

UNIVERSITY OF OKLAHOMA  
GRADUATE COLLEGE

IMPACT OF ASSIMILATING LOWER ATMOSPHERIC BOUNDARY LAYER  
OBSERVATIONS FROM UNCREWED AERIAL SYSTEMS ON SHORT-TERM  
PROBABILISTIC PREDICTIONS OF A TORNADIC SUPERCELL EVENT

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PROBABILISTIC PREDICTIONS OF A TORNADIC SUPERCELL EVENT

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BY THE COMMITTEE CONSISTING OF

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weather forecasts. So long as others are impacted by adverse weather, I will strive to do my part as meteorologist, continuously learning about the bizarre but beautiful world of atmospheric sciences around us.

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# Abstract

One limitation of convective-scale NWP ensemble modeling systems is the inadequate representation of the pre-convective and near-convective environment in the model, particularly in the lower level (0–2 km) of the atmospheric boundary layer (BL). This limitation is largely due to the unavailability of thermodynamic and kinematic BL observations with high spatial and temporal resolutions. This study aims to assess the impact of assimilating the emerging Uncrewed Aerial System (UAS) lower atmospheric BL measurements in convective-scale ensemble modeling systems. The case used to conduct the study is the violent EF4 24–25 March 2023 Rolling Fork tornado event. The event was sampled using various instrumentation during the PERiLS 2023 field campaign, including three CopterSonde UAS instruments located at three separate, stationary profiling sites near the Arkansas/Louisiana/Mississippi border. The CopterSondes collected lower atmospheric BL observations every 15–30 minutes, with cadence depending on storm motion and other environmental factors. Several retrospective experiments are conducted using the National Severe Storm Laboratory’s Warn-on-Forecast (WoFS) data assimilation and modeling system to assimilate temperature, dewpoint temperature,  $u$ -, and  $v$ -wind components from the CopterSonde in addition to all other routinely available observations in the baseline WoFS.

Results indicate that assimilating the CopterSonde observations more accurately predict the evolution of the Rolling Fork tornadic supercell and its shape, intensity, location, and associated low-level updraft helicity (UH). Assimilating those observations more realistically represented the extent of low-level moisture advection and the strength of horizontal winds as they evolve throughout the observation period, thus limiting northward and westward displacement and better locating the most intense parts of the supercell. Even with the limited dataset, the CopterSonde UAS observations show promise in analyzing the storm environment and predicting the probability of severe thunderstorms with higher accuracy in the model. However, while the results from this single case study with only three profiling sites give us glimmers of hope, the results cannot be generalized. More studies need to be performed to assess the

robustness of these results by assimilating a network of UAS BL measurements over a diverse set of cases in a convective-scale ensemble DA and prediction system.

# Chapter 1

## Introduction and Motivation

The skill of Numerical Weather Prediction (NWP) convection allowing ( $\sim 3$  km) ensembles (CAEs) for hazardous weather forecasting increased rapidly during the past three decades (Xue et al. 1996, 2007, 2008; Kain et al. 2006; Kong et al. 2007; Smith et al. 2008; Weisman et al. 2008, and references therein) and are now operational at many national centers (e.g., Gebhardt et al. 2011; Peralta et al. 2012; Hagelin et al. 2017; Raynaud and Bouttier 2017; Klasa et al. 2018; Jirak et al. 2018). The CAEs are typically initialized by downscaling from coarser-resolution ensembles and are better at predicting next-day regional thunderstorm threats than the coarser-resolution, convection-parameterizing ensembles (e.g., Clark et al. 2009; Duc et al. 2013; Iyer et al. 2016; Schellander-Gorgas et al. 2017). However, for short-term predictions of hazards from individual thunderstorms, it is crucial to generate accurate model initial conditions. One state-of-the-science ensemble-based data assimilation (DA) technique to generate skillful CAE initial conditions (e.g., Jones and Stensrud 2012; Melhauser and Zhang 2012; Schumacher and Clark 2014; Schwartz et al. 2015, 2019; Johnson et al. 2020) is the ensemble Kalman filter (EnKF; Evensen 1994; Houtekamer and Zhang 2016) that utilizes flow-dependent analysis ensembles.

The exponential growth in computing power over the past two decades enabled frequent (i.e., sub-hourly) assimilation of in-situ and remote sensing atmospheric measurements using the EnKF DA technique to improve the accuracy of CAEs' initial

conditions. One such instrument, which is the key observing platform for thunderstorm measurements, is the Weather Surveillance Radar-1988 Doppler (WSR-88D). The assimilation of high spatial and temporal resolution WSR-88D observations for initializing NWP models was envisioned in the early 1990s (Lilly 1990) and is now a reality. Accurate analyses of thunderstorms in the CAEs can be obtained with the frequent assimilation of WSR-88D radar observations (e.g., Xue et al. 2002, 2003; Hu et al. 2006; Hu and Xue 2007). However, one outstanding challenge is to get accurate pre-storm and near storm environments in CAE initial conditions, particularly in the planetary boundary layer (BL). The lowest few ( $\sim 0\text{--}3$ ) km of the BL are where some of the most important atmospheric features that influence severe and high-impact weather events occur. The rapid changes in the near-storm environment, for example, drylines, cold fronts, or near surface boundaries, are not well represented in CAEs, largely due to the lack of thermodynamic and kinematic BL observations at high spatial and temporal resolutions. The only BL observations that are routinely available are from radiosondes that are launched only twice per day at  $\sim 70$  locations across the United States. Aircraft observations are available, but only at certain airports at certain times, and clouds obscure satellites' view of the lower BL. Therefore, while the frequent assimilation of WSR-88D storm observations analyze the storms in CAEs correctly, the pre-storm and during-storm environments are not analyzed properly due to the lack of BL observations. As a result, the predicted thunderstorms often weaken or intensify unrealistically resulting in poor 0–6-h forecasts. To improve the accuracy of CAE initial conditions and short-term probabilistic predictions of hazards associated with individual thunderstorms (e.g., tornadoes, flash flooding, large hail, severe winds, and lightning), better representation of the near-storm environment in model initial conditions is needed.

The daytime BL represents a turbulent mixed layer that acts as a buffer between the rough surface and the more uniform, strong wind speeds above (Stull 1988; Haby 2024). This turbulence is critical to the transport of heat, momentum, and moisture (Stull 1988; Luo and Zhou 2006; Lappin et al. 2022; Bauer et al. 2023), which makes the BL sensitive to a wide range of mesoscale and convective processes such as wind convergence, convection initiation, updraft rotation, tornadogenesis, and more (Stull 1988; Bell et al. 2020; Lappin et al. 2022; Liu et al. 2023; Markowski 2024). These processes occur at very high temporal and spatial resolution, and properly representing these processes in both NWP model initial condition and physics parameterization schemes is extremely important (Dabberdt et al. 2005; Stalker et al. 2013; Geerts et al. 2018; Bell et al. 2020; Houston et al. 2020; Bauer et al. 2023; Markowski 2024). The CAEs are too coarse to explicitly resolve these BL processes, and therefore, utilizing sophisticated parameterization schemes to approximate the BL sub-grid-scale processes and assimilating those observations to accurately initialize the BL in CAEs is necessary for short-term prediction of convective thunderstorms. Many of these BL phenomena are very difficult to measure because they occur at a higher/finer temporal and spatial scale than what can typically be measured with traditional observing instruments, leading to a gap in the availability, quality, and consistency of BL data (Stull 1988; Stalker et al. 2013; Geerts et al. 2018; Bell et al. 2020; Houston et al. 2021; Pinto et al. 2021). As mentioned earlier, radiosondes are typically launched twice daily at 0000 UTC and 1200 UTC from National Weather Service (NWS) Weather Forecast Offices (WFOs) across the country, and collect measurements of pressure, temperature, and moisture. Since WFOs are often located hundreds of miles apart, the horizontal resolution of these data do not provide an adequate three-dimensional profile of the BL for assimilation into NWP models (Reeves et al. 2014; Bell et al. 2020; Pinto et al. 2021). Radiosondes usually ascend at  $\sim 5 \text{ m s}^{-1}$  with a sampling rate on the order of

seconds, thus providing measurements on the order of tens of meters, which is not a fine-enough vertical resolution for improving CAE forecasts (Ko et al. 2019). Moreover, the radiosondes were primarily developed to sample full profiles of the atmosphere within a timely manner for operational forecasting needs (DuBois et al. 2002), rather than for the purpose of gathering high-resolution vertical measurements of the BL to understand storm processes and improving NWP. To address the observation data gap, in 2009, the National Research Council (NRC) released a report which called for the development of a “nationwide network of networks” (NoN) to improve observation quality control, increase observational data availability, and encourage wider data usage to produce more localized forecasts (National Research Council 2009). Some of the highest priority observations proposed by the NRC to improve our understanding of mesoscale processes and prediction of severe weather include higher-resolution vertical profiles of humidity, temperature, and wind observations. Nearly a decade after the NRC report on the need to establish a vertical mesoscale observing network, the National Academies of Sciences, Engineering, and Medicine produced a report that reemphasized the crucial significance of understanding BL processes to improve NWP models (National Academies of Sciences and Medicine 2018).

One of the recommended emerging instruments to improve the sampling of the BL, bridge the BL data gap, and improve convective NWP forecasts by the NRC and NASEM over the past 15 years (National Research Council 2009; National Academies of Sciences and Medicine 2018) is through the use of Uncrewed Aerial Systems (UASs) that observe the lower atmospheric boundary layer at high temporal frequency. Many of the studies that have identified gaps in the understanding and prediction of the BL have also recommended UASs as a tool to enhance lower level sampling (Geerts et al. 2018; Bell et al. 2020; Houston et al. 2021; Pinto et al. 2021; Lappin et al. 2022; Greene and Salesky 2023). Because of their ability to gather high-resolution temporal

and spatial in-situ vertical profiles of the BL, UASs present a unique opportunity to provide convective NWP models with high-quality observations as well. The lowered cost of operating UASs compared to radiosondes adds another benefit of regularly assimilating these types of observations (Pinto et al. 2021). A UAS network to routinely collect lower atmospheric BL observations will not only benefit NWP models, but also improve our understanding of storm processes. Chilson et al. (2019) proposed a network of three-dimensional Oklahoma Mesonet sites equipped with self-operating UASs to improve observations and understanding of the BL, and can be complimented with other ground-based remote sensing instruments (McFarquhar et al. 2020; Fiebrich et al. 2021). The utilization of UASs as a means of profiling the lower atmosphere might help to overcome some of the limitations, such as flexibility in observing at spatial and temporal resolution, targeted sampling, and in-situ measurements, as well as bridge some of the data gaps of the BL, and consequently improve forecasts of severe weather events.

This study explores the utility of UAS observing technologies for the analysis and prediction of a severe tornadic supercell event. The assimilation of UAS temperature, moisture, and wind observations of the lower atmospheric BL in CAEs is examined through ensemble DA and prediction experiments. This study strives to answer the following questions:

1. How does the assimilation of UAS observations impact the prediction of the storm environments in the CAEs?
2. Does the assimilation of UAS observations help to improve the CAEs' prediction of the evolution of a tornadic supercell event, and if so, how?



3. What are the effects of assimilating the different UAS variable types, namely, the temperature, dewpoint temperature, and winds? How are the predictions impacted?

Several DA and prediction experiments are conducted by assimilating the UAS observations at sub-hourly intervals in The National Oceanic and Atmospheric Administration (NOAA) National Severe Storm Laboratory’s (NSSL) Warn-on-Forecast System (WoFS; Stensrud et al. 2009; Heinselman et al. 2023). The WoFS is a state-of-the-science CAE EnKF DA and prediction system, which is designed to provide continuous, frequent update cycle, 0–6-h probabilistic model guidance of individual thunderstorm hazards with high temporal and spatial specificity (e.g., Wheatley et al. 2015; Yussouf et al. 2016; Yussouf and Knopfmeier 2019, 2020; Skinner et al. 2018). The WoFS was run at NSSL in real-time on several severe weather days to support the National Science Foundation (NSF) and NOAA funded 2022–2023 Propagation, Evolution, and Rotation in Linear Storms (PERiLS; Kosiba et al. 2024) field campaign. One of the instruments deployed during PERiLS to collect lower BL measurements was the CopterSonde UAS (Segalés et al. 2020). Among all Intensive Operating Periods (IOPs), the most suitable event for the DA experiment was the 24–25 March 2023 Rolling Fork tornado event that occurred in year 2 of PERiLS during IOP 3. The Rolling Fork supercellular thunderstorm formed downstream of a linear convection system and generated an EF-4-rated (NWS enhanced Fujita scale category 4) tornado that resulted in 17 fatalities in Mississippi (Jackson, Mississippi, NOAA National Weather Service 2023).

As mentioned above, a critical limitation of CAEs, such as the WoFS, is the poor representation of the pre-convective and near convective BL environment. This study assimilates the UAS temperature, moisture, and wind observations in conjunction with

other weather observations that are assimilated in the baseline WoFS in order to examine any improvement to the predictive skill of WoFS. The current NSSL experimental WoFS configuration is considered the baseline from which the impacts of assimilating UAS observations are assessed. The selected case study and accompanying UAS observations are described in Chapter 2, and the experimental methodologies applied in this study are detailed in Chapter 3. Results are discussed in Chapter 4 followed by a summary and steps for future work in Chapter 5.

## Chapter 2

# Description of the Case, UAS Instrument, and Observation Dataset

## 2.1 Description of the PERiLS campaign and profiling sites

The purpose of the 2022–2023 PERiLS field campaign was to “characterize the nearstorm environments and internal storm processes associated with tornado-producing QLCs [quasi-linear convective systems] and other non-classical tornadic storms,” across the Mississippi River Valley (MRV) region, where tornadic storms often do not behave like those in the Great Plains and can be hard to predict (Long et al. 2018). Dozens of in-situ and ground-based remote sensing platforms were deployed to collect measurements in the Arkansas-Louisiana-Mississippi (ArkLaMiss) region as part of the PERiLS field campaign. The Rolling Fork tornadic event, which is part of the 24–25 March 2023 severe weather outbreak, was the third IOP (IOP3) of the 2023 PERiLS field campaign. For IOP3, the Lake Providence, LA subdomain (Fig. 2.1, highlighted in yellow) was selected based on its proximity to the Storm Prediction Center (SPC) Day 1 moderate risk and 15% hatched tornado probability area. Throughout the entire 2023 PERiLS field campaign, IOP3 was also the mission whose subdomain had the greatest overlap with the UAS profiling triangle configuration (Fig. 2.1, highlighted in pink).

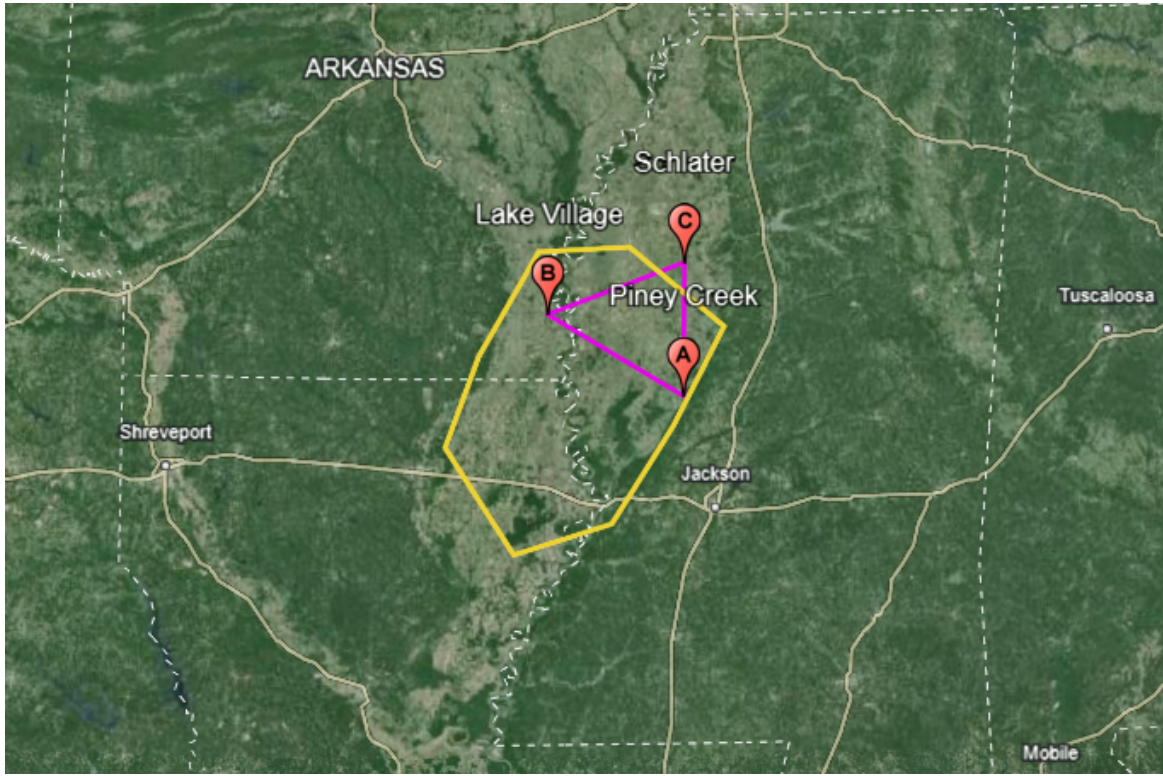


Figure 2.1: Google Earth image of the Lake Providence, LA subdomain from the 2023 PERiLS field campaign (highlighted in yellow) and the UAS domain (highlighted in pink) formed by the three profiling sites at Lake Village, AR (Point B), Piney Creek, MS (Point A), and Schlater, MS (Point C).

The UAS triangle configuration, or UAS domain, included three CopterSonde instruments stationed at Lake Village, AR, Piney Creek, MS, and Schlater, MS for every IOP of the PERiLS field campaign. The general area for the UAS domain was selected based on the desire to co-locate the Collaborative Lower Atmospheric Mobile Profiling System - 2 (CLAMPS-2; Wagner et al. 2019) and UAS platforms in a “network-within-network” configuration of other nearby observing instruments in the PERiLS campaign, and as part of the 3D Mesonet Concept (Chilson et al. 2019; Fiebrich et al. 2021). This idea is in support of the frequent, routine deployment of UASs at fixed sites that can

be used to gather high-resolution measurements of key environmental variables needed to improve the understanding and characterization of BL and near-surface processes.

The trailer-based CLAMPS-2 instrument, owned by the researchers at NOAA NSSL and the University of Oklahoma, was co-located with CopterSonde flights stationed at Lake Village, AR, during the PERiLS field campaign. CLAMPS-2 carries three remote sensing instruments on board, namely the Doppler Lidar (DL; Pearson et al. 2009) for wind measurements, and the Microwave Radiometer (MWR; Rose et al. 2005) and Atmospheric Emitted Radiance Interferometer (AERI; Knuteson et al. 2004) for temperature and moisture measurements. The thermodynamic profiles from the MWR and AERI are obtained using the Tropospheric Remotely Observed Profiling via Optimal Estimation retrieval technique (TROPoe; Turner and Löhnert 2014; Turner and Blumberg 2019; Bell et al. 2023) every 10 minutes. This retrieval technique also provides uncertainty information, unlike other statistical retrieval methods. A velocity-azimuth display (VAD) technique is applied to retrieve DL horizontal wind speed and direction of the BL every 10 minutes (Smith et al. 2023).

These measurements of the BL are especially important to gather in traditionally under-sampled areas, such as in the ArkLaMiss region, which is located close to a zone of limited radar coverage (Fig. 2.2). The closest NWS office to the UAS observing locations is the NWS JAN WFO office, which is located  $\sim 71$  km from Piney Creek, the nearest UAS observing site. The KDGX radar (NWS JAN’s NEXRAD radar) is located  $\sim 79$  km from Piney Creek.

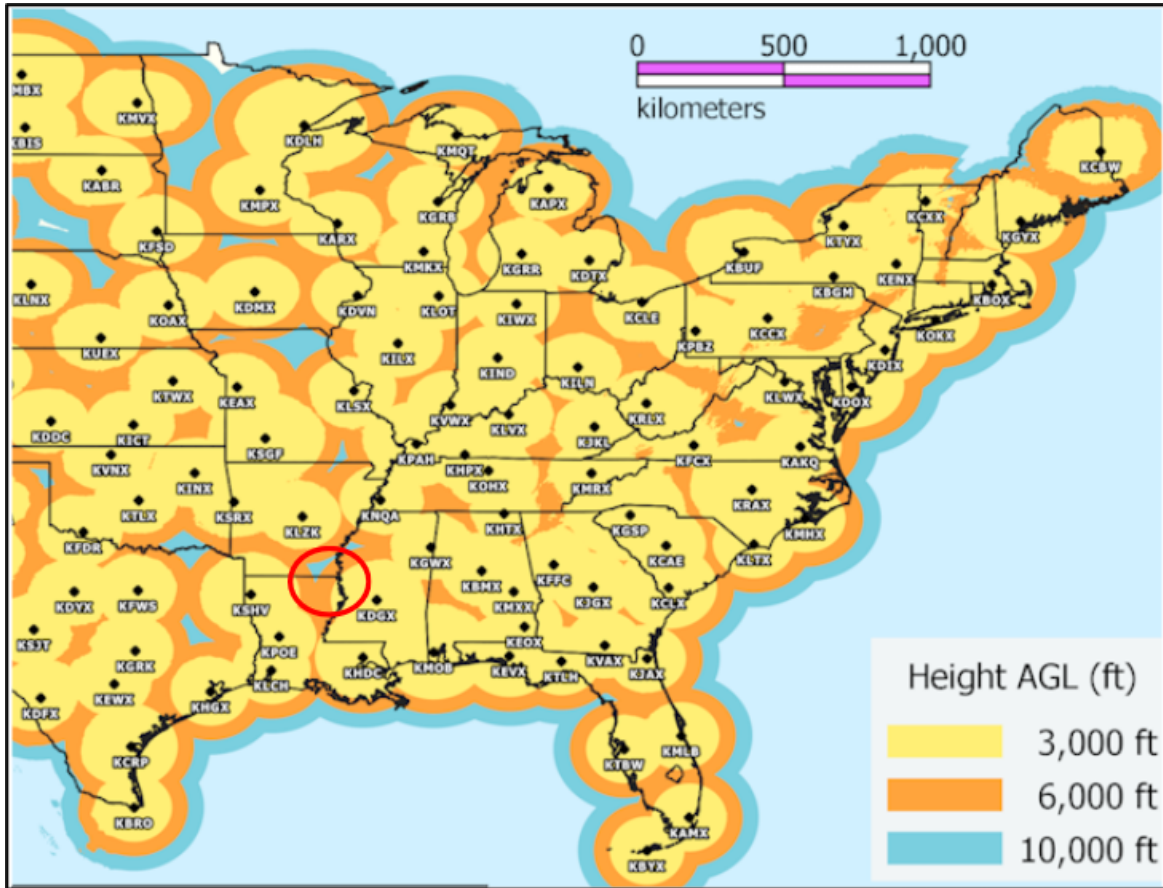


Figure 2.2: The NEXRAD WSR-88D radar sites and ranges of full volumetric coverage. The red circle encompasses the region of WSR-88D coverage located near the Arkansas-Louisiana-Mississippi (ArkLaMiss) region where the Rolling Fork Supercell touched ground.

As part of Federal Aviation Administration (FAA) regulations, which currently require at least a pilot and visual observer to be present while operating a UAS, the potential sites for flying the CopterSondes were limited to a flight ceiling of 5,000 ft AGL, or  $\sim 1,500$  m AGL, and could not be located near heavily populated areas. These stationary profiling sites were also chosen based on a climatological analysis of CLAMPS observations, in which scientists at the University of Oklahoma's Boundary Layer Integrated Sensing and Simulation (BLISS) group examined horizontal time

scales of variability for different meteorological parameters, such as moisture, in the BL. Depending on how long the imprint of each environmental feature was present in various levels of the BL, the recommended spacing between observing instruments was calculated to capture the full variability of the BL environmental characteristics. For the PERiLS campaigns,  $\sim 90$  km was determined to be an appropriate spacing between the CopterSondes in order to observe the BL processes associated with tornadic QLCSs and other tornadic storms in the Southeast. Therefore, due to the requirements for observing meteorological features, power, airspace logistics, and social consideration, the three profiling sites at Lake Village, AR, Piney Creek, MS, and Schlater, MS were selected.

## **2.2 Overview of the 24–25 March 2024 Rolling Fork, MS tornadic supercell event**

During 24–27 March 2023, a severe tornado outbreak occurred over the lower MRV in the southeastern United States. The meteorologists at the NOAA SPC forecasted the potential for severe thunderstorms a week before the event and issued a Day 6 Convective Outlook with a 15% regional severe risk across the ArkLaMiss area. With time, the forecast evolved into a moderate risk area in the SPC’s Day 1 Categorical Outlook (Fig. 2.3a) that was issued on 24 March 2023 at 0600 UTC with a 15% hatched tornado risk (Fig. 2.3b). This outbreak was the result of an eastward moving mid-level trough that interacted with an abundantly moist and unstable air mass advected northward from the Gulf of Mexico, leading to the development of a large QLCS and subsequent Mesoscale Convective Systems (MCSs) and isolated supercells along the lower MRV. The first two days of this severe weather outbreak were the most destructive, with an isolated supercell producing one EF4 and two EF3 tornadoes

across west-central Mississippi (Fig. 2.3c). The focus of this study is the supercell tornadic event that went through Rolling Fork, MS.



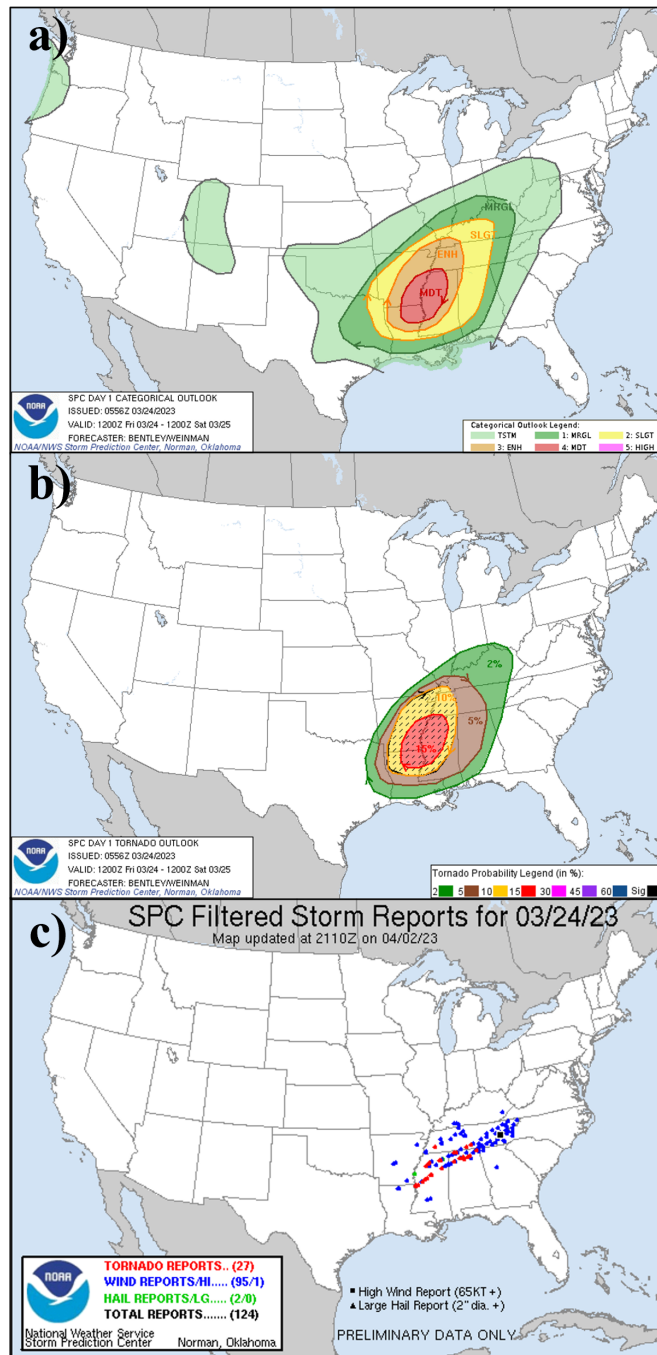


Figure 2.3: (a) NOAA’s Storm Prediction Center (SPC) Day 1 Categorical Outlook issued at 0600 UTC, valid for 1200 UTC 24 March–1200 UTC 25 March 2023, (b) Day 1 Tornado Outlook, and (c) Filtered Storm Reports.

A cluster of small storm cells began to initiate from  $\sim 2130$ – $2200$  UTC along an eastern confluence band in south-central Louisiana (in the lower left of Fig. 2.4a). Over the next hour, these isolated cells remained loosely organized, propagating northeast toward a more destabilized portion of the warm sector. The cell to the north (which would later evolve into the Rolling Fork tornadic supercell, circled in red) began to strengthen and the trailing southern cells merged by 2300 UTC (Fig. 2.4b). During the next hour, the trailing southern cells began to dissipate (Figs. 2.4c, d). The Rolling Fork supercell in central Louisiana continued to trek northeast along the eastern edge of the warm sector, towards a convectively enhanced environment featuring a strengthening southerly low-level jet (LLJ), large scale ascent, falling surface pressure, and increasing BL moisture in Mississippi (Figs. 2.4c, d, e). Ahead of this storm, “a favorable overlap of boundary-layer instability and low-level shear,” was identified, priming the environment for tornadogenesis just before local sunset (NOAA/NWS/SPC 2023b). 27 minutes before the Rolling Fork tornado touched the ground, a new cell formed in place of the previous trailing cells southwest of the Rolling Fork supercell (Fig. 2.4e). Around 0040 UTC, the small trailing cell merged into the inflow region of the Rolling Fork supercell, and the Rolling Fork supercell rapidly intensified. At 0057 UTC, the storm produced a tornado, immediately after crossing the Mississippi River (Fig. 2.4f).

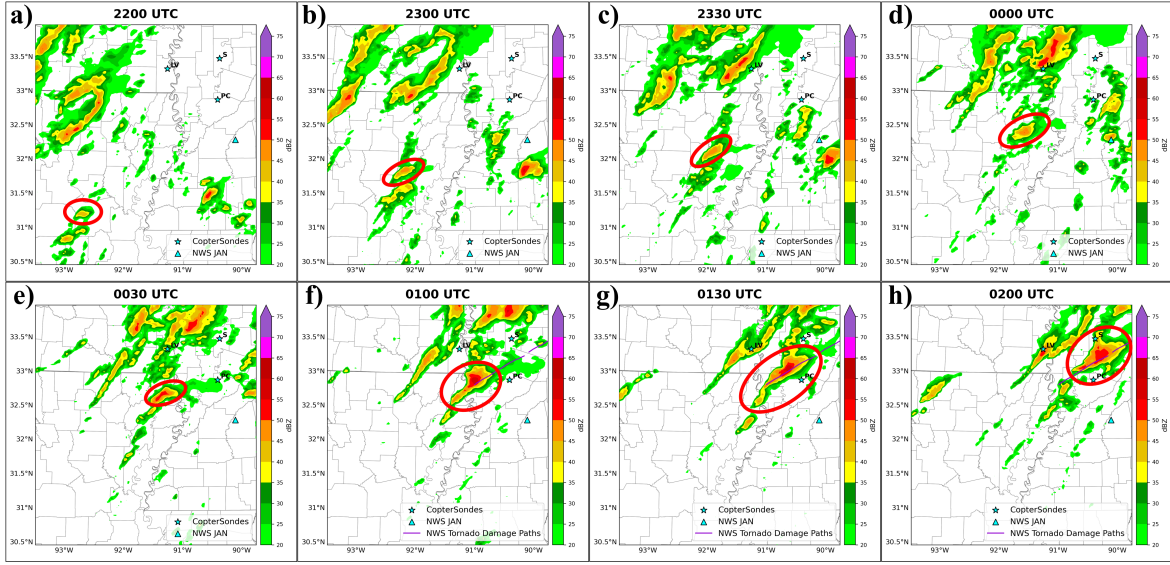


Figure 2.4: MRMS composite reflectivity (CREF; in dBZ) interpolated onto the WoFS domain at 3-km grid spacing showing the development of the Rolling Fork tornadic supercell (circled in red) at (a) 2200 UTC, (b) 2300 UTC, (c) 2330 UTC, (d) 0000 UTC, (e) 0030 UTC, (f) 0100 UTC, (g) 0130 UTC, and (h) 0200 UTC 24–25 March 2023. The purple line overlaid is the NWS damage path of Rolling Fork tornado.

The Rolling Fork tornado began near Grant Road in Issaquena County, MS. Shortly afterwards, the National Weather Service office in Jackson, MS (NWS JAN) issued a rare Particularly Dangerous Situation (PDS) warning for the storm that would soon evolve into the violent, long-track EF4 Rolling Fork tornado. At 0104 UTC, NWS JAN WFO issued a Tornado Emergency, which is the most urgent wording used by NWS meteorologists for significant, damage-causing tornadoes entering populated areas. After beginning to cause catastrophic damage in Rolling Fork, the tornado minorly weakened, but restrengthened again by 0130 UTC (Fig. 2.4g). The EF4 tornado subsequently reached its peak intensity near US Highway 61 and Walnut Street, going on to cause further damage in Rolling Fork, Midnight, and Silver City, MS, before

ending at 0208 UTC (Fig. 2.4h). The timing of the Rolling Fork tornadic supercell and subsequent EF4 tornado are shown below in Fig. 2.5.

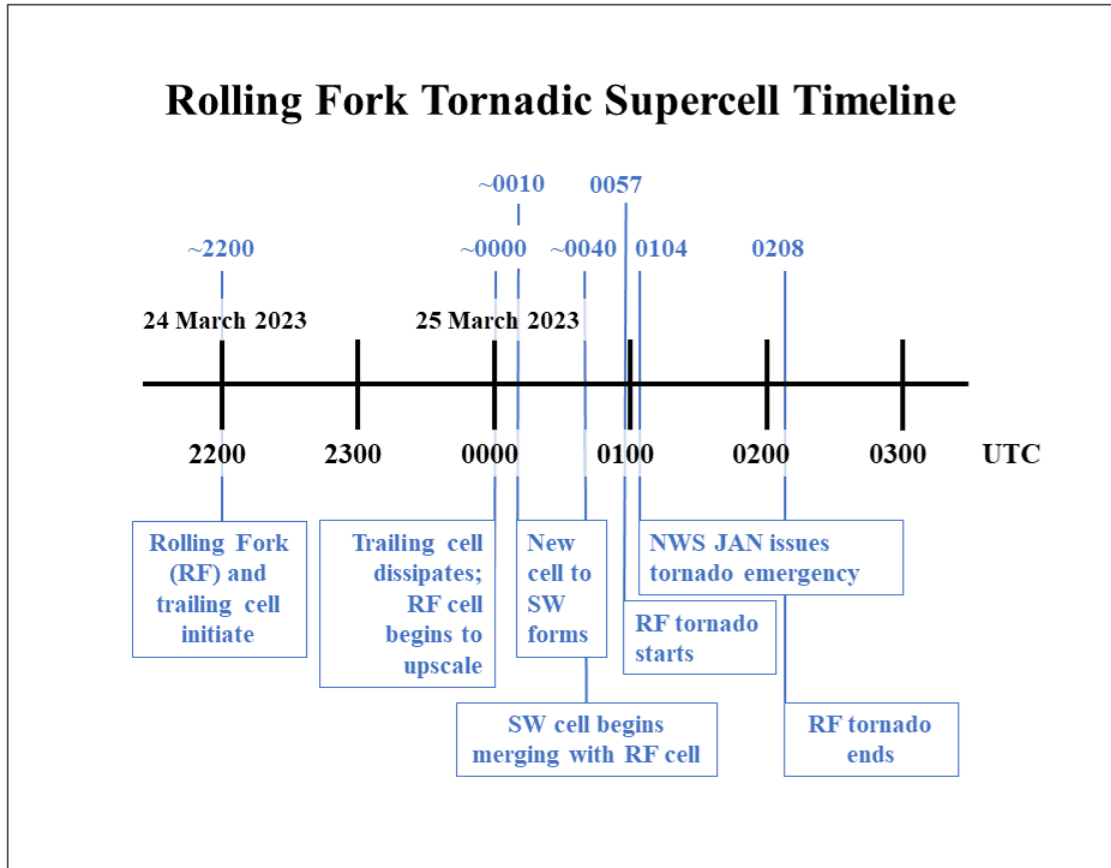


Figure 2.5: Rolling Fork tornadic supercell timeline.

The violent Rolling Fork tornado went through four different counties over a 71-min period, before the same parent supercell produced two shorter-lived EF3 tornadoes across Black Hawk–Winona from 0212–0237 UTC and Egypt–New Wren–Amory–Smithville from 0338–0409 UTC (Jackson, Mississippi, NOAA National Weather Service 2023). Throughout the entirety of the severe weather outbreak, this long-track EF4 tornado was the most severe with an estimated peak wind speed of 195 mph and a maximum path width of  $\sim 3/4$  mile (Jackson, Mississippi, NOAA National Weather Service 2023). It remained on the

ground through Rolling Fork, Midnight, and Silver City, MS, for 59.4 miles and caused structural damage and fatalities from the time it began at 0057 UTC until the time it lifted at 0208 UTC on 25 March 2023. Tragically, 17 lives were lost and 165 others were injured, making the Rolling Fork tornado the deadliest to strike the Jackson, MS County warning area in over 52 years. There was relatively little warning time for this rapidly intensifying tornadic supercell, with the first tornado warning issued at 0045 UTC, 12 minutes before the tornado began.

## **2.3 Description of the CopterSonde UAS instrument and collected measurements**

The UAS instrument utilized in this study is the CopterSonde (Fig. 2.6) which was developed, tested, and calibrated by scientists (Greene et al. 2018, 2019; Bell et al. 2020; Segalés et al. 2020) at the University of Oklahoma Center for Autonomous Sensing and Sampling (CASS), now part of the Cooperative Institute for Severe and High-Impact Weather Research and Operations (CIWRO). The CopterSonde measurements of temperature are accurate to within  $\pm 0.1$  °C, relative humidity are accurate to within  $\pm 2\%$ , and wind speed are accurate to within  $\pm 0.6$  m s<sup>-1</sup> (Bell et al. 2020). The CopterSonde observations of the atmosphere are well within acceptable UAS and meteorological community error ranges (Argrow et al. 2017). Additionally, the CopterSonde samples ascending measurements of pressure, temperature, dewpoint temperature, and wind speed and direction every  $\sim 10$  Hz, starting from  $\sim 10$  m AGL (Segalés et al. 2020). With an ascent speed of 3 m s<sup>-1</sup>, and using sample averaging techniques, observations are collected every 3 m or every 1 s, thus allowing for high-resolution (5-m) vertical profiling of the BL.



Figure 2.6: Front-view of the CopterSonde (Segalés et al. 2020).

For the PERiLS campaign, the CopterSondes were permitted to fly up to 1,500 m AGL, but the highest level reached by a CopterSonde during IOP3 was 1,338 m AGL at the Schlater, MS site. This height limit was encountered as a result of one of the fail-safe mechanisms built into the CopterSondes, which causes the CopterSonde to automatically return to the landing site when the maximum wind threshold is encountered (Segalés et al. 2020); for this campaign, the maximum wind threshold was set to  $25 \text{ m s}^{-1}$ . Although the CopterSondes were not able to fly up to the maximum allowed height, out of the five PERiLS IOPs, IOP3 featured the largest number of flights with the highest vertical profiles. This provides yet another reason for choosing to analyze IOP3 from the PERiLS 2023 field campaign, aside from the co-location of the profiling sites with the Day 1 Convective Outlook moderate risk and the path of the Rolling

Fork, MS tornado. Prior to the beginning of the Rolling Fork tornado, the CopterSondes collected ascending measurements of temperature, dewpoint temperature, wind speed and direction, every 15–30 minutes (depending on local environmental conditions) from 1700–0000 UTC for a total of seven hours. The flight periods were limited to no more than eight hours during the daytime to ensure visible line-of-sight and also to limit operator fatigue.

The raw measurements from these CopterSondes are quality-controlled, pre-processed (Greene et al. 2018, 2019; Segalés et al. 2020; Bell et al. 2020), and formatted for assimilating into the WoFS DA and prediction system. The CopterSondes sample the BL at a denser vertical resolution than the WoFS, so to avoid observation overfitting, the data are vertically thinned to predetermined analysis heights using a simple linear interpolation technique. For this case study, CopterSonde observations are thinned to every 50 m from 50 m AGL to 200 m AGL, and every 100 m from 200 m AGL to 2,000 m AGL. AGL heights are converted to MSL (m) heights by adding the elevation (in m) of the associated UAS profiling site; this helps to create a more accurate vertical level for the data to be interpolated to during assimilation. The first altitude in the dataset is measured to see if it is within 5 m of the desired analysis height. If so, this becomes the new lowest level of the CopterSonde data. If not, the cycle continues until the closest observed altitude to the desired analysis height is found. The same method is also applied to find the highest altitude in UAS data. For the rest of the levels in between, a basic averaging method is used to calculate the values of the UAS variables at each of the analysis heights. Some of the most important environmental characteristics to take note of from the time-height diagrams of the CopterSonde UAS observations (Fig. 2.7) are as follows:

1. Temperature (first row): Gradual warming followed by cooling near the surface (circled in black) especially at Piney Creek and Schlater (middle and right columns)
2. Dewpoint Temperature (second row): Near-ground moistening (circled in black) with initial drying at Schlater (third column, circled in red)
3. *U*-wind (third row): Near-ground winds shift from eastward, to neutral, to slightly westward, with pronounced strong eastward winds at Schlater early in the observation period (third column, circled in red)
4. *V*-wind (fourth row): Northward winds increase in speed closer to the ground (shown by increased red shading and decreased profile heights)



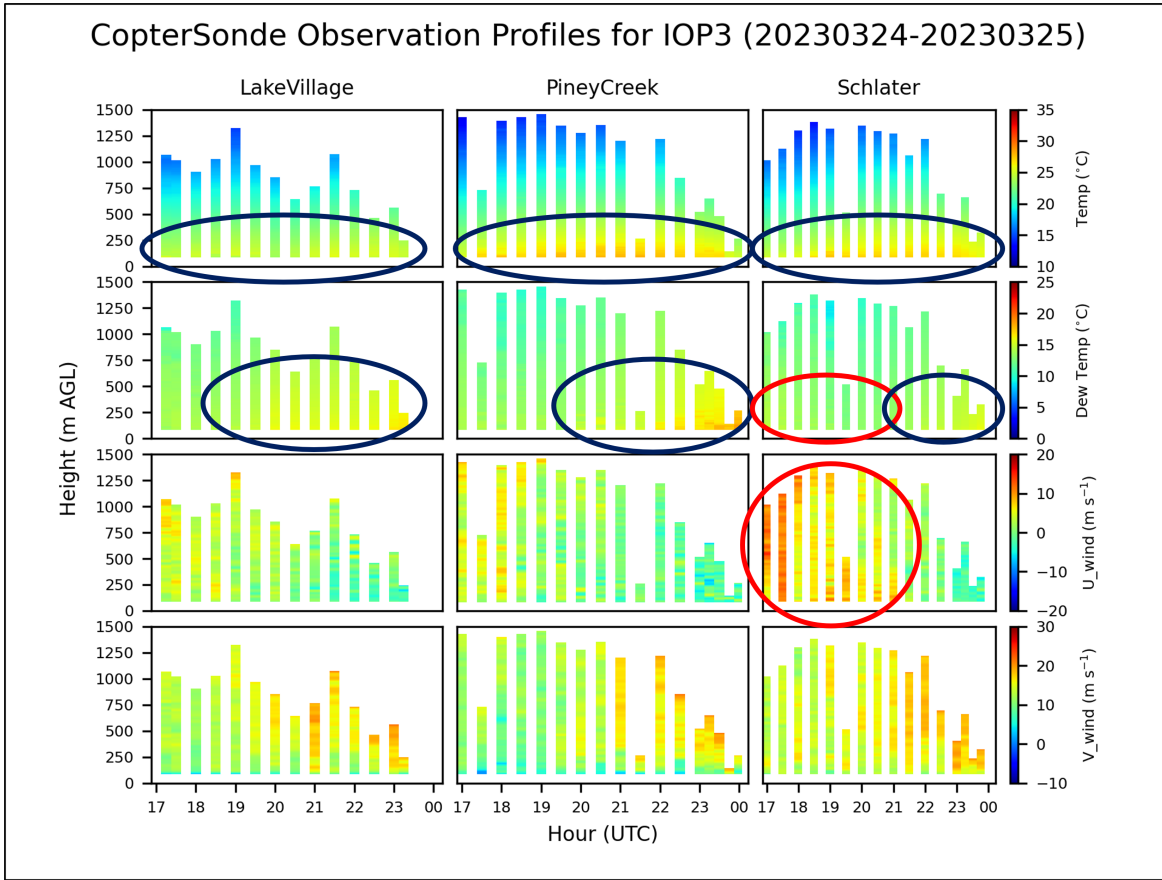


Figure 2.7: Time-height (m AGL) series plots of CopterSonde observation profiles of temperature ( $^{\circ}\text{C}$ ), dewpoint temperature ( $^{\circ}\text{C}$ ),  $u$ -wind component ( $\text{m s}^{-1}$ ), and  $v$ -wind component ( $\text{m s}^{-1}$ ) at Lake Village, AR, Piney Creek, MS, and Schlater, MS from 1700–0000 UTC on 24–25 March 2023. The colored gradients reflect the values of the respective observations listed to the right of the rows of plots.

The gradual warming near the surface, from  $\sim 1700$ – $2100$  UTC (12:00–4:00 p.m. CDT, local time), as well as the near-ground moistening, represent the local heating of the BL environment during the afternoon in addition to the passage of a rain band. After  $\sim 2000$  UTC (3:00 p.m. CDT, local time), the BL environment was also enhanced by moisture advection from the influx of warm, saturated air transported from the Gulf of Mexico by a strengthening LLJ (NOAA/NWS/SPC 2023a). Around this time, the

development of a strong southerly/southwesterly LLJ was triggered by increasing cyclogenesis to the north-northwest over the ArkLaTex region coming into contact with the stationary high-pressure system over the Southeast. Additionally, the increase in northward winds closer to the surface, in combination with the weakening eastward winds and lowered flight ceiling after  $\sim 2200$  UTC (5:00 p.m. CDT, local time), reflect the intensification of the southerly/southwesterly LLJ throughout the region. Weak precipitation from east of a MCS that started merging with the QLCS to the west began to reach the Lake Village and Schlater sites after  $\sim 2230$  UTC (5:30–6:30 p.m. CDT, local time), contributing to the near-surface cooling and moistening of the BL environment prior to the local sunset at 0018 UTC (7:18 p.m. CDT). After  $\sim 2330$  UTC, the LLJ continued to intensify with increasing BL moisture over the ArkLaMiss region, providing an increasingly favorable environment for convection. The assimilation of these UAS CopterSonde data available from 1700–0000 UTC should correct the thermodynamic and kinematic environment in the WoFS ensemble, helping to improve the forecast of the evolution of a tornadic supercell event.

## Chapter 3

### Methodology

#### 3.1 A Brief Description of the Warn-on-Forecast System (WoFS)

The WoFS is an ensemble data assimilation (DA) and prediction system that is designed to provide 0–6-h probabilistic guidance of hazards associated with individual thunderstorms, such as excessive rain, large hail, tornadoes, and more. The current configuration of this system is described in Heinselman et al. (2023). The WoFS uses the Advanced Weather Research and Forecasting (ARW-WRF, version 3.9.1) Model (Skamarock et al. 2008) and Gridpoint Statistical Interpolation (GSI; Kleist et al. 2009; Hu et al. 2019) ensemble square root filter (EnSRF; Whitaker and Hamill 2002) DA technique. The WoFS is also a multiphysics ensemble with 36 members. The ensemble uses the NSSL two-moment microphysics scheme (Mansell et al. 2010) and Noah-MP (Niu et al. 2011; Yang et al. 2011) land surface model. The diversity in PBL and radiation parameterization schemes for the ensembles are listed in Table 1 of Kerr et al. (2023), including the Yonsei University (YSU), Mellor–Yamada–Janjić (MYJ), and Mellor–Yamada–Nakanishi–Niino (MYNN) PBL schemes as well as the Dudhia, Rapid Radiative Transfer Model–Global (RRTMG), and Rapid Radiative Transfer Model (RRTM) radiation schemes. The WoFS domain covers a 900 km by 900 km area with 3-km horizontal grid spacing, and is stretched from the surface to  $\sim 20$  hPa with 51

staggered hybrid coordinate vertical levels. The observations that are assimilated in the WoFS include conventional observations from METAR, ASOS, and the Oklahoma Mesonet, WSR-88D-derived Multi-Radar Multi-Sensor (MRMS) radar reflectivity and radial velocity (Smith et al. 2016), and GOES-16 satellite cloud water path (CWP) and clear-sky radiance data (Jones et al. 2020). The prior adaptive inflation technique from Anderson and Collins (2007) and additive noise (Dowell and Wicker 2009; Sobash and Wicker 2015) are utilized to maintain ensemble spread. The WoFS is initialized at 1500 UTC and assimilates all available observations every 15-min, before beginning to launch forecasts at 1700 UTC. A depiction of the WoFS workflow is shown in Fig. 3.1.

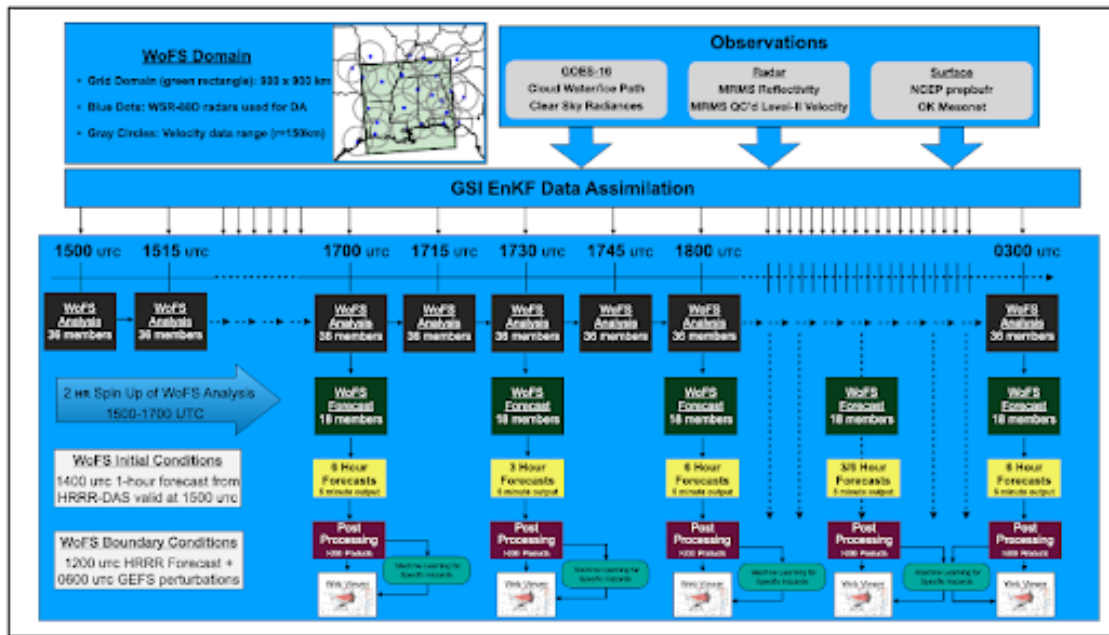


Figure 3.1: Flowchart showing the workflow for WoFS from Heinselman et al. (2023).

## 3.2 Experiment Design

This study analyzes the impact of assimilating UAS observations to predict the 24–25 March 2023 Rolling Fork tornadic event. As mentioned in Chapter 2, the event was sampled using three CopterSonde instruments located at three separate, stationary profiling sites near the ArkLaMiss border. To answer research questions 1 and 2, two sets of experiments are conducted. The first experiment is the control experiment that uses the baseline WoFS configuration (WoFS\_CNTRL), while the second experiment assimilates the temperature (T), dewpoint temperature (TD),  $u$ -wind (U), and  $v$ -wind (V) components from the CopterSonde UAS observations (WoFS\_UAS), in addition to all other observations in WoFS\_CNTRL. A third experiment is conducted to explore the sensitivity of the horizontal localization of the UAS observations. The WoFS\_UAS\_200km experiment is the same as WoFS\_UAS, but instead of utilizing a 400-km horizontal localization radius, a reduced localization radius of 200 km is applied to limit the influence of the spatial extent of the CopterSonde observations over the domain. The errors and the horizontal and vertical localization radii (Gaspari and Cohn 1999) for the observations assimilated in the DA experiments are listed in Table 3.1.

Table 3.1: Observation types and their observation errors, horizontal localization radii (H-Local), and vertical localization radii (V-Local, in normalized pressure space) for WoFS-3km and WoFS-1km (Wheatley et al. 2015; Jones et al. 2016; Wang et al. 2022). Cloud water path (CWP) observation error has a range due to nonlinearity (Jones et al. 2016). Surface observations have varying H-Local based on the observation platform (Mesonet, etc.).

| Observation Type                  | Observation Variable Type | Observation Error                 | Horizontal Localization Radius (km) | Vertical Localization Radius [ln(p/pref)] |
|-----------------------------------|---------------------------|-----------------------------------|-------------------------------------|-------------------------------------------|
| METAR, ASOS, and Oklahoma Mesonet | Temperature               | 1.5 (K)                           | 60-460                              | 0.85                                      |
|                                   | Dewpoint                  | 2.0 (K)                           | 60-460                              | 0.85                                      |
|                                   | U-wind                    | 1.75 (m s <sup>-1</sup> )         | 60-460                              | 0.85                                      |
|                                   | V-wind                    | 1.75 (m s <sup>-1</sup> )         | 60-460                              | 0.85                                      |
|                                   | Surface Pressure          | 1.0 (hPa)                         | 60-460                              | 0.85                                      |
| MRMS                              | Reflectivity              | 7 (dBZ)                           | 18                                  | 0.8                                       |
|                                   | Clear Air Reflectivity    | 5 (dBZ)                           | 18                                  | 0.8                                       |
| WSR-88D                           | Radial Velocity           | 3 (m s <sup>-1</sup> )            | 18                                  | 0.8                                       |
| GOES                              | Cloud Water Path          | 0.025 – 0.2 (kg m <sup>-2</sup> ) | 36                                  | 0.9                                       |
|                                   | clear sky radiances       | 1.25 (K)                          | 36                                  | 4                                         |
|                                   | clear sky radiances       | 1.75 (K)                          | 36                                  | 4                                         |
| Coptersonde UAS                   | T                         | 0.5 (K)                           | 400                                 | 0.45                                      |
|                                   | Td                        | 0.7 (K)                           | 400                                 | 0.45                                      |
|                                   | U                         | 0.6 (m s <sup>-1</sup> )          | 400                                 | 0.45                                      |
|                                   | V                         | 0.6 (m s <sup>-1</sup> )          | 400                                 | 0.45                                      |

The WoFS domain covers the moderate risk and enhanced tornado risk area over the ArkLaMiss region outlined in the SPC’s Day 1 Convective Outlook (Fig. 2.3) and overlaps with the UAS profiling sites from IOP3. One thing to note is that the Rolling Fork supercell initiated, developed, and matured quite far south-southwest of the three UAS profiling sites as it was approaching the profiling sites located in the center of the WoFS domain (Fig. 3.2).

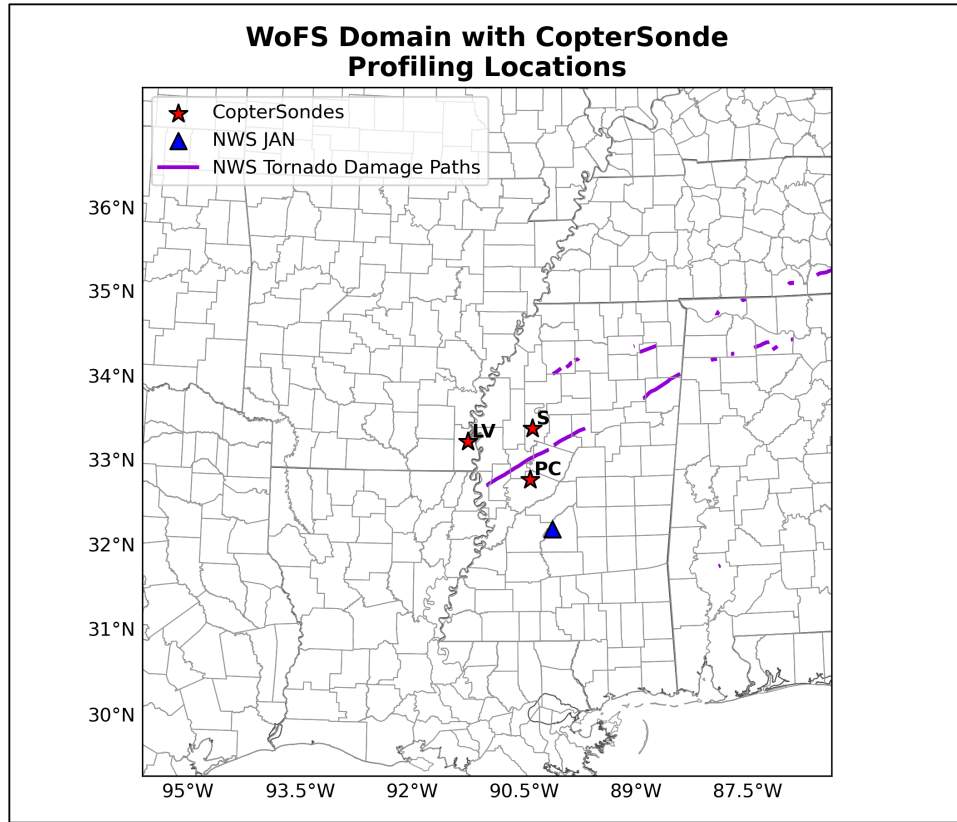


Figure 3.2: The WoFS domain for the 24–25 March 2023 Rolling Fork tornado event. The red stars represent the locations of the CopterSonde profiling sites at Lake Village, AR (LV); Piney Creek, MS (PC); and Schlater, MS (S). The blue triangle represents the location of the nearest NWS office in Jackson, MS (NWS JAN). The solid purple lines represent NWS damage paths; the longest, westernmost line represents the Rolling Fork EF4 tornado damage path.

The CopterSonde observation period started at 1700 UTC and ended at 0000 UTC,  $\sim 1$  hour before the start of the Rolling Fork tornado, which touched down northwest of the Piney Creek site, southeast of the Lake Village site, and south of the Schlater site, before moving through and exiting the UAS profiling domain. Since the CopterSondes were not launched simultaneously every 15 minutes, the launch time from each flight is binned and checked to see if it is within 7.5 minutes of the nearest 15-min

DA interval in the WoFS. The only difference between the WoFS\_CNTRL experiment and the WoFS\_UAS experiment is the assimilation of CopterSonde observations every 15 minutes based on the availability of the data during the 1700–0000 UTC observation period. This DA cycle repeats through 0000 UTC, at which point the last set of CopterSonde observations are assimilated into the WoFS\_UAS experiment. Approximately one hour after the end of the UAS observation collection, the Rolling Fork supercell produced a tornado that lasted over more than an hour. Ensemble forecasts are launched half-hourly starting from 1700 UTC out to 0000 UTC analyses using the first 18 ensemble members. For each WoFS forecast cycle, 5-min forecast output files are generated from the initialization time out to 6 h. The flowchart of the DA and prediction experiments and the period of UAS DA is shown in Fig. 3.3.

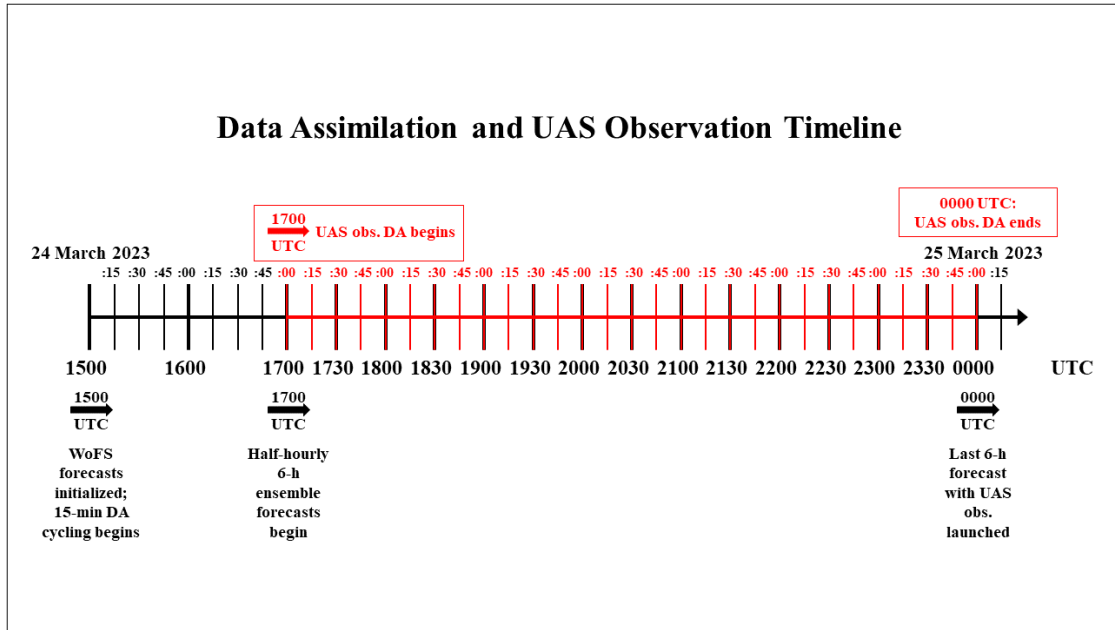


Figure 3.3: UAS DA cycling timeline for the Rolling Fork tornado event. The areas highlighted in red represent the period in which UAS observations were assimilated into the WoFS\_UAS ensemble.



Three additional “data denial” experiments are conducted to examine the sensitivity of the WoFS\_UAS experiment to the different variable types as posed in research question 3. The three experiments are similar to the WoFS\_UAS experiment, except for, instead of assimilating all three CopterSonde variable types, observations of temperature (T), dewpoint temperature (TD), and horizontal wind ( $u$ - and  $v$ -wind components) are assimilated individually in addition to the baseline WoFS observations. Those experiments are the WoFS\_UAS\_T, WoFS\_UAS\_TD, and WoFS\_UAS\_U\_V experiments (Table 3.2), which assimilate the different types of UAS measurements by themselves. The forecasts from the various ensemble experiments are compared to one another and to the WoFS\_UAS experiment (row 2 in Table 3.2) to determine how the specific types of assimilated UAS observations impact the prediction of the evolution of the Rolling Fork tornadic supercell.

Table 3.2: Experiment names and their descriptions.

| <b>Experiment Names</b> | <b>DA Experiment Descriptions</b>                                      |
|-------------------------|------------------------------------------------------------------------|
| WoFS_CNTRL              | Baseline variables                                                     |
| WoFS_UAS                | Baseline + UAS T, TD, U- and V-wind variables with 400 km localization |
| WoFS_UAS_200km          | Baseline + UAS T, TD, U- and V-wind variables with 200 km localization |
| WoFS_UAS_T              | Baseline + UAS T variable                                              |
| WoFS_UAS_TD             | Baseline + UAS TD variable                                             |
| WoFS_UAS_U_V            | Baseline + UAS U- and V-wind variables                                 |

Since the focus of this study is the Rolling Fork tornadic event, a zoomed-in domain that is centered on the Rolling Fork tornadic supercell (Fig. 3.4) is used for plotting figures in Chapter 4. Additionally, since the UAS observation period ended at 0000 UTC, and the Rolling Fork tornado began approximately one hour after the end of measurement collection, forecasts initialized at 0000 UTC out to 2 h are examined to demonstrate the full impact of assimilating all available UAS observations on the short-term probabilistic forecasts of the Rolling Fork tornadic event lifecycle. This also helps to further answer research questions 1 and 2 by breaking down the impacts for differences in the WoFS modeling of the Rolling Fork tornadic supercell environment and evolution across different experiments.

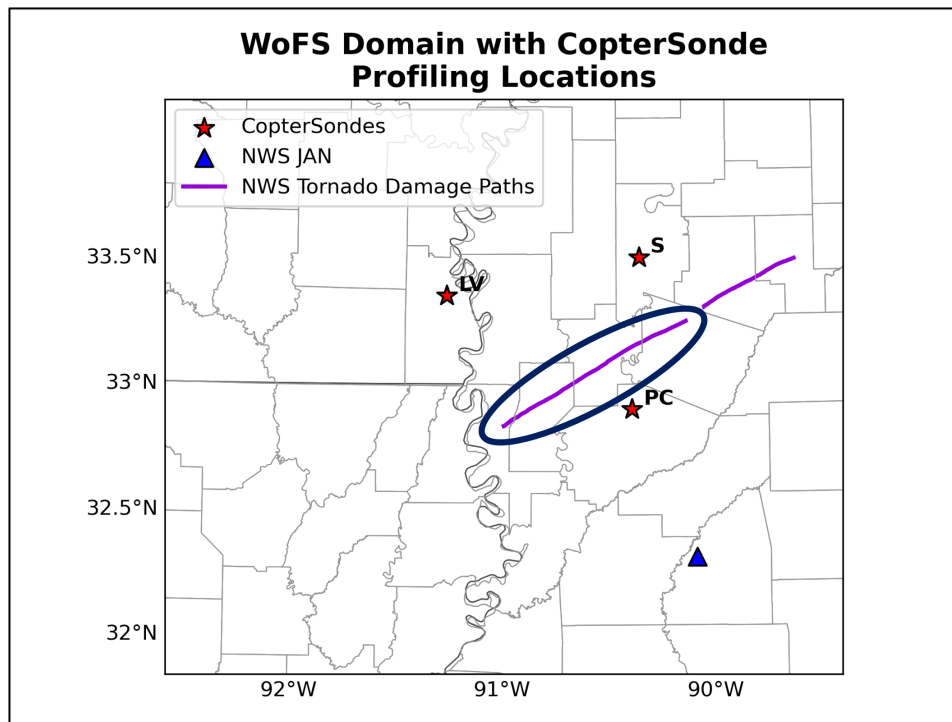


Figure 3.4: As in Fig. 3.2, but zoomed-in over the ArkLaMiss region. The Rolling Fork tornado damage path is circled in black.

Although the placement of the CopterSonde sites surrounds the area where the Rolling Fork EF4 tornado traversed through after touching down (Fig. 3.4, circled in black), it is important to note that the placement of the UAS sites is far from ideal for the Rolling Fork tornadic supercell case study. These sites are located far downstream from the location of where the Rolling Fork supercell initiated in, developed, grew upscale, and matured, eventually spawning the tornado. The placement of the instruments in the inflow and surrounding region of the storm is necessary to accurately represent the storm environment in the model.

## Chapter 4

### Results

#### 4.1 Comparison between the baseline WoFS and UAS WoFS experiments

##### 4.1.1 Ensemble prediction of environmental soundings

To understand the impact of CopterSonde observations in the WoFS ensemble environment, the forecast soundings from the WoFS\_CNTRL and WoFS\_UAS experiments are compared using the Skew T-log $p$  diagrams from the lower atmosphere (1000–700 hPa). The ensemble members are interpolated to the nearest NWS Jackson, MS (NWS JAN) Rawinsonde station, which is  $\sim 71$  km south-southeast of Piney Creek. The eSRH shown in the Skew T-log $p$  diagrams is a useful tool to help discriminate between tornadic supercells (higher values of eSRH) and non-tornadic supercells (lower values of eSRH), and measures the potential for cyclonic updraft rotation in right-moving supercells within the layer where parcels have buoyancy but are not as constrained by a warm cap (Thompson et al. 2007). The critical angle represents the angle between the surface storm-relative wind vector and the 0–500 m AGL shear vector, with a critical angle of  $\sim 90^\circ$  being indicative of a tornado. This is because a critical angle near  $90^\circ$  implies that low-level streamwise vorticity is being ingested by the storm (Esterheld

and Giuliano 2008), and is thus favorable for tornadic supercells when paired with high values of SRH.

The differences between the 1-h forecast sounding and hodograph from the WoFS\_CNTRL and WoFS\_UAS ensembles initialized from the 2300 UTC analyses (Figs. 4.1a, b), which is  $\sim 2$  hours prior to the beginning of the Rolling Fork tornado, showcase the impact of assimilating UAS observations on the environment during the preceding 1700–2300 UTC period, with a total of 25 DA cycles. While both soundings and hodographs are primed for convection with ample dewpoint temperatures in the mid-upper 60s, warm temperatures in the upper 70s, lowered lifting condensation levels (LCLs), and elongated hodographs, there are still differences between the WoFS\_CNTRL and WoFS\_UAS ensemble forecasts and the NWS JAN radiosonde observations (Figs. 4.1a, b). In the 1-h WoFS\_CNTRL forecast (Fig. 4.1a), there is a  $3^\circ$  cool bias at the surface that transitions to a warm bias in the  $\sim 930$ – $870$  hPa layer (top row, circled in dark orange); a  $2^\circ$  moist bias at the surface and a large dry bias above the surface up to  $\sim 850$  hPa (top row, circled in dark blue); an eastward wind bias in the 0–1 km layer and above (top row, circled in dark green); a slight northward wind bias near the surface and a larger bias above into the 1–3 km layer (top row, also circled in dark green); a low effective storm relative helicity (eSRH) bias; and a low critical angle bias.

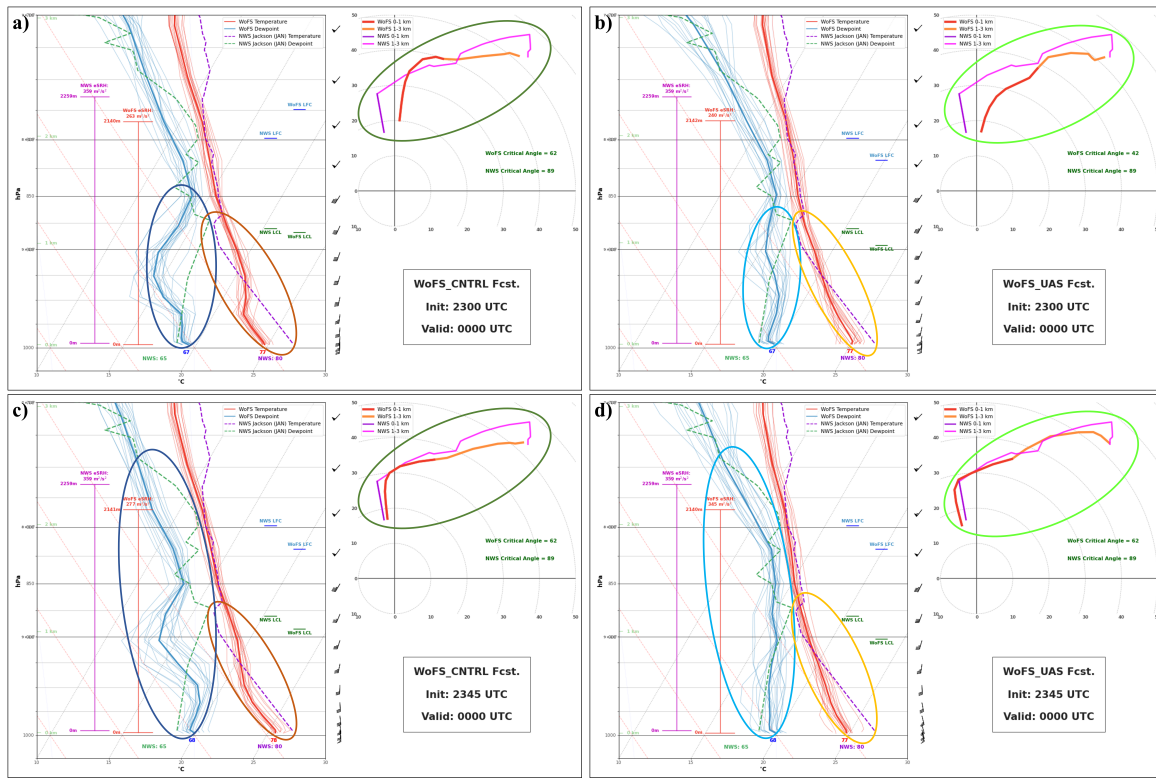


Figure 4.1: Low-level environmental sounding (Skew T-log $p$  from 1000–700 hPa) and hodograph forecasts from the 18-member ensembles with temperature (thin red lines) and dewpoint temperature (thin blue lines) from the (a), (c) WoFS\_CNTRL (left column) and (b), (d) WoFS\_UAS (right column) experiments at the NWS JAN station. Forecasts are initialized at (a), (b) 2300 UTC (first row), at (c), (d) 2345 UTC (second row), and valid at 0000 UTC. Overlaid are the ensemble mean (thick red and blue lines) and radiosonde observations (dashed purple and green lines). The thick lines are the model hodograph from 0–1 km (red) and 1–3 km (orange) and the thin lines are the NWS JAN hodograph from 0–1 km (purple) and 1–3 km (pink).

The 1-h WoFS\_UAS forecast (Fig. 4.1b) initialized at the same time as in WoFS\_CNTRL (Fig. 4.1a) is also supportive of a supercellular environment; however, the WoFS\_UAS thermodynamic profiles up to the  $\sim 850$  hPa level are generally more

accurate than in the WoFS\_CNTRL experiment. The WoFS\_UAS forecast (Fig. 4.1b) also has a  $3^\circ$  cool bias at the surface, but shows a smaller cool bias above the surface and a smaller warm bias in the  $\sim 925$ – $875$  hPa layer (top row, circled in light orange); a  $2^\circ$  moist bias at the surface that then fits closer to the NWS JAN dewpoint temperature profile up to  $\sim 850$  hPa (top row, circled in light blue; which makes sense due to the low-level moistening feature observed by the CopterSondes up through 2300 UTC in Fig. 2.7); an increased eastward wind bias extending from the top of the 0–1 km layer into the lower 1–3 km layer (top row, circled in light green); a decreased northward wind bias throughout the 0–1 km layer into the lower 1–3 km layer (top row, also circled in light green); a slightly lower eSRH bias; and a higher critical angle bias, all compared to the WoFS\_CNTRL experiment. The WoFS\_UAS experiment (Fig. 4.1b) improves the depiction of the thermodynamic environment the most, especially for the dewpoint temperature profile just above the surface up to  $\sim 850$  hPa. The cool and warm biases in the temperature profile above the surface up to  $\sim 875$  hPa are also improved in the WoFS\_UAS forecast, which also presents less of a northward wind bias in the lower levels of the atmosphere. On the other hand, the WoFS\_CNTRL forecast (Fig. 4.1a) predicts less of an eastward wind bias in the lower levels of the atmosphere and a generally more accurately-shaped hodograph. Overall, the 1-h the WoFS\_UAS forecast valid at 0000 UTC provides a more accurate prediction of the thermodynamic BL environment prior to the beginning of the Rolling Fork tornado, while the WoFS\_CNTRL experiment predicts the kinematic environment slightly better.

A 15-min forecast with an additional three DA cycles (initialized at 2345 UTC and valid at 0000 UTC) reveals a few changes in the soundings, with the most pronounced changes in the WoFS\_UAS forecast (Fig. 4.1d). The largest changes to the WoFS\_CNTRL forecast (Fig. 4.1c) are in the dewpoint temperature profile and the hodograph; the hodograph shifts closer to the observed NWS JAN sounding (bottom

row, circled in dark green), but the dewpoint temperature profile generally strays farther from the NWS JAN observations throughout the depth of the BL (bottom row, circled in dark blue). Smaller changes to the WoFS\_CNTRL forecast include the cool bias at the surface decreasing by  $1^\circ$ ; the eastward wind bias decreasing just above the ground; the northward wind bias decreasing in the 0–1 km layer; and the low eSRH bias slightly decreasing. As expected, the changes to the WoFS\_UAS experiment are more noticeable than in the WoFS\_CNTRL experiment, with greater improvements to the WoFS\_UAS forecast. The cool bias near the surface somewhat worsens in the WoFS\_UAS forecast (Fig. 4.1d), likely due to the cooling trend observed at all three UAS profiling sites after 2300 UTC (Fig. 2.7), but both the cool and warm biases above the surface shift closer to the NWS JAN observations than in the WoFS\_CNTRL experiment (bottom row, circled in light orange). The WoFS\_UAS experiment also more accurately predicts the BL environmental moisture above the surface than the WoFS\_CNTRL experiment. The WoFS\_UAS forecast increases the moisture bias by  $1^\circ$  just above the surface, but adjusts its moisture profile closer to that of the observed dewpoint temperature profile upwards to  $\sim 865$  hPa (bottom row, circled in light blue); shifts to a slight westward wind bias in the lower 0–1 km layer (bottom row, circled in light green); decreases the low northward wind bias throughout the 0–1 and 1–3 km layers (bottom row, circled in light green); increases the low bias eSRH to  $345 \text{ m}^2 \text{ s}^{-2}$  (much closer to NWS JAN’s observed eSRH of  $359 \text{ m}^2 \text{ s}^{-2}$ ); and improves the critical angle bias by  $20^\circ$  to match that of the WoFS\_CNTRL’s forecast.

Looking at the time-height CopterSonde diagram (Fig. 2.7), all three UAS profiling sites indicate moistening near the surface from 2300–2345 UTC, as well as an increase in northward winds above the surface due to the strengthening of the LLJ. Although somewhat difficult to detect, the slightly eastward/neutral winds turn slightly westward near the ground, as seen by the increase in blue shading in the  $u$ -wind plots in Fig. 2.7.



This is also associated with the strengthening of the LLJ over the region, as well as the slight backing of winds above the surface associated with the south-southeastward advancement of the low-pressure system into southern Arkansas. Prior to 2300 UTC, all three sites reveal tendencies of moistening and warming near the surface (with the exception of the Schlater site which initially experiences some drying), shifting winds from eastward, to neutral, to slightly westward throughout the lower 0–1 km layer, and an increasing magnitude of northward winds above the surface (although this magnitude of northward winds still likely helped to limit the northward wind bias in the baseline WoFS). Throughout the forecast periods, the assimilation of UAS data first helps to improve the forecasts of the BL thermodynamic environment, before helping to improve the forecasts of the BL kinematic environments at the NWS JAN station. Going back to research question 1, the assimilation of UAS data helps to improve the thermodynamic environment more than the kinematic environment near Jackson, MS. Overall, the WoFS\_UAS experiment improves both the thermodynamic and kinematic BL environment at the JAN station more than compared to the WoFS\_CNTRL experiment.

#### **4.1.2 Ensemble prediction of 100 hPa MLCAPE**

The 100 hPa MLCAPE, which is the mean CAPE for parcels of air in the lowest 100 hPa of the mixed layer lifted to the level of free convection (LFC), is a good measure of instability in the atmosphere (Bunkers et al. 2006). Because MLCAPE focuses on the energy available to the air parcels in the lowest 100 hPa of the mixed layer when lifted to the LFC, it is more representative of the near-surface air available to be ingested by the storm’s updraft than other measures of CAPE, such as most unstable CAPE (MUCAPE) or surface-based CAPE (SBCAPE). One reason why MLCAPE, and CAPE in general, are important forecast parameters to analyze is because of the

contributions from thermodynamic UAS observations. Although storms in the Southeast U.S. are commonly characterized by high-shear, low-CAPE (HSLC) environments (Sherburn and Parker 2014; Anderson-Frey et al. 2019; Wade and Parker 2021), the Rolling Fork thunderstorm was characterized by moderate instability and 0–1 km shear of  $\sim 40\text{--}50$  kts. There are no large differences in the structure or magnitude of the low-level shear forecasts between the WoFS\_CNTRL, WoFS\_UAS, and WoFS\_UAS\_200km experiments, except for slightly enhanced 0–1 km shear south of the Rolling Fork supercell in the WoFS\_UAS and WoFS\_UAS\_200km experiments. Because this environment does not feature high values of shear, or shear values that vary significantly between forecasts, wind shear is not discussed. On the other hand, the ensemble 90th percentile forecasts of 100 hPa MLCAPE do reveal moderate values in the ArkLaMiss region up to  $2,750 \text{ J Kg}^{-1}$  (Fig. 4.2); therefore, forecasts of MLCAPE are especially important to analyze when wind shear forecasts are less affected by assimilated UAS observations.

In addition to the WoFS\_CNTRL and WoFS\_UAS (with 400 km horizontal localization for the UAS observation assimilation) experiments, the WoFS\_UAS\_200km experiment with a reduced 200 km horizontal localization radius is shown to assess the impacts of changing the localization radius of the UAS observations in DA. To evaluate how the CopterSonde observations are impacting the stability of the environment, ensemble 90th percentile forecasts of 100 hPa MLCAPE are shown in Fig. 4.2. The ensemble 90th percentile is the highest 90th percentile of all ensemble members' values for a particular variable that represents a reasonable worst-case scenario which is useful to understand the severity of the event.

The ensemble 90th percentile forecasts of 100 hPa MLCAPE valid at 0010 UTC (a reasonable assumption of the DA analysis valid at 0000 UTC to allow the model variables to adjust to the DA) show increased regions of MLCAPE up to  $2,750 \text{ J Kg}^{-1}$  around the model-generated 40.0 dBZ Rolling Fork supercell contours in both of

the WoFS\_UAS (Fig. 4.2b) and WoFS\_UAS\_200km (Fig. 4.2c) experiments (circled in red), with slightly weaker MLCAPE around the Rolling Fork cell in the WoFS\_CNTRL experiment (Fig. 4.2a, circled in red). The WoFS\_UAS forecast in Fig. 4.2b reveals the best placement of the highest values of MLCAPE in the inflow region of the Rolling Fork storm, and the highest values of MLCAPE directly ahead of the storm, compared to the other experiments, which would likely draw the attention of forecasters due to the favorable overlap and placement of the MLCAPE, moisture, and the model-depicted supercell. Enhanced MLCAPE and moisture initially extend further north-northeastward into the ArkLaMiss region in the WoFS\_CNTRL and WoFS\_UAS experiments (seen in the northward extension of the dryline, circled in black in Figs. 4.2a, b), but the WoFS\_UAS\_200km experiment limits the MLCAPE and moisture more southward (Fig. 4.2c, circled in black). Integrating forward to the 50-min forecast, the three experiments begin to resemble each other more closely (Fig. 4.2, bottom row). The WoFS\_UAS experiment features a more southward-extending dry pocket into central Louisiana (Fig. 4.2e, circled in black), while the other experiments continue to increase the northward advection of moisture (Figs. 4.2d, f, circled in black). The WoFS\_UAS experiment also features the weakest MLCAPE values north of the storm in the 50-min forecast, which helps to limit the northward displacement bias (Fig. 4.2e, circled in red). The WoFS\_UAS\_200km experiment is similar to the WoFS\_UAS experiment, but the model-generated Rolling Fork supercell is displaced southwest, despite the further advancement of moisture into the ArkLaMiss region (Fig. 4.2f, circled in red).

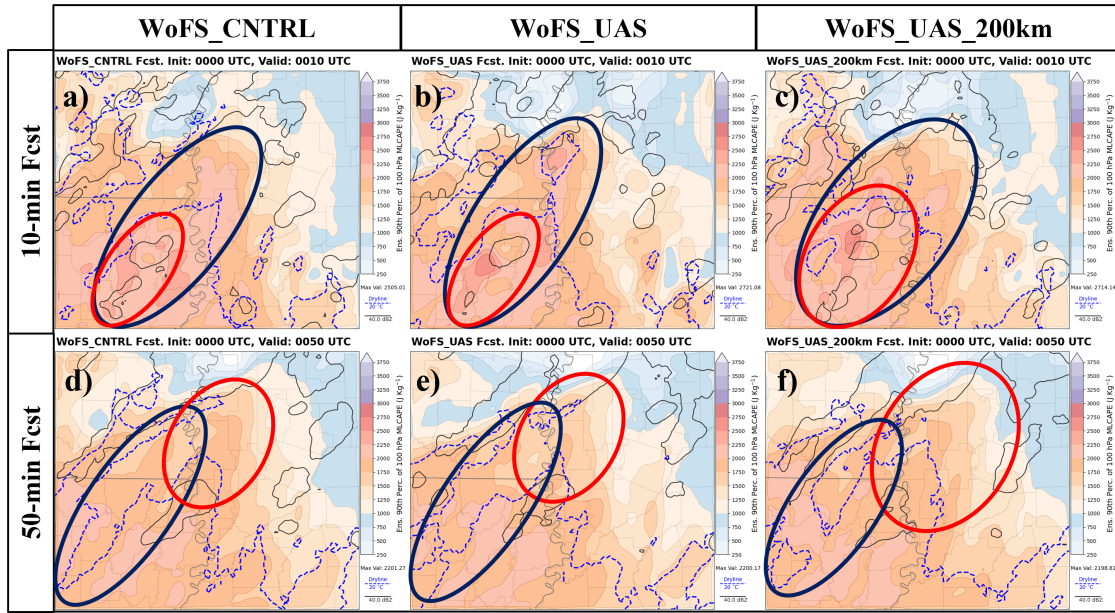


Figure 4.2: Ensemble 90th percentile 100 hPa MLCAPE ( $\text{J Kg}^{-1}$ ) (a), (b), (c) 10- min and (d), (e), (f) 50-min forecasts initialized at 0000 UTC from the WoFS\_CNTRL (left column), WoFS\_UAS (middle column), and WoFS\_UAS\_200km (right column) experiments. The model-generated 90th percentile composite reflectivity (CREF)  $> 40.0$  dBZ (solid black contours) and ensemble mean  $20^\circ\text{C}$  isodrosotherms (dashed blue contours) are overlaid. The red circles in the top row encompass the MLCAPE in the inflow region, while the red circles in the bottom row encompass the northeastward extent of MLCAPE. The black circles in the top row encompass the moisture around and ahead of the Rolling fork storm, and the black circles in the bottom row encompass the dry pockets extending into north-central Louisiana.

The slightly weaker MLCAPE values north-northwest of the WoFS\_UAS depiction of the Rolling Fork cell (Fig. 4.2e, circled in red), in combination with the northeast oriented moist sector southwest of and into the storm (circled in black), help to limit the north-northwestward displacement of the Rolling Fork cell in the WoFS\_UAS run compared to the other experiments. This is because MLCAPE, acting as a measure

of instability to fuel the supercell, is primarily drawn from the south-southwest of the Rolling Fork cell in its inflow region, which helps the ensemble to model the storm and its environment better. This further supports the answer to research question 1 in that the forecasts of the spatial extent and magnitude of the low-level moisture and MLCAPE in the BL environment seems most realistic in the WoFS\_UAS experiment, compared to the WoFS\_CNTRL and WoFS\_UAS\_200km experiments.

### 4.1.3 Ensemble prediction of composite reflectivity (CREF)

CREF, as opposed to reflectivity at different levels in the BL, is a measure of the maximum reflectivity value scanned from each radar elevation angle within a vertical column. CREF is useful for assessing the intensity of storms, while base and low-level reflectivity scans are useful for analyzing fine-scale features, such as hook echoes and low-level mesocyclones. Since reflectivity scans at various heights can reveal details in storm structures that typically get masked in CREF imaging, examining reflectivity at lower levels in the BL is important to understand differences in storm structure and evolution. However, the current 3-km horizontal resolution of the WoFS cannot resolve such fine scale storm reflectivity features and do not reveal significant differences in storm structure (Kerr et al. 2023). Therefore, the Rolling Fork tornadic supercell forecasts in the experiments are evaluated using CREF.

The 10-min forecast (which is a reasonable proxy for WoFS ensemble analyses) from all three experiments analyzed the Rolling Fork supercell in the model (Fig. 4.3, top row, circled in dark gray) with the core of the supercell slightly displaced northwest. Arguably, the shape of the Rolling Fork supercell core matches that of the observed core (MRMS 40.0 dBZ CREF contours overlaid) better in the WoFS\_UAS experiment (Fig. 4.3b). The trailing cell southwest of the Rolling Fork storm (which later dissipated) is also analyzed better in the WoFS\_UAS experiment. Unlike the other two experiments,

the WoFS\_UAS\_200km experiment incorrectly depicts three supercells in the same area (Fig. 4.3c). The supercell in the middle seems to capture the Rolling Fork storm, but with weaker echoes than in the other two experiments. The model-generated supercell catches up more quickly to the observed Rolling Fork supercell in the WoFS\_CNTRL and WoFS\_UAS experiments (Figs. 4.3a, b), showing the positive impacts of the larger 400 km localization radius.

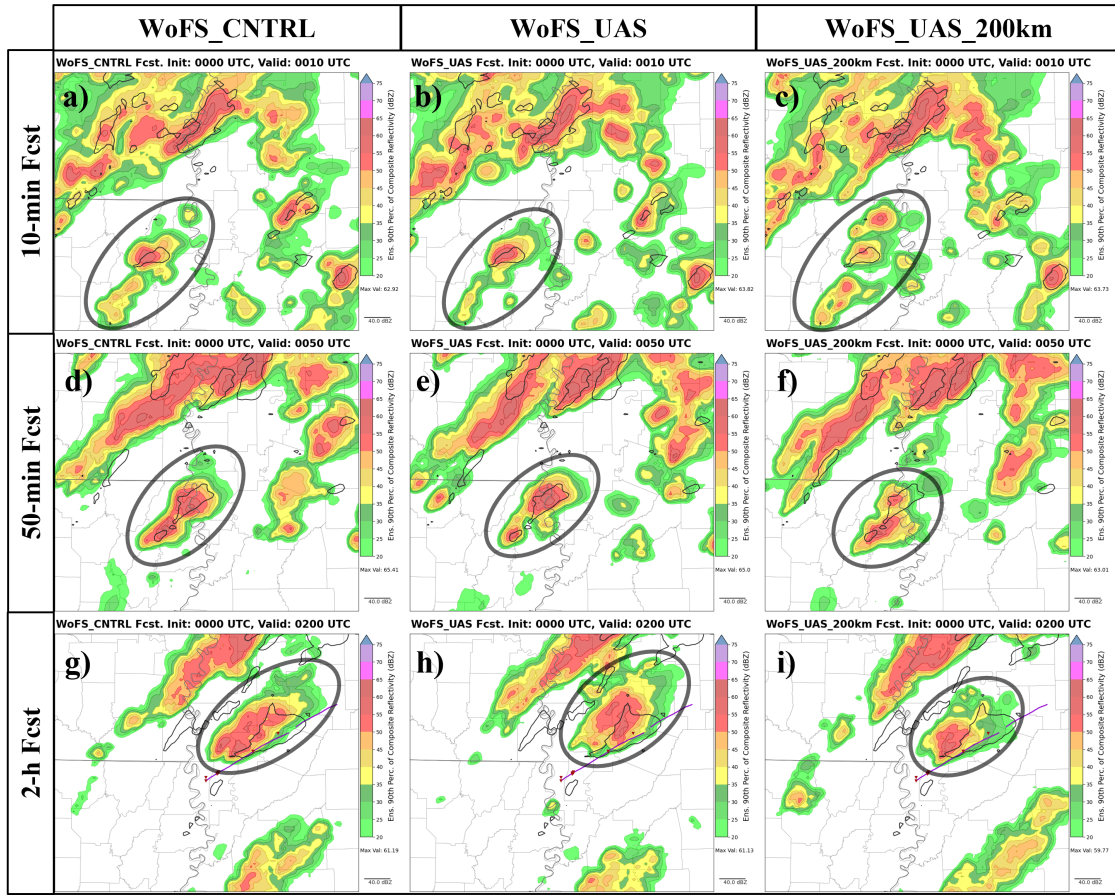


Figure 4.3: Ensemble 90th percentile composite reflectivity (CREF; dBZ) (a), (b), (c) 10-min, (d), (e), (f) 50-min, and (g), (h), (i) 2-h forecasts initialized at 0000 UTC from the WoFS\_CNTRL (left column), WoFS\_UAS (middle column), and WoFS\_UAS\_200km (right column) experiments. The black contours overlaid represent observed MRMS CREF > 40.0 dBZ. NWS damage paths (solid purple lines) and NWS tornado reports (red triangles) for the EF4 Rolling Fork tornadic event are overlaid. The dark gray circle encompasses the Rolling Fork supercell.

The 50-min forecasts (Fig. 4.3 middle row), valid seven minutes before the Rolling Fork supercell touched the ground (i.e., spawned a tornado), show the intensification of the Rolling Fork supercell and a group of small trailing cells that form southwest of the

Rolling Fork storm (circled in dark gray). The WoFS\_CNTRL experiment (Fig. 4.3d) predicts a very intense Rolling Fork supercell that extends farther south-southwest of the observed Rolling Fork storm. The WoFS\_UAS experiment (Fig. 4.3e) more realistically predicts the Rolling Fork supercell and the trailing cells southwest of the Rolling Fork storm compared to the WoFS\_CNTRL experiment, as shown by the better separation between the storms. In the WoFS\_UAS\_200km experiment, the northernmost of the cells located in the ArkLaMiss region incorrectly weakens and dissipates, and is overcome by the more intense trailing cell to the southwest (Fig. 4.3f). This causes the southwestward displacement seen in the WoFS\_UAS\_200km forecast of the 100 hPa MLCAPE (Fig. 4.1, right column). The WoFS\_UAS 50-min forecast (Fig. 4.3e) still shows the best depiction of the shape and intensity of the Rolling Fork supercell and its trailing storm which does not intensify as much as in the other experiments, with a more realistic separation between the cells. This is important because in reality, the Rolling Fork supercell originated from the northernmost of the cells (Figs. 2.4b, c), while the first trailing cell to the southwest had fluctuations in intensity before dissipating (Fig. 2.4d), followed by the quick initiation of a new cell to the southwest that merged into the Rolling Fork supercell shortly before it produced the violent EF4 tornado (Fig. 2.4e).

By 0200 UTC (Fig. 4.3, bottom row), all three experiments show northwestward/westward displacement of the Rolling Fork tornadic supercell (circled in dark gray) which is consistent with previous studies of the baseline WoFS (Yussouf et al. 2015; Supinie et al. 2017; Stratman et al. 2018; Kerr et al. 2023). At 0200 UTC, both the WoFS\_CNTRL and WoFS\_UAS experiments (Figs. 4.3g, h) predict a larger storm core than the observed core, and the WoFS\_UAS\_200km depiction of the Rolling Fork supercell is the least accurate out of the three experiments (Fig. 4.3i). Overall, both



the WoFS\_CNTRL and WoFS\_UAS experiments predict the Rolling Fork supercell realistically; the WoFS\_UAS experiment does a better job of predicting the shape and location of the Rolling Fork tornadic supercell during the early hours in the forecast. Referring back to research questions 1 and 2, the sensitivity of the WoFS to the localization radii also shows that the experiment that assimilates UAS observations with the larger 400 km is more realistic compared to the reduced 200 km localization radius for this case study. The positive impacts of the UAS DA are most pronounced in shorter forecast lead times, and have a significant effect on the southward limitation of moisture advection, as well as the decrease in northwestward displacement.

#### **4.1.4 Ensemble prediction of low-level updraft helicity (UH)**

The low-level 0–2 km UH represents the co-location of low-level vertical vorticity with storm updrafts, or vertical motion; as a result, UH is used as a good proxy to evaluate the presence of a low-level mesocyclone (Thompson et al. 2007; Kain et al. 2008; Clark et al. 2013; Miller et al. 2013; Milne et al. 2020; Jahn et al. 2022; Laser et al. 2022). Although not all supercellular mesocyclones produce vortices or tornadoes, evidence suggests that 40% of low-altitude mesocyclones produce tornadoes (Trapp et al. 2005), and most produce some mode of severe weather (Coffer et al. 2023). Therefore, the ensemble generated swaths of 90th percentile low-level UH are evaluated to identify the presence of rotation in Rolling Fork supercells, with the highest values representing the area in which tornadogenesis is most likely to occur (Markowski and Richardson 2009). The NWS-surveyed tornado damage path and the Warning Decision Support System–Integrated Information (WDSS-II; Lakshmanan et al. 2007) generated 0–2 km mesocyclone circulations (azimuthal wind shear; Miller et al. 2013) are used to compare with the model generated UH swaths (circled in dark gray). Note that while these fields derived from observations are useful for validating model forecasts of severe storms,

caution must be exercised when doing so because the observed and predicted quantities are not the same and may not always correlate strongly. However, the NWS tornado damage paths, NWS tornado reports, and azimuthal wind shear contours should generally overlap with one another, with some northeastward displacement of the azimuthal wind shear track occurring due to its averaging over the 0–2 km layer.

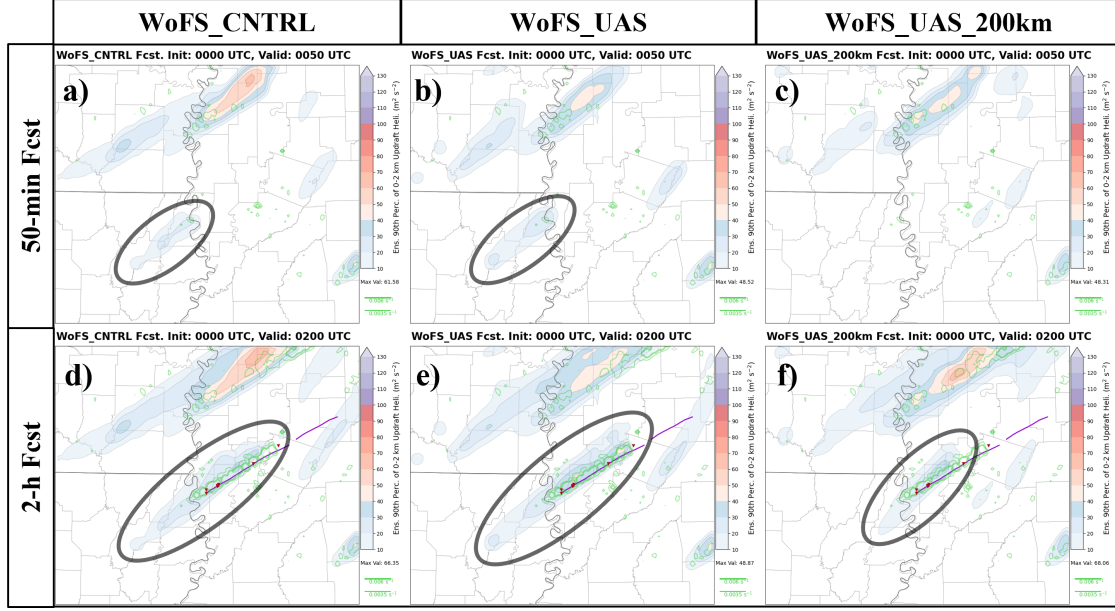


Figure 4.4: Ensemble 90th percentile 0–2 km updraft helicity (UH;  $\text{m}^2 \text{s}^{-2}$ ) (a), (b), (c) 50-min and (d), (e) and (f) 2-h forecasts initialized at 0000 UTC from the WoFS\_CNTRL (left column), WoFS\_UAS (middle column), and WoFS\_UAS\_200km (right column) experiments. The green contours represent observed MRMS 0–2 km azimuthal wind shear ( $\text{s}^{-1}$ ) greater than  $0.0035 \text{ s}^{-1}$  and  $0.006 \text{ s}^{-1}$ . NWS damage paths (solid purple lines) and NWS tornado reports (red triangles) for the EF4 Rolling Fork tornadic event are also overlaid. The dark gray ovals encompass the model-generated rotation swaths.

The 50-min forecast of low-level UH initialized at 0000 UTC (Fig. 4.4, first row), which is seven minutes prior to the beginning of the Rolling Fork EF4 tornado, shows

a UH swath of magnitude as high as  $30 \text{ m}^2 \text{ s}^{-2}$  in the WoFS\_CNTRL experiment (Fig. 4.4a). The WoFS\_UAS\_200km experiment (Fig. 4.4c) fails to initialize any UH over the ArkLaMiss region during this period. The 50-min WoFS\_UAS forecast (Fig. 4.4b) reveals a slightly wider and more northeast-extended UH swath compared to the WoFS\_CNTRL experiment, indicating that the WoFS\_UAS ensemble is predicting the intensity of the rotation better than the other experiments. The 2-h forecast shows that the WoFS\_CNTRL experiment predicts the UH swath with slight northwestward displacement from the observed rotation swath (Fig. 4.4d). The 2-h WoFS\_UAS forecast (Fig. 4.4e) of the UH swath, on the other hand, aligns better with the observed rotation swath, with a small area of higher UH magnitude up to  $50 \text{ m}^2 \text{ s}^{-2}$  co-located with the observed azimuthal wind shear contour. The WoFS\_UAS\_200km forecast (Fig. 4.4f) UH swath valid at 0200 UTC is displaced north-northeast with a shorter swath, and is the least realistic. Overall, the WoFS\_UAS experiment predicts the low-level UH swath placement and intensity better during the 0–2-h forecast period compared to the WoFS\_CNTRL and WoFS\_UAS\_200km experiments. Going back to research question 2, overall, the WoFS\_UAS experiment seems to do a better job of predicting the shape and location of the tornadic supercell, as well as the low-level rotation swath compared to the WoFS\_CNTRL experiment, especially for shorter forecast lead times. Therefore, the assimilation of UAS observations seems to be helping the prediction of the evolution of the Rolling Fork supercell when using a larger localization in data assimilation.

## 4.2 Comparison of the impact of assimilating individual UAS variables

To gain understanding of how the CopterSonde temperature, dewpoint temperature, and horizontal wind components influence the WoFS forecasts of the evolution of the Rolling Fork tornadic supercell and which CopterSonde variables have the most significant impact, another set of three data denial experiments are conducted. This set of experiments, namely, the WoFS\_UAS\_T, WoFS\_UAS\_TD, and WoFS\_UAS\_U\_V, assimilates only UAS temperature, dewpoint temperature and  $u$ - and  $v$ -wind components, respectively, in addition to all baseline WoFS observations (Table 3.2). The following subsections discuss the impacts of the individual UAS variables in the prediction of the Rolling Fork supercell.

### 4.2.1 Ensemble prediction of 100 hPa MLCAPE

Ensemble 90th percentile forecasts of the 100 hPa MLCAPE with the ensemble mean 20 °C dryline overlaid (Fig. 4.5) show that the 10-min WoFS\_UAS\_T experiment (Fig. 4.5a) analyzes weaker values of MLCAPE around the model-analyzed Rolling Fork cells (circled in black), with slightly more northward advection of moisture and MLCAPE compared to the WoFS\_UAS\_TD analysis (Fig. 4.5b, circled in black). Higher magnitude of MLCAPE and moisture extend further northeastward in the WoFS\_UAS\_U\_V experiment (Fig. 4.5c, circled in black) compared to the other experiments. The WoFS\_UAS\_TD shows more spread-out areas of higher MLCAPE values surrounding the model-analyzed Rolling Fork cells with MLCAPE and the dryline not extending as far north-northeast into the ArkLaMiss region as in the other two experiments. The WoFS\_UAS\_TD experiment also predicts the highest values of MLCAPE up to  $2750 \text{ J Kg}^{-1}$  in the inflow region southwest of the model-generated Rolling Fork

storms (Fig. 4.2c), whereas the WoFS\_UAS\_U\_V experiment predicts a decrease in MLCAPE west-southwest of the model-analyzed Rolling Fork cells (Fig. 4.2c). By 0050 UTC, the WoFS\_UAS\_T experiment predicts weakened values of MLCAPE and extends the dryline slightly farther west into Mississippi (Fig. 4.5d, circled in black), the WoFS\_UAS\_TD experiment predicts slightly higher values of MLCAPE behind/west of the Rolling Fork storm with a more southward-bound dryline (Fig. 4.5e, circled in black), and the WoFS\_UAS\_U\_V experiment predicts higher values of MLCAPE extending northward into western Mississippi with a wider dry pocket and weaker MLCAPE west of the Rolling Fork cells (Fig. 4.5f, circled in black). As part of the answer to research question 3, the assimilation of just the dewpoint temperature observations increases the MLCAPE in the forecast and helps to limit the northward extent of the moisture, while the influence from just the wind observations shifts the MLCAPE and dryline north-northeastward, as expected. Not surprisingly, both of the WoFS\_UAS\_T and WoFS\_UAS\_TD experiments experience more southwestward displacement of the model-analyzed Rolling Fork supercell (Fig. 4.6, discussed in the following section), due to lack of influence from north-northeastward winds observed by the CopterSondes.

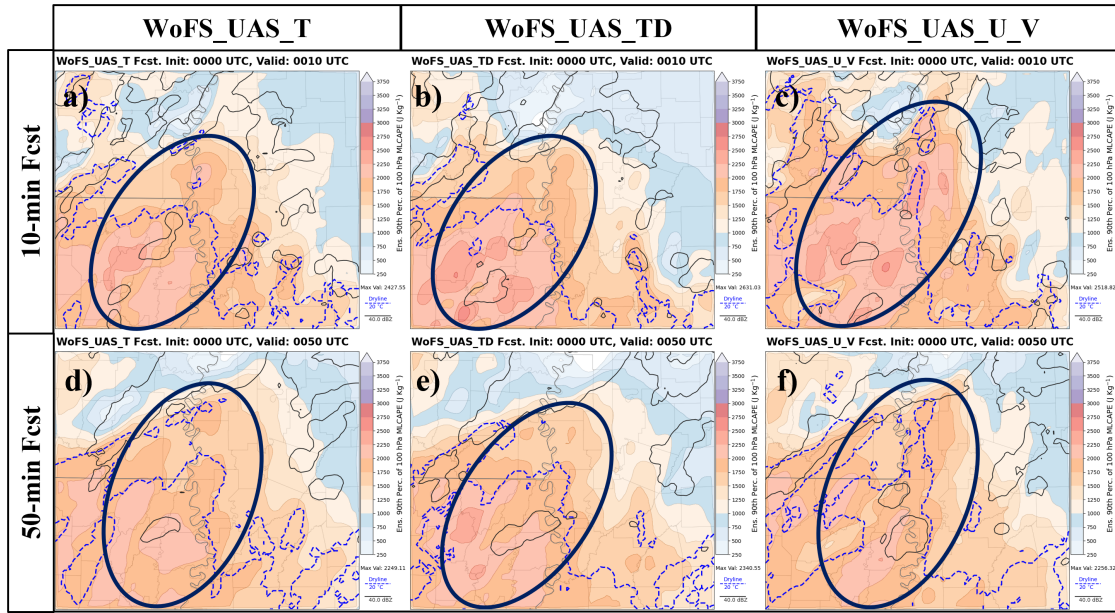


Figure 4.5: Ensemble 90th percentile 100 hPa MLCAPE ( $\text{J Kg}^{-1}$ ) (a), (b), (c) 10-min and (d), (e), (f) 50-min forecasts initialized at 0000 UTC from the WoFS\_UAS\_T (left column), WoFS\_UAS\_TD (middle column), and WoFS\_UAS\_U\_V (right column) experiments. The model-generated 90th percentile composite reflectivity (CREF)  $> 40.0$  dBZ (solid black contours) and ensemble mean  $20^\circ\text{C}$  isodrosotherms (dashed blue contours) are overlaid. The black circles encompass the north-northeastward extension of MLCAPE and moisture around and ahead of the Rolling Fork supercell.

Since the moisture and kinematic content of the BL can change rapidly, it makes sense that these features are more accurately captured earlier in the forecast, prior to the beginning of the Rolling Fork tornado. Overall, the MLCAPE in the WoFS\_UAS\_TD experiment resembles the WoFS\_UAS forecast more closely than the other two data denial experiments throughout the forecast period, reflecting the importance of the assimilating low-level moisture observations. Furthermore, assimilating only the UAS temperature also seems to not be enough to sustain the storm's intensity, which is shown in the following section.

### 4.2.2 Ensemble prediction of composite reflectivity (CREF)

The ensemble 90th percentile of CREF in the three data denial experiments (Fig. 4.6, top row) reveals that all three experiments placed the Rolling Fork storm to the southwest (circled in dark gray) of the observed Rolling Fork supercell (MRMS 40.0 dBZ CREF contour overlaid in black). Another storm cell is incorrectly placed to the north-northeast of the analyzed Rolling Fork storm (circled in red) in all three experiments which is in close proximity to the observed Rolling Fork supercell (MRMS 40 dBZ CREF contour). In the 50-min forecast, the WoFS\_UAS\_TD experiment (Fig. 4.6e) shows a more representative shape of the Rolling Fork supercell and its trailing cell (circled in dark gray) compared to the other two experiments, but the supercell is slightly displaced southwest of the observed Rolling Fork supercell. The northern cell weakens and starts to dissipate (Fig. 4.6e, circled in red). In the WoFS\_UAS\_U\_V forecast (Fig. 4.6f), both northern and southern storms continue to propagate north-eastward, intensify, and move closer to one another (circled in red and dark gray). The entire Rolling Fork storm in the 50-min WoFS\_UAS\_T forecast (Fig. 4.6d, circled in dark gray) is displaced to the southwest of the observed Rolling Fork storm and the northern cell weakens (Fig. 4.6d, circled in red).

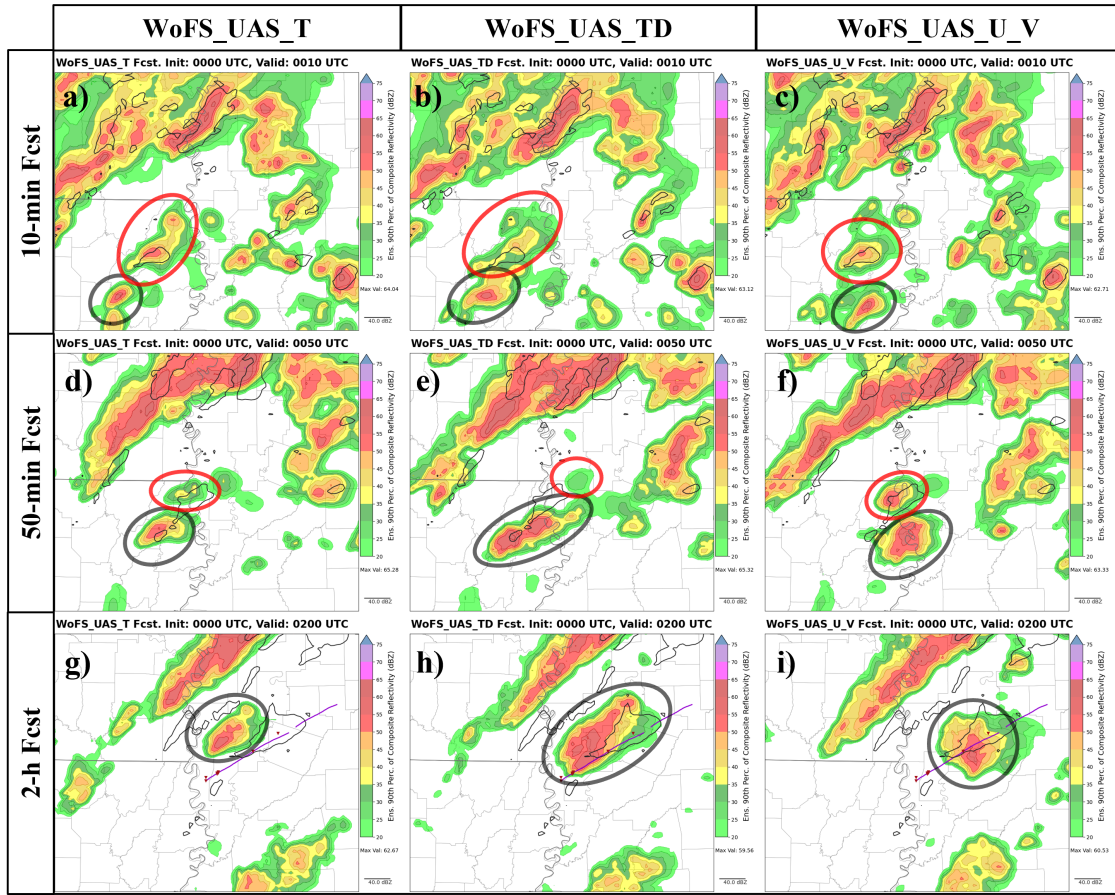


Figure 4.6: Ensemble 90th percentile composite reflectivity (CREF; dBZ) (a), (b), (c) 10-min, (d), (e), (f) 50-min, and (g), (h), (i) 2-h initialized at 0000 UTC from the WoFS\_UAS\_T (left column), WoFS\_UAS\_TD (middle column), and WoFS\_UAS\_U\_V (right column) experiments. The black contours overlaid represent observed MRMS CREF > 40.0 dBZ. NWS damage paths (solid purple lines) and NWS tornado reports (red triangles) for the EF4 Rolling Fork tornadic event are overlaid. The dark gray circles encompass the model-generated Rolling Fork supercell and while the red circles encompass storm cells to the north-northeast, which align more closely with the observed Rolling Fork supercell MRMS contour.



By 0200 UTC, the WoFS\_UAS\_TD experiment (Fig. 4.6h) predicts the shape and intensity of the Rolling Fork supercell more realistically than the other two experiments (circled in dark gray). The predicted Rolling Form storm in the WoFS\_UAS\_TD experiment traverses north-northeastward and tries to catch up with the observed Rolling Fork storm during the forecast period (Fig. 4.6, middle column, circled in gray), which helps to account for the initial south-southwestward displacement more than in the other experiments. In the WoFS\_UAS\_U\_V experiment, the less intense cell to the north weakens and merges with the stronger southern supercell (Fig. 4.6i, circled in dark gray). This is likely due to the influence from the CopterSonde’s eastward winds that help to reduce the northward displacement bias in the baseline WoFS. The WoFS\_UAS\_U\_V experiment also maintains the intensity of the Rolling Fork supercell (Fig. 4.6i, circled in dark gray), although it is not as intense as in the WoFS\_UAS\_TD experiment (Fig. 4.6h, circled in dark gray). The Rolling Fork storm in WoFS\_UAS\_T forecast valid at 0200 UTC (Fig. 4.6g) is displaced (circled in gray) to the west compared to the observed Rolling Fork storm. It also fails to simulate the intensification of the observed Rolling Fork tornadic supercell. Referring back to the temperature profiles of the soundings in Fig. 4.1, there is slightly more of a cool bias in the WoFS\_UAS forecasts near the surface than in the WoFS\_CNTRL forecasts, due to the decrease in CopterSonde temperature observations close to the ground towards the end of the UAS observation and DA period (Fig. 2.7). This cool bias is potentially reflected in the 0000 UTC initialization of the WoFS\_UAS\_T forecast, which contributes to the dissipation of the accurate Rolling Fork supercell (Fig. 4.6, left column) and the decreased CREF intensity compared to other forecasts.

Overall, the WoFS\_UAS\_TD experiment performs better at predicting the evolution of the Rolling Fork supercell than the WoFS\_UAS\_T and WoFS\_UAS\_U\_V experiments, indicating that the CopterSonde moisture variable helps more in analyzing

the supercell in the model. However, the displacement and over-intensification of the supercell in the WoFS\_UAS\_TD experiment (Fig. 4.6, middle column) compared to the WoFS\_UAS experiment (Fig. 4.3, middle column), indicates assimilating the horizontal wind components and temperature variables helps to improve the location of the predicted storm, as well as limit the intensity. The WoFS\_UAS\_TD experiment resembles the WoFS\_UAS experiment the most later in the forecast period compared to the other two data denial experiments, but the WoFS\_UAS\_TD forecast (Figs. 4.6e, h) experiences more westward displacement and over-intensification than the WoFS\_UAS forecast (Figs. 4.3e, h). All these indicate the importance of assimilating the UAS variables together, as the WoFS\_UAS experiment predicts the Rolling Fork supercell's shape, placement, and intensity better than the three data denial experiments.

### 4.2.3 Ensemble prediction of low-level updraft helicity (UH)

The ensemble 90th percentile forecast of the UH swath for the Rolling Fork tornadic supercell does not begin to develop in any of the data denial experiments until 50-min into the forecast (Fig. 4.7, top row). The UH swath barely develops in the WoFS\_UAS\_T experiment (Fig. 4.7a, circled in dark gray). The swath is displaced to the south of the observed rotation in the WoFS\_UAS\_TD experiment (Fig. 4.7b, circled in dark gray), and is displaced more to the south of the observed rotation in the WoFS\_UAS\_U\_V experiment (Fig. 4.7c, circled in dark gray), though with slightly stronger intensity. This is consistent with the reflectivity forecast, which indicates the decay of the supercell to the north (which was more closely aligned with the observed Rolling Fork supercell) and strengthening of the smaller trailing cell to the southwest (Fig. 4.6). Recall that the Rolling Fork tornado touched the ground at 0057 UTC, and many of these UH swaths are not generated near the location of the observed mesocyclone (represented by the green contours) until after the tornado has begun.

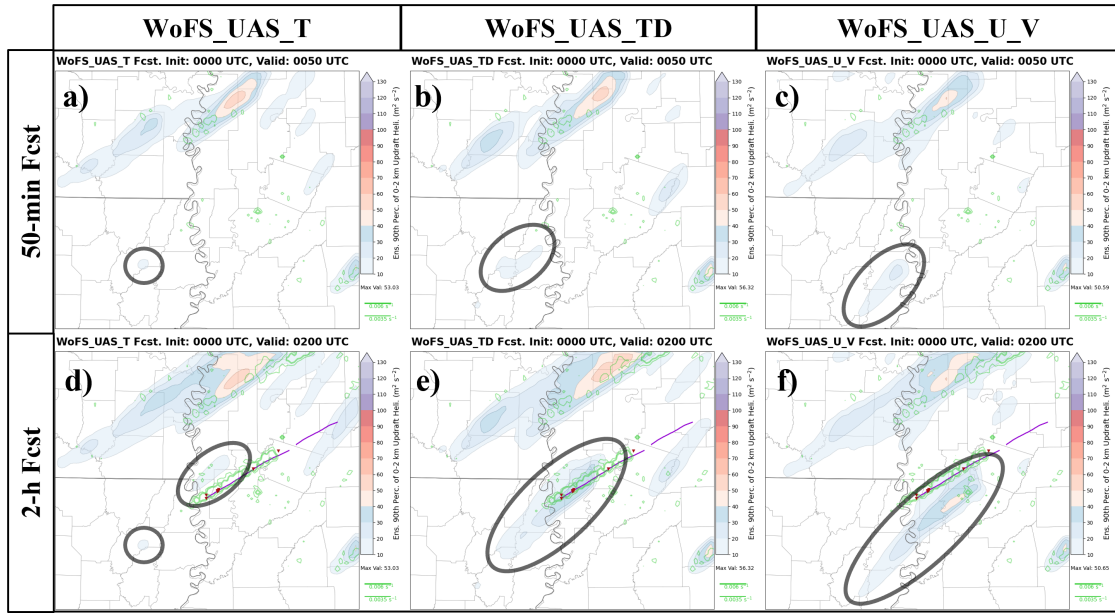


Figure 4.7: Ensemble 90th percentile 0–2 km updraft helicity (UH;  $\text{m}^2 \text{s}^{-2}$ ) (a), (b), (c) 50-min, and (d), (e), (f) 2-h forecasts initialized at 0000 UTC from the WoFS\_UAS.T (left column), WoFS\_UAS.TD (middle column), and WoFS\_UAS.U.V (right column) experiments. The green contours represent observed MRMS 0–2 km azimuthal wind shear ( $\text{s}^{-1}$ ) greater than  $0.0035 \text{ s}^{-1}$  and  $0.006 \text{ s}^{-1}$ . NWS damage paths (solid purple lines) and NWS tornado reports (red triangles) for the EF4 Rolling Fork tornadic event are also overlaid. The dark gray ovals encompass the model-generated rotation swaths.

At the end of the 2-h forecast period the UH swath in the WoFS\_UAS.T experiment is displaced northwest, parallel to the observed MRMS rotation. The WoFS\_UAS.TD experiment simulates the storm rotation more realistically (Fig 4.7e, circled in dark gray) compared to the other two experiments. The WoFS\_UAS.U.V experiment (Fig 4.7f, circled in dark gray) predicts UH with higher intensity values (up to  $50 \text{ m}^2 \text{s}^{-2}$ ) but displaced southeast and parallel to the observed MRMS rotation. However, it should be noted that these swaths are generated from the stronger trailing cell to the southwest (Fig. 4.6) that eventually overtook the storm to north-northeast. Out of all

UAS WoFS experiments, the WoFS\_UAS experiment produces the most accurate UH swath, especially since it originates from the correctly analyzed Rolling Fork supercell. This again indicates that assimilating all three UAS variables are necessary to predict the Rolling Fork tornadic supercell.

In summary, out of the three data denial experiments, the WoFS\_UAS\_TD experiment appears more realistic, followed by the WoFS\_UAS\_U\_V, and the WoFS\_UAS\_T experiments. This is likely because assimilating the moisture variable properly limits the northward advection of moisture. The WoFS\_UAS\_TD experiment predicts higher intensity CREF out of the three UAS data denial experiments (Fig. 4.6, middle column), which could be due to the enhanced moisture and MLCAPE in the inflow region of the model-generated Rolling Fork supercell in the warm sector (Fig. 4.5, middle column). The southwestward displacement of the analyzed Rolling Fork storm is possibly resulting from the enhanced moisture and MLCAPE southwest of the Rolling Fork supercell's inflow region in the warm sector (Fig. 4.5e). By 0050 UTC, the WoFS\_UAS\_TD CREF forecast (Fig. 4.6e) resembles the CREF forecasts from the WoFS\_CNTRL experiment in terms of shape, placement, and intensity (Fig. 4.3d), even though the core is displaced more to the south. This is also seen in the 2-h WoFS\_CNTRL (Fig. 4.3g) and WoFS\_UAS\_TD CREF forecasts (Fig. 4.6h).

The assimilation of only UAS horizontal wind components likely leads to underpredicting the magnitude of the northward wind and overpredicting the magnitude of the eastward wind, resulting in the splitting of the Rolling Fork storm and the increased southward displacement over time (Fig. 4.6, right column). The WoFS\_UAS\_U\_V experiment predicts higher values of UH swaths than any of the other experiments (Fig. 4.7f; including the first set of WoFS experiments), perhaps because of the enhanced low-level wind shear from the assimilated low-level wind observations, which

are uninhibited by decreased UAS temperature observations and/or more spatially-limited UAS moisture observations. Despite the increased intensity, the UH swath is still displaced south of the observed rotation and damage paths potentially as a result of the experiment’s southward displacement of the initial Rolling Fork supercell. The WoFS\_UAS\_TD experiment (4.7e) again presents a UH forecast that resembles that of the WoFS\_CNTRL experiment more closely (Fig. 4.4d), although with slightly higher intensity and southeastward displacement from the WoFS\_UAS\_TD ensemble’s more southeastward placement of the Rolling Fork supercell (Fig. 4.6, middle column). The WoFS\_UAS\_T experiment performs the worst out of the three UAS data denial experiments and compared to the WoFS\_CNTRL experiment, possibly because of a reduction in observed temperatures in the warm sector where the Rolling Fork supercell organized and intensified. This low-level environmental cooling feature is seen in the decrease of the temperature profile below  $\sim 860$  hPa from the 2300 UTC to the 2345 UTC initialization of the 0000 UTC sounding in the WoFS\_UAS experiment (Fig. 4.1b, d).

Overall, all data-denial experiments perform worse than both the baseline WoFS\_CNTRL and WoFS\_UAS experiments. Further investigation is needed to understand why the data-denial experiments perform worse than the WoFS\_CNTRL experiment. This includes additional DA experiments evaluating the sensitivity of the UAS observation assimilation to the vertical localization radii, vertical observation thinning methods, and prescribed observation errors in the DA experiments.

## Chapter 5

### Summary and Next Steps

#### 5.1 Summary

The near-surface BL weather-sensing UAS instruments have been increasingly used to measure in-situ kinematic and thermodynamic observations in the lowest  $\sim 0\text{--}3$  km above ground. The finer vertical resolution of the UAS measurements, coupled with frequent every  $\sim 15$ -min UAS flights can effectively monitor the rapid thermodynamic and kinematic changes in BL storm environments. To explore the potential of UAS observations in analyzing the representations of the BL in CAEs better, CopterSonde measurements collected from the 24–25 March Rolling Fork tornadic event during the PERiLS field campaign are assimilated into an experimental WoFS. Although limited to only three profiling sites, several experiments are conducted to understand the impact of UAS observations in WoFS. Results show that the assimilation of UAS observations helped to correct the depiction of the lower BL in the ensemble when compared with the soundings at the NWS JAN station. The MLCAPE and moisture within the inflow region of the Rolling Fork storm are represented more realistically, as there is enhanced MLCAPE along the south-southwestern edge of the storm and less MLCAPE to the north, further helping to limit the supercell’s northward displacement. The MLCAPE and dryline in the UAS experiment are more bounded to the east into west-central Mississippi than to the north into west-central/northwest Mississippi, which further helps to correct the track of the supercell.

The larger localization radius of 400 km for the CopterSonde observation assimilation in the DA system performs better than the smaller 200 km localization radius. The location, shape, and intensity of the Rolling Fork supercell is improved in the 0–2-h CREF forecasts with the assimilation of CopterSonde observations. More specifically, the data denial experiments reveal that the CopterSonde measurements of the dewpoint temperature and the horizontal wind help to properly intensify and position the storm, as well as limit the initial westward displacement of the supercell. The WoFS\_UAS experiment is able to more accurately represent the northward extent of the moisture advection, induce model stability where necessary via capturing a shallow layer of warm air near the surface, and increase eastward storm motion while limiting northward motion. The WoFS\_UAS experiment seems to do a better job of predicting the shape and location of the evolution of the Rolling Fork tornadic supercell, as well as the low-level rotation swath compared to the WoFS\_CNTRL experiment, which is most pronounced in shorter forecast lead times. The UAS observations also appear to increase the intensity closer to where damage was reported. The CopterSonde measurements of the horizontal wind components that are assimilated and contribute to improving the forecasts include stronger eastward winds than what are originally identified by the baseline ensemble. As for the moisture content, the UAS experiment is able to model the more southbound but robust region of warm Gulf humidity located within the warm sector, thus helping to identify the most convectively conducive parts of the environment.

Overall, the CopterSonde observations help to improve the WoFS modeling of the low-level moisture advection and its extent, as well as improve the north-northwestward displacement by better capturing the magnitude of eastward winds and limiting the magnitude of northward winds as a result. Although all of the UAS variable types are important to help analyze the storm environment, the moisture and horizontal

wind measurements have the most positive impacts on the baseline forecasts. These findings are also supported by the Hu et al. (2019) study that was conducted with the same WoFS experiment but with the assimilation of AERI and DL observations from CLAMPS instead of UAS observations. Their results showed the most improvement to predictions of convection initiation when assimilating thermodynamic observations from the AERI instrument, followed by wind observations from the Doppler Lidar instrument. However, while the results from this single case study with only three profiling sites give us glimmers of hope, the results cannot be generalized and should be interpreted cautiously. More studies need to be performed to assess the robustness of the results obtained in this study, which includes assimilating UAS observations using a network of UAS BL profiling instruments over a diverse set of cases in a convective-scale ensemble DA and prediction system. The CopterSonde measurements collected as part of the recent 2023–2024 *Oklahoma UAS Targeted Flights for Low-level Observations of Weather* (OUTFLOW) field experiments will be assimilated in the WoFS to draw a robust conclusion.

The near-surface BL weather-sensing UAS instruments have been increasingly used to measure in-situ kinematic and thermodynamic observations in the lowest  $\sim 0\text{--}2$  km above ground. The finer vertical resolution of the UAS measurements, coupled with frequent every  $\sim 15$ -min UAS flights can effectively monitor the rapid thermodynamic and kinematic changes in BL storm environments. To explore the potential of UAS observations in analyzing the representations of the BL in CAEs better, CopterSonde measurements collected from the 24–25 March Rolling Fork tornadic event during the PERiLS field campaign are assimilated into an experimental WoFS. Although limited to only three profiling sites, several sensitivity and data denial experiments are conducted to understand the impact of UAS observations in WoFS. Results show that the assimilation of UAS observations helped to correct the depiction of the lower BL in the



ensemble when compared with the soundings at the NWS JAN station. The MLCAPE and moisture within the inflow region of the Rolling Fork storm are improved, as there is more CAPE along the western edge of the storm and less CAPE to the north, further helping to limit the supercell’s northward displacement. The MLCAPE and dryline in the UAS experiment are more bounded to the east into west-central Mississippi than to the north into west-central/northwest Mississippi, which further helps to correct the track of the supercell.

The larger localization radius of 400 km for the CopterSonde observation assimilation in the DA system performs better than the smaller 200 km localization radius. The location, timing, and intensity of the Rolling Fork supercell is improved in the 0–2-h CREF forecasts with the assimilation of CopterSonde observations. More specifically, the data denial experiments reveal that the CopterSonde measurements of the dewpoint temperature and the horizontal wind help to properly intensify and position the storm, as well as limit the initial westward displacement of the supercell. The UAS forecasts are able to more accurately represent the northward extent of the moisture advection, induce model stability where necessary via capturing a shallow layer of warm air near the surface, and increase eastward storm motion while decreasing northward motion. The location, timing, and intensity of the 0–2 km UH swath are also improved, as the UAS observations help to limit the northward displacement of the track and increase the intensity closer to where damage was reported. The CopterSonde measurements of the horizontal wind components that are assimilated and contribute to improving the forecasts include stronger eastward winds than what are originally identified by the baseline ensemble. As for the moisture content, the UAS experiment is able to model the more south-bound but robust region of warm Gulf humidity located within the warm sector, thus helping to identify the most convectively conducive parts of the environment.

Overall, the CopterSonde observations help to improve the WoFS modeling of the low-level moisture advection and its extent, as well as improve the westward and northward displacement by better capturing the magnitude of eastward winds and limiting the magnitude of northward winds as a result. Although all of the UAS variable types are important to help analyze the storm environment, the moisture and horizontal wind measurements have the most positive impacts on the baseline forecasts. However, while the results from this single case study with only three profiling sites give us glimmers of hope, the results cannot be generalized and should be interpreted cautiously. More studies need to be performed to assess the robustness of the results obtained in this study, which includes assimilating UAS observations using a network of UAS BL profiling instruments over a diverse set of cases in a convective-scale ensemble DA and prediction system. The CopterSonde measurements collected as part of the recent 2023–2024 *Oklahoma UAS Targeted Flights for Low-level Observations of Weather* (OUTFLOW) field experiments will be assimilated in the WoFS system to draw a robust conclusion.

## 5.2 Next Steps

Active research is ongoing in the observations and modeling research community to improve understanding storm processes and the representation of those processes in NWP. While the CopterSondes observe the in-situ vertical profiles of temperature, moisture, and horizontal wind components, the CLAMPS-2 instrument remotely observes the same BL variables. The MWR and DL instruments (AERI was unavailable) on board CLAMPS-2 retrieved thermodynamic and kinematic profiles of the BL at the Lake Village, AR site during the same time as the CopterSonde observation collection period prior to the Rolling Fork EF4 tornado. The profiles of temperature,

water vapor mixing ratio, dewpoint temperature, wind speed, and wind direction at the same locations provides the opportunity to compare the time-height evolution of those variables from these two complementary instruments. A future goal of this study is to assimilate profiles from the remote sensing platforms alongside profiles from the in-situ UAS instrument.

While the in-situ CopterSonde is able to sample the BL with higher vertical resolution, the ground-based MWR retrieves the measurements (Figs. 5.1 and 5.2) every 10 minutes. Since the CopterSonde sample observations at different ascending levels during each flight, the observations that are originally sampled every  $\sim 3$  m, are thinned to every 5 m as a means of standardizing the observation vertical levels of all UAS flights. The MWR retrieves data closer to the ground compared to the CopterSonde that begins collecting measurements at 50 m MSL. The BL vertical depth of the MWR measurements is higher than UAS instruments due to the FAA flight restriction ceiling of 1.5 km AGL. The MWR can collect more information through low-level cloud coverage compared to the CopterSonde. The width of the bars for the UAS profiles (Fig. 5.1, right column) are expanded to aid the visual analysis of the 15-min to 30-min interval CopterSonde BL profiles.

The CopterSonde temperature profile sustains a layer of slightly warmer air near the surface compared to the MWR temperature profile (Figs. 5.1a, b, circled in black) that shows gradual cooling of the BL into the afternoon hours. The near surface water vapor mixing ratio is slightly higher in the MWR profile with values  $\sim 12$  g  $\text{kg}^{-1}$  (Fig. 5.1c) compared to  $\sim 10$  g  $\text{kg}^{-1}$  from the CopterSonde (Fig. 5.1d) during the 1715–1930 UTC observation period (second row, circled in black). The MWR profile also features a slight drying of the BL above the surface from  $\sim 1800$ – $1900$  UTC followed by slight re-moistening, while the UAS profile features more persistent, drier

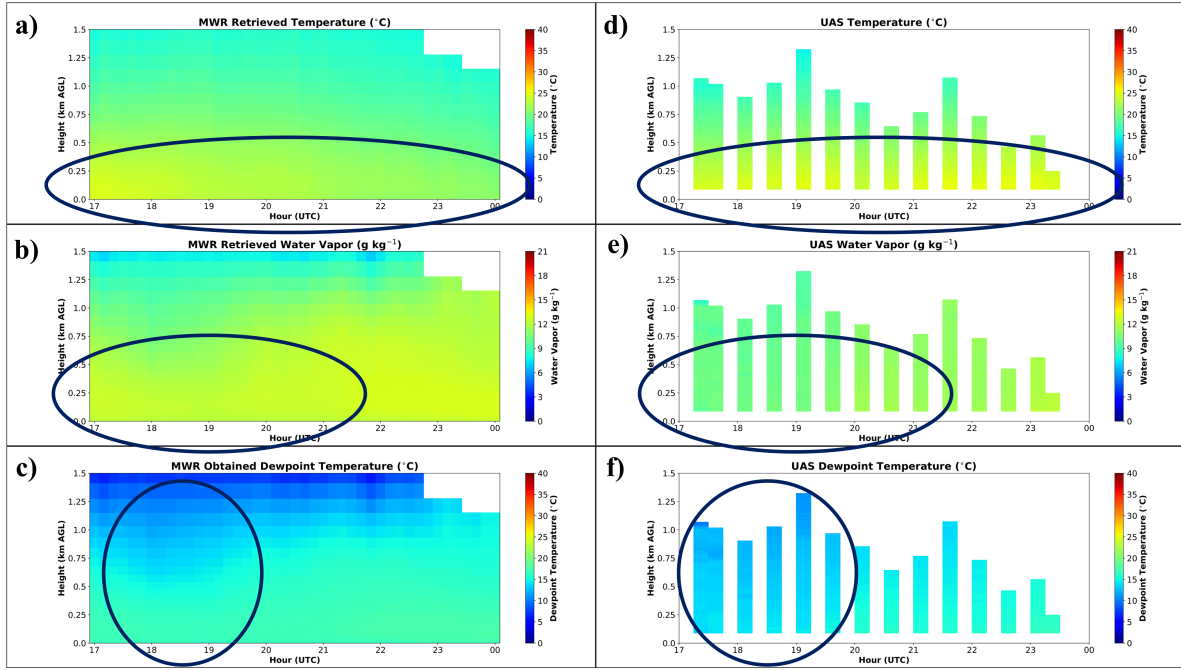


Figure 5.1: The time-height cross sections of (a), (b) temperature, (c), (d) dewpoint temperature, and (e), (f) water vapor mixing ratio from the MWR TROPoe retrieval (left column) and UAS observations (right column) during 1700–0000 UTC on 24–25 March 2023 at the Lake Village, AR site.

conditions at Lake Village through  $\sim 1930$  UTC, followed by slight moistening that plateaus throughout the rest of the observation period. Because of the CopterSonde's higher vertical resolution, it is able to capture more small-scale influences upon the BL. This is why the CopterSonde dewpoint temperature profile from 1700–2000 UTC (Fig. 5.1f) shows the drier environment aloft (from Fig. 5.1c) extending further down toward the surface than in the MWR profile of dewpoint temperature. The slight moistening in both environmental profiles after  $\sim 1900$ – $1930$  UTC is to be expected with the passage of weak showers, as well as the moistening after  $\sim 2000$ – $2200$  UTC due to enhanced northward BL moisture advection.

Unlike the TROPoe-retrieved temperature and water vapor mixing ratio (observed by remote-sensing platforms), the dewpoint temperature in the MWR is derived from both the temperature and water vapor mixing ratio profiles. The CopterSonde, on

the other hand, derives dewpoint temperature from in-situ relative humidity measurements. It is possible that the CopterSonde’s dewpoint temperature profile is a more realistic representation of the BL since these measurements originate from an in-situ instrument compared to the MWR dewpoint temperature profile which is retrieved from remote-sensing platforms. Larger differences are seen between the MWR and UAS dewpoint temperature than between temperature and water vapor mixing ratio. The MWR shows drier air in the atmosphere, mixing down to around 0.5 km AGL from  $\sim 1800$ – $1900$  UTC, similarly to water vapor (Fig. 5.1e, circled in black). Below this drier layer aloft, the MWR profile shows a more stagnant environment with dewpoint temperatures around  $\sim 16$ – $17$  °C. Due to a lowered cloud base height near the end of the observation period, some data is missing from near the top of the MWR profile during  $\sim 2300$ – $0000$  UTC. Although somewhat unclear, it appears that the atmosphere above the surface began to dry slightly ( $\sim 15$  °C) around 1 km AGL (Fig. 5.1e).

The dewpoint temperature profile from the CopterSonde (Fig. 5.1f) exhibits the same extension of drier air towards the surface earlier in the observation period, but with greater vertical detail (bottom row, circled in black). This enhanced vertical resolution reveals drier air much closer to the surface, especially before  $\sim 2000$  UTC, compared to that from the MWR observations. The environment moistens throughout the observed depth of the BL after  $\sim 1945$  UTC, with near-surface values becoming closer to those obtained with MWR (Fig. 5.1f). Moreover, the MWR-derived dewpoint temperature profile does not reveal any significant changes to the lower BL near the surface throughout the observation period, much unlike the UAS. Knowing that both the AERI and MWR struggle to capture the moisture profile of the atmosphere, it is likely that the CopterSonde was able to capture a persistent, shallow layer of stable air just above the surface that was not detected by other instruments.

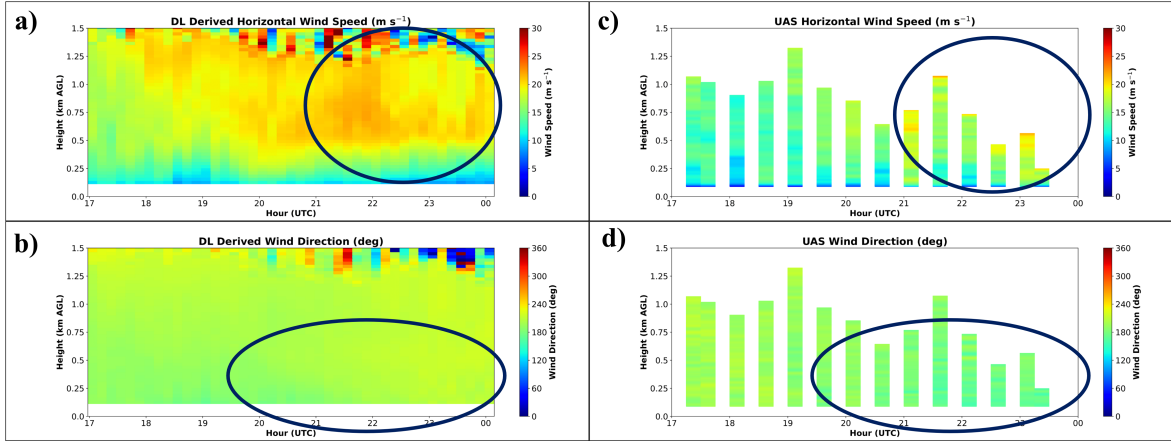


Figure 5.2: The time-height cross sections of (a), (b) horizontal wind speed and (c), (d) horizontal wind direction profile from VAD derived DL (left column) and UAS observations (right column) during 1700–0000 UTC on 24–25 March 2023 at the Lake Village, AR site.

Even though the DL provides higher temporal resolution BL profiles than the CopterSonde, the vertical resolution of the DL is not as fine as that of the CopterSonde. One of the known weaknesses of the CopterSonde is the underestimation of the wind speed when encountering higher velocity winds (Bell et al. 2020), which is most likely to occur near the top of the UAS profiles (Figs. 5.2b, d). Because the winds generally increased throughout the afternoon of 24 March 2023, it is likely that CopterSonde stationed at Lake Village, AR contains more uncertainty towards the latter of the observation period. Uncertainties are also likely to exist near the top of the DL wind profiles later in the observation period, likely due to cloud cover as shown as the noisy data that gradually extend deeper into the BL in (Fig. 5.2a, c).

The largest differences between CLAMPS-2 and CopterSonde BL observations occur in horizontal wind speed (Figs. 5.2a, b). The UAS profile shows weaker wind speeds than the MWR profile overall, however, this could be a result of the CopterSonde underestimating the higher wind speeds at higher velocities near its instrumental threshold. Throughout the observing period, most of the UAS profiles show weaker

winds around  $0 \text{ m s}^{-1}$  close to the surface, which act as a sort of base measurement as the CopterSonde begins to ascend and gather data (Fig. 5.2b). From  $\sim 1800$ – $2000$  UTC (1:00–3:00 pm CDT, local time), the DL profile shows increasing wind speeds near the surface, which captures outflow from the first initial rain band (Fig. 5.2a). After  $\sim 2000$  UTC (3:00 pm CDT, local time), though, the DL profile also begins to capture the development and strengthening of the LLJ over Lake Village, AR, as depicted by the descent of the higher wind speeds of  $\sim 20$ – $22 \text{ m s}^{-1}$  near 0.5 km AGL level (top row, circled in black). Although somewhat difficult to detect due to the increased noise from more frequent vertical measurements, the UAS wind speed profile also reflects the descent of increased wind speeds closer to the ground after 2100 UTC at the latest (Fig. 5.2b, circled in black). Because the height of each CopterSonde flight varies depending on environmental conditions, it is also more difficult to detect the development of the LLJ in the UAS profile. However, the decreased maximum heights, coupled with the increased wind speeds near the top of the CopterSonde profiles, likely suggest the development of the LLJ after  $\sim 2000$ – $2100$  UTC (3:00–4:00 pm CDT, local time), in agreement with the DL data. Despite the additional noise, which is easily filtered out, the UAS profile provides the advantage of capturing smaller changes in the wind speeds at different heights, whereas the DL wind speed profile is more smoothed vertically. This detection of finer details is representative of the CopterSonde better capturing the wind shear profile of the environment, however, further testing and comparison of the CLAMPS data with the CopterSonde data are necessary to determine this.

The wind direction in both profiles mostly stays around  $180^\circ$  with minor fluctuations closer to the surface during 1700–0000 UTC (12:00–7:00 pm CDT; Figs. 5.2c, d). The lower BL (primarily below 0.5 km AGL) shows signs of a slight easterly component in the southerly wind from  $\sim 1800$ – $2000$  UTC (1:00–3:00 pm CDT, Fig. 5.2c).

After  $\sim 2100$  UTC (4:00 pm CDT), the environment maintains a more southerly wind, possibly with a slight westerly component (Fig. 5.2c, circled in black). Compared to the UAS profile of the BL (Fig. 5.2d), the wind gradually shifts from a more southerly, possibly slight southwesterly wind, to a more southeasterly wind near the surface (bottom row, circled in black). Although the shift in the UAS wind direction profile is opposite of the DL wind direction profile, these changes in wind direction are not large enough to cause concern for the slight discrepancy between the observing platforms. The weaker wind speeds near the surface (Figs. 5.2a, b) also make it somewhat harder to accurately estimate the direction of the wind. Overall, both the DL and the CopterSonde reflect a predominantly southerly wind throughout the entire observation period.

The impact of assimilating AERI and DL retrievals in the WoFS (Hu et al. 2019) shows promise. The assimilation of AERI and DL measurements in the WoFS enhanced the low-level convergence and moisture in the near-storm environment that helped lifting parcels to reach the LFC, which in turn helped forecasting convection initiation. The assimilation of AERI and DL predicted the initiation of the storm with 1-h lead time compared to the baseline WoFS. Therefore, the addition of the CLAMPS data can help to fill in temporal frequency gaps as well as provide additional measurements higher up in the PBL where the CopterSondes cannot fly up to due to FAA regulations. Given the strength and limitation of in-situ UAS and ground-based remote sensing MWR and DL instruments, carefully designed DA experiments to assimilate these measurements is likely have a higher impact (Dabberdt et al. 2005; Stalker et al. 2013; Geerts et al. 2018; Bell et al. 2020; Houston et al. 2020; McFarquhar et al. 2020; Bauer et al. 2023; Markowski 2024). The development of a 3D Mesonet network of these types of BL profiling instruments over the CONUS may benefit a wide range of applications,



in particular the short-term prediction of hazardous convective weather by providing better NWP initial conditions.

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