm sector, with the cold front approaching the Texas and Louisiana border (Fig. 3.17d).

The environment ahead of the line was conducive for severe weather, with all the severe weather parameters defined in Johns and Doswell lll (1992) present. Lift, instability, and moisture are the required ingredients for thunderstorms, and the addition of wind shear further promotes an environment conducive for tornadogenesis. Lift is required for parcels to reach the level of free convection, at which point they become positively buoyant. Instability is a measure of buoyancy, typically expressed in terms of CAPE. Moisture is required throughout the depth of the lower troposphere to support any precipitation or cloud formation. Greater moisture content lowers the lifted condensation level, which increases instability. Wind shear is the directional change of winds at different heights. Vorticity can be generated this way, increasing the favorability of tornadoes.

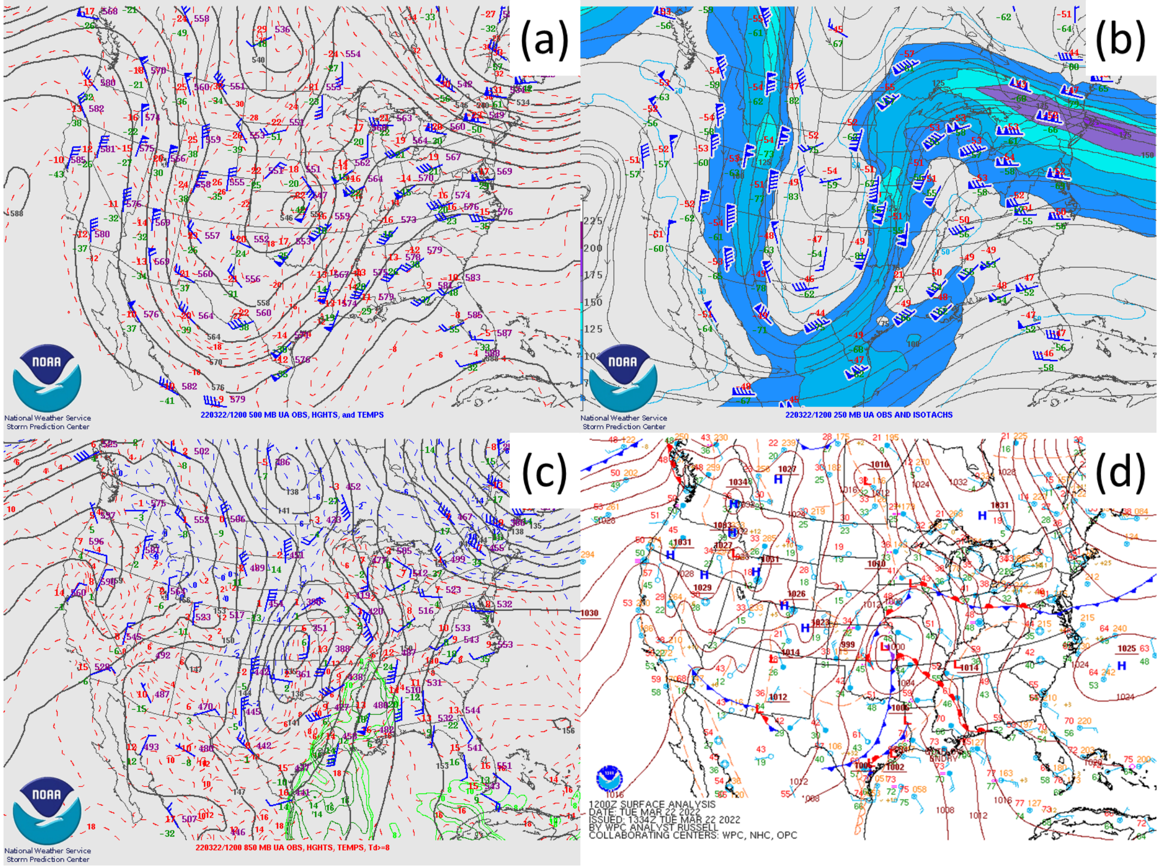


Figure 3.17: SPC upper air analysis from 1200 UTC 22 March 2022 at (a) 500 mb, (b) 250 mb, (c) 850 mb, and (d) the surface.

In the warm sector, surface temperatures ranged from 70–74° F in southern Louisiana with dewpoint temperatures ranging from 66–69° F. Surface temperatures (dewpoint temperatures) decreased to 60° F (57° F) in the northern part of the state. Across Arkansas and Mississippi, temperatures were constant at 65° F, with dewpoint temperatures running from 56–63° F (Fig. 3.18a). Surface winds were out of the southeast with 30–40 kts of 0–1-km shear and 60–70 kts of 0–6-km shear (Fig. 3.18b-c). SPC mesoanalysis analyzed CAPE values ahead of the line between 2000–3000 Jkg^{-1} and significant tornado parameter values of 2–3 (Fig. 3.18d).

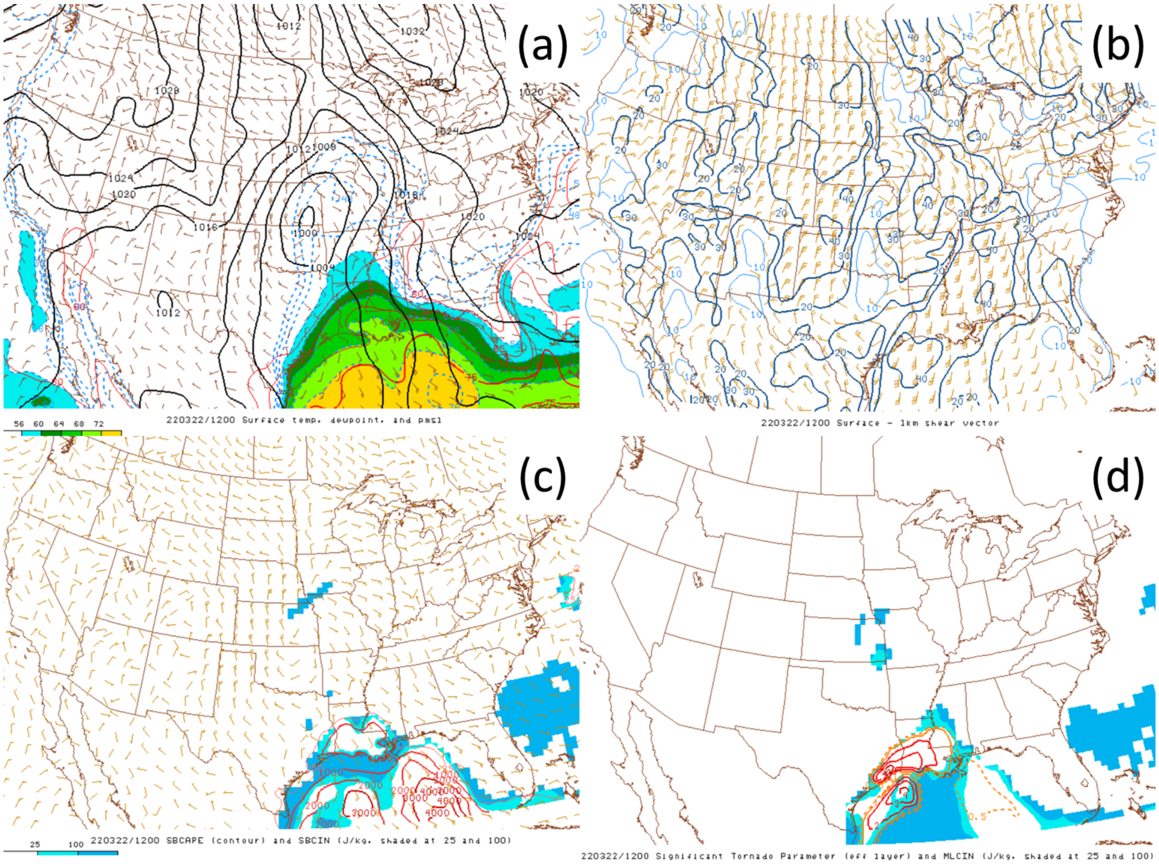


Figure 3.18: SPC mesoanalysis from 1200 UTC 22 March 2022 analyzing (a) surface temperature and dewpoint temperature, (b) 0–1-km shear, (c) surface-based CAPE and convective inhibition, and (d) significant tornado parameter.

The 0000 UTC 22 March 2022 JAN sounding showed an unsaturated surface with an inversion between 900–800 mb. By 1200 UTC, the surface had moistened, and the inversion had cooled and became saturated (Fig. 3.19). An 1800 UTC special sounding from JAN was released and showed that the surface had warmed, but more critical to the case, the CAPE and shear values had increased. From 1200–1800 UTC, surface-based CAPE increased from near 0–900 $\mathrm{Jkg^{-1}}$ CAPE. The 0–1-km wind shear remained similar at around 45 kts, but 0–6-km shear doubled from 40–80 kts of shear.

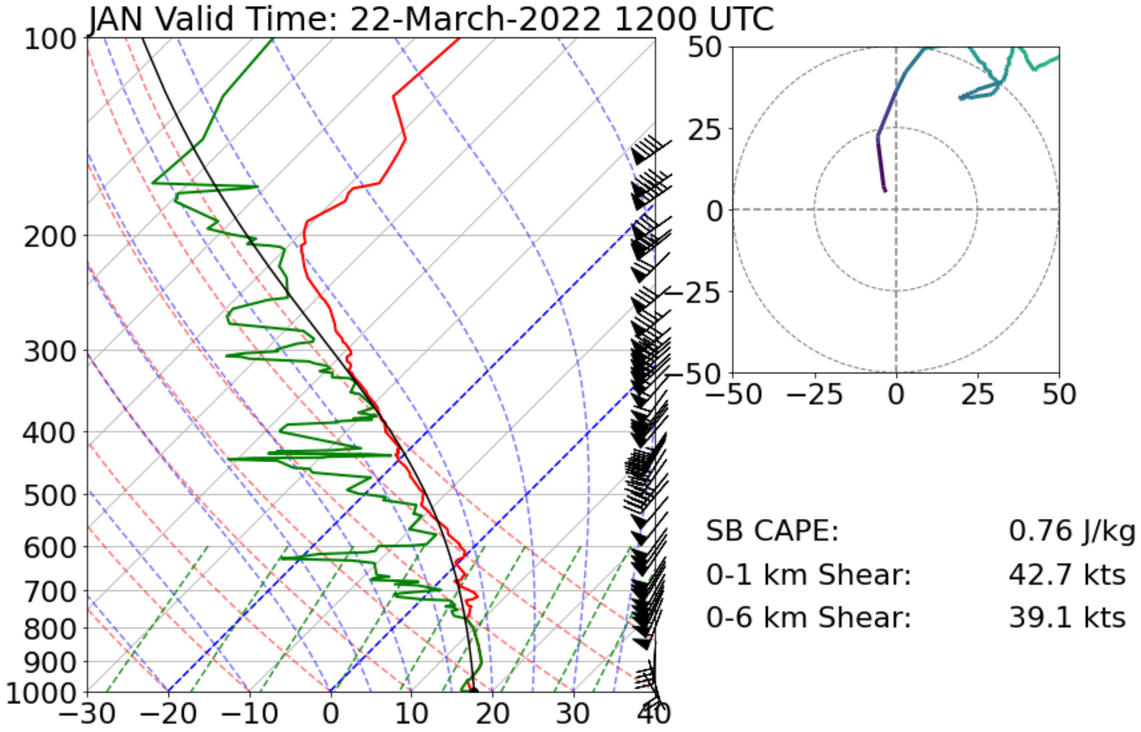


Figure 3.19: 1200 UTC JAN sounding from 22 March 2022.

Along and ahead of the cold front was an ongoing severe warned squall line. By 1500 UTC, the line approached the Louisiana, Arkansas, and Mississippi border. Embedded in the line were multiple strong convective cores (Fig. 3.20a-b). Prior to reaching the border, there were a few hail and wind storm reports (Fig. 3.21). As the line continued to move into Mississippi, multiple tornadoes occurred. In total, there were over 50 tornado reports and 50 wind reports within the CWA. Where the CopterSonde was sampling (Location D), there was a severe wind and a tornado report around 1730 UTC (Fig. 3.21).

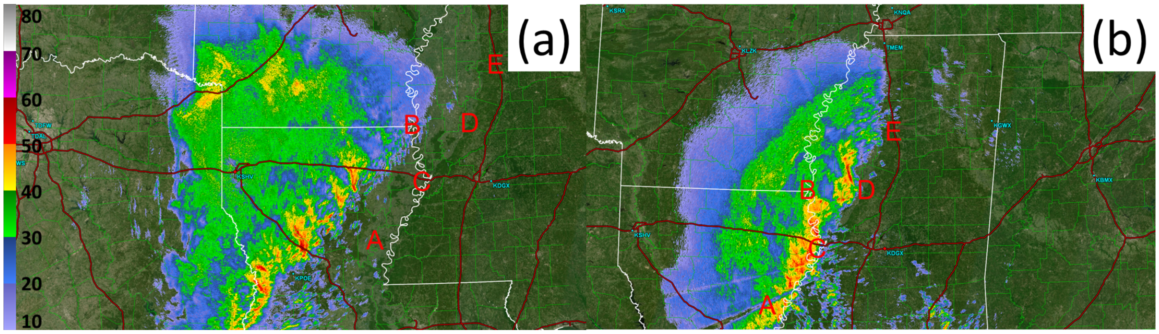


Figure 3.20: GR2Analyst displaying 0.3° reflectivity from (a) KSHV radar at 1400 UTC on 22 March 2022, (b) KDGX radar at 1630 UTC on 22 March 2022.

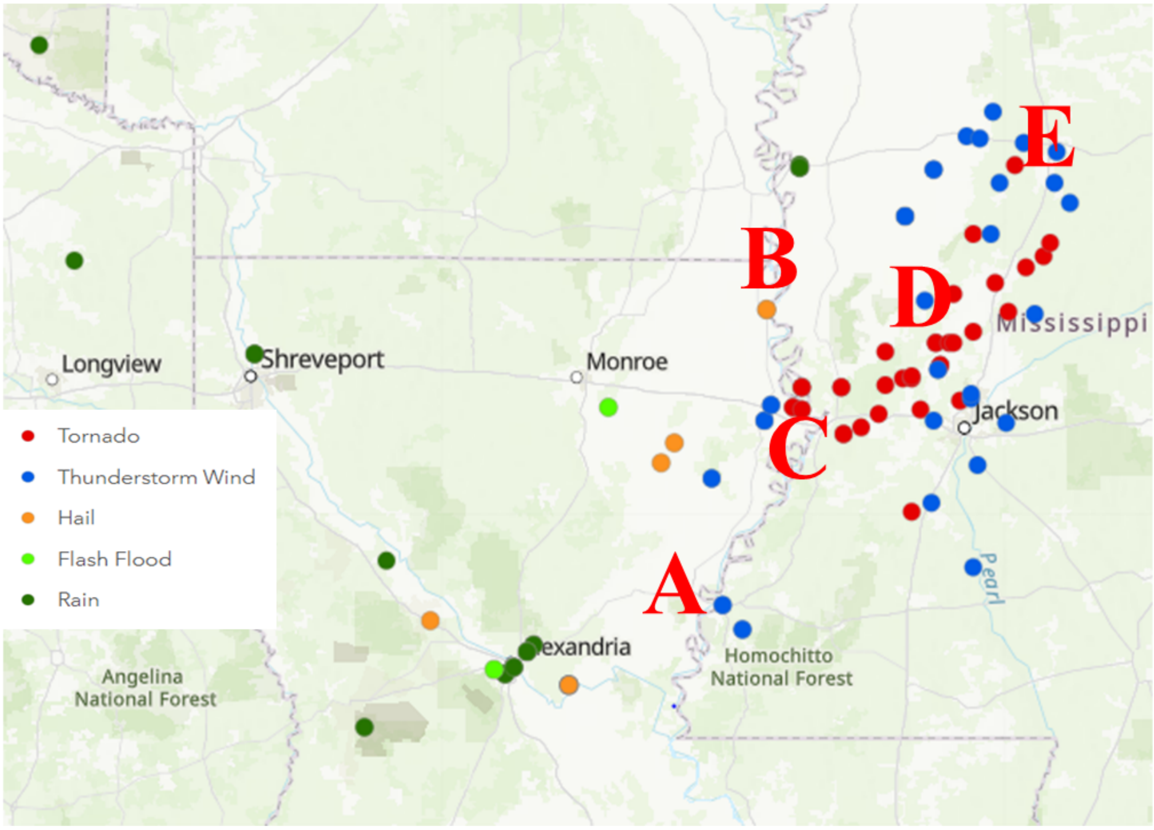


Figure 3.21: SPC storm reports from 22 March 2022 up until 1830 UTC formatted using ArcGIS software by Esri.

3.6 Severe Weather Case Study Results

The severe weather case occurred in a much more favorable environment for impactful weather than the winter weather case. The severe weather case began with an ongoing QLCS approaching the CWA from the west with a history of severe wind, severe hail, and tornado reports (not shown). At each time step, forecasters were asked to identify the severe hazards likely at each location within the next hour (Fig. 3.1b). The CopterSonde data were collected at one of the furthest eastward locations in the domain (Fig. 3.1b, Location D). Figure 3.22 displays the forecasters' hourly hazard identifications at Location D. To show how the CopterSonde data impacted forecasters' situational awareness decision-making processes, the case analysis is presented in time as the QLCS approached. For this case, P1–8 had access to the CopterSonde data. Quotes from forecasters will be denoted using "P#."

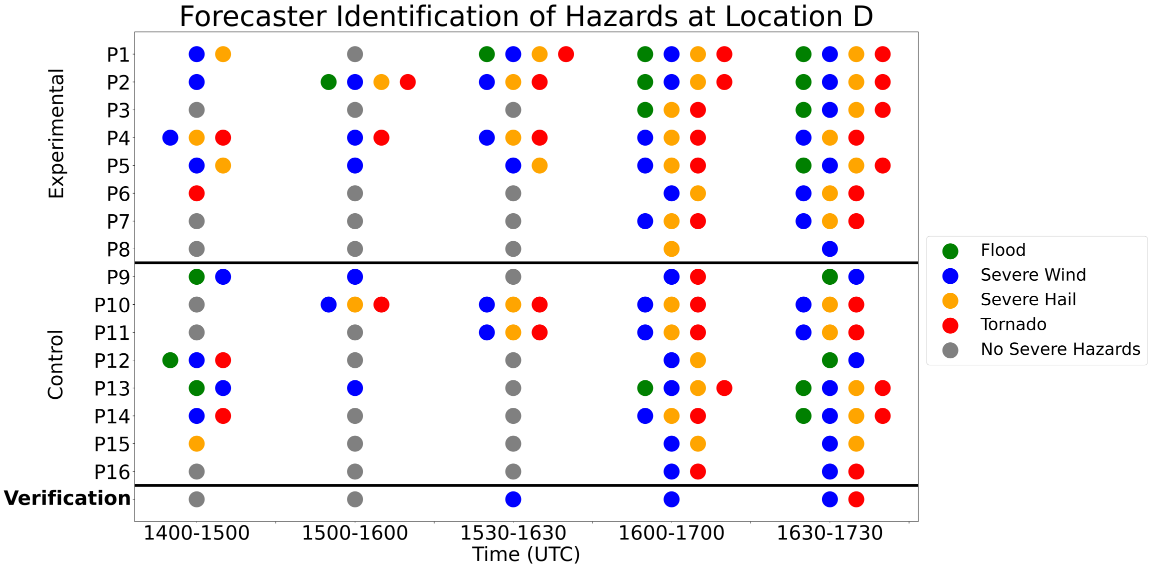


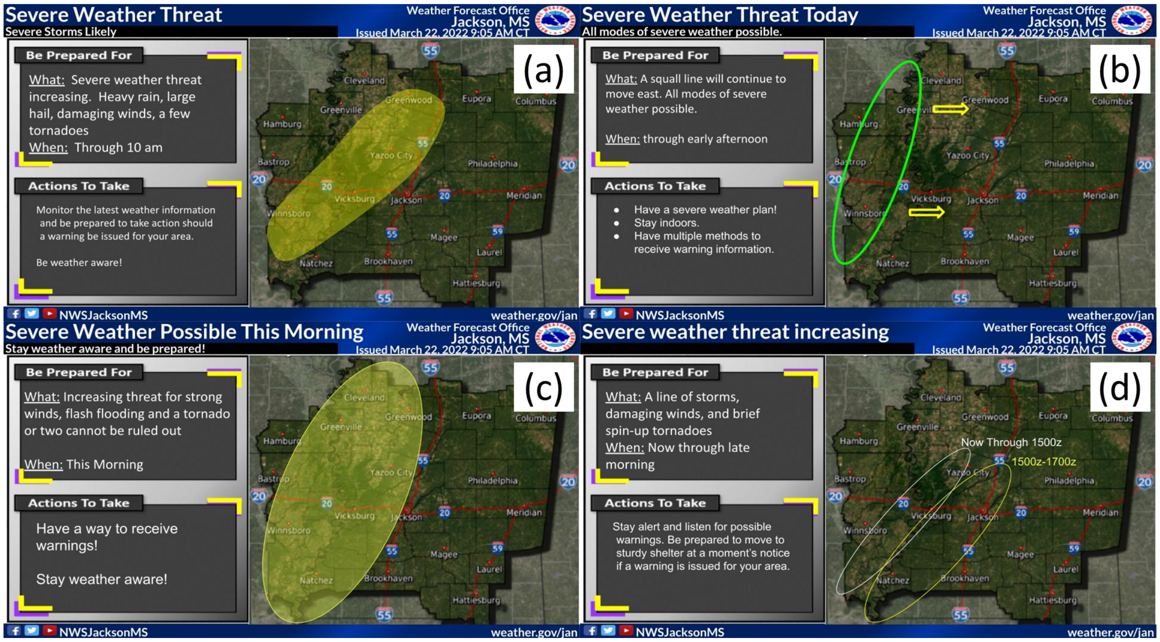
Figure 3.22: Identification of severe hazards selected by all forecasters at Location D. The bottom line is the verification of severe hazards as determined by local storm reports.

3.6.1 Initial Time step: 1405 UTC

At the first time step (1405 UTC), the QLCS had reached Location B, and no weather hazards had been reported at any of the sites. However, at this time, most forecasters identified potential weather hazards within the next hour at all locations, including site D, which was located more than 200 km east of the squall line's leading edge (Fig. 3.22). Both groups used the generic radar representations heavily in their analysis. Due to the limitations in the display of the radar, specific features were not focused on, rather, forecasters monitored where the line was and how fast it was progressing to determine which sites would be impacted. P11 discussed how radar was used in their analysis, "the radar presentation helped key this," referencing the hazards they identified. Similarly, P2 discussed that "KDGX appears most useful here" when discussing the different data used.

Forecasters began to hone their hazard expectations after using radar data to assess the speed and location of the QLCS. The only difference between the control and experimental group's environmental analysis was their use of the RAP soundings. The experimental group used the CopterSonde data to evaluate the RAP sounding characteristics and identify any biases. P5 discussed this use as follows: "CopterSonde data seems to match well with sounding data out ahead of the line of storms... which provides confidence in using CopterSonde data moving forward." Most of the forecasters in the experimental group noted how the CopterSonde data were in agreement with the RAP. The control group focused on the SPC mesoanalysis and RAP soundings. P14 "... gained synoptic awareness" by viewing the SPC mesoanalysis in addition to the forecast briefing. The RAP soundings at Locations A and C had greater than 50 Jkg^{-1} of CAPE, and all locations had greater than 20 kts of 0–1-km wind shear. P13 was able to determine that "either way, all hazards (TOR, flooding, severe hail and wind, and lightning) are in play today given this environment." The experimental group also determined that all hazards were possible across the CWA.

Forecasters from both groups communicated about the increasingly favorable environment ahead of the line in their NWSChat messages (P2, P8, P10, P14, and P15). Most of the NWSChat messages included the possibility of spin-ups and that tornadoes were likely. The primary focus of the graphics issued was the location of the squall line, its potential hazards, and where it would propagate into the future. Figure 3.23 shows the first graphics issued by P2 (EX), P4 (EX), P12 (C), and P14 (C).



(a)

Severe Weather Threat

Severe Storms Likely

Weather Forecast Office Jackson, MS

Issued March 22, 2022 9:05 AM CT

Be Prepared For

What: Severe weather threat increasing. Heavy rain, large hail, damaging winds, a few tornadoes

When: Through 10 am

Actions To Take

Monitor the latest weather information and be prepared to take action should a warning be issued for your area.

Be weather aware!

NWSJacksonMS

weather.gov/jan

(b)

Severe Weather Threat Today

All modes of severe weather possible.

Weather Forecast Office Jackson, MS

Issued March 22, 2022 9:05 AM CT

Be Prepared For

What: A squall line will continue to move east. All modes of severe weather possible.

When: through early afternoon

Actions To Take

- Have a severe weather plan!
- Stay indoors.
- Have multiple methods to receive warning information.

NWSJacksonMS

weather.gov/jan

(c)

Severe Weather Possible This Morning

Stay weather aware and be prepared!

Weather Forecast Office Jackson, MS

Issued March 22, 2022 9:05 AM CT

Be Prepared For

What: Increasing threat for strong winds, flash flooding and a tornado or two cannot be ruled out

When: This Morning

Actions To Take

Have a way to receive warnings!

Stay weather aware!

NWSJacksonMS

weather.gov/jan

(d)

Severe weather threat increasing

Weather Forecast Office Jackson, MS

Issued March 22, 2022 9:05 AM CT

Be Prepared For

What: A line of storms, damaging winds, and brief spin-up tornadoes

When: Now through late morning

Actions To Take

Stay alert and listen for possible warnings. Be prepared to move to sturdy shelter at a moment's notice if a warning is issued for your area.

NWSJacksonMS

weather.gov/jan

Figure 3.23: Graphics issued at the first time step (1405 UTC) of the severe weather case by (a) P2, (b) P4, (c) P12, and (d) P14.

3.6.2 Middle Portion of the Case: 1505–1535 UTC

At the beginning of the second time step, the leading edge of the line had strengthened and contained multiple strong convective cells (Fig. 3.24a). By the third time step (1535 UTC), the line was beginning to grow upscale (Fig. 3.24b). Utilizing the storm reports, forecasters could see that hail was reported near Location B, and severe wind damage was reported near Location A. At Location D, no hazards were reported. Radar continued to be an important data source for all forecasters' analysis. P12 described how "the radar data gave me a sense of timing... The soundings helped determine the meteorological parameters for the environment and how much instability and shear persists at the location." In addition to P12, many forecasters paired the radar data with their environmental analysis.

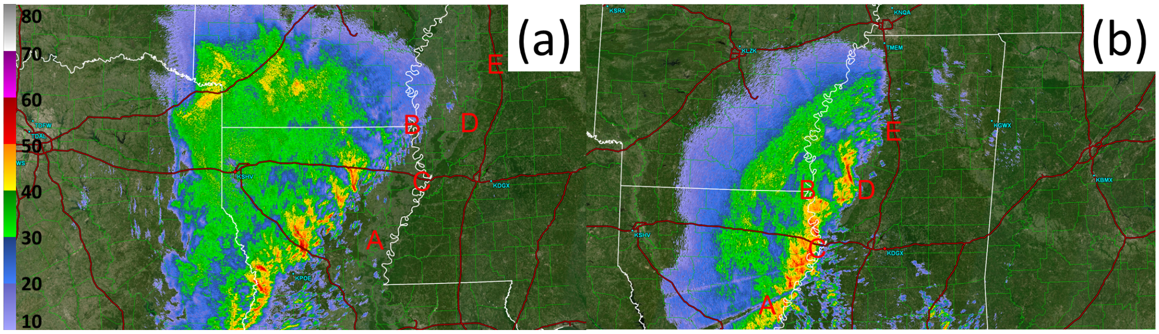


Figure 3.24: GR2Analyst displaying 0.4° reflectivity from KDGX at (a) 1501 UTC and (b) 1535 UTC.

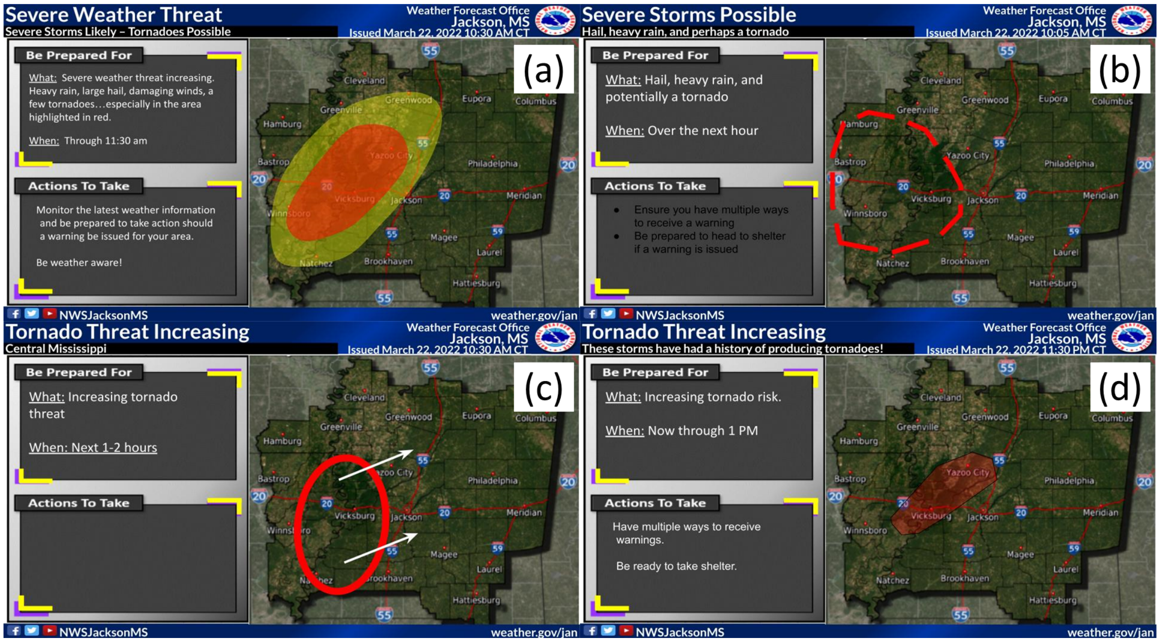
The sub-hourly sampling frequency allowed the CopterSonde data to be used more than hourly RAP analysis in environmental analysis. In one of P5's survey responses, they discussed how the "CopterSonde data confirms rapidly changing, unstable environment out ahead of the line of storms." One feature that was not depicted in the radar data was an outflow boundary that passed over Location D. Unlike the control group, the experimental group was able to identify this feature using the CopterSonde data. P2 and P6 interpreted weakened instability at 1505 UTC due to calmer northerly winds and cooler temperatures compared to the time step before (1405 UTC). P6 discussed how this development was likely due to "... outflow from nearby showers and storms." This forecaster initially had a tornado threat at 1435 UTC, but due to the effects of the outflow boundary, they lowered their hazard expectations to none. P6 included the following in their response to the impact of the CopterSonde data at 1505 UTC.

> "The CopterSonde reinforced my decision for no severe weather threat for location D because the addition of the data it observed resulted in an

> SBCAPE [surface-based CAPE] of 0 $\mathrm{Jkg^{-1}}$. If anything, there would be a low tornado threat, but without any CAPE, the tornado threat would be zero at this location. Since no other threats are expected, this reinforced my decision of no severe weather threats."

By 1535 UTC, more forecasters in the experimental group began to notice this feature. P1 commented how "the temporary weakness of the low-level flow near site D seems to be recovering." In the prior time step P1 lowered their hazard expectation for Location D. With the increase in instability at 1535 UTC, P1 identified all hazards possible at Location D since they expected "... the cap to be completely eroded within the next hour." Similarly, P2 discussed at that the temporary weakened instability sampled was recovering and the CopterSonde data reinforced their decisions to include a tornado threat at Location D.

The control group's answers provided descriptions of how the environment continued to become more unstable. P15 discussed how "... the environment is rapidly improving and could support the most intense storms (including tornado risk)." In addition, forecasters explained how all hazards were possible and that the line was slowly propagating. P11 noted, "sites A, C, and D are all at risk of tornadoes, wind, and hail as the warm sector continues to erode CIN [convective inhibition] and instability increases." Similar to the control group, forecasters in the experimental group discussed how the unstable environment was expanding and all hazards were likely. Both groups discussed the increased tornado possibilities within messages in NWSChat and graphics on Twitter. Forecasters updated or issued new graphics during these time steps with broad areas for severe weather and specific highlighted areas for tornadoes. A few examples are shown in Figure 3.25. Though the outflow boundary was detected by some of the forecasters in the experimental group, none of the forecasters communicated via NWSChat or Twitter about a temporary decrease in the likelihood of severe weather at Location D.



Severe Weather Threat
Severe Storms Likely – Tornadoes Possible
Weather Forecast Office
Jackson, MS
Issued March 22, 2022 10:30 AM CT

Be Prepared For

What: Severe weather threat increasing. Heavy rain, large hail, damaging winds, a few tornadoes…especially in the area highlighted in red.

When: Through 11:30 am

Actions To Take

Monitor the latest weather information and be prepared to take action should a warning be issued for your area.

Be weather aware!

NWSJacksonMS
weather.gov/jan

Severe Storms Possible
Hail, heavy rain, and perhaps a tornado
Weather Forecast Office
Jackson, MS
Issued March 22, 2022 10:05 AM CT

Be Prepared For

What: Hail, heavy rain, and potentially a tornado

When: Over the next hour

Actions To Take

- Ensure you have multiple ways to receive a warning
- Be prepared to head to shelter if a warning is issued

NWSJacksonMS
weather.gov/jan

Tornado Threat Increasing
Central Mississippi
Weather Forecast Office
Jackson, MS
Issued March 22, 2022 10:30 AM CT

Be Prepared For

What: Increasing tornado threat

When: Next 1-2 hours

Actions To Take

NWSJacksonMS
weather.gov/jan

Tornado Threat Increasing
These storms have had a history of producing tornadoes!
Weather Forecast Office
Jackson, MS
Issued March 22, 2022 11:30 PM CT

Be Prepared For

What: Increasing tornado risk.

When: Now through 1 PM

Actions To Take

Have multiple ways to receive warnings.

Be ready to take shelter.

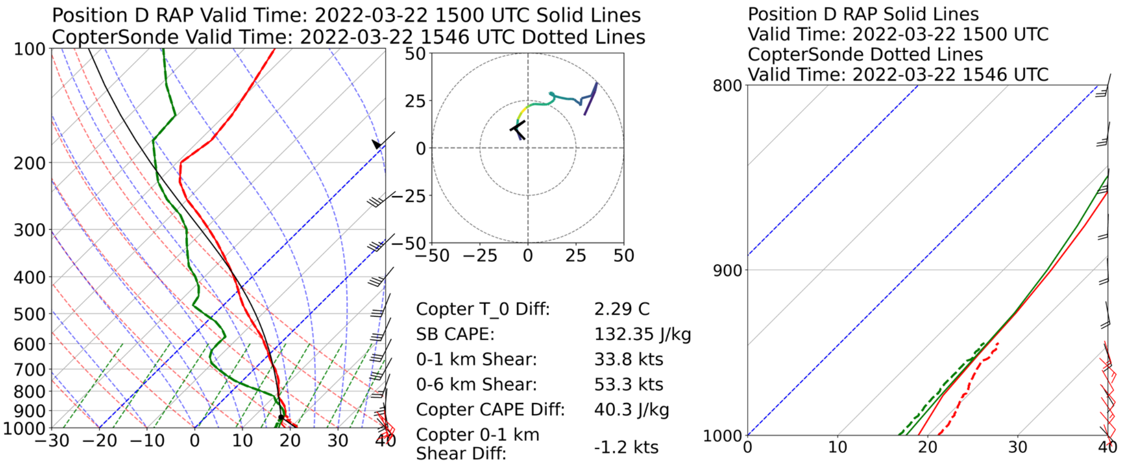
NWSJacksonMS
weather.gov/jan

Figure 3.25: Graphics issued by (a) P2 at 1535 UTC, (b) P3 at 1535 UTC. (c) P11 at 1535 UTC, and (d) P16 at 1535 UTC,

3.6.3 QLCS Began Impacting Location D: 1605 UTC

The squall line continued to move eastward through the domain. Locations A, B, and C were impacted, and embedded convective cells within the line were approaching Location D. On the ArcGIS dashboard displaying local storm reports, a few more wind and hail reports were recorded, including near Location D (not shown). Some forecasters in the experimental group previously noted that the use of CopterSonde data were limited due to storms being well off to the west. During the prior time step (1535 UTC), P3 shared that they "should begin to utilize CopterSonde in the next few time steps as the showers and thunderstorms approach point D." At this time step (1605 UTC), P3 reported that "with storms approaching point D, I heavily incorporated CopterSonde data for the first time." The CopterSonde sampled a warmer profile than the RAP analysis (Fig. 3.26). An increase of 40 Jkg^{-1} of surface-based CAPE was calculated with the addition of the CopterSonde observations. For P3, this 45% increase in CAPE increased their confidence to include a tornado threat at

Location D in their hazard expectations (Fig. 3.22). Many forecasters in the experimental group continued using the CopterSonde data to confirm the environmental information within the RAP and SPC guidance. P4 discussed comparing the different data types. “The steady flow of new data not only helps to support model data like RAP analysis, it also helps confirm the amount of moisture present in the lower levels of the atmosphere.”



Copter T_0 Diff:	2.29 C
SB CAPE:	132.35 J/kg
0-1 km Shear:	33.8 kts
0-6 km Shear:	53.3 kts
Copter CAPE Diff:	40.3 J/kg
Copter 0-1 km Shear Diff:	-1.2 kts

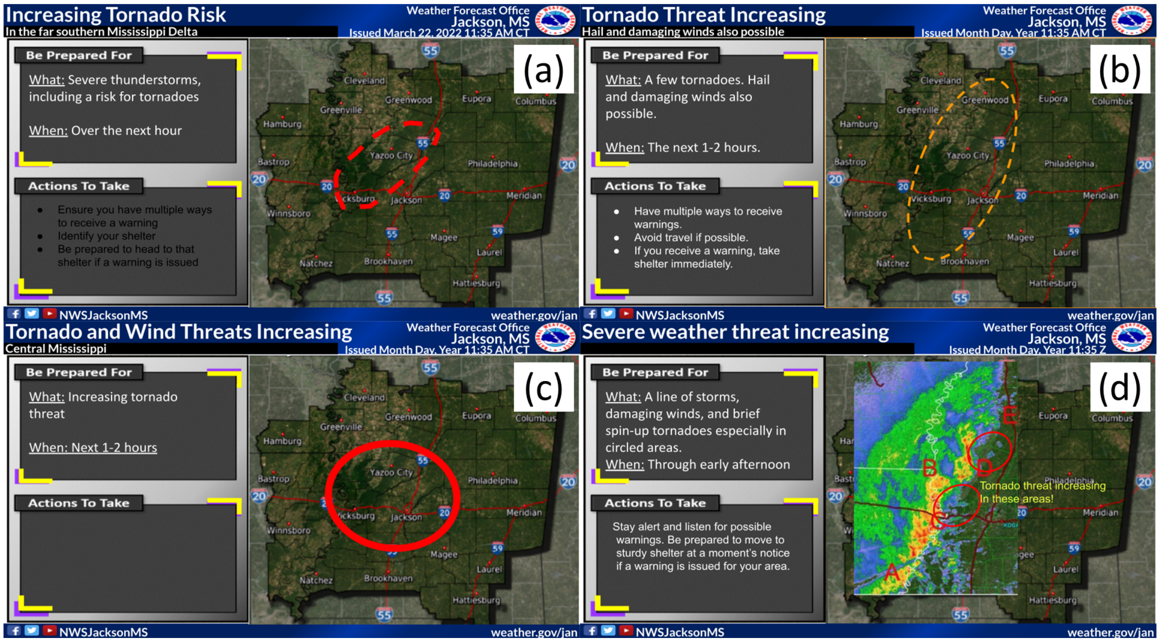
Figure 3.26: 1500 UTC RAP sounding for Location D in solid lines with CopterSonde measurements from 1546 UTC of temperature and dewpoint temperature in dashed lines. Black wind barbs are from the RAP sounding, and red barbs are from the CopterSonde. The RAP hodograph is colored, and the CopterSonde hodograph is black. Calculated values show the difference in surface temperature between the CopterSonde and RAP, the surface based CAPE and shear values calculated with the addition of the CopterSonde data to the RAP sounding, the difference between the new CAPE value and the original RAP CAPE value, and the difference between the new 0–1-km shear value and the original RAP 0–1-km shear value.

Using the RAP soundings and SPC mesoanalysis, forecasters from both groups were able to see that CAPE values exceeded 500 Jkg^{-1} at Location D and that the 0–1-km shear was greater than 30 kts at all locations. In one of P12’s survey answers, they commented that “the environment will only continue to improve for tornadoes through the day.” Forecasters in the control group used radar data to identify cells that were moving into “untapped, very moist airmasses.” P14 added a tornado threat to Location D at this time due to the favorable environment for tornadoes. The communications for this time step remained largely unchanged due to the already communicated tornado threat. All changes in graphics and NWSChat messages were associated with where the line was now positioned.

3.6.4 Last Time step: 1635 UTC

During this final time step, forecasters in the experimental group noted their increased use of CopterSonde data due to severe weather impacting Location D. Nearly all forecasters in the experimental group, except P8, reported an increase in confidence in their decisions and continued reinforcement of the environmental conditions portrayed in the RAP and SPC mesoanalysis. Just prior to this time step, a tornado occurred near Location C (1623 UTC), and severe wind reports were recorded near Location D (1629 UTC) (not shown). Using the finer resolution CopterSonde data P1 noticed the tornado report and determined that "the warm sector was slowly expanding slightly to the north and east, and I could hone in on the threat area pretty well - at least the tornadic threat area."

Both groups' communications were concentrated on the areas of the greatest tornado threat. Nearly all of the forecasters communicated in NWSChat about the tornado report, the environment ahead of the line, and how it was conducive for tornadoes. Figure 3.27 shows examples of graphics issued from both groups highlighting the increased tornado threat since the 1505–1535 UTC time steps. A similar characteristic between all four graphics show a concentrated area around Yazoo City, with the message of an increasing tornado threat. Figures 3.27a-b are from the experimental group (P3 and P6), and 3.27c-d (P11 and P14) are from the control group.



(a)

Increasing Tornado Risk

In the far southern Mississippi Delta

Weather Forecast Office Jackson, MS

Issued March 22, 2022 11:35 AM CT

Be Prepared For

What: Severe thunderstorms, including a risk for tornadoes

When: Over the next hour

Actions To Take

- Ensure you have multiple ways to receive a warning
- Identify your shelter
- Be prepared to head to that shelter if a warning is issued

NWSJacksonMS weather.gov/jan

(b)

Tornado Threat Increasing

Hail and damaging winds also possible

Weather Forecast Office Jackson, MS

Issued Month Day, Year 11:35 AM CT

Be Prepared For

What: A few tornadoes. Hail and damaging winds also possible.

When: The next 1-2 hours.

Actions To Take

- Have multiple ways to receive warnings.
- Avoid travel if possible.
- If you receive a warning, take shelter immediately.

NWSJacksonMS weather.gov/jan

(c)

Tornado and Wind Threats Increasing

Central Mississippi

Weather Forecast Office Jackson, MS

Issued Month Day, Year 11:35 AM CT

Be Prepared For

What: Increasing tornado threat

When: Next 1-2 hours

Actions To Take

NWSJacksonMS weather.gov/jan

(d)

Severe weather threat increasing

Weather Forecast Office Jackson, MS

Issued Month Day, Year 11:35 Z

Be Prepared For

What: A line of storms, damaging winds, and brief spin-up tornadoes especially in circled areas.

When: Through early afternoon

Actions To Take

Stay alert and listen for possible warnings. Be prepared to move to sturdy shelter at a moment's notice if a warning is issued for your area.

NWSJacksonMS weather.gov/jan

Figure 3.27: Graphics issued at 1635 UTC by (a) P3, (b) P6, (c) P11, and (d) P14.

Between the second (1505 UTC) and third (1535 UTC) time steps, and then between the fourth (1605 UTC) and last (1635 UTC) time steps, only updates from the radar and CopterSonde were provided. P6 described the benefit of having observations between updates in the RAP, such that "the CopterSonde provided data that helped me determine that the environment at Point D had changed over the past 30 minutes and had become more supportive of a tornado threat" Most of the experimental groups' responses to the survey at this time, focused on the use of CopterSonde data. The highlights of the control group's survey responses and focus group discussions were on the bowing nature of the line (P11, P14, and P16), locations behind the line having decreased threats (P10, P11, P12, P13, and P14) and storm reports (P9, P10, P12, P15 and, P16).

3.7 CopterSonde Preferences and Ideas

The study's primary goal was to identify situations where CopterSonde data could impact forecasters during two case studies. Forecasters were asked about their level of comfort in using the CopterSonde data in the background survey and again after using the CopterSonde data during the case studies. Additionally, the background survey, case study surveys, and focus groups queried forecasters on their opinions about the future of the CopterSondes in NWS operational forecasting. During the focus group discussions, forecasters were able to introduce ideas, discuss them among themselves, and consider their feasibility.

3.7.1 Comfort and Trust

Comfort was not defined to the forecasters, but questions about comfort and trust were asked separately. By asking questions separately more robust analysis of forecasters' comfort in using the data could be conducted. In addition, the concepts of comfort and trust were able to be analyzed separately. The CopterSonde concept was introduced during the background survey, but no examples were given of how the data would be displayed. Then, during the forecast experiment, forecasters had the opportunity to use the data. The CopterSonde data were displayed in two ways during the case study: time-height plots (Fig. 3.9) and the modified soundings (Fig. 3.11). The same Likert scale question regarding the forecasters' level of comfort with the data was asked during each phase of this study (Appendix 1 and 2). Figure 3.28 shows forecasters' comfort ratings for using CopterSonde data. The median choice from the background survey, not having used or visualized the data in any way, was *Somewhat Comfortable*. During the severe weather case, the median choice was also *Somewhat Comfortable*, whereas the median choice from the forecasters who used the data during the winter weather case was *Very Comfortable*. No forecaster identified that they would be either *Not Comfortable* or *Somewhat uncomfortable* using high-resolution real-time data like the CopterSonde data. The IQR for each group spanned two adjacent rating levels, demonstrating agreement between forecasters in their high level of comfort in using the data.

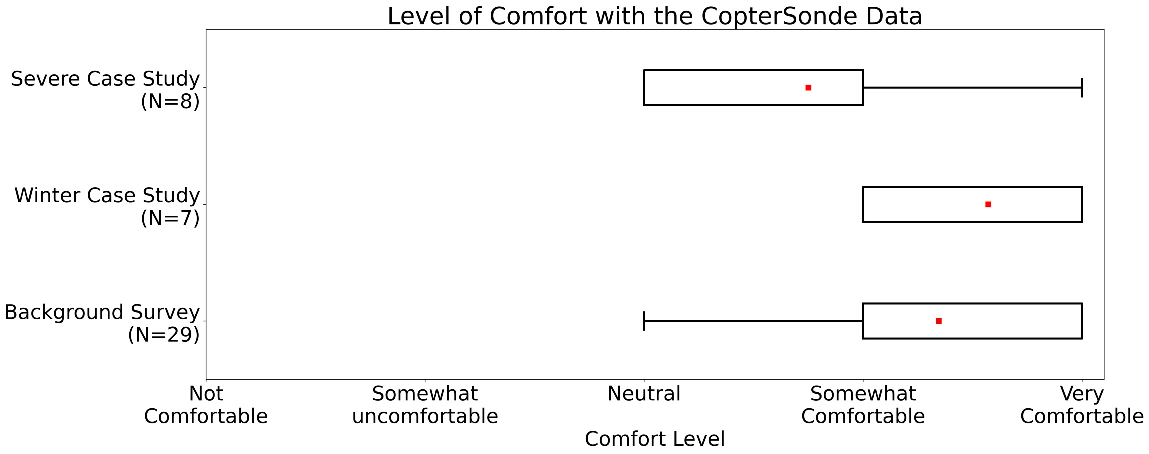


Figure 3.28: Forecasters anticipated level of comfort using the CopterSonde data from the background survey and their reported level of comfort after each case study.

One of the topics explored in the focus group was the participants' level of trust in the CopterSonde data. It was explained to forecasters that the CopterSonde has and currently is participating in numerous field campaigns, and extensive testing has been done to ensure the accuracy of the observations during the introductory meeting. Toward the end of each focus group, forecasters were asked if they trusted the CopterSonde data during the case studies. All 16 forecasters addressed their trust and the benefits of the CopterSonde data. Forecasters expressed varying levels of trust, with some saying they "trusted it 100%." Others said, "I didn't have any reason to not trust the data itself. I had not so much confidence in my interpretation of the data." Other forecasters indirectly addressed the concept of trust by saying, "the CopterSonde data, I like that," or "... the CopterSonde data really bridged the gap between each hour's worth of data. So that really helps me."

Follow-up questions to forecasters about their case study responses led to examples and explanations of their level of trust in the CopterSonde data. For example, P1 said, "I kind of accepted the CopterSonde data, as you know, the truth of what was happening in the lowest 500 meters or so. I never really questioned the data at all." P5 similarly discussed how the CopterSonde data allowed them to observe better what was occurring in the boundary layer. P5 also commented that their confidence was much higher with their better understanding of the boundary layer. P9 also discussed the idea of knowing what was occurring in the boundary layer. This forecaster explained that they trusted CopterSonde data much more than model guidance.

Not only did forecasters trust the data, but they were comfortable using it, which led to the CopterSonde data influencing forecasters' decisions. During each time step, forecasters had multiple data types to analyze. The CopterSonde data conflicted with the other available data at some time steps. P12 discussed how "the CopterSonde data did kind of make me question myself a little bit." The CopterSonde data did not agree with their analysis from the other data types. A follow-up question asked if they trusted their initial analysis or changed their decisions due to the CopterSonde data. P12 responded that they trusted and used the CopterSonde data to make their final decisions. One of the reasons P12 trusted the CopterSonde data was because "it looked like it was valid throughout the beginning of the simulation or the case basically, and so I kind of went with it."

3.7.2 Visualization Ideas

Forecasters utilized both displays of the CopterSonde data (time-height plots Fig. 3.9 and the modified soundings Fig. 3.11) and found value in both of them. The time-height plot showed the changes in the boundary layer on a single plot, which the forecasters appreciated. During discussions on the future of CopterSonde data, Forecasters focused on skew-Ts. Regarding skew-Ts, forecasters found the overlay of the RAP and radiosonde data very helpful in seeing the changes in the boundary layer. One idea to improve the skew-T plots was to keep the CopterSonde and other sounding data (RAP or radiosonde) separate but still on the same plot. In the current form, the CopterSonde data, in dashed lines, reconnected to the original sounding at the maximum height where data were collected (Figure 3.11). Forecasters were not able to determine the maximum height of CopterSonde data and where the interpolation began. This design confused most of the forecasters, and their preference was to have the data displayed without interpolation.

During the focus group, a third way of displaying the data was shown to forecasters. Figure 3.29 shows temperature and dewpoint temperature plotted on a linear scale versus the typical skew-T diagram. In this visualization, more subtle features could be noticed. For example, Figure 3.29a shows a cloud layer at 700 m, and 3.29b shows a temperature inversion near 100 m. This inversion is from the outflow boundary identified in the severe weather case. While this feature is prominent in the linear plot, it is mostly washed out in the skew-T (Fig. 3.30). The zoomed in sounding in Fig. 3.30 does show the surface is cooler and less moist than the RAP, but the roughly 100 m inversion is not visible.

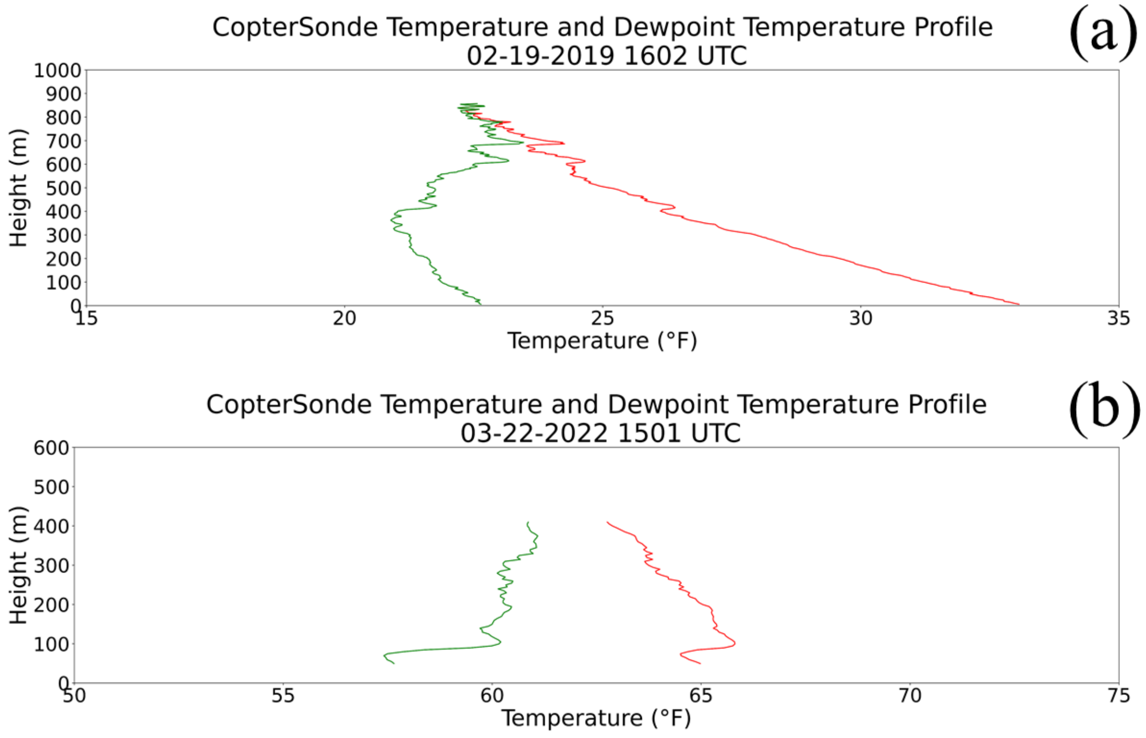


Figure 3.29: Temperature and dewpoint temperature from the CopterSonde plotted on a linear scale from (a) the winter weather case at 1602 UTC 19 February 2019 and (b) the severe weather case at 1501 UTC 22 March 2022.

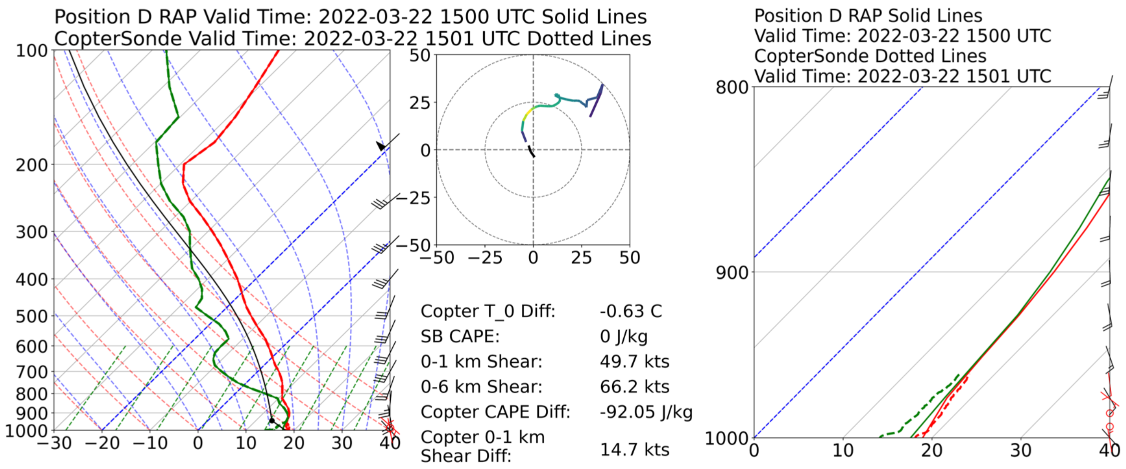


Figure 3.30: 1500 UTC RAP sounding for Location D in solid lines with CopterSonde measurements from 1501 UTC of temperature and dewpoint temperature in dashed lines. Black wind barbs are from the RAP sounding, and red barbs are from the CopterSonde. The RAP hodograph is colored, and the CopterSonde hodograph is black. Calculated values show the difference in surface temperature between the CopterSonde and RAP, the surface based CAPE and shear values calculated with the addition of the CopterSonde data to the RAP sounding, the difference between the new CAPE value and the original RAP CAPE value, and the difference between the new 0–1-km shear value and the original RAP 0–1-km shear value.

Even though more subtle features can be noticed, forecasters preferred the data in a skew-T format. Only 4 out of 14 forecasters commented that they liked it or found it interesting for the severe weather case, and 7 out of 16 liked it for winter weather. P10 explained their preference, "I think this is a great option to have. I mean, you know, like you said, the ability to see very subtle changes as it's going up. Almost meter by meter, I think that's really great... I think I would maybe even almost prefer a skew-T just because that's what I'm used to." P15 also commented that they prefer to compare "apples to apples," referencing skew-T data from upper air soundings or NWP models.

Ideas were introduced to make this plot a better comparison to traditional skew-Ts. During one of the focus groups, all four forecasters discussed adding reference lines (e.g., dry and moist adiabats, zero-degree isotherm) so that the plot would be more easily understood. This modification would reduce some of the confusion the plot introduced since some of the forecasters have been working with skew-Ts for multiple decades.

3.7.3 Operational Ideas

Forecasters not only found CopterSonde data beneficial but wanted more of it. In both cases, forecasters discussed where else they would have wanted to see the data in the CWA. In P10's final survey response during the winter weather case, they said, "I found myself most wanting the CopterSonde data for areas where the mixed precip types were occurring (B and C) as being able to see the thermodynamic evolution above the ground would prove invaluable in forecasting changes to precip type here." This forecaster wanted the data in places where the forecast was less confident. This desire was similar during the severe weather case. P7 discussed in their survey that "points B and A would have potentially been better locations for CopterSonde data as I had a lower confidence forecast (conflicting information from SPC mesoanalysis and what I was seeing on radar)." The CopterSonde data boosted confidence where the forecasters had the data, but if data were available at every site, forecasters may have been able to make more accurate decisions across the whole CWA. Such an outcome has yet to be tested.

During the focus groups, questions were asked to explore forecasters' preferences on the ways to bring CopterSonde data into operations. One of the questions asked during the focus group was, *What ideas do you have to increase the value of the CopterSonde data if they were displayed across regions similar to the Oklahoma and West Texas Mesonets?* The idea of having CopterSondes deployed at every mesonet site was introduced to them in the focus group. One forecaster offered, "I mean, you know forecasters are kind of greedy." This comment was in reference to the desire to have CopterSondes stationed at every Mesonet site to collect a high-resolution network of observations. Most of the forecasters echoed the idea of having a CopterSonde at every Mesonet site, but the group's consensus was that this idea was not feasible. The cost to build and maintain CopterSondes at every Mesonet site is not currently economical in terms of cost and time. P2 discussed how the Oklahoma Mesonet has begun ingesting their observations from 12 sites into the fire weather information management system. These observations offer "pretty good sampling across the area." P2 connected this idea to the CopterSondes and suggested that if 12–20 CopterSondes could be deployed across Oklahoma, it would likely be sufficient to provide forecasters with a network of observations.

There was no complete agreement between the focus groups about the best way to station a CopterSonde network. Some forecasters would prefer the observations not to be taken at Mesonet sites. P8 explained, "I've already got some good data, you know, right there." Instead, they preferred that CopterSondes be located in more data-sparse regions to increase the observational coverage across CWAs further. For example, P9 discussed how outside one of the major cities in their CWA, "you can drive for three hours and you can't or won't hit an ASOS [automated surface observing system] again." CopterSondes have the potential to fill in the data gap throughout the CWA by deploying CopterSondes between Oklahoma and West Texas Mesonet sites. Near big cities, P10 explained how they receive mPING and local storm reports, and the reports provide ground truth of what is happening. A stationary network of CopterSondes would provide similar consistent, and reliable data.

In addition to a stationary network of CopterSondes, forecasters also discussed having targeted observations. This effort would involve positioning CopterSondes in advance of an impactful weather event. P1 and P10 discussed how during severe weather, if the dry line or warm front could be sampled with multiple CopterSondes, it would reduce uncertainty about the environment and their hazard expectations. If an impactful weather event is occurring between Mesonet sites, a stationary network would not provide the most beneficial data. Targeted observations would allow specific areas to be sampled. P11 explained, “we just can’t send balloons up, especially in the lowest levels of the atmosphere where it really matters.” Being able to control where the CopterSondes collect data would give forecasters greater access to boundary layer observations “where it really matters.”

During one of the focus groups, the idea of targeted observations was being discussed when P14 brought up the logistical issues for this type of data collection. “I worry about having forecasters keep track of where it is from day to day... It’s like the mesosector for GOES... the problem is from day to day, we don’t keep track of where the mesosector is, and sometimes we’re under a mesosector, and we don’t know that we are until somebody spots it. I worry that you come into that same issue with the CopterSonde.” The NWS headquarters decides where the mesosector are, and forecasters do not always know when their is a mesosector. The same thing could happen with CopterSondes if they are not repositioned daily. Once this idea was introduced, all the forecasters in this focus group agreed that the logistics of a targeted network was a great idea but not realistic. Houston et al. (2020) also found similar findings in their survey regarding targeted networks of UASs.

In addition to feasibility, building trust with the CopterSondes was discussed. To build trust, P14, and P16 discussed placing a single CopterSonde at automated surface observing system sites or near big cities. This way, the observations are there every day, and forecasters can begin to use them, trust them, and integrate them into their workflows. Another benefit of having CopterSondes at airports is personnel are available to maintain the CopterSondes. Placing them in remote locations or even at Oklahoma Mesonet sites requires technicians to travel to service them. Automated surface observing system sites have teams available to service them when needed, and they could be trained to maintain the CopterSonde. Also, P16 discussed how forecasters have to write terminal aerodrome forecasts, and having this data at these locations would make the reports easier and more accurate.

A final area forecasters discussed was a desire for the CopterSonde to fly higher. Forecasters asked why the data stopped at a certain elevation. The elevation limitation is due to the mechanical limitations of the craft and rules from the Federal Aviation Administration. Flying the CopterSonde higher would allow warm noses, capping inversions, and low-level jets to be better sampled. These features are poorly sampled currently, although they can drastically impact a forecast or decision. The overall message from forecasters was “the more, the merrier,” but even having a single CopterSonde in their CWA sampling to one kilometer is anticipated to improve their forecasts.

Chapter 4

Discussion

The study presented here evaluated the effects of CopterSonde data on decision-making activities within a forecast experiment. In this study's first phase, a background survey was conducted, and forecasters anticipated benefits from incorporating CopterSonde data into their operational forecasting workflow were identified. Those anticipated benefits were then tested during two case study activities. During the case studies, forecasters found benefits in having access to the high-resolution CopterSonde data. Forecasters' situational awareness was a key area identified in the background survey where CopterSonde data could benefit forecasters. Forecasters anticipated being able to have a better understanding of the boundary layer, which could potentially lead to better identifying precipitation types and areas conducive for severe weather. In both cases, forecasters were able to diagnose the thermodynamic and kinematic structure of the boundary layer. This better understanding during the winter weather case led to more accurate precipitation type classifications and earlier communication of the impacts compared to the control group. Using Endsley's 1995 and McGuiness and Foy's 2000 models for situational awareness, the CopterSonde influenced all four levels of situational awareness.

Repeatedly throughout both cases, forecasters compared the CopterSonde data to RAP and radiosonde soundings and other surface data. This process was one of the most prominent uses of CopterSonde data. The forecasters were able to determine biases in the RAP and project those in their analysis in both time and space. Model guidance is heavily used in current NWS operations, and by being able to have more confidence in them, forecasters were able to expedite their analysis. Tripp et al.

(2021) found that the HRRR model had up to a 3° C bias during the winter weather case used in this study. This led to the model incorrectly classifying precipitation as freezing rain versus ice pellets across the state throughout the event. The addition of CopterSonde data led to the correct classification of precipitation types. In this study, a similar effect of the CopterSonde data was seen, with forecasters correctly identifying the precipitation type with the addition of the CopterSonde data. NWP models are moving towards sub-km grid-spacing. The high-resolution data collected by the CopterSondes have the potential to positively impact boundary layer calculations in NWP.

Forecasters use pattern recognition when analysing observations and NWP to characterize the environment. R28 addressed their environmental analysis process during the background survey by saying, "As a forecaster, I have a good idea of forecast evolution based upon coarser boundary layer data and NWP performance. I think higher resolution measurements of the boundary layer would increase my confidence in a forecast or more quickly and more readily identify where a forecast needs improvement." As mentioned above, forecasters compared the CopterSonde data to RAP and radiosonde soundings, but also used it to update their conceptual model. They had more confidence in their analysis and ultimately decisions. This result supported the findings from the background survey regarding increases in forecaster confidence and situational awareness.

These benefits are similar to the findings in Gravelle et al. (2016); Smith et al. (2016); and Wilson et al. (2017). These studies explored the use of technology that enhanced observing capabilities of the atmosphere in the hazardous weather testbed. GOES-R satellite data and analysis products were tested in Gravelle et al. (2016). The NearCase model and convective products produced using GOES satellite data increased forecaster situational awareness. Additionally, forecasters were comfortable using it. The products were able to highlight areas of expected convection initiation and rapid development. Forecasters were able to shift their attention to these areas and be prepared for when storms did initiate. Similarly, Multi-Radar Multi-Sensor data was evaluated in Smith et al. (2016). New products like composite reflectivity were produced by blending multiple radars and other observations into gridded datasets. This product reduces the need for forecasters to alternate between radars and provides a greater view of their CWA. A final study that evaluates new technology with NWS forecasters was Wilson et al. (2017). One-minute rapidly updating phased array radar data was evaluated against the traditional five-minute updating radar data. After using the one-minute data, forecasters did not want to return to five-minute data. They were able to identify features in the one-minute data that were not visible in the five-minute data. Overall, the faster-updating data enhanced their situational awareness. During the two case studies in this experiment, forecasters' situational awareness was improved, and they expressed a desire for the new data. This finding demonstrates how there are data gaps in current NWS operations. Moreover, forecasters find benefits in new and rapidly updating technology.

There was not a full consensus on the benefits of CopterSonde data used for some weather events explored in the background survey. Overall, the impacts of CopterSonde data were positive throughout both case studies, specifically during the winter weather case, which contrasted with what R16 anticipated. In one of R16's responses to the background survey, they anticipated CopterSonde data would not be useful in operational winter weather forecasting. This forecaster described that in their experience, after a winter weather event has started, the forecast will not change significantly, regardless of what the real-time data is showing. This expectation was not seen during the winter weather case study. Using the CopterSonde data allowed forecasters to change their precipitation type classifications on sub-hourly time frames accurately. Without the additional data, the control group had fewer changes to their precipitation classifications, and they made more consistency-based forecasts. Though statistical significance was not established for the case as a whole, it was established during a time when the precipitation type was rapidly changing. Forecasters' PoD may have been impacted as a result of the calculation being based on point classification, whereas forecasters typically make area forecasts rather than point classifications during actual events.

Many of this study's findings complement the focus groups and survey conducted in Houston et al. (2020, 2021). In Houston et al. (2020), one of the key findings was that UAS data needs to be collected at least throughout the lowest one kilometer of the atmosphere. Throughout this study, forecasters expressed that the minimum height for UAS data collection depends on the day. For example, warm noses and capping inversions can extend above one kilometer, and the minimum sampling depth would depend on these features. This study corroborates the findings from Houston et al. (2021) regarding skew-Ts being the primary display type, and that forecasters do not want to be responsible for coordinating flights during operational deployments. Both Houston et al. (2020) and the background survey conducted in this study found severe weather as an event where UAS data could greatly benefit forecasters (Fig. 2.1). Despite this focus on severe weather events, our analysis found that more prominent effects of the CopterSonde data on forecasters' decision-making process, situational awareness, and communication were more during the winter weather case.

The results from this study also enhance the findings from Koch et al. (2018) by demonstrating that accurate UAS data can be collected and used in a forecast experiment. During the EPIC field campaign, NWS forecasters were provided UAS data in NWS operations and rated it a 3 out of 10 regarding usefulness (Koch et al. 2018). In Koch et al. (2018), the focus of the study was on the data collection and distribution rather than the use of the data. Focusing on the use of UAS data in this study yielded much more positive results.

One of the possible reasons for the difference in impact between cases is the overall confidence in the environmental analysis. Conditional environments have more uncertainty associated with them and may lead to a variety of outcomes. The winter weather event was a conditional setup, whereas the severe weather event was a more confident setup. During the winter weather case, the surface and boundary layer temperatures hovered near the 32° F isotherm. Without the CopterSonde data, forecasters struggled to identify where the precipitation was refreezing and where it was melting, demonstrating the value of CopterSonde data on forecasters' decision-making processes in this case. Forecasters had more confidence in the severe weather event owing to the environment being conducive for the development of hail, damaging winds, and tornadoes. There was sufficient shear, lift, instability, and moisture for severe weather based on the surface observations and soundings. Forecasters used the CopterSonde data to recalculate key quantities in the boundary layer, like CAPE, convective inhibition, and wind shear. These calculations increased their confidence in assessing the environment and in their overall hazard expectations.

Another possible explanation for the lesser impact of the CopterSonde data during the severe weather case is the current use of environmental data compared to radar data during warning operations in the NWS. Currently, all official NWS tornado warnings are issued based upon detection. Tornado detections are observed either directly by spotters or inferred from radar observations (Brotzge and Donner 2013). Andra Jr. et al. (2002) also explored forecasters' warning decision-making process and found that severe weather operations begin with environmental analysis. During the 3 May 1999 tornado analyzed in Andra Jr. et al. (2002), it was found that after storms had initiated and became severe, the warning operator solely viewed radar data in the Advanced Weather Interactive Processing System-2.

Similar findings to Andra Jr. et al. (2002) and Brotzge and Donner (2013) were documented in this study. All the forecasters, with and without the aid of the CopterSonde data, used radar during the severe weather case to interrogate where the QLCS was and where it was moving. Forecasters focused on using radar since they were confident in the environment producing severe weather and were more concerned about determining the location of storms. The use of radar was different in the winter weather case. There were very few or no radar echoes for the first half of the case. Forecasters with the CopterSonde data identified where it was precipitating based upon the CopterSonde and other boundary layer observations more so than radar data. By comparison, the control group relied on radar and mPING reports to classify precipitation and subsequently classified the precipitation as wintry later. This effect led to less accurate precipitation type classifications and later communication by the control group to the OKC metro.

Chapter 5

Conclusion

This study sought to evaluate the impacts of CopterSonde data within two case studies. During the winter weather case study, a borderline mixed-phase precipitation event was beginning to occur throughout Oklahoma. Due to the uncertainty in the thermal profiles across the state, the CopterSonde data had a significant impact on forecasters' decisions and communications. NWS forecasters were able to use the data to better classify different precipitation types. Forecasters were able to classify the precipitation types more accurately, and communicate to their core partners and the public more efficiently using mock Twitter and NWSChat platforms. By 1645 UTC (third time step), all forecasters in the experimental group, with the CopterSonde data, had communicated via NWSChat or Twitter about the impending impacts. At this time, only three forecasters in the control group had communicated about impacts to the OKC metro. It was not until 1815 UTC (fifth time step), that all the forecasters in the control group communicated about the ongoing threats to the OKC metro.

At the beginning of the severe weather case a QLCS event was ongoing. The CopterSonde data did not lend to a much greater understanding of the potential hazards since forecasters were confident in their initial analysis of the environment. The parameter space was highly conducive for severe weather and a severe line of storms already underway. Even though the overall impact of the CopterSonde was less noticeable during the severe weather case, the higher-resolution data did allow for subtle features to be identified by forecasters in the experimental group. An outflow boundary, not observed via radar, passed over the location where the CopterSonde was sampling. This feature temporarily weakened the instability, which forecasters with the CopterSonde data were able to observe. Even with the identification of the outflow boundary, forecasters did not communicate about any decreased threats as the thermal and moisture profiles reintensified 30 minutes later.

The findings from the two case studies confirmed anticipated benefits from the first part of this study. The main findings from the background survey were that CopterSonde data would impact forecasters' situational awareness, communication, and confidence. With the addition of the CopterSonde data, forecasters were more confident in their decision-making in both cases. Instead of basing their forecasts only on model data or previous forecasts, forecasters were able to use real-time observations as the foundation. Not only did this increase their situational awareness and confidence, but they communicated earlier and added more specificity to their messages. The communications focused not only on the areas currently being impacted, but also on the areas that would be impacted in the future. This communication style differed from the control group, where the focus was only on the areas currently receiving precipitation.

Findings from the background survey and focus group informed ideas on the best way to implement CopterSondes into operations. One priority was to initially deploy a CopterSonde at a single location within CWAs. This would allow forecasters to use the data and build trust and confidence in their analysis. Evaluating and building workflows with a single site would also lead to a smoother transition to a full three-dimensional mesonet. A second priority discussed was that the most beneficial way to display the data would be to overlay it on radiosonde or model skew-Ts. During the forecast experiment, the CopterSonde data were displayed on modified skew-Ts and time-height plots. The ability to overlay the CopterSonde data on skew-Ts was found to be very beneficial. One forecaster commented that they currently do this in their operations with surface observations and having CopterSonde profiles to make this comparison proved more beneficial. Before implementing UAS data in operations, the data display must be proven beneficial. This study serves as a first step in testing three displays and finding value in two.

A third priority of forecasters was receiving the data in a timely manner. The CopterSonde currently can provide real-time data displays of flights. The raw data is displayed rather than formatted figures, like the ones provided in this study. One observation platform that currently can provide observations and formatted figures in near real time is the Collaborative Lower Atmospheric Mobile Profiling System (CLAMPS; Wagner et al. 2019). This mobile observing platform is built within a trailer where data can be processed and formatted in near real time using computers. The data is then uploaded to a web viewer. The CopterSonde platform, when deployed autonomously, can adopt a similar approach. For autonomous flight, a recharging and storage unit will be required. Computers can be housed inside or connected to this unit, and they can perform data processing, formatting, and display in near real time.

A goal of UAS, and specifically CopterSonde, research is to have autonomous sampling capabilities. A key component is the ability to conduct flights beyond visual line of sight of the pilot or visual observer, which currently require special waivers. The relationship with the Federal Aviation Administration is important for continued and expanded support in research and operational activities that require autonomous flights. Towards that end, conducting field campaigns during varying types of weather can build confidence in the UAS platform's durability. A recommendation for future UAS studies is for organizations using the same UAS platform to have similar flight requirements (e.g., maximum flight altitude). Uniform and repeated data collection will continue to prove the safety, reliability, and accuracy of the UAS platform. This process will aid in providing the Federal Aviation Administration confidence in the fidelity of the UAS platform to grant beyond visual line of sight waivers.

Future UAS studies can address some of the limitations of this study. One finding was that forecasters do not conduct mesoanalysis, make forecast decisions, and communicate alone. These jobs are usually split between separate forecasters. By asking forecasters to complete all these tasks during the case studies their communication and decision-making processes may have impacted. Different tasks can be developed in future experiments to determine the impact of the CopterSonde data on each individual element of operational forecasting. Another limitation of this study is the sample size. 16 forecasters are not a representative population of the NWS. Similar to how Houston et al. (2021) followed up their focus groups with a nationwide survey, the findings in this study can be followed up by similar studies to determine the impacts of CopterSonde data on a greater population. Additionally, the forecast experiment was conducted in a case study environment. This environment is not representative of NWS operations, but does allows for evaluating new technologies like UAS.

All the findings from this study will be shared with the CopterSonde development team and can serve as a foundation for future studies. With more field campaigns ongoing and planned, the number of datasets collected will increase. In future studies, conditional severe weather cases should be evaluated to determine if the impacts seen in the winter weather case during this study are also observed during conditional severe weather cases. These new datasets can also be assimilated into ensemble forecasting systems, like the Warn-on-Forecast System. The Warn-on-Forecast System is an example of an innovative technology that has been found to improve forecasters' processes and performance (Stensrud et al. 2013; Wilson et al. 2019; Yussouf et al. 2020). Observing system simulation experiments can be designed to evaluate the benefit to both the Warn-on-Forecast System and forecasters using the ensemble guidance. Flagg et al. (2018); Cione et al. (2020); Leuenberger et al. (2020); Jensen et al. (2021); and Tripp et al. (2022) have found reduction in errors of the low level thermodynamic environment with the inclusion of UAS observations.

This study reveals that the CopterSonde data has the potential to fill a critical data gap in forecasting. The CopterSonde was able to sample in the near-storm environment of a winter and severe weather case. High-resolution kinematic and thermodynamic vertical profiles of the boundary layer were collected. These observations were also collected in the presence of cloud cover. The Coptersonde was able to document the height of the melting level and the thermodynamics relevant for convection within the lower troposphere. The type of observations collected by the CopterSonde are becoming increasingly important. There is a growing need for high resolution, accurate, short-term forecasts of high impact weather events (Brunet et al. 2023). Due to the limitations of the current observation systems (e.g., radar and satellites), forecasters and NWP models are left without a complete set of observations to base their forecasts and guidance on.

Radar network provides important information on the character of hydrometeors and a component of the winds within the boundary layers, convective storms, and other precipitation systems. However, radar does not provide any information about the thermodynamic structure of the atmosphere. Radars are also only measuring a component of the wind, while the CopterSonde captures actual horizontal winds. Satellites systems also generally lack high-resolution estimates of thermodynamic profiles. This issue is especially true for infrared observations from satellites which can not provide measurements within and below clouds.

The primary finding of this study confirmed the CopterSonde data significantly impacts forecasters' environmental analysis during their forecasting process. During conditional events, this influence was further evident. Forecasters were enthusiastic about using CopterSonde data and wanted access to it now in their current WFOs. Currently, they rely on coarser resolution data from satellites and radiosondes. Further refinement of the CopterSonde platform can be done to increase the maximum wind speed the UAS can endure and the maximum flight altitude. These improvements will allow for the most use in operations by forecasters. Finally, forecasters found that with the addition of the CopterSonde data, they could make more accurate and confident decisions and issue more detailed and timely communications to their core partners and the public in the case study environment.

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1 Background Survey Questions

Demographics/Background:

1. Name
2. What is your highest level of education?
    - High School Diploma
    - Some College
    - Bachelor's Degree
    - Master's Degree
    - Ph.D.
3. Which WFO do you work for?
    - WFO1
    - WFO2
    - WFO3
    - WFO4
4. What is your forecast role in your current WFO?
5. How long have you been in your current forecast role?
    - <1 Year
    - 1–3 Years
    - 3–10 Years
    - 10+ Years
6. Please list the duties of your current forecast role.
7. Please describe your past NWS professional experience, including past duties at your current and other WFOs.
8. What, if any, professional meteorological experience have you had outside of the NWS?
9. What is your area of expertise in meteorology?

Boundary Layer

1. In a few sentences, please describe what boundary layer data you have access to.
2. How are these data used in your forecast process?

3. How does the use and value of the data you identified differ for calm weather and impactful weather?
4. Please list which atmospheric variables would be the most beneficial to be measured from the boundary layer.
5. What, if any, opportunities have you had to focus on boundary layer meteorology (including education and professional experiences)?

CopterSondes:

High-resolution data is being collected as part of this research project using CopterSondes, which are in-house constructed uncrewed drones that are retrofitted to collect thermodynamic and kinematic profiles in the lowest one to two kilometers of the boundary layer on the order of one second and five meter resolution. Some of the atmospheric variables collected are temperature, relative humidity, pressure, wind velocity, and wind direction.

1. Please describe in a few sentences if and how you think these data would be beneficial to your forecast process.
2. How comfortable do you think you would be using these real-time high-resolution observations?
    - Very Uncomfortable
    - Somewhat Uncomfortable
    - Neutral
    - Somewhat Comfortable
    - Very Comfortable
3. Which vertical increment of data would be most suitable for the below situations?
    (a) Calm Weather Days
    (b) Impractical Weather Days
        - 5 Meters
        - 10 Meters
        - 25 Meters
        - 50 Meters
        - 100 Meters
        - 500 Meters
        - 1000 Meters
4. Which temporal resolution of data would be most suitable for the below situations?

   (a) Calm Weather Days
   (b) Impactful Weather Days
       - 1 Second
       - 10 Seconds
       - 30 Seconds
       - 1 Minute
       - 5 Minutes
       - 15 Minutes
       - 30 Minutes

5. Using the slider bar below, select how useful you expect these real-time high-resolution boundary layer data to be to your forecast process for each scenario.
   (a) Severe Weather Events
   (b) Winter Weather Events
   (c) Fire Weather Events
   (d) Aviation Weather Events
   (e) Flooding Events
   (f) Air Quality Events
   (g) High Wind Events
   (h) Temperature Related events (e.g., frost, freezing temperature, excessive heat)
   (i) Visibility Events
       - Not Applicable
       - Not Very Useful
       - Infrequently Useful
       - Useful Sometimes
       - Useful Most of the Time
       - Useful Every Time

6. In a few sentences (<4), please describe the potential benefit these data could have on your forecasting ability for the scenarios you listed above.

7. If temperature, relative humidity, pressure, wind velocity, and wind direction measurements from the CopterSondes were made available, what ideas do you have for displaying these data?

Office:

1. During a typical shift, which forecast role(s) are responsible for analyzing and incorporating boundary layer data into the forecast process?

2. For the role(s) identified above, what are their responsibilities and processes for analyzing the boundary layer?
3. How do these processes differ for calm vs impactful weather conditions?

Miscellaneous:

1. Would you be interested in participating in further research activities related to this study topic (e.g., surveys, focus groups, individual interviews, forecasting exercises)?
   - Yes
   - No
2. Please provide your email so that we can invite you to participate in future research activities.

2 Case Study Survey Questions

1. Which group are you in?
   - A
   - B
2. Name
3. The time is `####` UTC. Please review all the data within the `####` UTC slide deck and identify the primary precipitation type (likely hazard(s)) at each location. The below links will open the slide deck containing all available data and an ArcGIS dashboard with mPING reports leading up to this time.
4. At each of the below sites, what do you believe is the primary form of precipitation at this time (`####` UTC)? (Winter weather case)
   - No Precipitation
   - Snow
   - Sleet
   - Wintry Mix
   - Freezing Rain/Freezing Drizzle
   - Rain/Drizzle
5. At each of the below sites, what do you believe is the most likely hazard(s) in the next hour (`####`–`####` UTC)? Select all that apply. (Severe weather case)
   - No Severe Hazards
   - Flooding/Flash Flooding

- Severe Wind
- Severe Hail
- Tornado

6. Did the addition of the CopterSonde data influence your decision, leading to a change in precipitation type or an increase in confidence in your original decision (Experimental group only)?
    - Yes
    - No
7. Please detail what led to any change or reinforcement in your decision (Experimental group only).
8. Please describe the (1) information used and (2) how it was used to assess the changes in the environment and associated precipitation types (hazards).
9. With the information available about the past and current weather, what areas are of the most concern for impacts within the next hour and why?
10. Would you communicate these concerns or call to action through social media, NWSChat, or another platform?
    - A
    - B
11. Proceed to your communication slides document and update as you see fit.
12. Overall, how did the CopterSonde data influence your ability to identify and communicate precipitation types and hazards (Experimental group only)?
13. How comfortable were you in using the CopterSonde observations (Experimental group only)?
    - Very Uncomfortable
    - Somewhat Uncomfortable
    - Neutral
    - Somewhat Comfortable
    - Very Comfortable
14. Thank you for completing this case. Please summarize any important nuances, challenges, or final thoughts about the case.

3 Data Examples

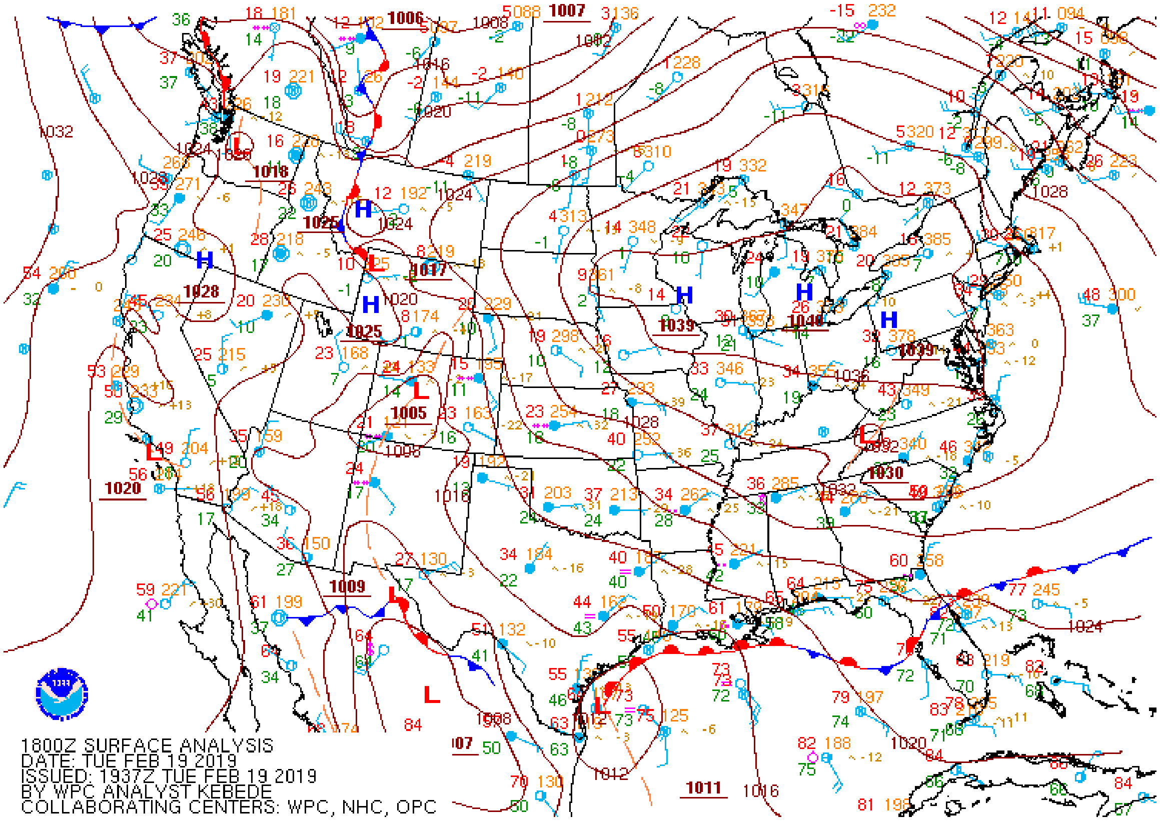


Figure A.1: Weather Prediction Center surface analysis from 1800 UTC 19 February 2019.

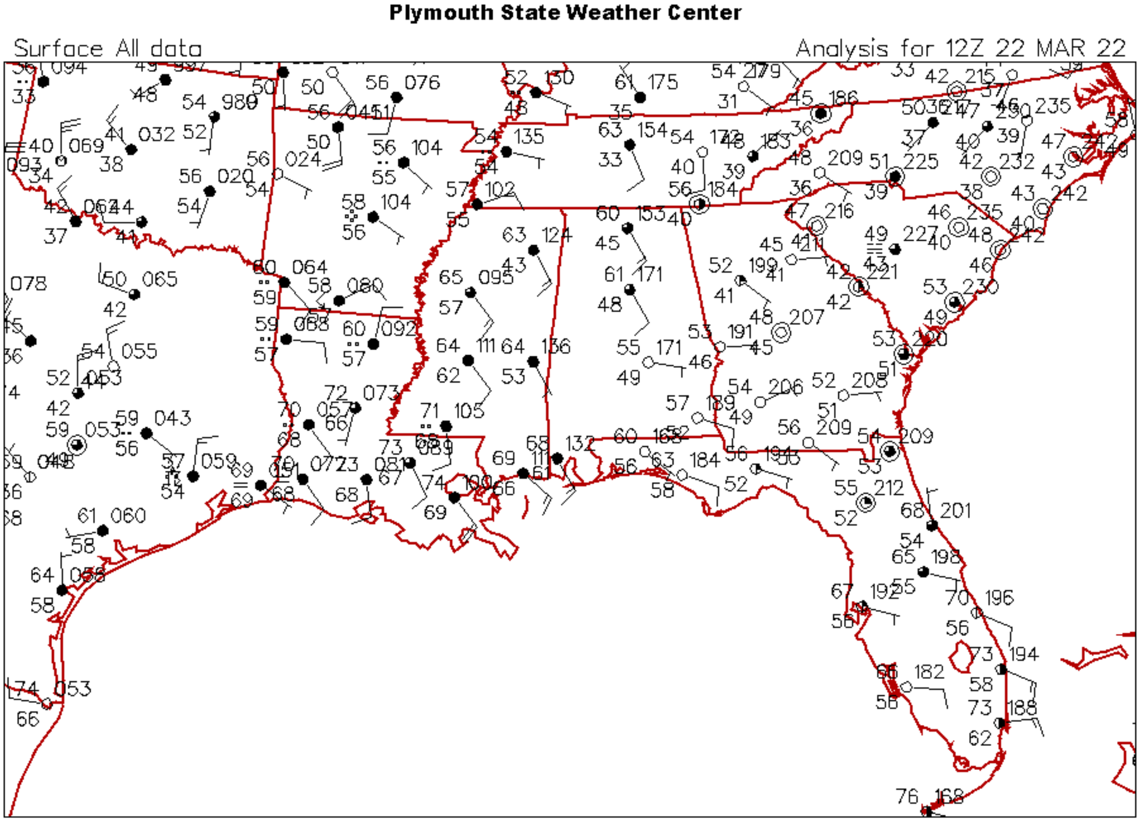


Figure A.2: Station plots from 1200 UTC 22 March 2022.

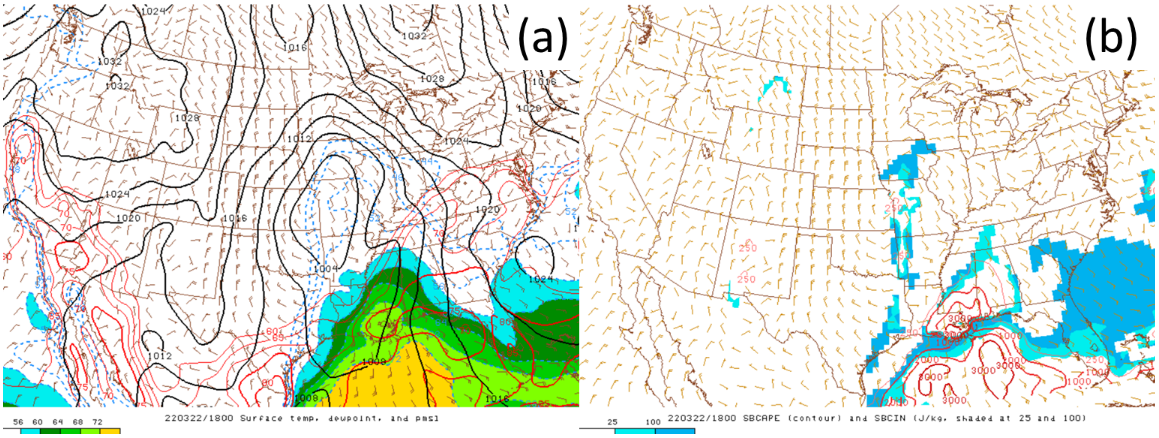


Figure A.3: SPC mesoanalysis from 1800 UTC 22 March 2022 analyzing (a) surface temperature and dewpoint temperature and (b) surface-based CAPE and convective inhibition.

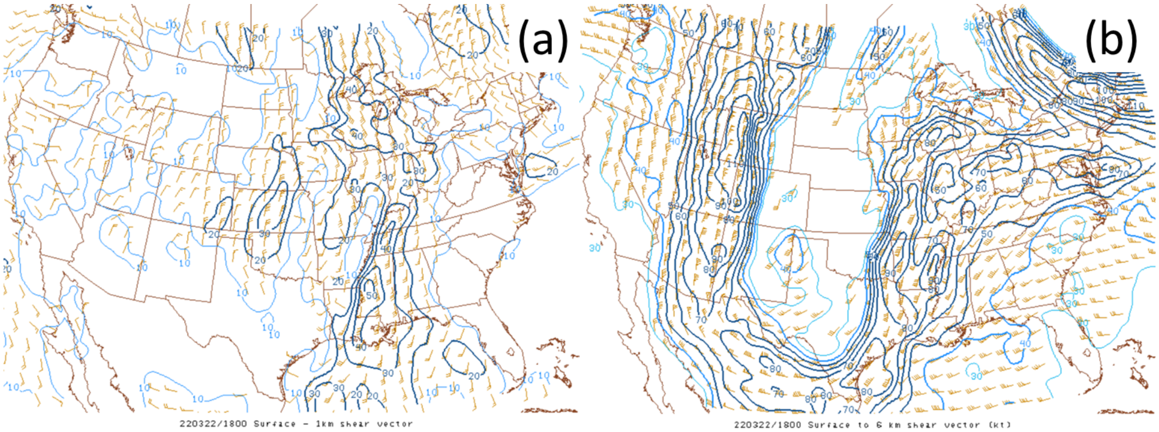


Figure A.4: SPC mesoanalysis from 1800 UTC 22 March 2022 analyzing (a) 0–1-km shear and (b) 0–6-km shear.

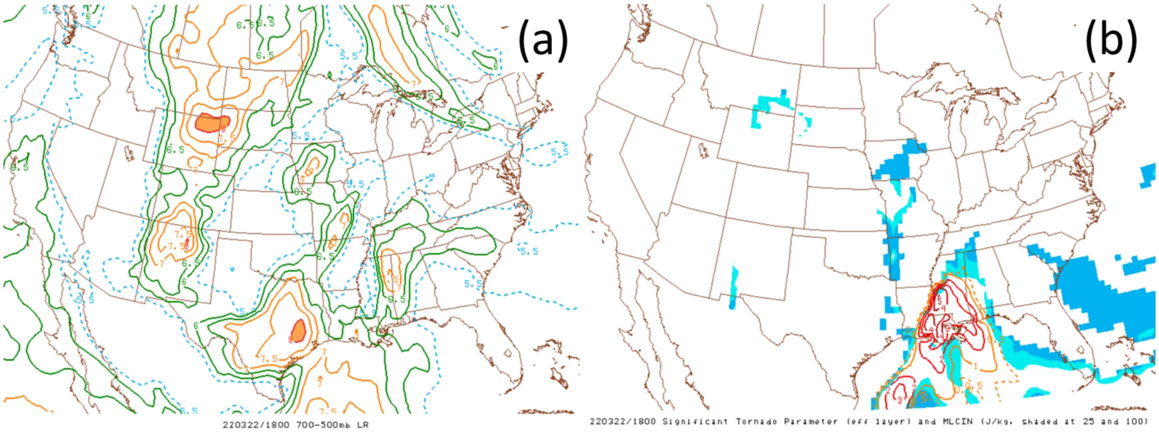


Figure A.5: SPC mesoanalysis from 1800 UTC 22 March 2022 analyzing (a) 700–500 lapse rates and (b) significant tornado parameter.

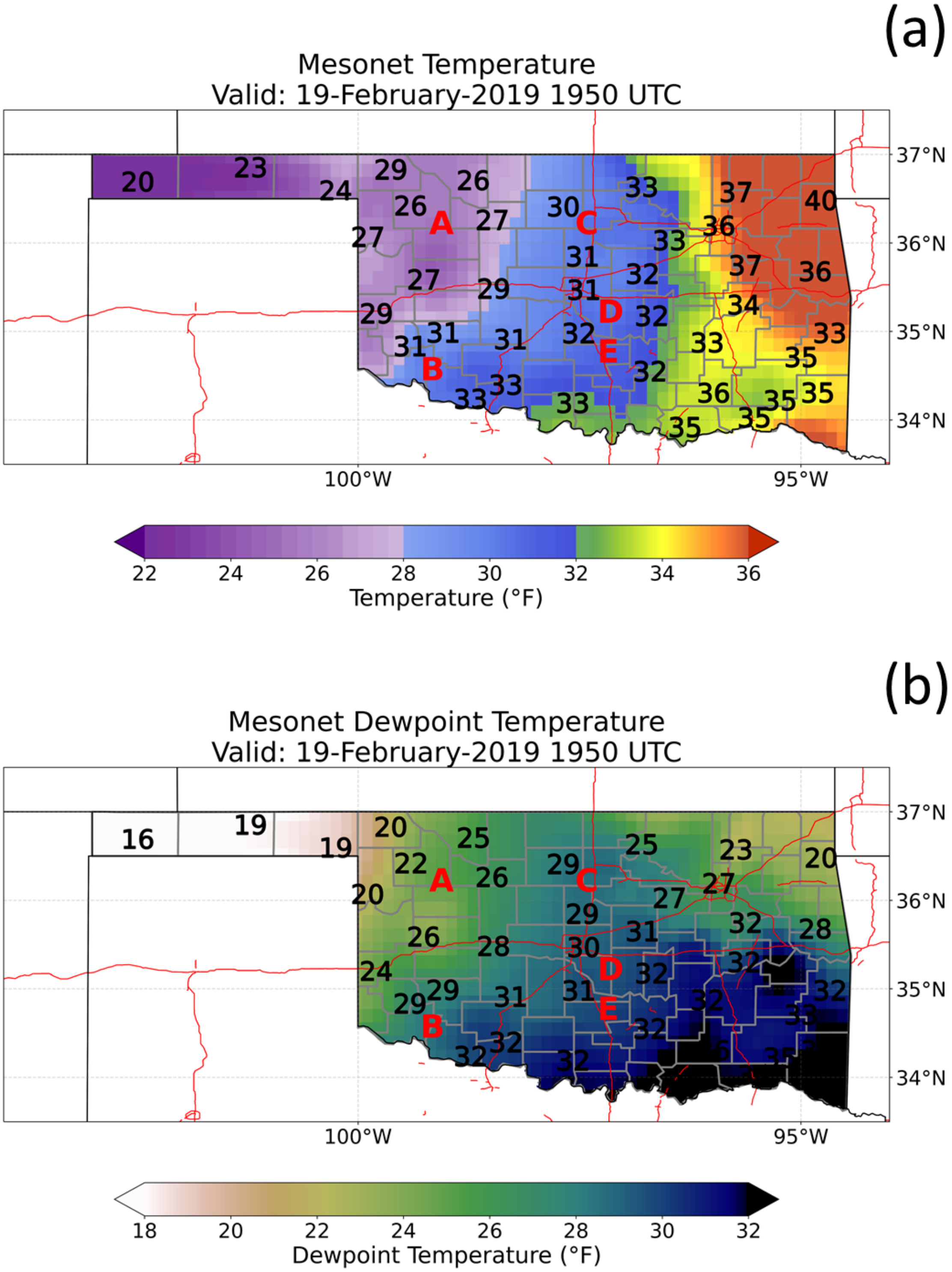


Figure A.6: Oklahoma Mesonet recorded (a) temperature and (b) dewpoint temperature from 1950 UTC 19 February 2019.

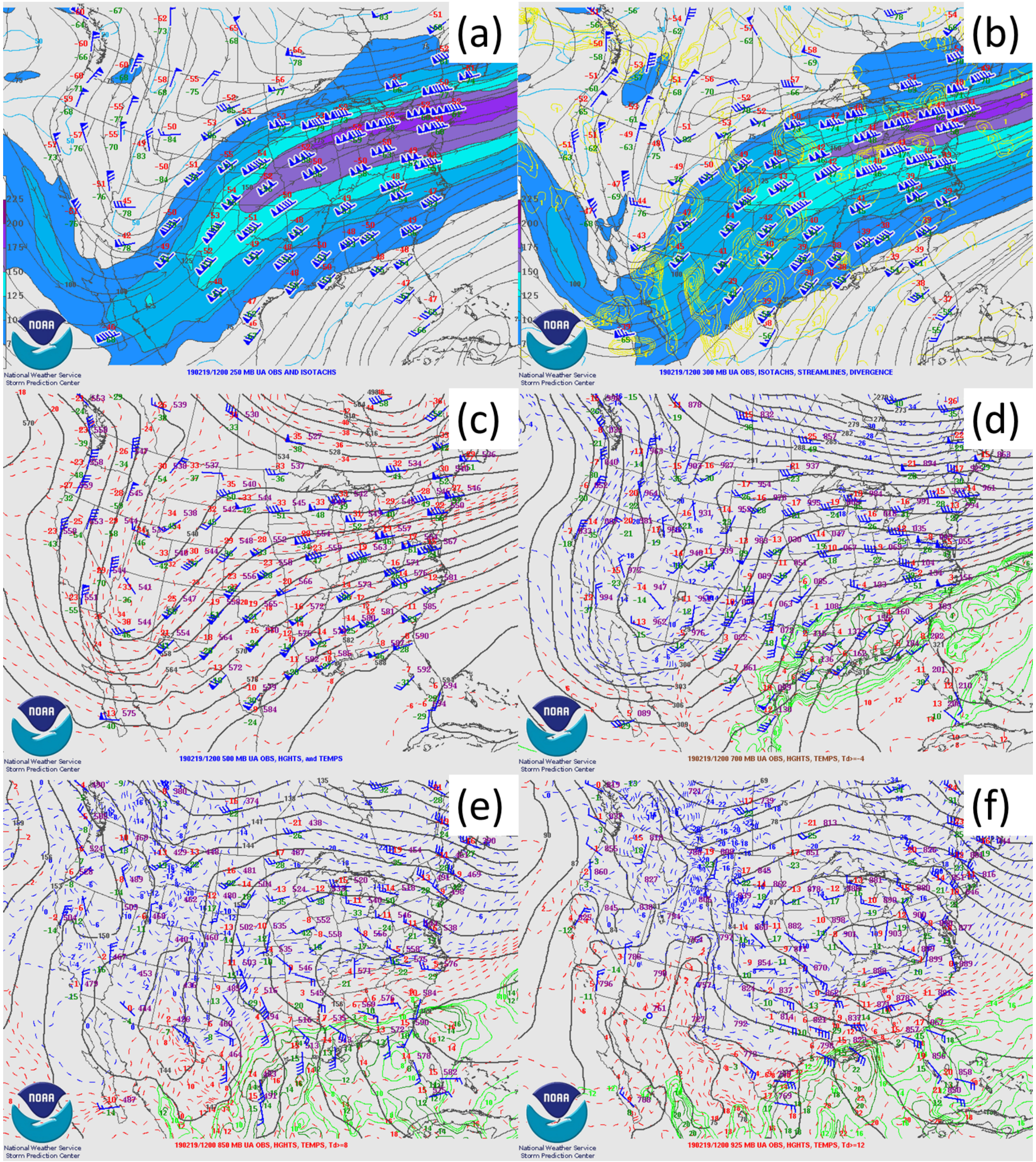


Figure A.7: SPC upper air analysis from 1200 UTC 19 February 2019 at (a) 250 mb, (b) 300 mb, (c) 500 mb, (d) 700 mb, (e) 850 mb, and (f) 925 mb.

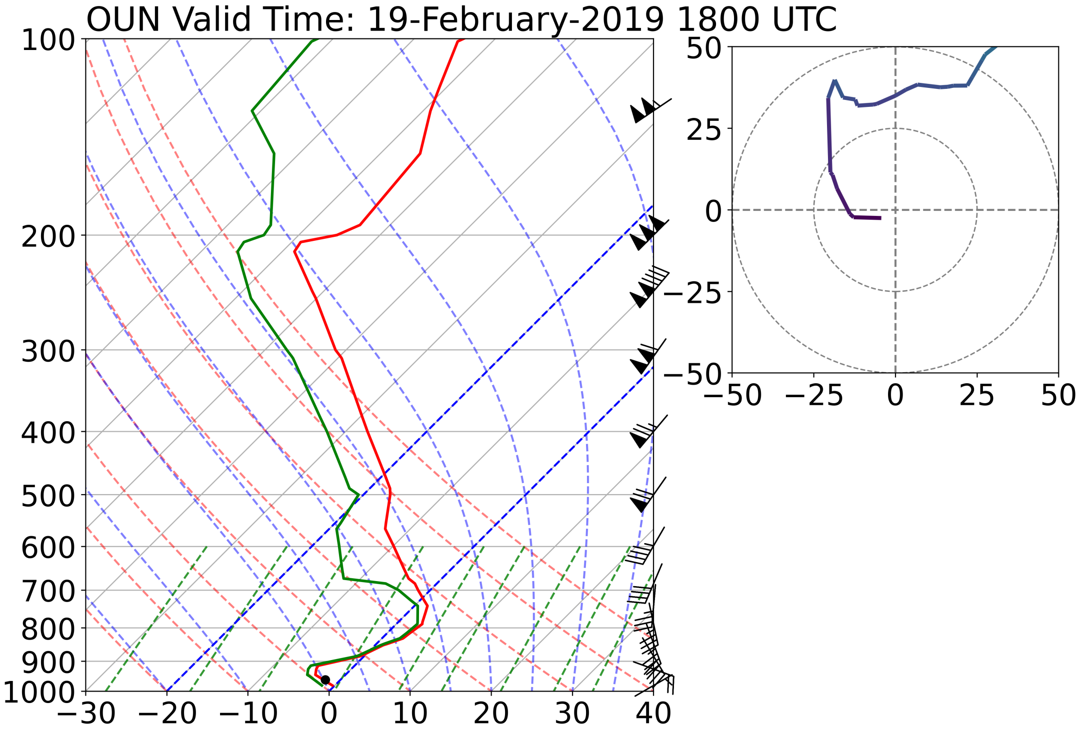


Figure A.8: 1800 UTC OUN sounding with associated hodograph.

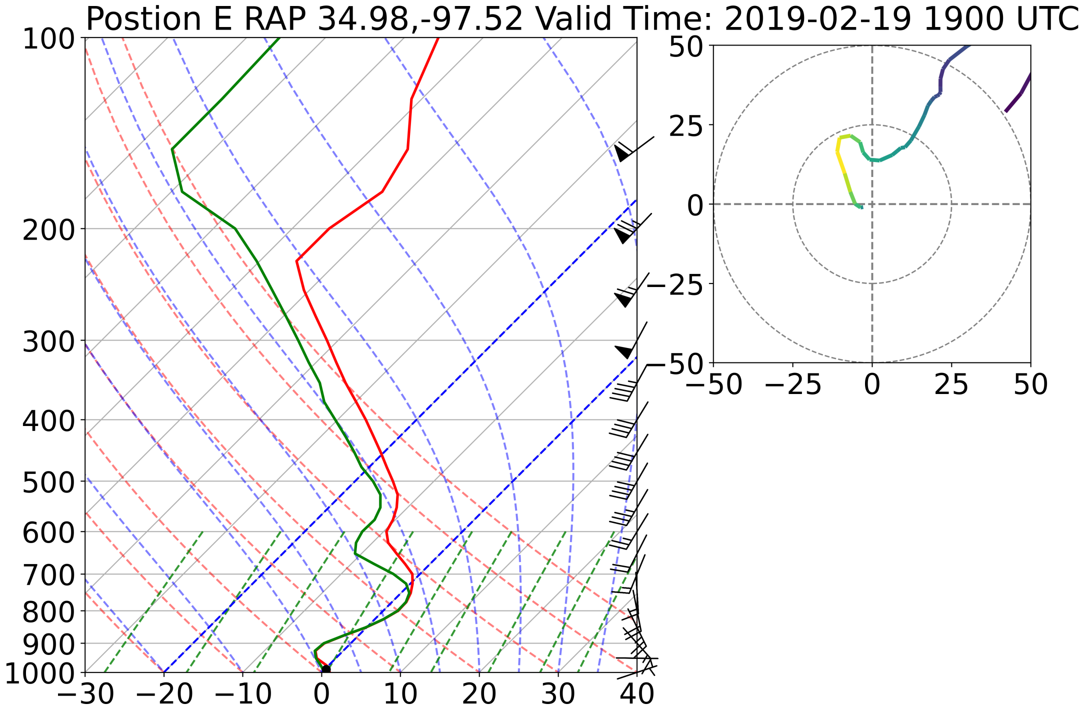


Figure A.9: 1900 UTC RAP sounding for location E with associated hodograph.

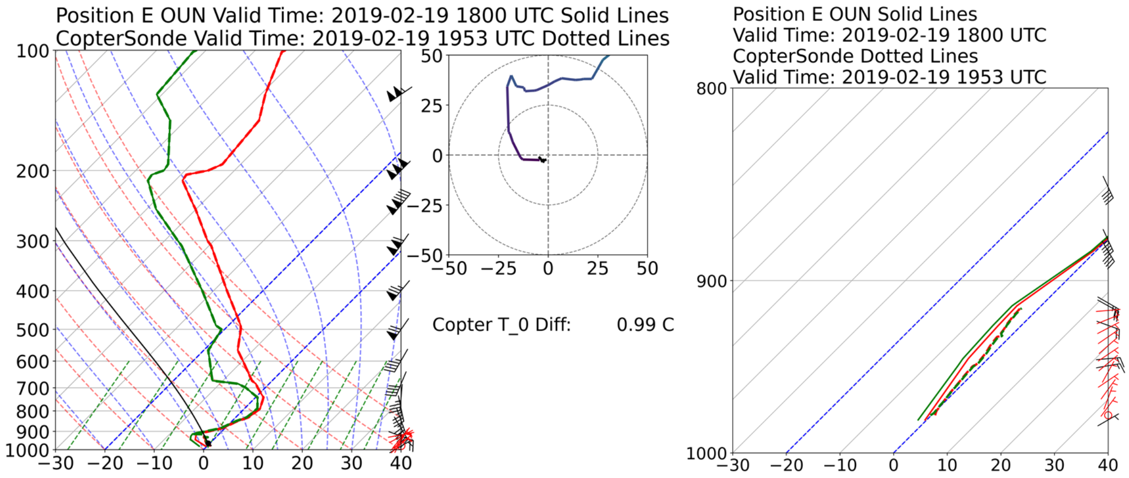


Figure A.10: 1800 UTC OUN sounding in solid lines with CopterSonde measurements of temperature and dewpoint temperature in dashed lines. Black wind barbs are from the OUN sounding, and red barbs are from the CopterSonde. The OUN hodograph is colored, and the CopterSonde hodograph is black.

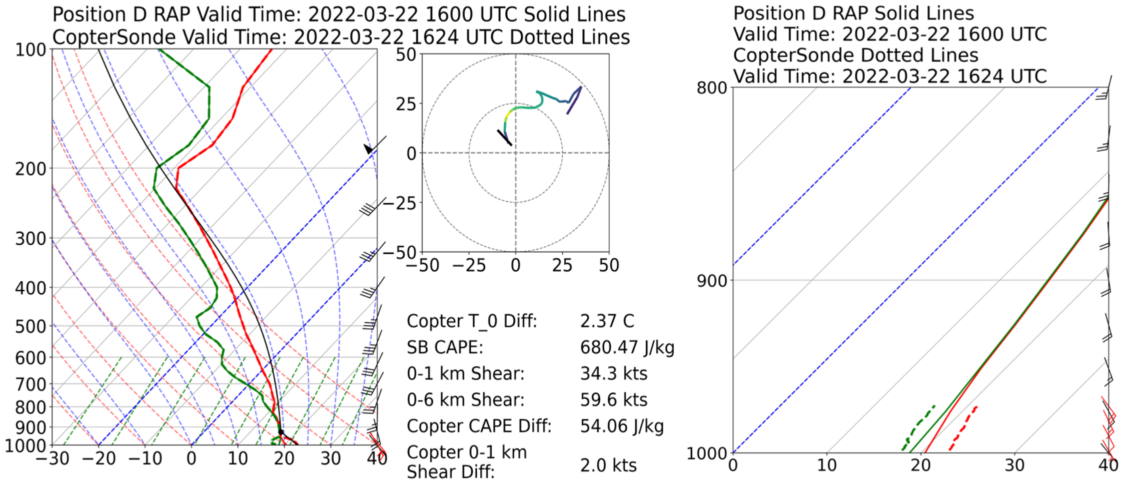


Figure A.11: 1600 UTC RAP sounding for Location D in solid lines with CopterSonde measurements of temperature and dewpoint temperature in dashed lines. Black wind barbs are from the RAP sounding, and red barbs are from the CopterSonde. The RAP hodograph is colored, and the CopterSonde hodograph is black. Calculated values show the difference in surface temperature between the CopterSonde and RAP, the surface based CAPE and shear values calculated with the addition of the CopterSonde data to the RAP sounding, the difference between the new CAPE value and the original RAP CAPE value, and the difference between the new 0–1-km shear value and the original RAP 0–1-km shear value.

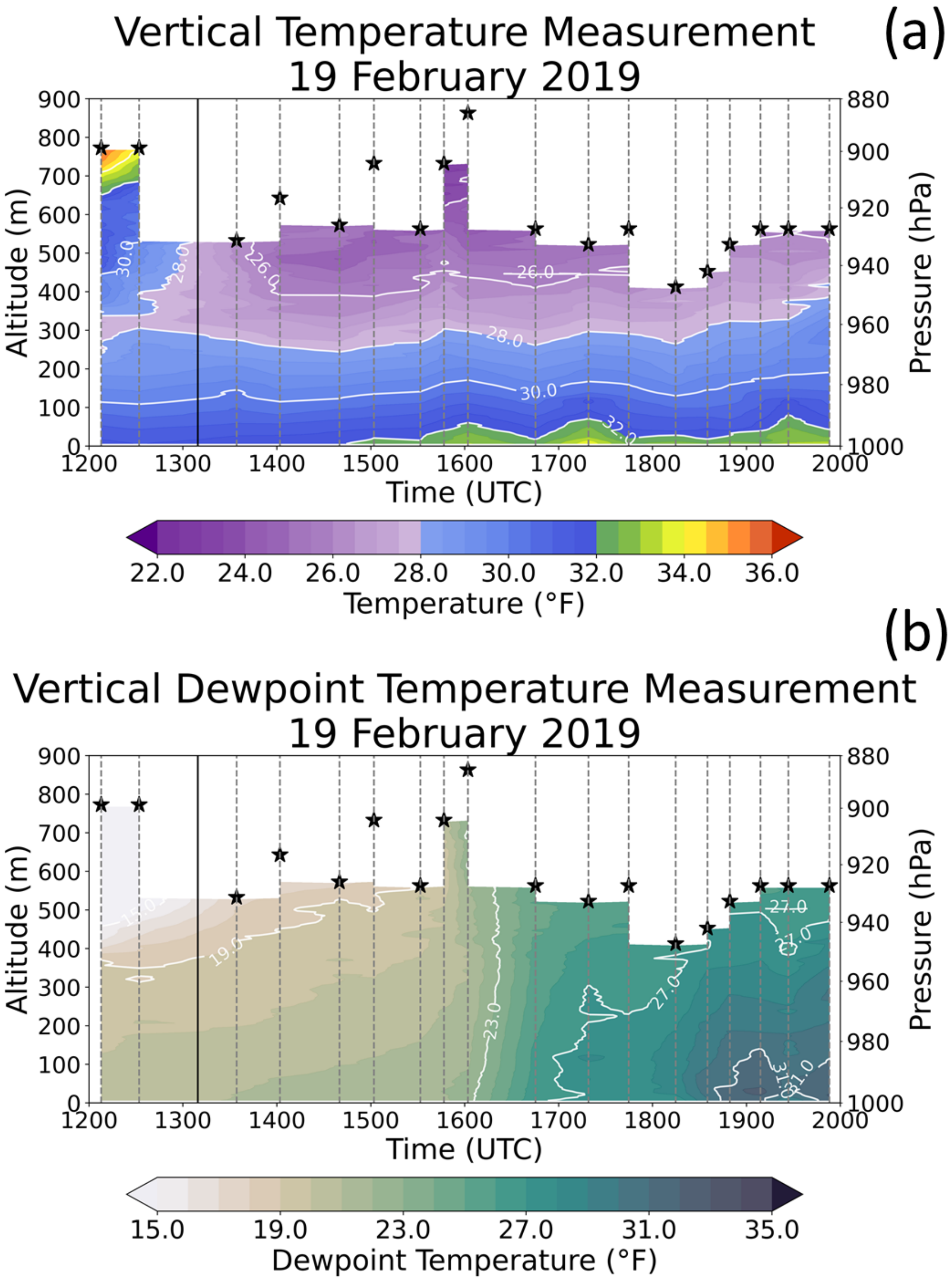


Figure A.12: Time-height plot of (a) temperature and (b) dewpoint temperature measured by the CopterSonde at Location E during the winter weather case. The solid black line denotes sunrise. The dashed gray lines denote the times of each CopterSonde profile. The black stars mark the maximum height reached for each flight.

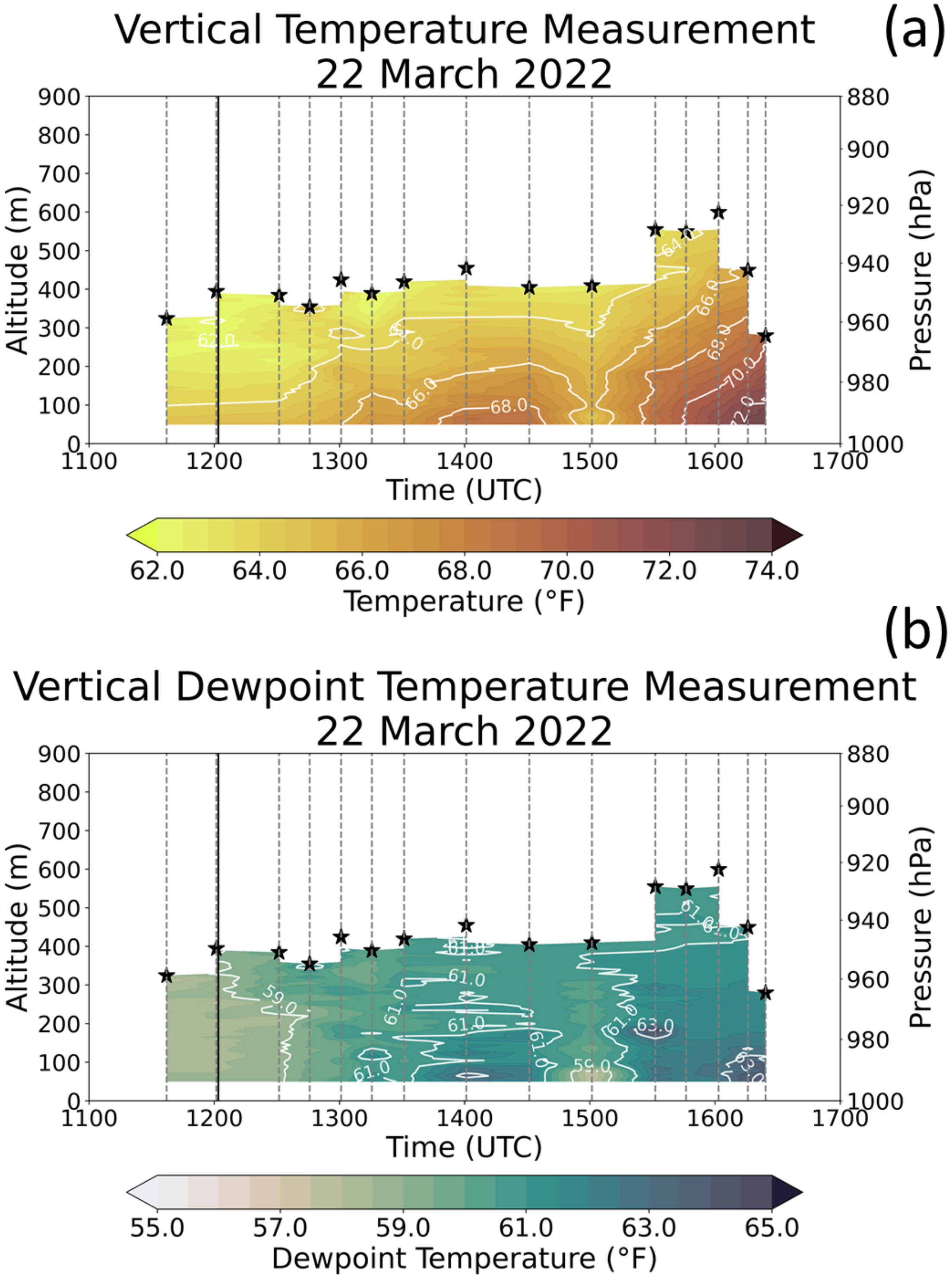
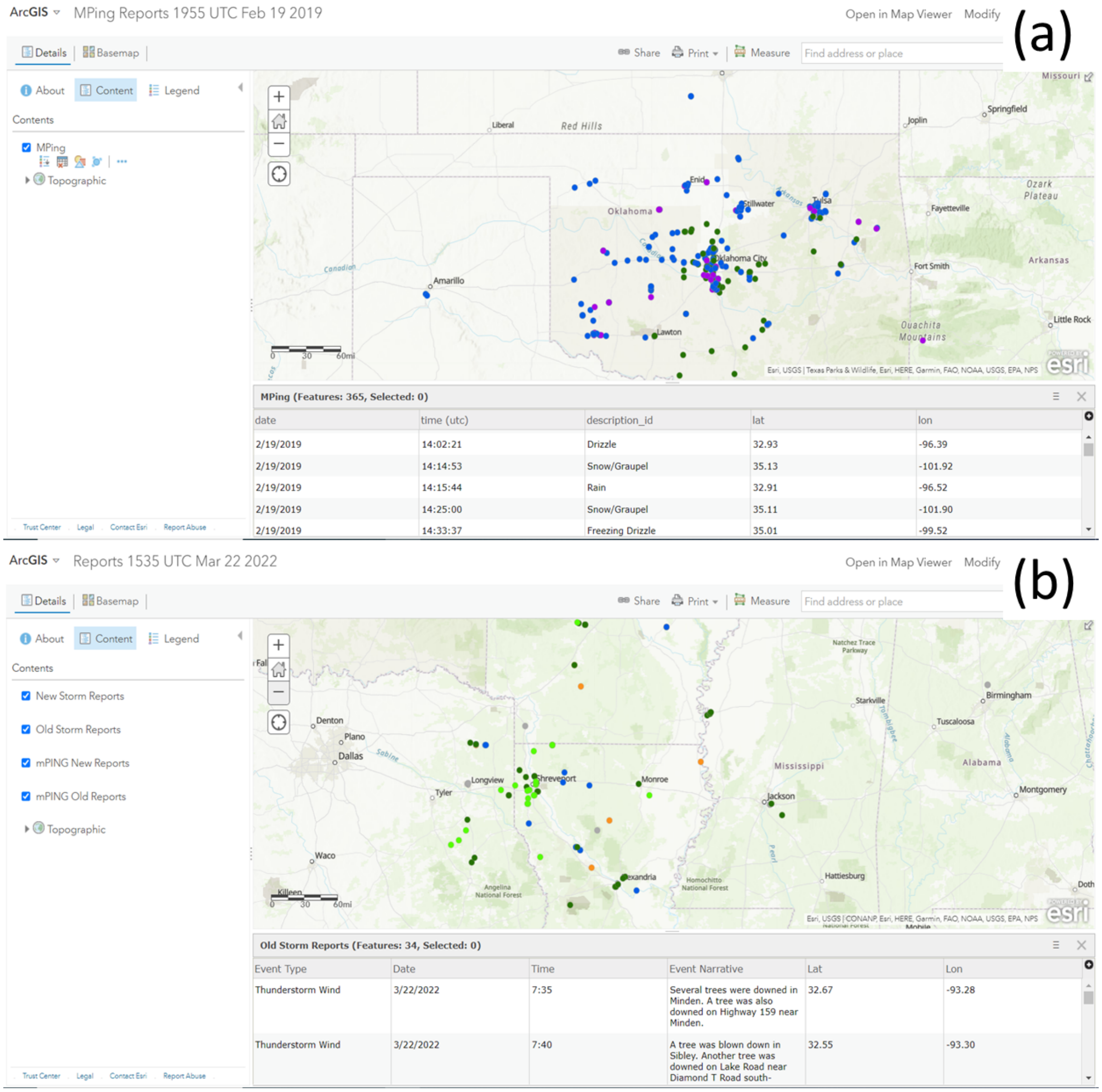


Figure A.13: Time-height plot of (a) temperature and (b) dewpoint temperature measured by the CopterSonde at Location D during the severe weather case. The solid black line denotes sunrise. The dashed gray lines denote the times of each CopterSonde profile. The black stars mark the maximum height reached for each flight.



MPing (Features: 365, Selected: 0)

date	time (utc)	description_id	lat	lon
2/19/2019	14:02:21	Drizzle	32.93	-96.39
2/19/2019	14:14:53	Snow/Graupel	35.13	-101.92
2/19/2019	14:15:44	Rain	32.91	-96.52
2/19/2019	14:25:00	Snow/Graupel	35.11	-101.90
2/19/2019	14:33:37	Freezing Drizzle	35.01	-99.52

Old Storm Reports (Features: 34, Selected: 0)

Event Type	Date	Time	Event Narrative	Lat	Lon
Thunderstorm Wind	3/22/2022	7:35	Several trees were downed in Minden. A tree was also downed on Highway 159 near Minden.	32.67	-93.28
Thunderstorm Wind	3/22/2022	7:40	A tree was blown down in Sibley. Another tree was downed on Lake Road near Diamond T Road south-	32.55	-93.30

Figure A.14: mPING and local storm reports valid through valid through (a) 1955 UTC on 19 February 2019 and (b) 1535 UTC on 22 March 2022 plotted using ArcGIS software by Esri.

4 Focus Group Questions

1. Overall, how did the experiment go?
2. Was it relatively easy or difficult to identify and communicate the hazards associated with the events?
3. What was the most difficult aspect of this case (asked for both cases)?
4. During the winter weather case, what time periods did you have trouble identifying the precipitation type, and what led to this?
5. During the severe weather case, what time periods did you have trouble identifying the severe hazards, and what led to this?
6. This is an image of your forecasting choices with the verification on the bottom. What are your thoughts about the impact of the CopterSonde data looking at this figure (asked for both cases)?
7. What was the first communication you issued, and what led to this (asked for both cases)?
8. How did the low-level data available affect your hazard expectations for this case (asked for both cases)?
9. For the case that you had the CopterSonde data, did you trust the data and rely on it heavily, or were other data sources used more to guide your forecast?
10. Here is an example of a different way to display CopterSonde data. The data is plotted on a linear height and temperature scale. Would you prefer it in a linear format or a skew-T?
11. What ideas do you have to increase the value of the CopterSonde data if they were displayed across regions similar to the Oklahoma and West Texas Mesonets?