**Report for**

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# Unmanned Aerial System (UAS) Research for Public Safety Applications

## Task 2: sUAS Open Source Weather Forecasting System

**Final Report**

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| | |
|---|---|
| AGL | Above Ground Level |
| API | Application Programming Interface |
| ASSURE | The Alliance for System Safety of UAS through Research Excellence |
| AUC | Area Under Curve |
| ASOS | Automated Surface Observing System |
| AWOS | Automated Weather Observing System |
| CONUS | Contiguous United States |
| DIP | Digital Information Platform |
| FAA | Federal Aviation Administration |
| FSS | Fractions Skill Score |
| GFAFB | Grand Forks Air Force Base |
| GRIB | Gridded Binary |
| GUI | Graphical User Interface |
| HRRR | High-Resolution Rapid Refresh |
| JSON | JavaScript Object Notation |
| LDM | Local Data Manager |
| MC | Mission Commander |
| MCS | Mesoscale Convective Systems |
| METAR | METeorological Aerodrome Report |
| mPING | Meteorological Phenomena Identification Near the Ground |
| MRMS | Multi-Radar/Multi-Sensor |
| NAS | National Airspace System |
| NASA | National Aeronautics and Space Administration |
| NDAWN | North Dakota Agricultural Weather Network |
| NOAA | National Oceanic and Atmospheric Administration |
| NPUASTS | Northern Plains UAS Test Site |
| NSSL | National Severe Storms Laboratory |
| PIC | Pilot in Command |
| PBL | Planetary Boundary Layer |
| PWA | Progressive Web Application |
| ROC | Receiver Operator Characteristic |
| RRFS | Rapid Refresh Forecast System |
| sUAS | Small Unmanned Aircraft System |
| UAS | Unmanned Aircraft System |
| UND | The University of North Dakota |
| UTM | UAS Traffic Management |
| VLOS | Visual Line of Sight |

# EXECUTIVE SUMMARY

Small Unmanned Aircraft System (sUAS) usage has increased dramatically over the past decade. Although sUAS have numerous recreational and commercial uses, their small size make them more prone to weather hazards than traditional aircraft. While sUAS pilots use a variety of websites and services to provide weather forecasts, many of these resources are black boxes with little to no documentation about the skill or performance of the systems.

This project, conducted by the University of North Dakota (UND) through the Alliance for System Safety of UAS through Research Excellence (ASSURE), created an open-source toolkit to provide low-level (< 400' Above Ground Level (AGL)) weather forecasts to sUAS pilots. Starting from the ground up, application development began by surveying sUAS pilots' needs and concerns and comparing this to currently available, operational weather models run by the National Oceanic and Atmospheric Administration (NOAA). An appropriate weather model was selected that updates hourly and provides forecasts out to 18 hours.

Design requirements were synthesized from survey results to create a web-based, multi-platform system to provide precipitation, sustained wind, wind gust, visibility, and ceiling forecasts. The platform also provides popular real-time weather data that is updated sub-hourly. The toolkit runs in the cloud and scales based on the number of user requests made. The overall computing requirements are low meaning that the system can be adapted to a variety of computing environments.

Unlike other tools, this project thoroughly evaluated the performance of wind and precipitation forecasts from the underlying model to understand strengths and weaknesses of the toolkit. This was accomplished using several student-directed projects. A sUAS flight-test campaign took place in rural North Dakota to compare observed to simulated low-level winds. Additional projects evaluated wind and precipitation forecasts across the Contiguous United States (CONUS).

Evaluations determined that the underlying weather model has good skill for both wind and precipitation forecasts. The quality of wind forecasts varied by land-use type, time of day, and the vertical structure of the atmosphere. The statistical study revealed that wind gust errors can be reduced by performing bias corrections, and this feature is included in the toolkit. While the model is skillful for precipitation forecasts, the project found that short-term forecasts can be improved by generating forecasts based on real-time weather data. Optimal precipitation forecasts should be made by aggregating data for a neighborhood surrounding a user request.

It is expected that the toolkit can improve sUAS pilots' decision making by providing probabilistic style forecasts. Despite having improved forecast information, a critical component is convincing and educating users about how this type of system outperforms other resources. Marketing and educational efforts are needed to increase usage and further refine the system.

# 1 INTRODUCTION & BACKGROUND

## 1.1 Introduction

Small Unmanned Aerial Systems (sUAS) usage is increasing for hobbyist and commercial users across the National Airspace System (NAS) (NAS; Lukaks et al. 2022). To assist in safely integrating these systems into the national airspace system, the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) commissioned the Unmanned Aerial Systems (UAS) Traffic Management (UTM) research program as one of many initiatives in this field (Bradford, 2018). The FAA launched an online registration tool for sUAS on 21 December 2015, requiring all sUAS weighing between 0.55 pounds and 55 pounds (0.25 – 25 kilograms) to be registered. As of December 2021, the FAA had registered more than 1.37 million recreational sUAS operators (Lukacs et al. 2022). Furthermore, the FAA forecasts there will be 1.8 million registered sUAS by the end of fiscal year 2026, indicating a continued interest and growth of sUAS hobbyist usage.

Although aviation has always had a strong connection between weather and safety, sUAS are especially prone to meteorological hazards. For example, light precipitation, including individual raindrops, can affect the performance and flight of sUAS operations, as many airframes are not weatherproof (Ranquist et al. 2017). Small-scale objects such as trees and buildings can generate turbulence or flows that impact sUAS flight (Roseman and Argrow 2020). Regardless of vicinity to objects, sUAS operations occur in the Planetary Boundary Layer (PBL), which is more prone to rapid changes than the free atmosphere, resulting in increased odds of hazards. The stationary piloting of the aircraft also presents unique risks compared to traditional general aviation. Rapid decreases in visibility from atmospheric effects or optics, and ground objects, can distort or even block the line of sight to the aircraft. A study into causes of sUAS crashes and near mid-air collisions revealed that 73 percent of incidents were caused by equipment malfunction, while only 3 percent were caused by adverse weather or turbulence (Joslin, 2015). Although this may seem like a small fraction of events, this is compounded by the large number of aircraft and flights flown along with the presumed frequency of unreported events.

As a result of the unique weather hazards that hamper sUAS operations, the FAA has defined specific regulations for all sUAS operators to abide to. These are under Title 14, Part 107, known as "Part 107." sUAS operated by hobbyists under Part 107 must weigh less than 55 pounds (25 kgs), be within Visual Line of Sight (VLOS), and must be flown below 400 feet (122 meters) Above Ground Level (AGL). Specifically, 107.51 defines the operating limits for sUAS. It indicates that sUAS may not be flown in visibility less than 3 statute miles, within 500 feet (152 meters) of a cloud vertically, and within 2000 feet (609.6 meters) of the cloud horizontally (eCFR, 2016). There is no specific requirement pertaining to precipitation although visibility and the occurrence of cloud are related to the presence of rain or snow. Further, subsection 107.23 states that no person may *'Operate a small unmanned aircraft system in a careless or reckless manner so as to endanger the life or property of another'*. This may be interpreted as only flying a sUAS in conditions it can handle (e.g. outside of precipitation for airframes without weather proofing or within wind conditions it is rated for).

## 1.2 Objectives and Timeline of Task 2

In light of this background, the purpose of this task was to build an operational, open source tool-kit to provide forecasts and real-time weather data to sUAS operators. The general design strategy for this project was to first consult sUAS operators to understand their needs, identify the appropriate weather model for the project, and then build a cloud-based application to provide forecasts for both computer and mobile devices.

Unlike black-box applications that are commonly used by sUAS operators, a major component of this project was to build a **properly validated forecast system** such that its strengths and weaknesses are known. Further, the application was designed to give **probabilistic forecasts** (e.g. a range or probability of values) vs. deterministic (single value) forecast. This was accomplished through one non-thesis and two thesis research projects that investigated various aspects of the system. Four overreaching tasks and deliverables were developed for the project (Table 1).

Table 1. Project Tasks and Deliverables

| Task | Deliverable |
|---|---|
| **2.1**: Develop low altitude weather prediction models with different types of weather phenomena (e.g., winds, temperature, icing, thunderstorms, precipitation, etc.) that could impact the multi-copter, fixed wing, and hybrid small UAS. | Weather models particularly suitable for low altitude airspace operations. |
| **2.2:** Validate these limiting weather parameters using at least two (2) fixed wing, two (2) hybrid, and two (2) multi-copter platforms. Include most popular consumer, prosumer, and/or professional models. | Interim report for prediction system. |
| **2.3**: Develop an open source toolkit for operator use that provides guidance based on type of vehicle and whether it is safe to operate the vehicle in the conditions experienced. | A web- and mobile-based, open source, easy-to-use application with online documentation to guide operators on safe and unsafe conditions based on the type of vehicle and supported by validated models and actual and predicted weather. |
| **2.4**: Conduct usability and feasibility assessment of the open source weather toolkit among consumer, prosumer, and professional UAS operators to ensure that the toolkit is highly relevant to their needs. Further, develop and implement an online crowdsourcing approach for updating the weather information as needed. | Usability and feasibility assessment; crowdsourcing approach for updating weather information. |

Task 2.1 largely encompassed a market research phase where sUAS operators were given a survey to understand their needs and tested over their understanding of application mock-ups. Based off of this feedback, the deliverable was the selection of a weather model appropriate for the system along with a prototype. A strategy was also developed to evaluate and improve weather model output specifically for the needs of sUAS operators.

Task 2.2 focused on the validation of the weather model through various efforts. This included an observational campaign from May 2022 – March 2023 which measured actual winds at heights < 400 ft. AGL. This was accomplished with the help of the Northern Plains UAS Test Site (NPUASTS) who provided logistical support for the campaign including an airframe, pilots, and safety management personnel. UND students launched weather balloons coordinated with UAS flights for comparison purposes. Additional validation of the system was carried throughout the duration of project via two thesis projects that focused on wind and precipitation forecasts. The deliverable was an interim report (the first thesis). This final report represents the final stage of this task, summarizing all efforts to date.

Task 2.3 covered the development of the open-source application from start to finish. Project tasks were carried out by WxByte LLC, a software firm that focuses on web/mobile applications. Development used common Application Programming Interface (API) and backend packages to facilitate future reliability and development of the system. The application was and is still operated on a Google cloud server. The deliverable is the application itself and its open-source code.

Task 2.4 centered on contacting users, requesting feedback, and implementing or fixing issues that users noticed during the duration of the project. A major thrust of this effort was engaging potential users through several marketing efforts. The deliverable is this final report which summarizes all activities and provides guidance and best practices for future efforts.

The remainder of this report is organized by specific task and subtasks. Within the conclusions, best practices and lessons learned are provided.

# 2 TASK 2.1: DEVELOPMENT OF THE PREDICTION SYSTEM

Task 2.1 was divided into four subtasks (Table 2) and was carried out from project start to T+22 months (Figure 1). Major activities completed in support of Tasks 2.1.1-2.1.3 included the creation and analysis of a Qualtrics survey for sUAS pilots and a review of available weather models appropriate for the project. Task 2.1.4 included the initial evaluation of the predictive system. For the sake of cohesion with similar tasks, it is discussed under Task 2.2.

Table 2. Task 2.1 Subtasks

| Task | Team |
|---|---|
| 2.1.1: Identify weather phenomena of importance for low-altitude sUAS operations. | UND |
| 2.1.2: Define weather-based products (decision support elements) for system. | UND |
| 2.1.3: Identify base weather model best suited for this application. | UND |
| 2.1.4: Develop prediction system that produces weather-based products (diagnostics and error-correction prognostics). | UND |

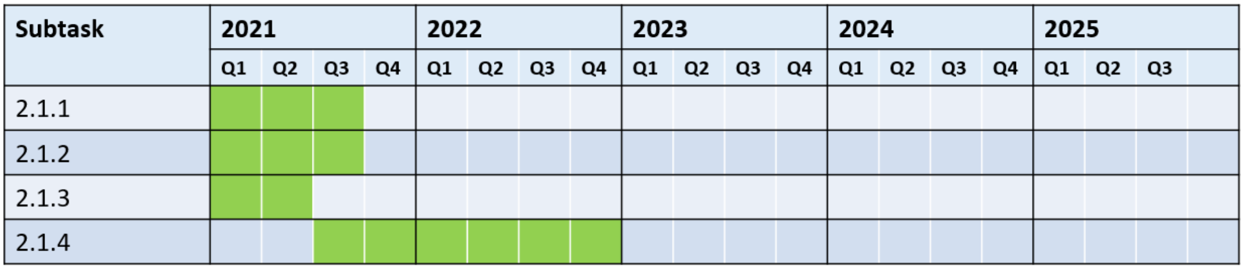


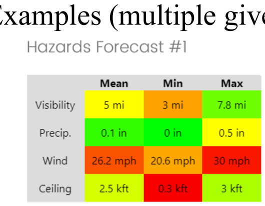

Figure 1. Timeline of Task 2.1.

## 2.1 sUAS Operators Survey

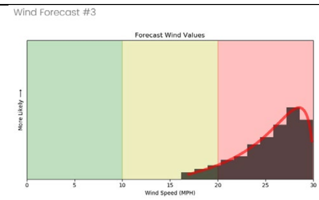
An online Qualtrics Survey was developed and distributed to sUAS operators. This survey was advertised via social media (Facebook / Twitter), email/ASSURE/college channels, and an autonomy conference held in Grand Forks, ND (Figure 2). Feedback was open for a ~2 month period in the fall of 2021. The survey collected demographics information, surveyed users about weather information, and tested their ability to interpret mock-ups of the application (Table 3). A total of 108 responses were recorded although only 82 responses answered a sufficient number of questions to be included in the analysis.


Figure 2. Example advertisement for the survey.

Table 3. Primary questions for the sUAS Survey

<table>
<tr><td>Demographic Information</td><td>What is your UAS piloting experience?<br>What type of UAS do you fly?<br>What size is the UAS you pilot?<br>At what height do you fly?<br>In which state do you typically fly?<br>Over what terrain types do you fly?</td></tr>
<tr><td>Weather Hazards and Tools</td><td>Rank the following hazards in order of importance:<br>What weather sites or applications do you currently use?<br>When do you typically check the weather forecast?</td></tr>
<tr><td>Feedback on Mock-Ups</td><td>Examples (multiple given)<br>

<br>How likely is a flight?<br>What hazard is most likely?</td></tr>
</table>

| | |
|---|---|
| |  <br>How likely is a flight for this period? |

### *2.1.1 Demographic Results*

Survey users were typically knowledgeable with 80% falling under the intermediate or expert category for piloting experience. The majority (67%) had flown both fixed- and rotor wing UAS, while an additional 27% flew rotor wing UAS. 84% of responses for UAS size fell under Groups 1 (0-20 lb) or 2 (21-55 lb) categories. A large fraction of surveyed pilots flew in North Dakota (46%) with other responses spread throughout the US. Operators reported they flew over a variety of terrain types with rural areas being the most frequent (Figure 3). Overall, these responses demonstrated that the survey reached users who fly under Part 107 and that the application should be thoroughly evaluated across the CONUS.

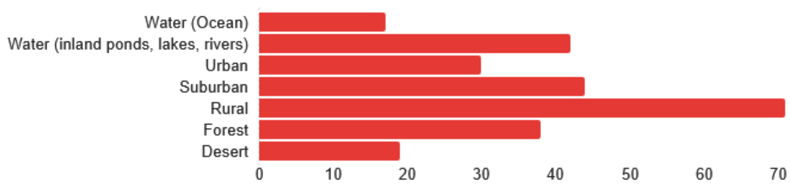



Figure 3. Survey responses for types of terrain flown over.

### *2.1.2 Weather Hazards and Tools Results*

The second section of the survey polled users on the most important weather hazards, when they check forecasts, and resources they utilize. These responses were ranked in order of importance to focus efforts for this project (Table 4). Results showed that precipitation and wind forecasts for times < 24 hours of flight were the most important to survey users. As such, development focused on short-range weather models with the ability to forecast small-scale changes in these variables. While visibility (and then cloud ceiling) were also higher-ranking responses, these fields are known to be problematic in weather models. These variables were not analyzed as part of this project.

Table 4. Top ranked survey responses for weather hazards and forecasts.

| Weather Hazard of Concern | Time of Weather Check |
|---|---|
| 1) Precipitation | 1) Time of flight |
| 2) Wind Gusts | 2) Morning of flight |
| 3) Sustained Winds | 3) Night before flight |
| 4) Visibility | 3) Hour before flight |

Users reported a variety of tools to address UAS forecasting needs. As this was an open-field response, tabulations of data were compiled manually. Popular tools (in no particular order) included 1800wx, ForeFlight, aviationweather.gov, weather.com/gov, and Weather Underground. Other listed tools generally focused on point, time of flight type data including METeorological Aerodrome Report (METAR) reports or radar data suggesting this type of information would be useful in the application.

#### *2.1.3 Feedback on Mock-Ups*

The last portion of the survey tested user's ability to correctly interpret mock-ups of the application Graphical User Interface (GUI). Three different weather scenarios were created and data was presented in two ways (Figure 4). The first presented tabular data providing an average, minimum, and maximum expected value for variables. The second provided a color-coded distribution of expected winds. These values came from the hypothetical situation where data was polled for a circular region surrounding a user's requested forecast. In practice, this would mean querying multiple grid cells of a weather model to provide a probability or range in possible solutions.

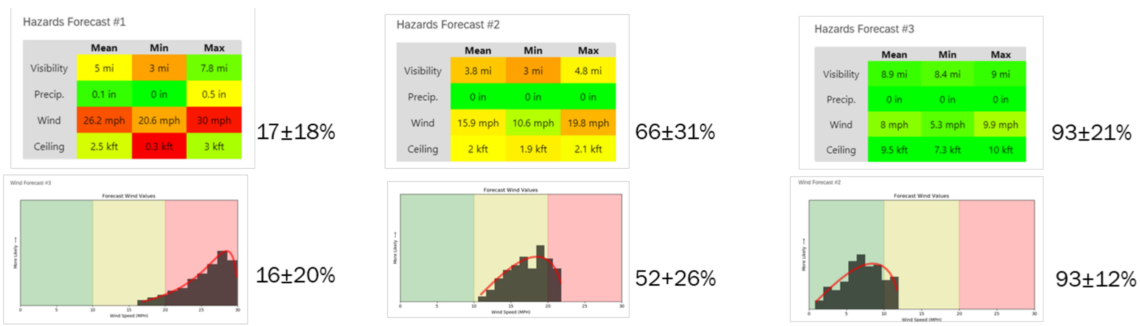



Figure 4. Survey responses for the question: 'How likely is a flight' based on two GUI mock-ups. Numbers represent the percentage giving a 'Y'.

While there is no correct response due to different comfort levels with meteorological hazards and the varying abilities of UAS airframes, results demonstrated that users correctly interpreted the presented scenarios. The most uncertainty occurred for scenario #2 that featured winds spanning from low to high values. Scenarios for low and high winds were surprisingly similar in interpretation with 16-17% suggesting they could fly for the high wind scenario and 93% for the low wind scenario. Overall, it was concluded that the mock-ups were appropriate for the application and development could proceed.

### 2.2 Survey and Selection of a Weather Model

Identification of an appropriate weather model for the application began with an inventory of federally supported, operational weather models (Table 5). Characteristics were compared to the needs of the users. The accessibility of data was also identified. While all models are available directly from NOAA, the inventory primarily focused on weather models that have data sharing agreements with cloud services via Amazon and Google. Shared cloud platforms for hosting of data and the application greatly simplifies data acquisition, decreasing both compute time and cost.

Table 5. Operational weather models funded by the US with accessible data. Selected model is in bold.

| Model | Frequency (hours) | Forecast Range (hours) | Time Output (hours) | Horizontal Spacing (kilometers) | Availability |
|---|---|---|---|---|---|
| **High-Resolution Rapid Refresh (HRRR)** | **1** | **18** | **1** | **3** | **NOAA Amazon Google** |
| Rapid Refresh (RAP) | 1 | 21 | 1 | 13 | NOAA Amazon |
| North American Mesoscale (NAM) CONUS Nest | 6 | 60 | 3 | 3 | NOAA |
| North American Mesoscale (NAM) | 6 | 84 | 3 | 12 | NOAA Amazon |
| Global Forecast System (GFS) | 6 | 384 | 3-6 | 28-70 | NOAA Amazon Google |

Users stated the need for weather forecasts within 24 hours of flight time, and for variables such as wind speed and precipitation that are characterized by significant variability across both space in time. This highlighted the need of a model with frequent updates and a high resolution capable of simulating various types of precipitation. When combined with accessibility needs, the High-Resolution Rapid Refresh (HRRR) model (Dowell et al. 2022) was selected.

Once the HRRR was selected, literature reviews were carried in Horan (2023) and Britt (2025) to understand known strengths and weaknesses. For the sake of brevity, these literature reviews are only summarized here. Prior studies that focused on HRRR wind forecasts found the model to be skillful (Fovell and Gallagher 2020;2022). Some issues were noted in the first hour, presumably due to model spin-up, but the larger issue was wind bias that was negatively correlated with wind strength. There was also evidence that these systematic biases were dependent on land-use.

James et al. (2022) summarized numerous studies that evaluated precipitation. Many of these studies focused on the convection (thunderstorm) allowing nature of HRRR and found it tends to over produce convective storms along with having issues with the evolution of Mesoscale Convective Systems (MCS). Many of these studies focused on precipitation amount vs. precipitation occurrence, obscuring their utility for this project that was focused on whether precipitation would occur or not. Overall, the lack of literature regarding forecasts specific to low-altitude (sUAS) flights encouraged us to perform our own evaluation studies summarized under Section 3.

# 3 TASK 2.2: VALIDATION OF THE PREDICTION SYSTEM

Task 2.2 was divided into five subtasks (Table 6) and was carried out from project start to T+27 months (Figure 5). Note that Task 2.2.5 was adjusted to represent an interim report that covered evaluation of the project to date. An additional evaluation project, Britt (2025), occurred under Task 2.4 and is included in this final report. For the sake of organization, all validation activities for the program are included in this section.

Table 6. Task 2.2 Subtasks.

| Task | Team |
|---|---|
| 2.2.1: Identify representative aircraft (fixed-wind, rotary-wing, hybrid) | UND/NPUASTS |
| 2.2.2: Develop test plan for validation of prediction system | UND/NPUASTS |
| 2.2.3: Obtain validation sensors and integrate into unmanned aircraft | UND/NPUASTS |
| 2.2.4: Execute flight tests to collect data regarding prediction system. | UND/NPUASTS |
| 2.2.5: Produce evaluation report for prediction system. *(Interim Report)* | UND |

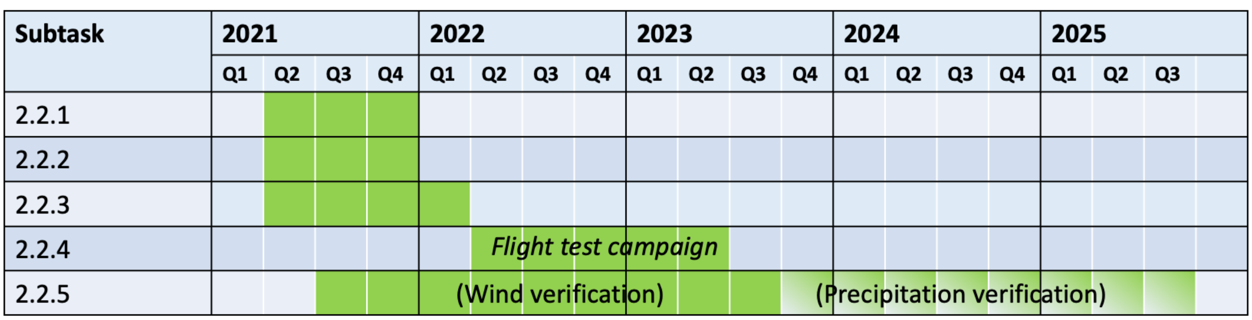



Figure 5. Timeline of Task 2.2.

Subtasks 2.2.1-2.2.4 encompassed the development and execution of a flight test campaign to measure low-level (0-400 ft AGL) winds to validate HRRR forecasts. Organized and executed in partnership with the NPUASTS, this effort is summarized in Section 3.1. Two student projects were completed to analyze results from this effort (Table 7) and are summarized in Section 3.2. Two additional thesis projects were undertaken to systematically evaluate wind and precipitation forecasts across the CONUS. These projects are discussed in Sections 3.3-3.4.

Table 7. Validation projects for the forecast system.

| **Evaluation** | **Student** | **Project Type** |
|---|---|---|
| A Comparison of Balloon-Borne and sUAS Observed Boundary Layer Winds | Blake Rafferty | Undergraduate |

| | | |
|---|---|---|
| Evaluation of Surface and Boundary Layer Winds in the HRRR over Eastern North Dakota | Joshua Kern | MS Non-Thesis |
| Verification of HRRR Surface Winds In Support Of An Open-Source sUAS Application | Brian Horan | MS Thesis |
| Precipitation Forecasts and Verification for sUAS Applications | Patrick Britt | MS Thesis |

## 3.1 Flight Test Campaign (Tasks 2.2.1-2.2.4)

### *3.1.1 Summary*

A flight test campaign was executed from May 2022 – April 2023 in partnership with the NPUASTS. The goal of the campaign was to measure atmospheric variables at heights where Part 107 flights occur (< 400 ft AGL) in a variety of meteorological conditions. Flight conditions were limited to surface winds/gusts < 25mph (~11 m/s). This data was compared to traditional weather balloon measurements and then to the HRRR model. Unlike originally proposed, it was determined that project goals could be accomplished using a singular, rotor-wing platform to collect measurements. This lowered costs for the execution of the campaign, allowing for additional flight test days and simultaneous launching of the weather balloons.

UND and NPUASTs identified the Oakville Prairie Biological Field Station located near Emerado, ND as the optimal location in the region for the campaign (Figure 6). The site was located approximately 13 miles west of Grand Forks, ND making travel logistics simple from UND and NPUASTS. It was also a location representative of ‘rural’ land use which was a common response in the sUAS survey. sUAS flights occurred in airspace that allowed Part 107 flights without needing coordination with the nearby Grand Forks Air Force Base (GFAFB). The rural road network and public land also allowed for simplified retrieval of the recoverable weather balloon instruments. A flight test plan and test cards were developed to guide the project (Appendix 1).

Over the flight campaign, a total of 151 flights were flown across 24 flight test days (Table 8). Of these 151 flights, 137 had complete flight profiles. In an effort to sample a range of meteorological conditions, flights were held hourly during transition periods from either morning to daytime, or daytime to evening. This allowed for sampling of the ramp-up or ramp-down phases of surface/boundary layer winds. As the project progressed, modifications were made to the original test plan to fit in flights when weather allowed. Precipitation and clouds in the region were common hazards that limited flight days.

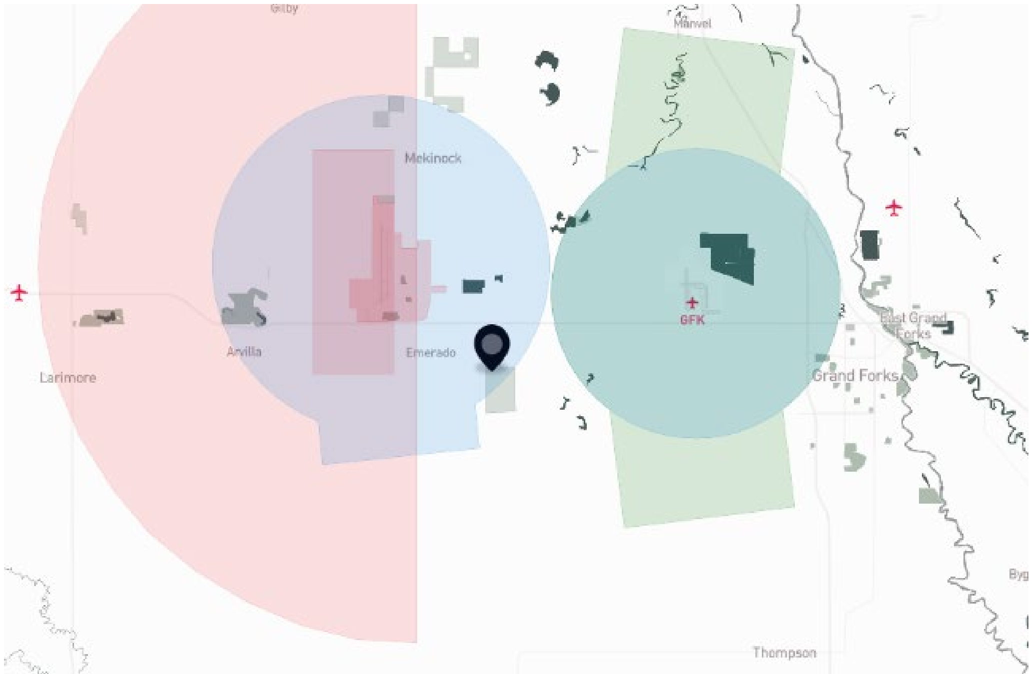



Figure 6. Location of the flight test campaign (black pin) overlaid with regional airspace classifications. Actual flight location was just outside of Class D (blue) airspace.

Table 8. Flight test days and number of fully executed flights.

| Date | Flights (#) | Date | Flights (#) |
|---|---|---|---|
| 15 June 2022 | 5 | 11 January 2023 | 6 |
| 12 July 2022 | 6 | 7 February 2023 | 7 |
| 9 August 2022 | 6 | 8 February 2023 | 6 |
| 13 September 2022 | 6 | 13 February 2023 | 6 |
| 14 September 2022 | 6 | 14 February 2023 | 6 |
| 17 October 2022 | 1 | 28 February 2023 | 6 |
| 18 October 2022 | 6 | 3 March 2023 | 6 |
| 21 October 2022 | 6 | 12 April 2023 | 6 |
| 20 November 2022 | 6 | 17 April 2023 | 5 |
| 1 December 2022 | 6 | 24 April 2023 | 6 |
| 27 December 2022 | 6 | 25 April 2023 | 5 |
| 28 December 2022 | 6 | 27 April 2023 | 6 |

### *3.1.2 sUAS Platform and Meteorological Instrumentation*

To carry out the campaign, NPUASTs used an xFold Spy quadcopter to lift widely used meteorological instruments including the LiCor TriSonica Mini anemometer and an IMET XQ2 UAS sensor (Figure 7). The former sensor provided three-dimensional wind information (only horizontal direction and magnitude used), while the latter provided pressure, temperature, and humidity. Based on the size of the platform and prior sUAS instrumentation studies (Green et al. 2018; Thielicke et al. 2021; Wilson et al. 2022) instruments were integrated onto a vertical boom approximately 1.2× the rotor diameter above the rotor plane. This minimized impacts due to rotors (turbulence) and heat generated by motors and avionics. Measurements were collected while the platform was in a stable hover at predefined heights to minimize issues with cross-flow.

Figure 7. Left: The xFold Spy sUAS integrated with instrumentation including the TriSonica Mini (being pointed at) and an IMET XQ2 (white box with sensor safety cover installed). Right: Students launching a Windsond weather balloon. High visibility balloons were used to improve visibility for the sUAS team.

In addition to the sUAS instrumentation, vertical profiles of the atmosphere were also obtained using launches from Windsond S1H2 sondes during the summer and fall portions of the flight campaign. These lightweight, reusable weather balloon packages were launched simultaneously during sUAS flights to provide additional verification data along with a way to assess sUAS performance. In practice, sondes were cut down from their balloon at heights around 1 km AGL, then retrieved for reuse. Table 9 provides a summary of instrument performance data.

Table 9. Instrument characteristics for the flight campaign.

| Instrument | Field | Resolution | Range | Accuracy |
|---|---|---|---|---|
| Li-Cor Trisconica Mini (LI-550) | Wind Direction | 1° | 0-360° | +/- 1° |
| | Wind Speed | 0.01 m/s | 0-50 m/s | +/- 2% |
| InterMet XQ2 | Temperature | 0.01°C | 90 - -50°C | +/- 0.03°C |
| | Humidity | 0.1% RH | 0-100% | +/-5% |
| | Pressure | 0.01hPa | 1200-10 hPa | +/- 1.5hPa |
| Sparv Windsond S1H2 | Wind Direction | 0.1° | 0-360° | *Depends* |
| | Wind Speed | 0.1 m/s | 0-150 m/s | +/- 5% |
| | Temperature | 0.3°C | 80 - -40°C | +/- 0.3°C |
| | Humidity | 0.05% RH | 0-100% | +/-2% |
| | Pressure | 0.02hPa | 11200-300 hPa | +/- 1hPa |

### *3.1.3 Results: sUAS vs. Windsond Weather Balloons*

sUAS measurements were first compared to observations collected by the Windsond weather balloons (Figures 8-9). Vertical profiles for the sUAS demonstrated more variability (weaker) winds within 100' AGL of the surface than the Windsond (Figure 8). This was attributed to the time it took for the weather balloon to lock GPS position that winds are measured from. Above this height, weather balloon measurements were generally within the range of data collected by the sUAS. Across the entire flight campaign, median values for the sUAS were typically < 1.5 m/s (3.4 mph) higher than the balloon measurements.

Thermodynamic measurements (Figure 9) suggested biases could be explained in part by micrometeorological differences between the sUAS and Windsond sites (up to a mile distant). Temperature biases were usually within 0.5°C except for heights < 100' (30m) AGL at night. This was evidence of the nocturnal temperature inversion forming differently between locations. It is expected this would also cause differences between the winds measured across the two platforms.

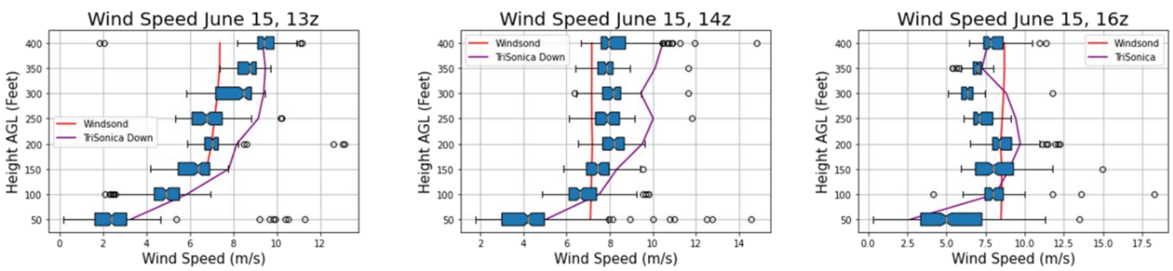



Figure 8. Vertical profiles of wind speed from 13-16 UTC on 12 June 2022. sUAS measurements are shown as blue box plots with median values given by the purple line. Windsond observations are the red lines.

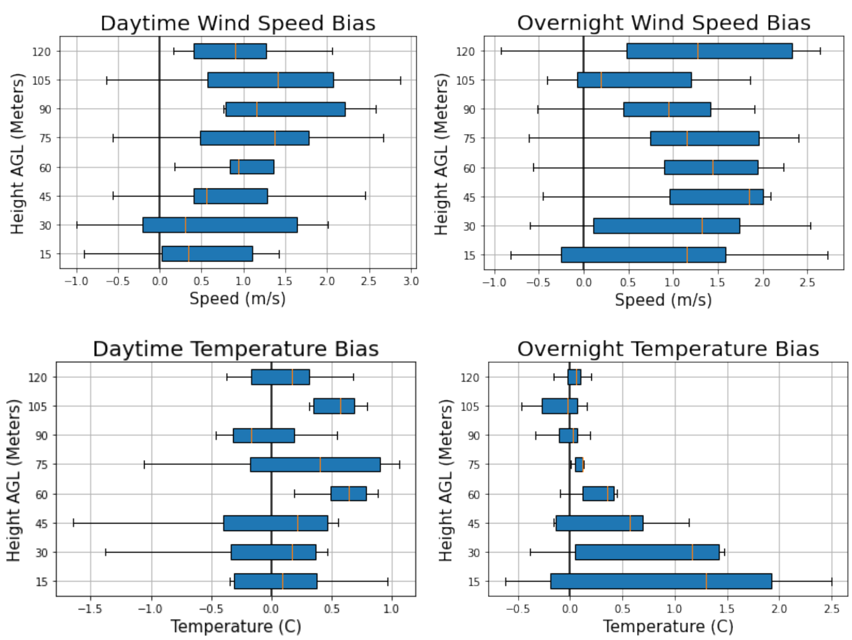



Figure 9. Wind (top) and temperature (bottom) bias (sUAS – Windsond) as a function of height for daytime (left) and nighttime (right) flights.

### *3.1.4 Results: sUAS vs. HRRR Wind Forecasts*

The sUAS wind observations from the flight test campaign were used to evaluate HRRR wind forecasts. This was done by taking surface wind, surface wind gusts, and 80m wind 1-hour forecasts from the nearest model grid point to the sUAS launch location near Emerado, ND. Wind measurements were also acquired from the North Dakota Agricultural Weather Network (NDAWN) station located at the Oakville Prairie Biological Field Station. The analysis was segregated by time of day (morning vs. evening) flights and by atmospheric lapse rate (rate in change of temperature with height).

Results for an example flight test day are shown in Figure 10. Day-to-day performance was highly variable depending on the stability of the atmosphere. For this particular day, observed surface winds were better predicted by HRRR wind gusts vs. sustained winds. At height (80m), HRRR forecast values were typically within 2 m/s of the observations. They also suggested model skill in time with a weakening of winds at 02 UTC.

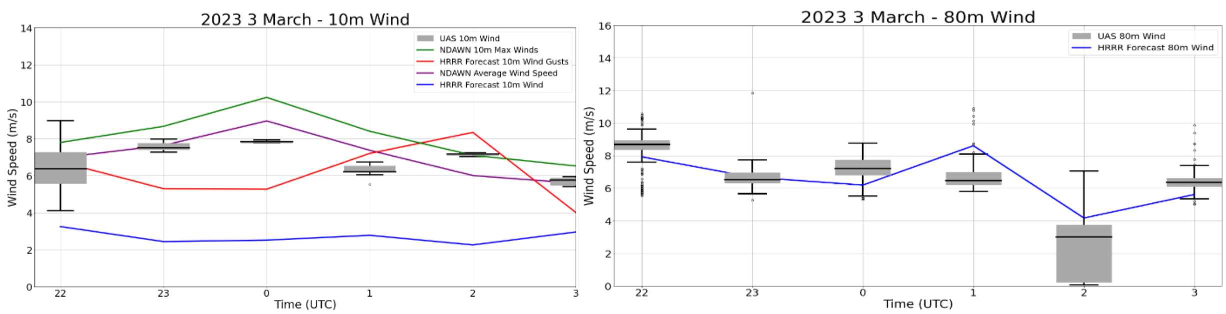



Figure 10. Observed and simulated surface (left) and 80m (right) winds on 3 March 2023.

Results were tabulated by time of day and height (Table 10). Winds were on average, under-forecast except for surface winds in the morning. Median biases were < 2 m/s although greater day-to-day variability was seen depending on atmospheric stability. Wind bias was sorted by near-surface lapse rate, but the only statistically significant (>95%) relationship was found for surface winds in the morning (Figure 11) with a correlation coefficient of 0.47 and a p-value of $6.4*10^{-4}$.

Table 10. Median bias (HRRR – sUAS) for the flight test campaign)

| | 10m | 80m |
|---|---|---|
| Morning | 0.66 | -0.73 |
| Evening | -1.59 | -0.34 |

Overall, the flight test campaign demonstrated the capability of the HRRR to simulate both surface winds and winds at flight level (80m). While median errors were typically within 2 m/s, significant variability was found on days with rapidly varying thermodynamic profiles as the boundary layer either developed in the morning or decoupled at night. From the application point of view, HRRR surface wind gusts were typically higher than flight level winds due to mixing above the limits of Part 107 flight. Although this campaign was considered a success, the limited nature of campaign (one rural location) and ~100 flights during weaker wind conditions < 25mph stressed the importance of also evaluating the forecast system for surface winds and gusts in a broader fashion.

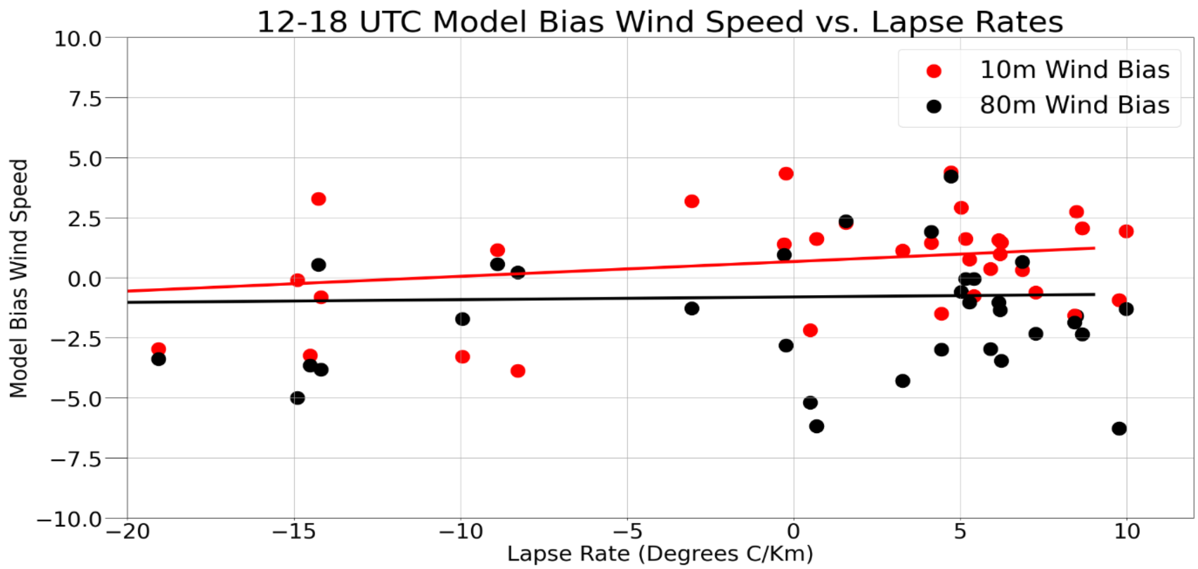



Figure 11. Wind bias as a function of low-level lapse rate for 10m (red) and 80m (black) winds.

## 3.2 Results: Horan (2023) – CONUS Evaluation of HRRR Surface Winds and Gusts

One year (January 1 – December 31 2021) of HRRR wind forecasts were evaluated against Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) across the CONUS (Figure 12). The analysis was performed for HRRR simulations at 00, 06, 12, and 18 UTC out to 48 hours (F48). Results were separated by land use and region (Figure 12), forecast time, time of day, and season. For a full description of the methods, the reader is referred to Horan (2023).

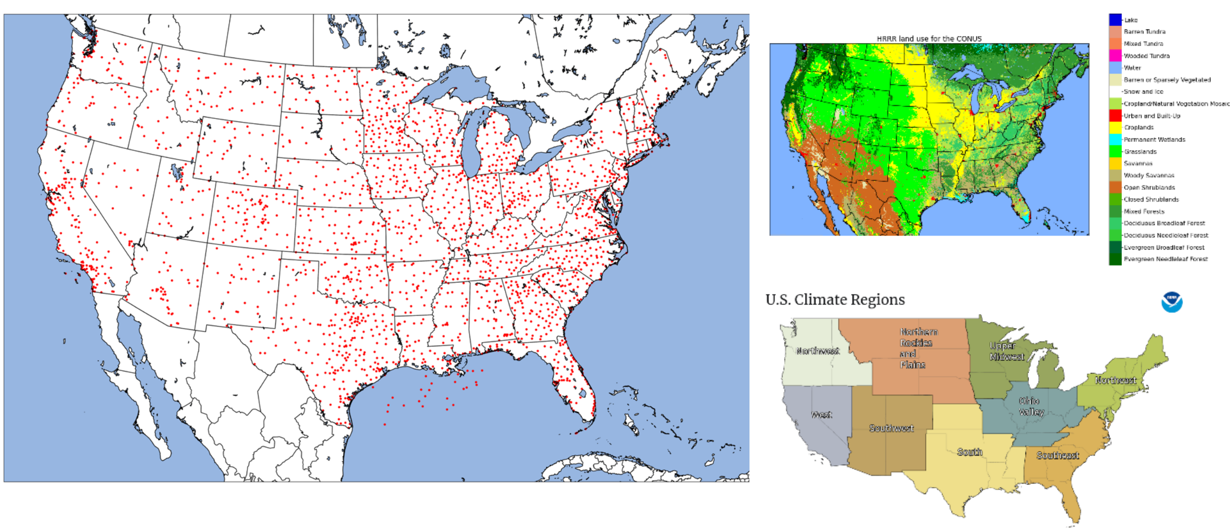



Figure 12. Left: ASOS/AWOS sites used for the evaluation. Top Right: HRRR land-use mask. Bottom right: US Climate regions as defined by NOAA.

### *3.2.1 Sustained Winds*

Sustained wind bias was first investigated as a function of forecast hour (F00-F48) across the CONUS (Figure 13). While median wind bias was small (< 1.5 m/s) for all hours, variations are seen as a function of time. First, a negative median bias was found at the F00 analysis hour, a known issue for HRRR (Fovell and Gallagher 2020). From F01-F18, median bias was near 0 and then increased to a positive ~1 m/s bias from F24 onward. Based on the input from sUAS survey and availability of HRRR forecasts to F18 for every hour (simulations are only made to F48 every 6 hours), it was decided to focus the rest of the analysis on F00-F18 as forecasts longer than F18 would not be included in the application.

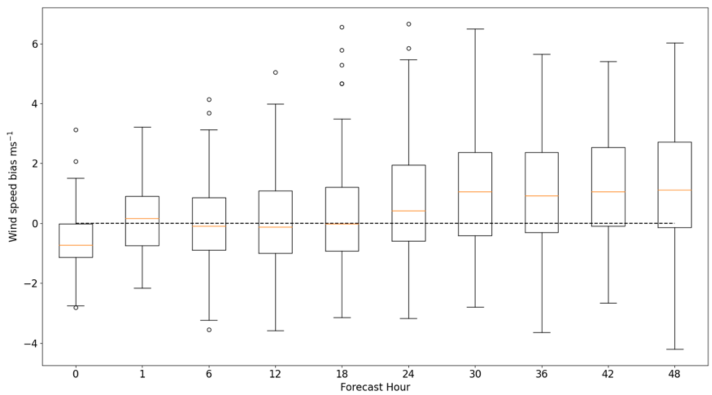



Figure 13. HRRR wind bias (HRRR – observations) for the CONUS as a function of forecast hour.

Forecast/observation pairs were then separated by season to understand variations throughout the year (Figure 14). The positive bias for HRRR winds was seen regardless of season, with similar correlation coefficients (0.73-0.78). Performance was slightly worse during the winter, which was hypothesized to be related to stable boundary layers as noted from the flight test campaign.

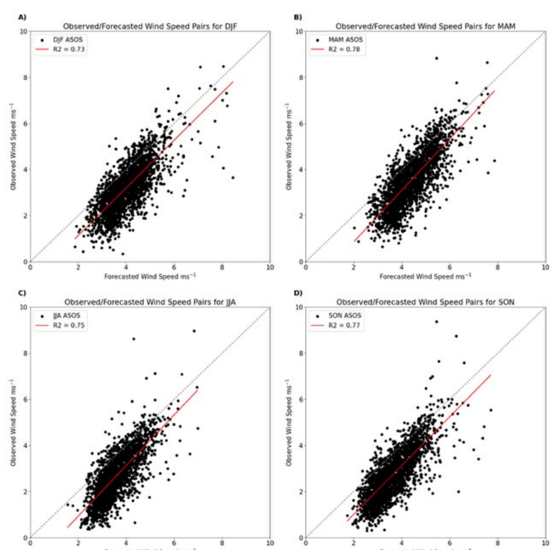



Figure 14. Scatterplots of HRRR/observation sustained wind pairs for a) Winter, b) Spring, c) Summer, and d) Fall. The red line is the line of best fit.

Sustained winds were finally analyzed as a function of region and land-use (Figure 15 and Table 11). Consistent with prior results, HRRR sustained winds had a positive bias regardless of region, although the magnitude varied by land-use and region. Urban areas had the smallest positive bias (0.38m/s) while open water the largest (1.31 m/s). Forest, cropland, and grassland fell in-between with biases ranging from 0.99-0.79 m/s. Overall, these values were similar year-round with no noticeable differences by season.

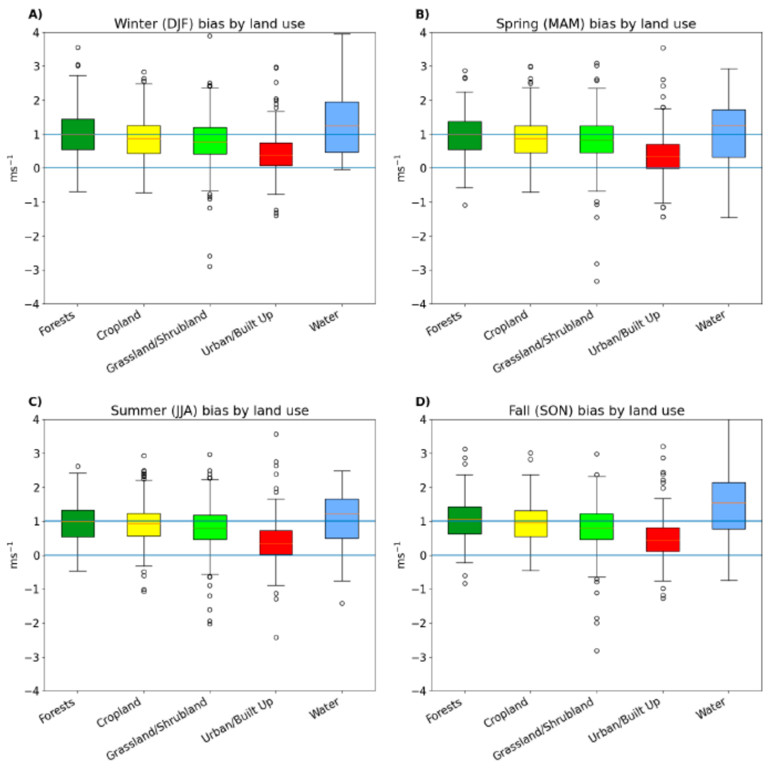



Figure 15. HRRR CONUS Wind bias at F01 separated by land-use type for a) Winter, b) Spring. c) Summer, and d) Fall.

When aggregated by region, biases were between 0.46 to 1.01 m/s (West and the Ohio Valley, respectively). These values mainly appeared to be tied to the amount of land-use in respective areas. For example, western regions (West, Northern Great Plains, and Northwest) were the three best performing regions and have significant portions of their regions covered by grassland or cropland land types. Areas with significant fractions of forest were the worst performing (Ohio Valley, Southeast, and Upper Midwest). Differences were also attributed to the number of cities that influenced the regional results. For example, more cities are in the Northeast and lower urban biases most likely offset the higher biases seen for forests. Overall, it should be noted that these biases < 1.5 m/s are small and overall, would be unlikely to be noticed by users of the system.

Table 11. Average sustained wind bias for land-use types and climate regions.

| Land-Use Type | Bias (m/s) | Climate Region | Bias (m/s) |
|---|---|---|---|
| Water | 1.31 | West | 0.46 |
| Forest | 0.99 | Northern Great Plains | 0.48 |

| | | | |
|---|---|---|---|
| Cropland | 0.9 | Northwest | 0.51 |
| Grassland | 0.79 | Southwest | 0.65 |
| Urban | 0.38 | Northeast | 0.73 |
| | | Upper Midwest | 0.88 |
| | | Southeast | 0.94 |
| | | Ohio Valley | 1.01 |

### *3.2.2 Wind Gusts*

Attention then turned to wind gusts which are a larger concern for sUAS operators. Given prior studies and the results of the field campaign, wind gusts for the CONUS were first analyzed by time of day (Figure 16). Overall, biases were 2-3 times higher than sustained winds with performance that varied by the diurnal cycle. Median biases were smallest (1-2 m/s) during the afternoon (18 UTC) and early evening (00 UTC) hours as well as during the summer and spring. Collectively, this suggested that performance was tied to the amount of mixing in the atmosphere. To confirm this hypothesis, biases were sorted by model simulated boundary layer height (Figure 17). As expected, wind biases were smallest for conditions for deep boundary layers that are associated with deep mixing. Overall, these results indicated that the HRRR is too likely to 'mix out' the atmosphere leading to a systematic positive bias for wind gusts as winds aloft are brought down to the surface.

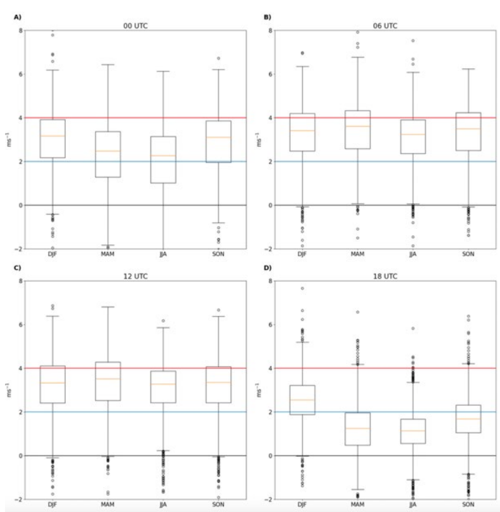



Figure 16. HRRR wind gust bias for the CONUS as a function of season and time of day a) 00 UTC, b) 06 UTC), c) 12 UTC, and d) 18 UTC.

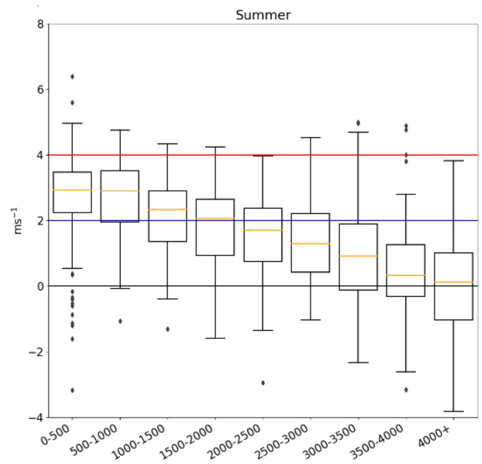



Figure 17. HRRR wind gust bias in the CONUS during the summer as a function of simulated boundary layer height (m).

Scatterplots of forecast-observation wind gust pairs demonstrate bias is dependent on wind magnitude and time of year (Figure 18). During the cool season (winter and fall), plots resemble those seen for sustained wind (Figure 14) with a positive bias but with more scatter and lower correlation coefficients. During the summer and spring there is more linearity to the data with a negative (positive) bias for the strongest (weakest) winds, consistent with Fovell and Gallagher (2020). Considering the *typical* flight abilities of sUAS that are limited to lower limits, these results suggest that the forecast system would over forecast winds within the flying envelope leading to false alarms vs. missed forecasts.

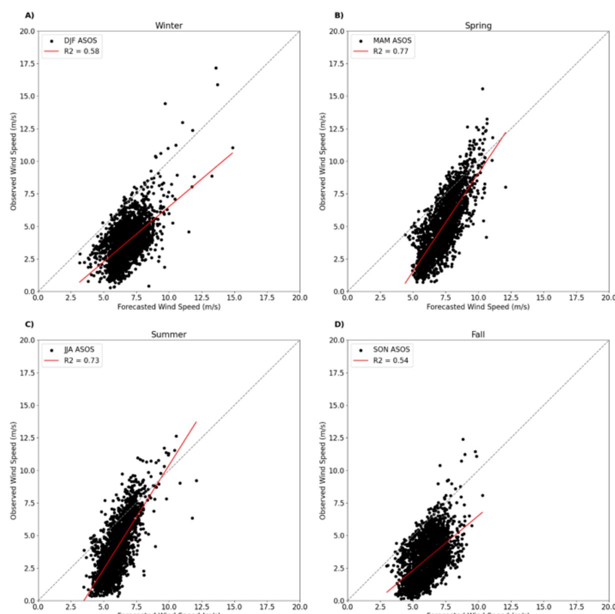



Figure 18. Scatterplots of HRRR/Observation wind gust pairs for a) Winter, b) Spring, c) Summer, and d) Fall. The red line is the line of best fit.

HRRR wind gusts biases were also segregated by land-type (Figure 15). Greater variability was seen across the land-types with median biases ranging from 1-4 m/s. Forested areas had the largest biases while lower biases were seen for water, urban, and grassland areas. Given the value of biases that were frequently larger than 2 m/s (~5mph), it was decided that wind gusts forecasts could impact the utility of the application. As a result, a bias correction experiment was developed to see if forecasts could be improved.

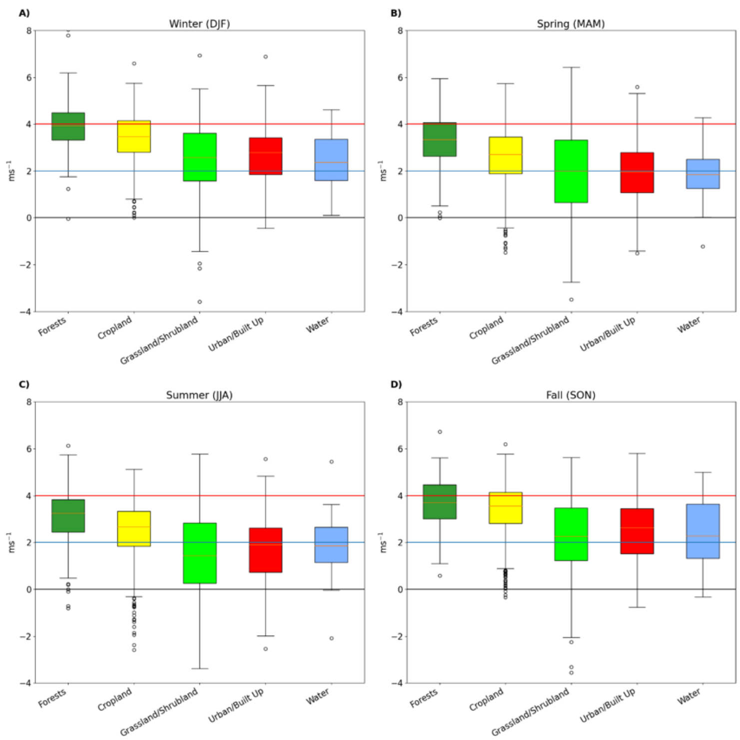



Figure 19. As in Figure 15 except for HRRR wind gusts.

### *3.2.3 Bias Correction of Wind Gusts*

Average wind gust biases were calculated for land types (Table 12) and used to correct an independent set of wind gust forecasts obtained from 1020 anonymous requests made in the beta version of the forecast application between 17 May 2022 – 17 May 2023 (Figure 20). Uncorrected and corrected forecasts demonstrate an average reduction (improvement) in wind gust forecasts of at least 2 m/s regardless of land type (Figure 21). Mock wind thresholds for fly/no fly decisions were also created to test skill scores for the bias corrected forecasts. False alarms (model = don't fly, observations = fly) were improved dramatically and this led to improvements in model skill scores regardless of threshold (see Tables 11-12 in Horan 2023). Based on these results, an option was included to bias correct observations in the application. Horan (2023) also proposed several different methods to further correct wind biases by time of day or by wind speed to further improve model performance.

Table 12. Wind gust bias corrections for the application.

| Land Type | Wind Gust Bias Correction (m/s) |
| --- | --- |
| Forest | 3.27 |

| | |
|---|---|
| Cropland | 3.09 |
| Grassland/Shrubland | 2.41 |
| Urban | 2.38 |
| Water | 1.92 |

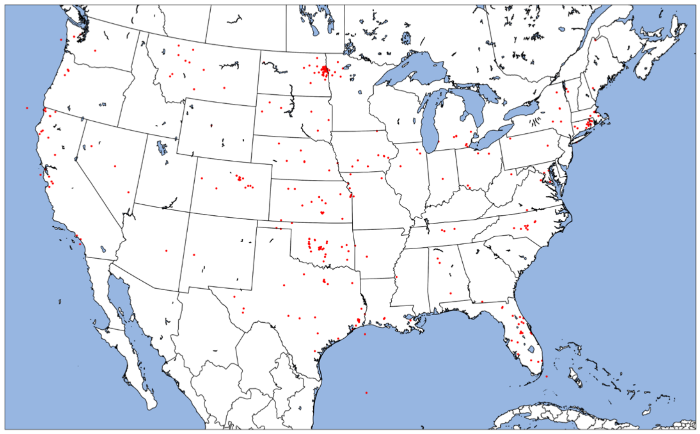


Figure 20. Anonymous user requests in the application between 17 May 2022 – 17 May 2023.

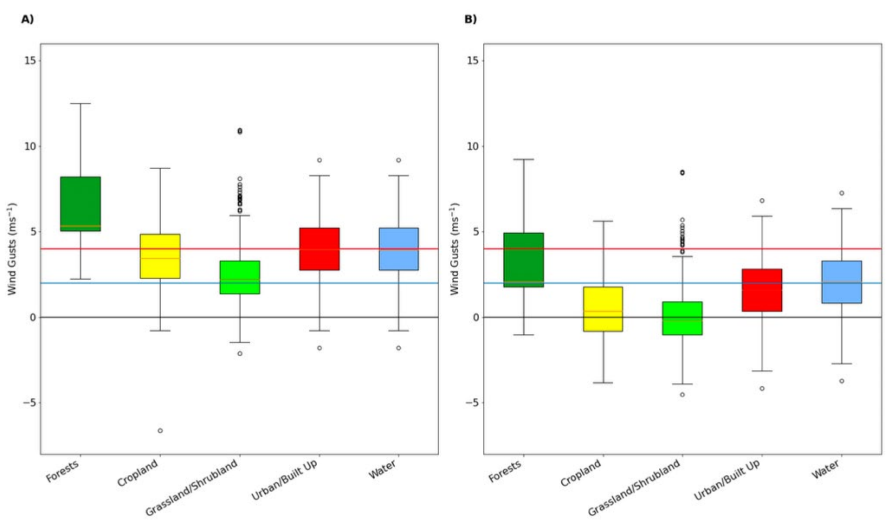



Figure 21. Uncorrected (a) and corrected (b) wind gusts biases for the anonymous user requests.

### 3.3 Results: Britt (2025) – CONUS Evaluation of HRRR Precipitation Forecasts

After the evaluation of HRRR wind forecasts, efforts shifted to identifying best practices for precipitation forecasts in the system. While raw model output provides an occurrence and amount of precipitation for a given time, any amount of precipitation could be considered hazardous for sUAS platforms, many of which do not have sufficient ingress protection from water. To that end, a strategy was developed to investigate the binary occurrence of precipitation in the HRRR model. Further, rather than providing a yes/no answer, this effort focused on generating probabilistic occurrence of the hazard (e.g. 0-100% chance of precipitation). The utility of using real-time radar data to provide short-term forecasts was also explored. Prior experience with HRRR-like weather models suggested observations could potentially outperform model forecasts which are subject to issues like spin-up and spatial displacement of small-scale precipitation events such as thunderstorms. This section provides a summary of these methods along with pertinent results. For a full description of the project, the reader is referred to Britt (2025).

### *3.3.1 Summary of Methods*

The application provides both HRRR precipitation forecasts along with real-time, quality-controlled radar data from the Multi-Radar/Multi-Sensor (MRMS) project developed by the NOAA National Severe Storms Laboratory (NSSL) (Zhang et al. 2016). The latter dataset merges radar data from both the CONUS and Canada to produce precipitation products on a unified grid. Britt (2025) re-gridded both the HRRR and MRMS to a common grid for the evaluation (Figure 22). MRMS data was polled hourly to match the frequency of HRRR forecasts.

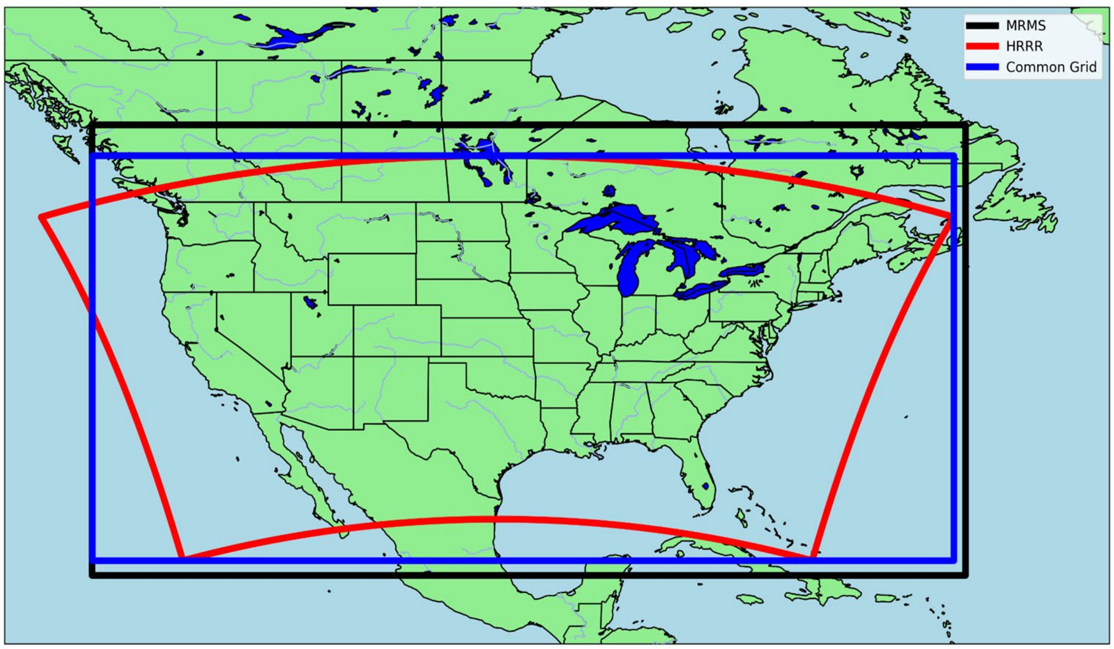



Figure 22. Grids for the evaluation. Note that portions of the common grid are masked due to lack of radar or model data.

Once a common grid was defined, data were smoothed using convolutions ranging in radii from 25-250 km (Figure 23). The probability of precipitation for a given point was then given by the fraction of points exceeding an observed or simulated radar reflectivity within the given radius from that point. The example in Figure 23 demonstrated that higher probabilities of precipitation were more likely for smaller smoothing kernels but were also more limited in space. Over the southeast for example, maximum precipitation probabilities ranged from 100% (r = 25 km) to 50% (r = 250 km). This led to confidence that the range in radii selected would encompass the 'best' radius that should be used for the application.

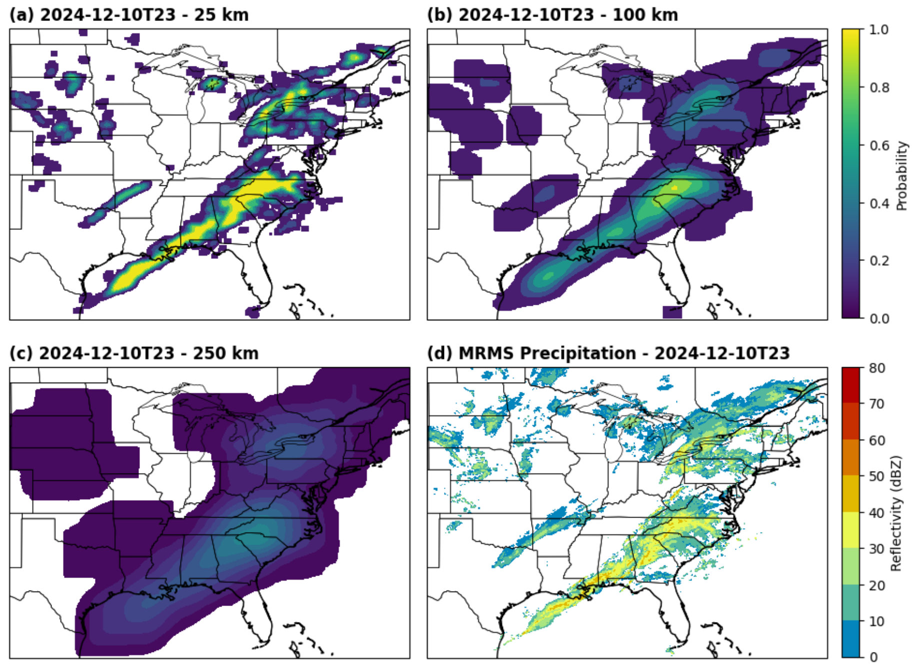



Figure 23. Examples of convolutional smoothing of MRMS data at 23Z on 10 December 2024 for radii of a) 25 km, b) 100 km, and c) 250 km. The original MRMS data are shown in d).

Three types of forecasts were tested including 1) HRRR, 2) MRMS (persistence), and 3) MRMS (optical flow). MRMS was used as verification meaning that at an analysis hour, the 2nd and 3rd forecast types would have perfect skill. Instead, the focus was on forecast skill in future hours (F01-F12) as precipitation events would move, develop, or dissipate with time.

The use of MRMS for verification greatly simplified the precipitation evaluation process as rain gauge data are discontinuous in space (leading to issues in generating probabilities), and there are large challenges in verifying actual precipitating echoes. Instead, we erred on the side of caution by using observed and simulated radar composite reflectivity which is the maximum value in the atmospheric column. This would include both precipitation and rain/snow at altitude (e.g. virga) and would include clouds that may be about to precipitate.

The 3rd forecast type (MRMS optical flow) was the most unique in that it involved projecting radar data forward in time using a computer vision technique known as optical flow. Six hours of MRMS data were used to understand the flow field associated with the composite reflectivity field (Figure 24). A semi-lagrangian technique known as the Lucas-Kanade (1981) method was used to compute the flow field.

The major perceived benefit of this exercise is the tendency for many precipitation events to move with motion associated with flow of the atmosphere. For example, in the mid-latitudes, upper-level flow is westerly meaning that thunderstorm complexes typically move from west-to-east at varying speeds. While the HRRR may or may not simulate a specific event, MRMS data would be able to detect it, still providing valuable short-term forecasts for a sUAS pilot. For a MRMS persistence forecast, MRMS data would be static in time meaning that there would be errors due to motion of the storm system. Optical flow would offer a chance to predict the movement and deformation of the system with time.

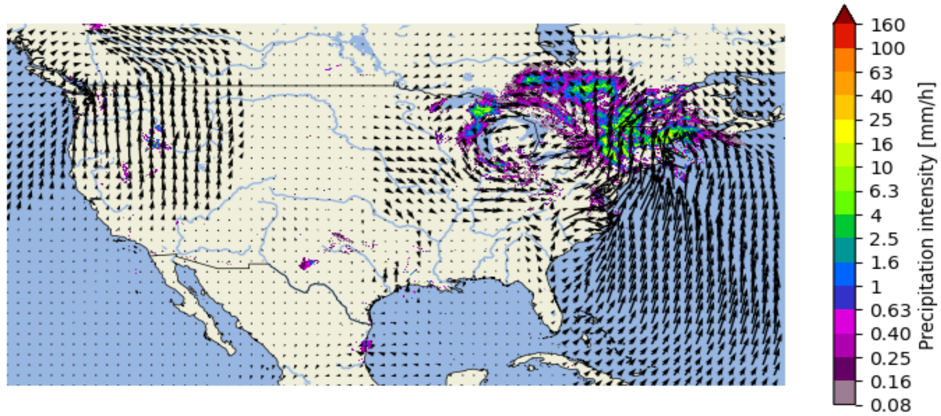



Figure 24. Example of the Lucas-Kanade (1981) method to determine a flow field from MRMS data.

To verify forecasts, a number of common statistical techniques were used including the calculation of Receiver Operator Characteristic (ROC) curves and the related Area Under Curve (AUC) value, Fractions Skill Score (FSS), and calibration curves. These results were analyzed by forecast hour, convolution radius, forecast type, and climate regions consistent with Horan (2023).

### *3.3.2 Results*

To gauge the general skill of precipitation forecasts, scores were first investigated for the entire CONUS (Figures 25-26). FSS values indicated varying levels of skill (0 = no skill, 1 = perfect skill, >0.5 = useful forecast) across the three techniques (Figure 25). HRRR results demonstrated skill nearly constant in time with values increasing by radius. While HRRR CONUS values for a radius of 100 km fell just below the 'useful' value of 0.5, regional analyses demonstrated that these values were artificially low due to radar issues such as beam blockage and bounding boxes that extended away from coastlines where radar data was not present. As such, a radius of at least 100 km was identified as being skillful for the model.

Observation results (MRMS – persistence and MRMS – optical flow) showed nearly perfect skill at F01 which was expected given it was validated against itself. Persistence FSS values decreased logarithmically as a function in time while optical flow values fell more linearly. The horizontal (time) displacement of these functions for a specific FSS value indicated the amount of performance gained by using the optical flow technique. This improvement was greater for smaller radii (50 and 100 km). Compared to HRRR forecasts, use of MRMS provided better FSS values to approximately F04-F06 for the smaller radii. Although this was even greater for a radius of 250 km, high FSS values can also indicated over-smoothing which can impact actual probability forecasts.

ROC curves were also calculated for varying radii. For the sake of discussion, only values are shown for a radius of 100 km which were similar to other radii other than vertical displacement of the functions (Figure 26). A perfect forecast for a ROC curve is represented by functions that become more square like (quickly rising to a true positive rate– TPR of 1.0 for a low false positive rate– FPR near 0.0). Results also demonstrate the increased skill for MRMS based observations for early hours (e.g. F01). By F06, HRRR and MRMS – optical flow was nearly identical, and by F12, the HRRR was clearly outperformed MRMS.

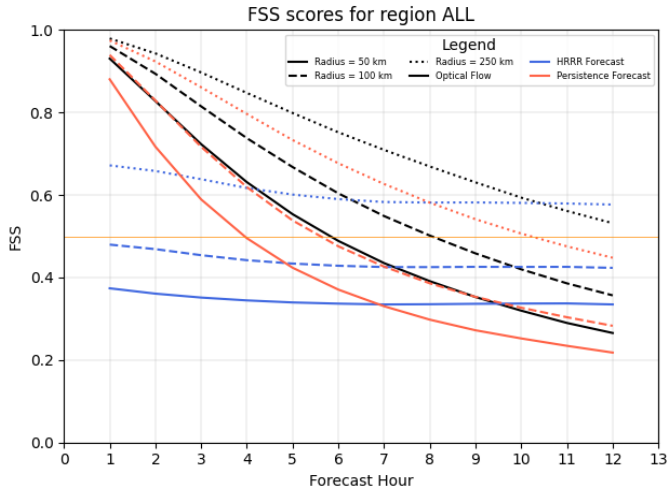



Figure 25. CONUS FSS values for varying forecast techniques and radii. Radii are indicated by the varying line style while forecast technique by line color. The orange line denotes the FSS value for a generally useful forecast.

Figure 26. CONUS ROC curves as a function of forecast hour for a radius of 100 km. The dashed 1:1 line represents the skill of a random forecast.

Regional analyses identified several unique properties of the various forecast techniques (Figure 27). AUC scores demonstrated MRMS optical flow forecasts had varying enhancements in skill compared to using persistence alone. In western regions (Northwest, West, and Southwest), there were only minor gains (~1 hour shift in skill). East of the Rockies, regions had higher skill scores suggesting that precipitation events were more often associated with ample atmospheric flow. In the West, it was presumed that precipitation was more likely to be orographically forced and tied to terrain.

Regardless of region, HRRR forecasts slightly increased in skill with time which may be evidence of some spin-up issues. Overall AUC scores varied across the CONUS with lower values seen for the Southeast and West regions. Investigation of bounding boxes used for the precipitation verification scores revealed that these regions were more likely to suffer from radar issues such as beam blockage by terrain or unknown precipitation occurrence due to distance from the coastline. In essence, the HRRR was unfairly scored for having precipitation in regions where MRMS could not detect in. Based on these results, it was decided to focus identifying best practices for precipitation forecasting in the system for a specific region, the Upper Midwest. This area has excellent US/Canadian radar coverage with minimal issues due to terrain.

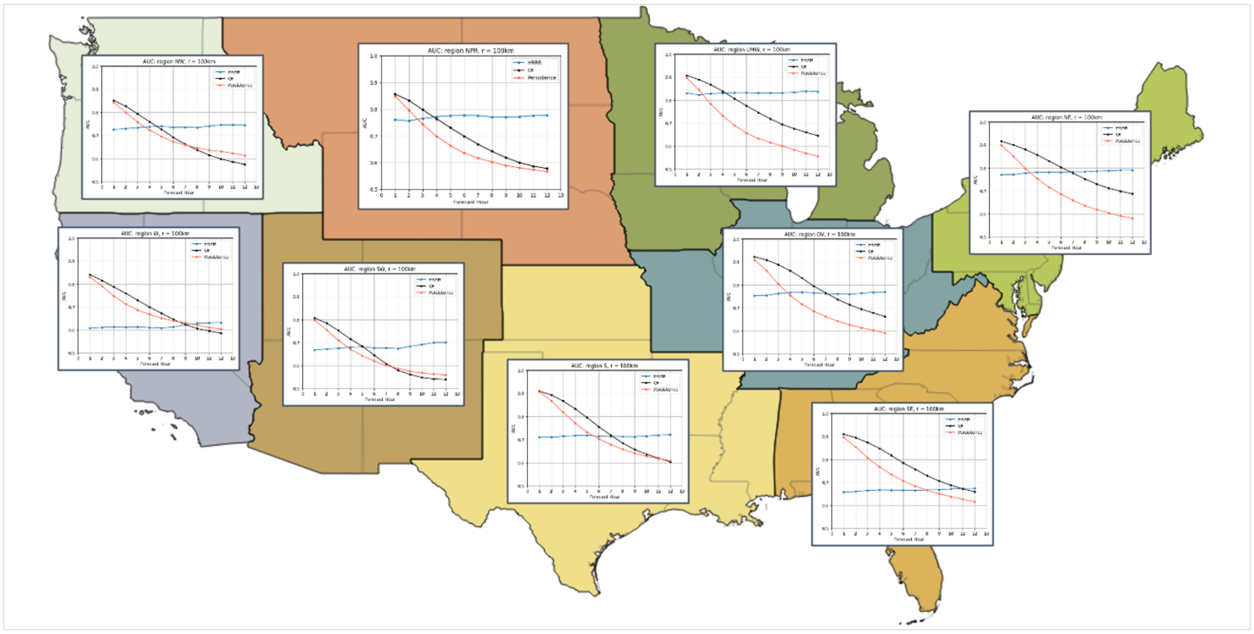


Figure 27. AUC scores as a function of climate region.

FSS values for the Upper Midwest region were systematically 0.1-0.2 higher than the CONUS (Figure 28). HRRR forecasts with a convolution radius of 100 km easily fell above the useful skill line of 0.5. This resulted in a change in the cross-over time in FSS scores between MRMS and HRRR forecasts. For a radius of 50-100 km, this was approximately 3-4 hours after which point the HRRR outperformed MRMS optical flow forecasts.

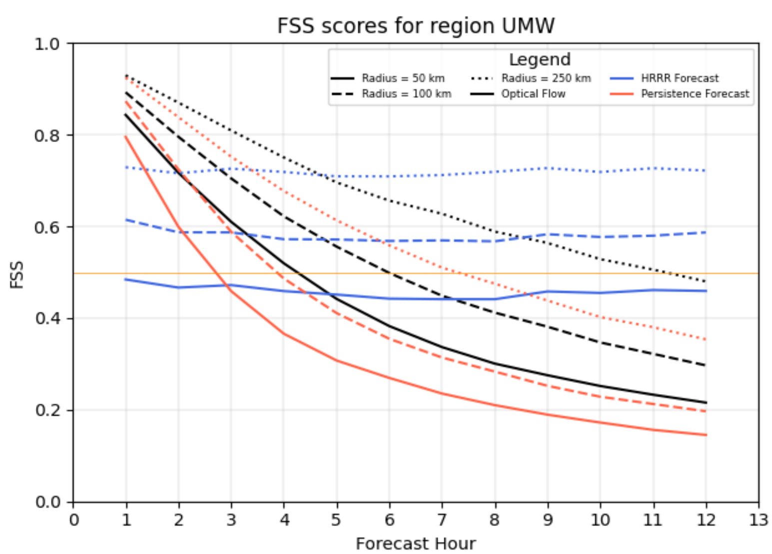



Figure 28. As in Figure 25 except for the Upper Midwest climate region.

This finding held true for other statistical scores such as the AUC (Figure 29). Only minor variations in AUC scores were found for the HRRR (0.78-0.83) which were remarkably similar regardless of radius. MRMS forecasts varied in skill with the highest AUC values (~0.9) seen for radii of 50-100 km for F01-F02. As convolutional radius increased, the rate in change of MRMS scores decreased but at the cost of lower scores in early forecast hours. Cross-over times for MRMS persistence forecasts were around F02-F03 while for MRMS optical flow they were around F03-F04.

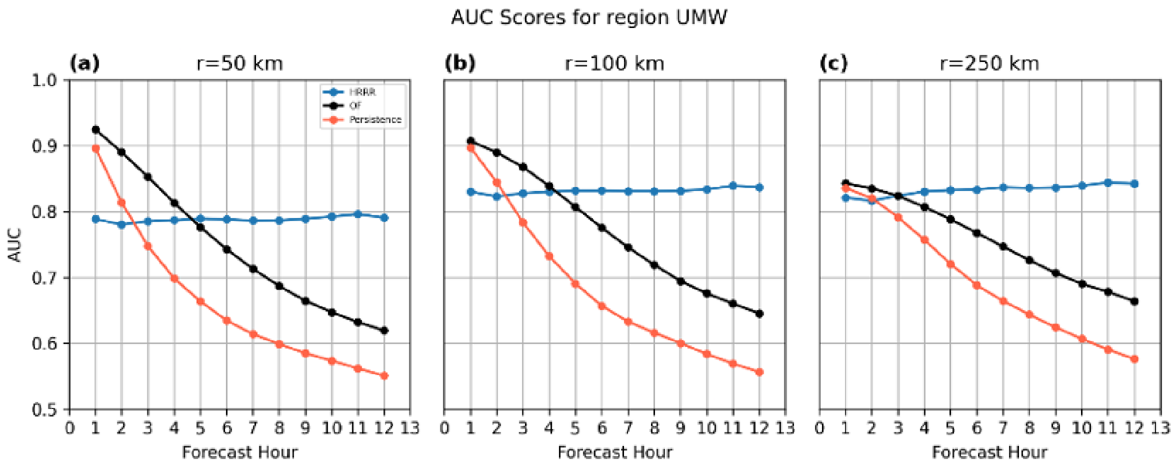



Figure 29. Upper Midwest AUC scores for radii of a) 50 km, b) 100 km, and c) 250km.

### *3.3.3 Best Practices for Precipitation Forecasts*

Based on the collective results of Britt (2025), general best-practice guidelines were identified for providing probabilistic precipitation forecasts for sUAS users. Given the important of forecasts in the short-term (e.g. time of flight), the forecasting application should at a minimum provide real-time radar data. While performance could be tuned by region, very broad settings can be made to improve forecasts for the CONUS. The work found that a convolution radius of 100 km offered the best benefits of probabilistic forecasting with not overly smoothing data. Further, short-term forecasts can be improved by leveraging convolution techniques on real-time MRMS data. With minimal computational time, persistence forecasts could be used out to F02 and beat HRRR forecasts. By implementing the optical flow technique, the optimal cross-over time can be increased to F04 before relying on HRRR forecasts. While not explored, future work should investigate whether a hard cut-off between methods should be used, or some blend of observation to model-based probabilities for precipitation.

# 4 TASK 2.3 – DEVELOPMENT OF THE OPEN-SOURCE TOOLKIT

This section provides details about the structure of the open-source toolkit along with documentation for the system. Full details are provided in the source code which was sent electronically to the funding agency. Four tasks were developed to carry out this objective (Table 13 and Figure 30). The solicitation of design requirements (Task 2.3.1) was discussed in Section 2.1 and completed Q4 2021. Task 2.3.2 was completed by Q1 of 2022 after survey results were synthesized. Tasks 2.3.3 and 2.3.4 covered the development of the API and associated GUI and back-end packages which began in Q1-2 of 2022. An initial alpha release of the application was made in Q3 of the same year. The tasks were essentially completed with the refined application by end of Q4 of 2023 at which point no major additions were made to the system. From Q1 2024-Present, WxByte maintained and monitored the application and fixed bugs as they turned up.

Table 13. Task 2.3 Subtasks.

| Task | Team |
|---|---|
| 2.3.1: Solicit design requirements from UAS operators and field experts. | UND/WxByte |
| 2.3.2: Synthesize design requirements to develop a web and mobile-friendly application user interface (UI) | WxByte |
| 2.3.3: Develop an API to provide access to data products based on user location and airframe. | WxByte |
| 2.1.4: Integrate backend API with the application and develop systems to display current hazards and alert the user of changing conditions. | WxByte |

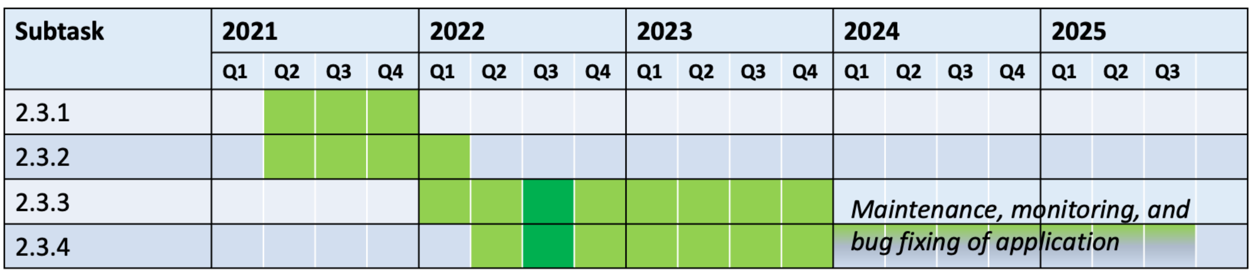



Figure 30. Timeline of Task 2.3. The dark green squares indicate when the application became available online.

## 4.1 Hardware and Software Description of the System

The general strategy for the open-source toolkit was to build something that could 1) be run in the cloud, 2) work on both mobile platforms and computes, and 3) be moved relatively easy to other systems. To this end, a Progressive Web Application (PWA) was developed and run on a Google Cloud Host. Domain names were registered that forwarded to the PWA instance (https://www.uasforecast.com and https://www.uas-forecast.com).

The PWA leveraged industry standard packages including Vite (https://vite-pwa-org.netlify.app/), React (https://react.dev), Redux (https://redux.js.org/), and Mapbox (https://www.mapbox.com/) for various components of the API and GUI. The API is contained in a Docker Container (https://www.docker.com) which has all necessary prerequisites for the runtime environment.

In practice, the API running in the cloud hibernates until a user makes a request. The server then spins up, and queriers data that were pre-processed from raw model files on a separate Local Data Manager (LDM) server based on Unidata code (https://www.unidata.ucar.edu/software/ldm/). This included a conversion of model GRIdded Binary (GRIB) files into a PostGreSQL (https://www.postgresql.org/) database and JavaScript Object Notation (JSON) files read by the API. In its current form, the spin up of the server takes approximately 5-6s, while a user request takes an additional 5-6s. If the server is already spun up, the total request time is only the length of the user request. Computer hardware requirements are considered minor, and frequent flushing of the database limits the total file space needed. Current hardware settings are provided in Table 14.

Table 14. Computer hardware used for the application.

| Server | CPUs (#) | Memory (GB) | Storage (GB) |
|---|---|---|---|
| LDM (WxByte) | 2-4 | 2-4 | 20GB (1.3GB used) |
| API (Google Cloud) | 8 | 8 | < 1GB |

### 4.2 Documentation

Upon visiting the website for the application on a computer or mobile device, the user is greeted with a map and box that outputs forecast information (Figure 31). The experience begins by the user selecting sUAS model (Figure 32) and either typing a location in, clicking the 'locate' button next to the location field, or double clicking on the map to query a forecast. Rather than selecting an sUAS model, the user can also enter custom weather limits based on their experience (Figure 33). The user can also select the length of time they expect to be flying. This data is transmitted anonymously to the server and a forecast is generated. This populates the forecast window with a color-coded forecast and brings up any current NWS hazards that overlap the forecast point (Figure 33). A color-coded slider on the bottom of the window allows for the user to see how forecast values change with time. Several options exist for the user to see other graphical displays (Figure 32).

The example in Figure 31 demonstrates an active weather environment with several complexes of severe thunderstorms as indicated by the areas of precipitation, the shaded red polygon indicating a severe thunderstorm watch, and shaded orange polygons indicating severe thunderstorm warnings. Example output for one of these warnings is shown in Figure 33. Crowd-sourced (Task 2.4.3) precipitation reports are indicated by the blue icons across the map.

Analysis of the forecast system demonstrates a complicated environment for flying. Wind gusts appear to be the dominate risk with average values leading to 'orange' level of risk. Significant variability exists for other fields due to model grid points either being in or out of forecasted thunderstorms (e.g. wide range if visibilities and ceilings). Overall, the system points towards a better window of flying later in the day starting at 22 UTC before conditions become poor again later in the night.

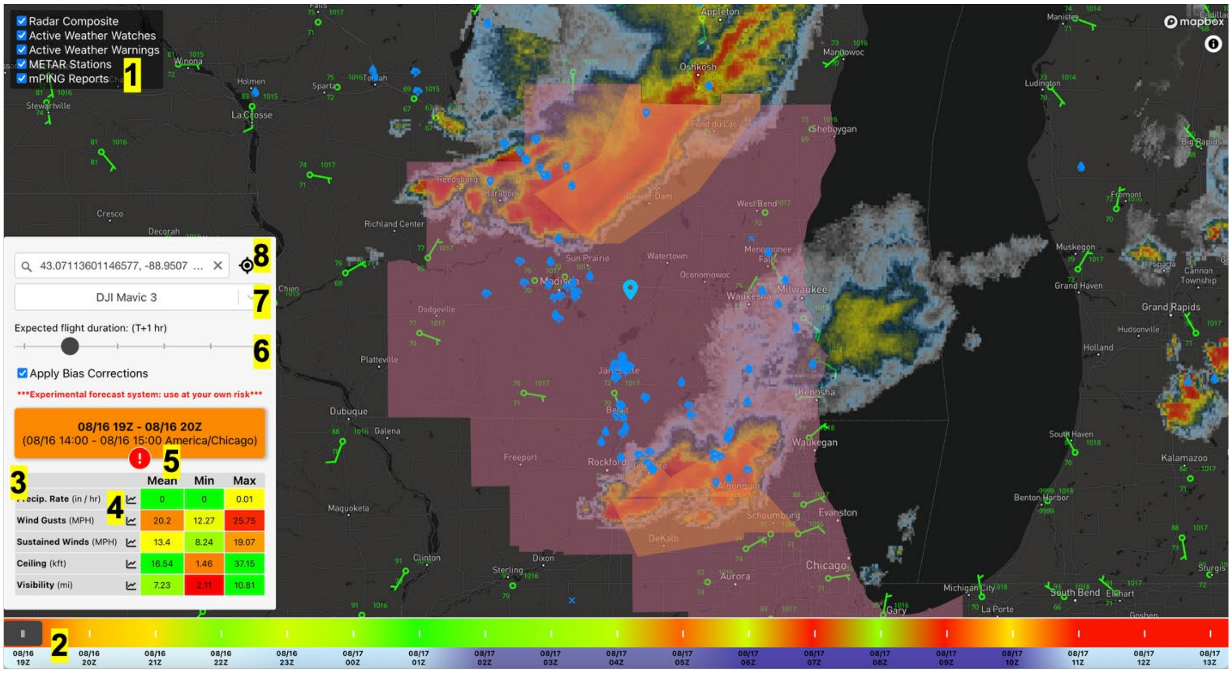



Figure 31. GUI for the Open Source Forecast Toolkit. Numbers highlight specific features shown in Table 15.

Figure 32. Left: The sUAS selection menu Center: Probability plot for a forecast variable. Right: Time-series plot for a forecast variable.

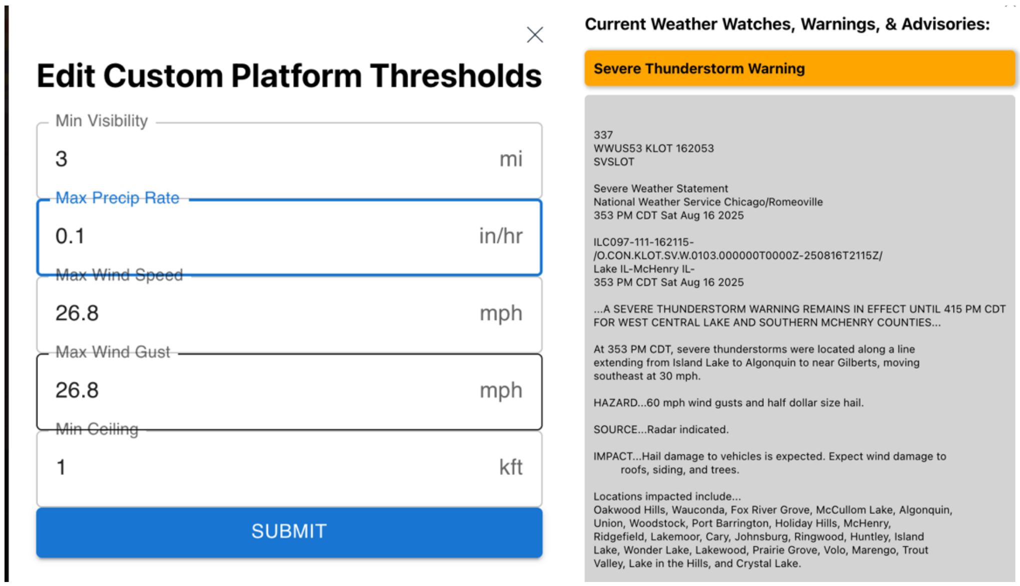



Figure 33. Left: Custom threshold menu. Right: Example NWS warning products.

Table 15. Features of the Toolkit GUI.

| Feature | Description |
|---|---|
| 1 | Selectable overlays including 1) current radar (MRMS), 2) Active NWS Watches, 3) Active NWS Warnings, 4) Surface METAR observations (green station plots), and 5) Crowd-sourced mPING reports (See Task 2.4.3 |
| 2 | Slider bar featuring color coded risk, time and a day (light blue) /night (dark blue) indicator. As the user moves the slider, the tabular data updates within the forecast window. |
| 3 | Tabular forecast data with mean, minimum, and maximum forecast values for the chosen point. |
| 4 | Clickable icons that open up alternative forecast plots shown in Figure 32. |
| 5 | Forecast time and maximum risk color. If watches or warnings are present, a warning '!' is shown. Click on this will reveal the NWS text products (e.g. Figure33). |
| 6 | Slider bar allowing users to select how long they will be flying. Dynamically changes calculated values by tabulating data over the varying period. |
| 7 | sUAS platform selection tab (see Figure 32). |
| 8 | Locator button. Allows user to type in address, double click map for location or click the icon to use the device's location. |

# 5 TASK 2.4: USABILITY AND FEASIBILITY ASSESSMENT

The final task was a collective assessment of the project to determine the usability and feasibility of the open-source tool kit. Subtasks are listed in Table 16 with the timeline for the task provided in Figure 34. Tasks 2.4.1 and 2.4.2 were dedicated to getting users for the system and identifying its strengths and weaknesses. This is addressed in Section 5.1 of this section. Task 2.4.3 identified a way to incorporate real-time, sourced weather data into the application (Meteorological Phenomena Identification Near the Ground (mPING) reports). This is discussed in Section 5.2. Task 2.4.4 was the final evaluation report for the toolkit and is completed with the completion of this report. Overall conclusions and recommendations for sustaining the project in the future are provided in Section 6.

Table 16. Task 2.4 Subtasks.

| Task | Team |
|---|---|
| 2.4.1: Identify evaluators/users and establish agreements for their evaluation of the system. | UND/NPUASTS |
| 2.4.2: Evaluate usability and feasibility using consumer, prosumer, and professional UAS operators | UND/NPUASTS |
| 2.4.3: Incorporate a crowdsourcing approach for updating weather information. | UND/WxByte |
| 2.4.4: Produce final evaluation report for toolkit | All |

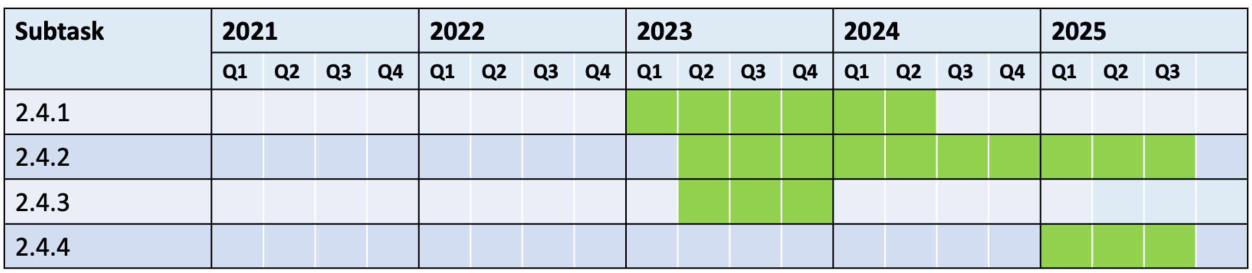



Figure 34. Timeline of Task 2.2.

## 5.1 Marketing and Feedback for the Toolkit

The most challenging aspect of the project was gaining users and feedback for the system. Tracking for the system began in ~Summer of 2023 (Figure 35), and monthly usage was tracked until project close. Initially, usage was low with only several dozen requests per month. Several marketing pushes were made using Facebook/Twitter social media posts and sending announcements via ASSURE channels. Within months of these pushes, usage fell off.

In response to low activity, a UND marketing class (MRKT311) was contacted, and marketing was tasked as a group project for several students in the class. These groups worked with the team to generate dialog and information to provide potential users. Despite suggesting to the groups that social media and online forums may be the best avenue for contacts, groups primarily used contact lists and calling sUAS focused companies. Overall, this effort saw only small, temporary gains to usage.

During Summer of 2024, the UND team made another concentrated push to market the application. Online forums including the MavicPilots suite of forums and a Commercial sUAS group on Facebook were targeted and conversation was sustained in threads with these groups during the summer months. Overall, this exercise proved to be the most fruitful, with a noticeable increase in usage to ~100 or so requests per month. Although usage still spiked, a clear gain in nominal use was found after this push and an additional push by ASSURE in Fall of 2024. At the current time, the application sees 100-150 requests per month.

Figure 35. Monthly user requests for the toolkit from June 2023 – June 2025.

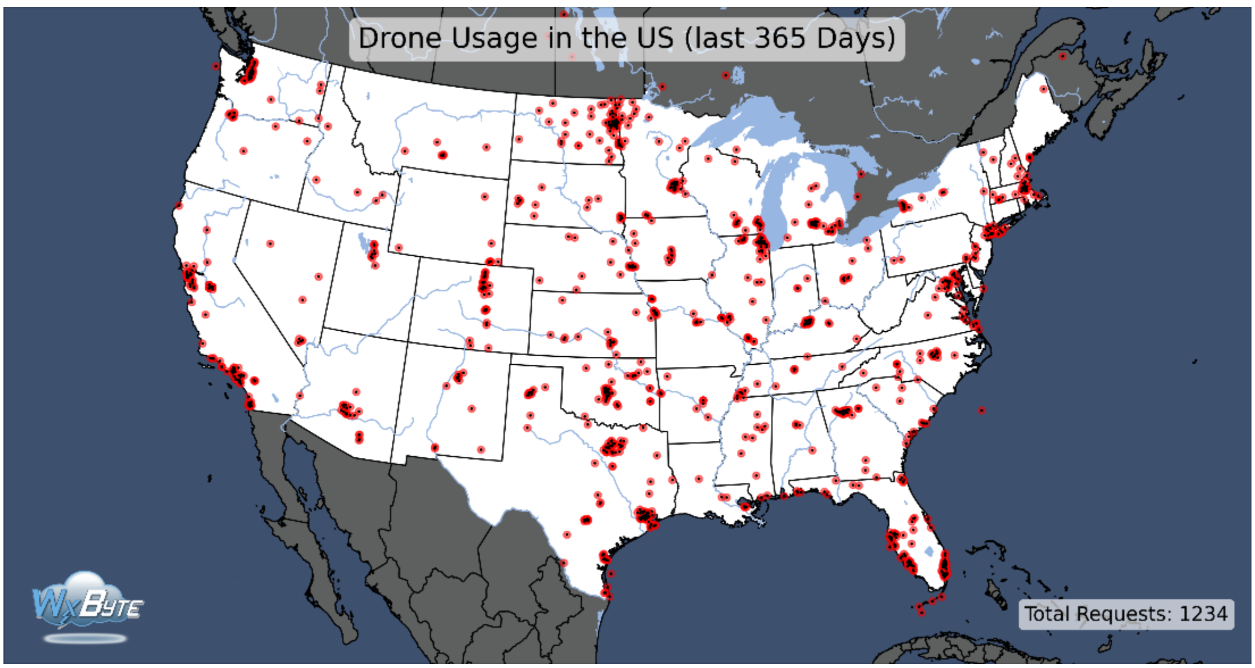



Figure 36. Locations of user request for the past year (valid August 10 2024 – August 9 2025).

While user requests are anonymous, location information was saved to post-evaluate forecasts (e.g. Section 3.2.3). In the past year, there were ~1200 requests located throughout the US (Figure 36). Not surprisingly, many of these requests were concentrated by larger cities and then eastern North Dakota where the UND and NPUASTs teams are located. Less usage was seen in mountainous areas; This is interesting given these areas also experience more difficult to forecast winds and precipitation events although this is more likely a function of population density.

Feedback for the application was generally positive with users appreciating the wide variety of information and 'slick' interface. Unlike the experienced users of the sUAS survey, the online audience had more individuals with more basic computer or meteorology knowledge. One of the key take-aways was the importance of providing guidance on even basic parts of the application such as how to interpret wind barbs on METAR station reports. Users contributed a variety of bug reports ranging from how ceilings were plotted, suggestions for the GUI, and additional airframes to be incorporated into the list. It was also suggested to provide different color modes which can be a direction for future work.

### 5.2 Incorporation of Crowd-Sourced Weather Data

Given the anonymity of the system with no user accounts and a small user-base, the team leveraged pre-existing efforts to provide crowd-sourced data into the application. The mPING (Elmore et al. 2024) project was developed by NSSL and has a separate mobile application that allows users to record weather events ranging from precipitation type to storm damage (Figure 37). At present date, hundreds of *daily* reports are made providing ground truth for precipitation. Examples of this data can be seen in the toolkit in Figure 31. While the mPING application is well known in the weather community, a future avenue of work is spreading info on this reporting system to sUAS operators.

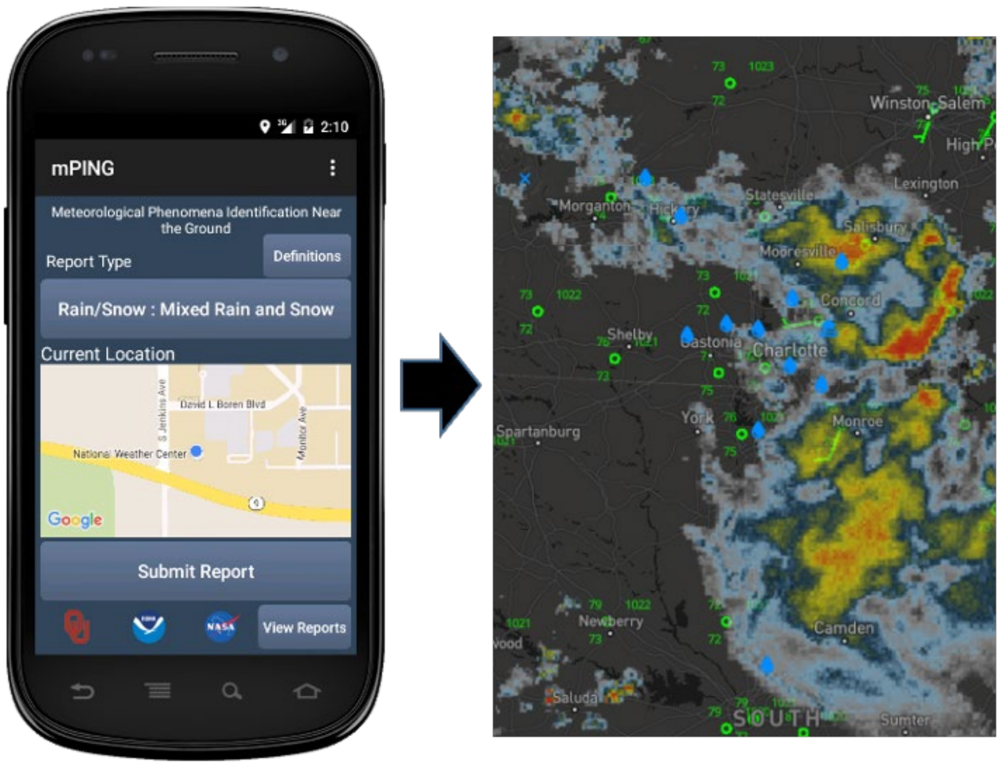



Figure 37. Example of the mPING mobile application and reports in the sUAS forecast toolkit.

## 6 PUBLICATIONS AND PRESENTATIONS

Publications include Horan (2023) and Britt (2025) which are listed in the references. A peer-reviewed publication based on this collective work is in preparation. Presentations made for the project (outside of ASSURE meetings) are provided in Table 17.

Table 17. Presentations for Task 2.

| Author | Title | Form | Name of Conference | Date |
|---|---|---|---|---|
| Brian Horan and Aaron Kennedy | Verification of HRRR Forecasts in Support of an Unmanned Aircraft Systems Weather Application | Poster | American Meteorological Society | January 2022 |
| Blake Rafferty | A Comparison of Balloon-Borne and sUAS Observed Boundary Layer Winds | Poster | American Meteorological Society | January 2023 |
| Brian Horan and Aaron Kennedy | Development of a small Uncrewed Aerial Systems Open-Source Forecasting Application driven by the High-Resolution Rapid Refresh | Oral | American Meteorological Society | January 2023 |
| Brian Horan | Verification Of High-Resolution Rapid Refresh Surface Winds In Support Of An Open-Source Small Unmanned Aerial Systems Application | Thesis Defense | N/A | July 2023 |
| Patrick Britt | Precipitation Verification for UAS Pilots | Presentation | Seminar for Local Atmospheric Sciences Research (ScalAR) | March 2024 |
| Patrick Britt and Aaron Kennedy | Precipitation Forecast and Verification for sUAS Applications | Presentation | American Meteorological Society Annual Meeting | January 2025 |
| Patrick Britt | Precipitation Forecasting and Verification for sUAS Applications | Thesis Defense | N/A | July 2025 |

# 7 CONCLUSIONS

## 7.1 Summary

Task 2 created an open-source toolkit to provide sUAS skillful weather forecasts. Elements of the toolkit were built upon feedback from sUAS pilots. To this end, the toolkit leverages high-resolution, hourly forecasts from the HRRR out to 18 hours. In addition to this forecast information, it also provides commonly checked weather data including a nationwide radar mosaic, NWS watches and warnings, crowd-sourced weather reports, and surface observations.

The application is compact and does not require extravagant computing hardware. The system has been running on a Google Cloud Server since 2022, leveraging LDM from WxByte. Since Fall of 2023, the application has been associated with registered web domains including uasforecast.com and uas-forecast.com.

The numerous validation efforts provide well documented details on system performance for wind and precipitation forecasts. Overall, sustained wind forecasts were quite good with median bias (model – observation) within 5 mph. Wind gust forecasts also had skill, but had 2-3 times larger bias. This bias was dependent on land-use which then fed back into regional performance. Afternoon forecasts were the best performing, and the model had the tendency to over-forecast wind gusts in the early morning and evening. Logistically, this means the application is more prone to false alarms than missed forecasts. A bias correction scheme for wind gusts was tested on an independent set of data and is implemented in the application.

Optimal settings for precipitation forecasts were explored. Overall, it was found that while the HRRR model is skillful, better performance can be gained by leveraging real-time radar observations for the first four hours of time. To generate the most skillful probabilistic precipitation forecasts, a radius of 100 km should be used around any user requested forecast point. While exact performance varies across the country and time of year, this setting offers the best blend across the CONUS.

## 7.2 Recommendations for Future Efforts

Given that the application has been providing skillful forecasts since Fall of 2022, Task 2 accomplished its primary goals. That said, the greatest single challenge to the project was building an ample user base for the application. A major emphasis in the future should be a marketing and educational campaign to promote usage and explain its benefits over other systems. Alternatively, the forecast methods for the study could be implemented into other digital systems that provide data to sUAS pilots. For example, weather forecast layers could be generated for efforts such as the NASA Digital Information Platform (DIP).

While the application is functional, users suggested several features that have not been implemented. Examples include alternative color modes, forecasts farther out into time, and continuous updates to listed sUAS platforms. Users also commented on the speed of the application; the current application structure generates forecasts in real-time vs. leveraging pre-calculated fields. The benefit of the currently implemented system is a savings in compute cost as cloud computing infrastructure is only spun up with demand. Finally, alternative precipitation forecast methods from Britt (2023) remain to be implemented. If done, methods to leverage radar data to provide short-term forecasts will add additional computational burden to the system, increasing day-to-day costs.

The final point of discussion includes future availability of model data. The HRRR model remains operational but is slated to be replaced by NOAA with the operational Rapid Refresh Forecast System (RRFS) model as early as 2026. It is unclear when the HRRR will be decommissioned. From an implementation point of view, it should straight-forward to replace HRRR with the RRFS. Logistically, this means swapping model data with the LDM and simply selecting the equivalent field in the new model. The variables used in the application are not considered unique and will be part of standard output in RRFS. More importantly, the switch from one model to another will impact the error verification statistics produced during this project. The question of how this will impact the quality of forecasts is one that will require future evaluation efforts.

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# 9 APPENDIX 1

03/24/2022

Version 1

NORTHERN PLAINS UAS TEST SITE

# NASA ASSURE Wx Test Plan

Weather Sensor Testing Through UAS Technologies

## 1 Introduction

Access to an open-source weather forecast tool that would assist in planning UAS flights is important to the UAS community. The goal of this project is to develop an open-source weather prediction tool that supports small UAS (sUAS) operations. The accuracy of such a system, however, must be evaluated. While some weather phenomena can be easily verified using existing sensors (e.g., precipitation), others are best examined using sUAS flights (e.g., low-altitude winds). Low altitude winds, in fact, are one of the most common weather phenomena that impact sUAS operations.

### *1.1 Project Overview*

The NPUASTS will work with UND and the ASSURE team to identify the proper suite of UAS on which to install weather sensors for data collection. The NPUASTS will work with its team, or a team of selected third party UAS operators that meets the desired UAS criteria, to integrate the acquired sensors. This integration includes developing a data management plan to ensure data integrity and hand-off for validation tasks. The NPUASTS and associated flight vendors will work to develop flight plans and test cards to support the desired goals and objectives of the project. This includes defining the proper operational location to best support the mission objectives.

Flight operations will be supported by one UAS (xFold Spy) over the course of multiple months with a three-day flight window each month near Emerado, ND. The NPUASTS will provide the required mission commander and flight crews to support the operations. All flights are expected to be within visual line of sight and operate under Part 107 rules and regulations.

### *1.2 Scope of Testing*

This effort is designed to assist the ASSURE team to identify the proper suite of UAS on which to install weather sensors. NPUASTS will support in the selection and integration of the weather sensors and developing a data management system to ensure data integrity and task validation. Flight events will consist of at least 10 non-consecutive flying days for sensor testing and data acquisition. Data collected by each event will be processed and used to define any changes needed in the test methodology. All flights will be within visual line of site and operate under 14 C.F.R. Part 107 regulations.

## 2 Test Architecture

The test methodology for the weather sensor testing will consist of integrating the weather sensors on the UAS and verifying the sensors will not adversely affect the performance of the aircraft and validating that sensor will capture the data required for the test. Flight testing will consist of a mostly vertical flight path up to and including 400 feet AGL while pausing the climb in 50 feet increments for at least 30 seconds to accurately capture data at each altitude. Following the flight test events, will consist of a data process and validation phase.

### *2.1 Deployed Assets*

The NPUASTS will deploy the following assets onsite to support the flight testing. The NPUASTS Operations Trailer will be deployed as needed along with its associated technologies. The NPUASTS will also work with UND to determine if other assets available may be beneficial to the flight activity.

Table 1. Available NPUASTS Asset Descriptions

| Asset | Category | Description |
|---|---|---|
| NPUASTS Operations Trailers | Infrastructure | 24 ft. long trailer will be used as a command center. |
| Davis Weather Station | Infrastructure | A local weather station will be deployed with the command center trailer to gather appropriate weather information for flight test days. |
| ADS-B Receivers | Sensor: ADS-B | Multiple local ADS-B receivers will be deployed and have already been integrated with Simulyze software. Sensors will provide data on cooperative aircraft in the region. |
| Simulyze Mission Insight™ Software Suite | USS / Airspace Display | The NPUASTS currently owns and operates this software for a variety of functions to include UTM, airspace awareness, and fleet management information. This system is always available during UAS operations. This system will likely be used in the command trailer only for situational awareness, range safety, and data collection as needed. |
| L3Harris RangeVue™ | Airspace Display | Symphony® RangeVue™ is the first airspace situational awareness tool designed specifically for test-range operations for UAS. The NPUASTS has access to the RangeVue™ software to support these operations. This system will only be used for added situational awareness, as the main system being tested is the L3H DAA system. |

| | | |
|---|---|---|
| L3Harris ADS-B XTend™ and VAS Data | Sensors: FAA ADS-B and Radar | The ADS-B XTend™ is a dual-band ADS-B receiver and relay that can provide surveillance coverage to ground for UAS tracking and local area surveillance. This data feed is paired with the FAA NexGen ADS-B network to provide a user with great surveillance coverage of the operational area. These data feeds will be provided to Simulyze and the L3Harris RangeVue system in the NPUASTS command center. These data will only be used as added situational awareness during flight-testing. |
| DVR & Cameras | Data Collection | The NPUASTS has a video collection system in the command center that can be used to capture operations in the command center trailer as well as exterior to the trailer. These cameras will feed a DVR and record video that can be made available to support data collection in the project as desired. |
| StoneCast Crew Communications | Communications | StoneCast by Stone's Mobile Radio allows two-way radio users to take radio communication to greater distances. The NPUASTS utilizes StoneCast as the primary source of crew communication during research efforts. |
| VHF Communications | Communications | A VHF base station will be used in the NPUASTS command center if required for manned aircraft communications with the intruder pilot and any local manned aircraft as needed. |
| Connectivity | Infrastructure | Network connectivity will be provided through Verizon LTE services, directly through UND network services, and through Grand Sky networking services. |

## 3 Aircraft

The NPUASTS will utilize the xFold Spy multirotor UAS. An information card on the UAS is provided below. This card shows technical specifications of the Spy aircraft.

### <u>xFold Spy UAS</u>

The xFold™ Spy platform features power and portability designed for action sports cameras and small payloads for industrial applications. The xFold™ Spy is configured as a quad (four motors and propellers).

| | | | |
|---|---|---|---|
| **Rotor Span** | 24.5 in | **Cruise Speed** | 15 knots |
| **Height** | 18 in | **UTM USS** | N/A |
| **Maximum Takeoff Weight** | 14 lbs | **UAS Operator** | NPUASTS |
| **Endurance** | 20 minutes | **GCS Type** | Mission Planner |
| **Line of Sight Range** | 2 miles | **Autopilot** | PixHawk 2.1/Cube Blue |

## 4 Flight Locations

The UAS will takeoff from approximately 47.911361°, -97.324828°, which is 1.6 NM East of Emerado, ND. The UAS will fly on a mostly vertical flight path up to the east of the LZ and up to 400 feet. The UAS will be pointed north to ensure the readings from the Trisonica sensor are accurate. The NPUASTS Operations trailer will be located near the entrance to the Oakville field site along the road at approximately 47.911619°, -97.325582°, and will be the location of the flight director. If the NPUASTS Operations trailer is not deployed the trailer located at the field site will be used to house the flight director.



## 5 Success Criteria

Success criteria include multiple, fully executed flight profiles on a given day with valid meteorological data.

## 6 Participants and Roles

The NPUASTS will work with the UND and associated industry partners to accomplish the goals and objectives of the weather sensor testing through ASSURE WX. NPUASTS will provide the required mission commander and flight crews to support the operations.

## 7 Schedule

Flight events will consist of 3 consecutive days each month spanning from May 2022 to April 2023. 1 of the 3 days will be UAS flights. Below are tentative dates of the flight events (subject to change per availability and weather):

May 17, 2022 - May 19, 2022

June 14, 2022 - June 16, 2022

July 12, 2022 - July 14, 2022

August 9, 2022 - August 11, 2022

September 13, 2022 - September 15, 2022

October 18, 2022 - October 20, 2022

November 15, 2022 - November 17, 2022

December 20, 2022 - December 22, 2022

January 10, 2022 - January 12, 2023

February 13, 2023 - February 15, 2023

March 2, 2023 - March 4, 2023

April 24, 2023 - April 26, 2023

Note: Actual flight dates during the winter and spring were not as confined to these dates due to the volatile nature North Dakota weather and availability of NPUASTS budget.

## 8 Data Management Plan

Data will be collected and stored throughout the flight event in multiple locations to prevent the loss of data. Data collected includes sensor data from the Trisonica and Intermet sensors as well as aircraft logs. Sensor and aircraft logs will be stored on the GCS for the xFold Spy and transferred to a USB drive at the end of each flight day. Data will be uploaded to Microsoft OneDrive for sharing with the UND team.

Sensor Data will come from two sensors onboard the aircraft, the Trisonica and the Intermet. Data from the Trisonica will be retrieved from the data logger board via SD card. A new log is created each time the sensor is powered on. For the Intermet sensor the data is retrieved via USB port on the back of the sensor casing. Aircraft data can be retrieved via the SD card in the autopilot or via a USB connection to the aircraft. Sensor and aircraft logs will be retrieved at the end of each flight day and stored on both the aircraft GCS laptop and a USB drive.

### *8.1 Photos and Video*

If deployed, the NPUASTS operations trailer has video cameras that can be used to capture the flight event. Additionally, any pictures taken of operations by the flight crew will be made available upon request.

## 9 Communication Plan

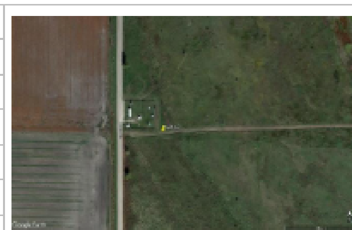
The flight operations will be overseen and organized by a flight test director in conjunction with an Mission Commander (MC) for the flight crew. Flight crews will have direct communications with any Visual Observers. The MC will also ensure that each flight crew adheres to the flight plan requirements and monitor conformance.

Each day will begin with a briefing to cover plans and safety information for the day's activities. This flight briefing may occur at the NPUASTS operations trailer or in a designated location by the Flight Director.

Communications will be accomplished in several ways. Primary flight operation communications will be accomplished via Stonecast handheld radios. Each flight crew and associated visual observers will utilize handheld radios for communication. In addition, cell phones and Microsoft Teams will be used as auxiliary means of communication as required. VHF radio will be used to communicate to ATC and local air traffic as required.

If a UAS incident occurs, the Pilot in Command (PIC) will communicate directly with their MC who will be in communications with the Flight Director. NPUASTS will then conduct the Aircraft Incident Checklist. If any incident happens to any one of the research team members, direct communications with the Flight Director will occur. The Flight Director will determine the best course of action for these instances. Specific instructions in case of emergencies will be conveyed to the research team during the daily briefings.

# ASSURE WX TEST CARD

| | | |
|---|---|---|
| Flight Card # | 1 of 1 |  |
| UAS Platform | Xfold Spy | |
| Location | 47.911361°, -97.324828° | |
| Pilot | TBD | |
| VO | TBD | |
| MC | TBD | |
| Target Flight Time | 9 minutes | |
| Test Objective | Identify the proper suite of UAS on which to install weather sensors for data collection | |
| Description | The UAS will take off to the east of the LZ, point the aircraft to the north to ensure accurate readings for the Trisonica sensor, and climb in a vertical flight path up to 400ft. During the climb, the UAS will pause every 50ft to accurately gather data at each altitude. This process will be completed at least once every hour at the top of the hour between 0700 and 1200. | |

| Flight 1 | | | | |
|---|---|---|---|---|
| ✓ | **Altitude** | **Action** | **Remarks** | **Time (aprox)** |
| | Take Off | Take off, position, and climb | | 1:00 |
| | 50ft AGL | Climb and hold for 30 seconds | | 1:45 |
| | 100ft AGL | Climb and hold for 30 seconds | | 2:30 |
| | 150ft AGL | Climb and hold for 30 seconds | | 3:15 |
| | 200ft AGL | Climb and hold for 30 seconds | | 4:00 |
| | 250ft AGL | Climb and hold for 30 seconds | | 4:45 |
| | 300ft AGL | Climb and hold for 30 seconds | | 5:30 |
| | 350ft AGL | Climb and hold for 30 seconds | | 6:15 |
| | 400ft AGL | Climb and hold for 30 seconds | | 7:00 |
| | Land | Descend and land | | 9:00 |