CLOUD-MAP: Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics

2018 Annual Report

NSF EPSCoR RII Track II FEC Award Number: 1539070

CLOUD-MAP: Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics

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CLOUD-MAP: Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics

Annual Report
NSF EPSCoR RII Track II FEC
Award Number: 1539070
Project Duration: 8/1/2015 – 7/30/2019
Reporting Period: 3/16/2017 – 3/15/2018

May 1, 2018

Executive Summary

The period of this report covers from March 16, 2017 to March 15, 2018.

In the year-long performance period, the team accomplished all of its objectives, including progress towards research goals, organization of the research and workforce development efforts, meeting with and generating input from the community of stakeholders, completion of the first flight campaign, and planning for the second flight campaign, in addition to many individual technical and outreach related tasks. These items are detailed in the report.

The overarching goal of the project is to develop integrated small unmanned aircraft systems (SUAS) capabilities for enhanced atmospheric physics measurements. This team includes atmospheric scientists, meteorologists, engineers, computer scientists, geographers, and chemists necessary to evaluate the needs and develop the advanced sensing and imaging, robust autonomous navigation, enhanced data communication, and data management capabilities required to use SUAS in atmospheric physics. Annual integrated evaluation of the systems in coordinated field tests also requires advancing public policy related to adoption of SUAS technology and integration of unmanned aircraft into the airspace. CLOUD-MAP builds on the team members' and combined partners' existing expertise and capabilities in atmospheric and meteorological observations, SUAS development, and STEM outreach and education. A primary long-term impact expected from CLOUD-MAP will be the indelible multidisciplinary scientific and educational collaboration of the early-career faculty who are involved. In the short duration of the project to date, new collaborations have already developed among team members leading to increased collaborative proposal development and subsequent collaborative publications.

Contents

List of Tables

List of Figures

Part I
Annual Report Summary and Highlights

1 Overview

1.1 RII Track-2 FEC Impacts on University Programs

A major focus of the Research Infrastructure Improvement Track-2: Focused EPSCoR Collaborations (RII Track-2 FEC) is to add significant value to increase scientific competitiveness at the national or regional level. Well-designed collaborative strategies are essential to EPSCoR's goal of enhancing the competitive position of research and research-based education in science and engineering. RII Track-2 FEC funding enables this by supporting competitive collaborative teams of EPSCoR investigators and providing a mechanism to coalesce investigator expertise into a critical mass for a sustained, effective research and education partnership. This approach can help overcome impediments posed by limited infrastructure or human capital within a single jurisdiction and can enable broad engagement at the frontiers of discovery and innovation in science and engineering.[6] As such, the impacts of the RII Track-2 FEC funding can have long-lasting impacts on the funded institutions. These impacts on the individual partner universities are discussed below.

1.2 Research Highlights

Two highlights of the previous year's efforts are presented here. The first includes field campaigns,

1.2.1 Field Campaigns

Three Oklahoma campaign flight operational areas include the OSU Unmanned Aircraft Flight Station (UAFS), the Marena Mesonet site, and the Department of Energy Southern Great Plains (SGP) Atmospheric Radiation Measurement (ARM) site. At this initial stage of technology development, comparison of flight measurements to "ground truth" is essential and is a primary objective of the 2017 sampling campaign. A sample of the UAVs and missions flown is shown in Figure 1, respectively. In some cases, custom vehicle solutions, such as OU's CopterSonde and OSU's MARIA, proved the best option.However, COTS (commercial off-the-shelf) options with minor modifications were the primary platform of choice.

The OSU UAFS allowed testing under controlled conditions and provided operators with network, power, runway, and hangar access. This first stop in the campaign was used to evaluate platforms, sensors, communication systems, and protocols prior to moving to the field sites. The Marena Mesonet, in addition to providing a dedicated Mesonet tower, also houses in-ground agricultural sensors, viz. the Marena Oklahoma In Situ Sensor Testbed (MOISST). MOISST was established in 2010 to evaluate and compare existing and emerg-

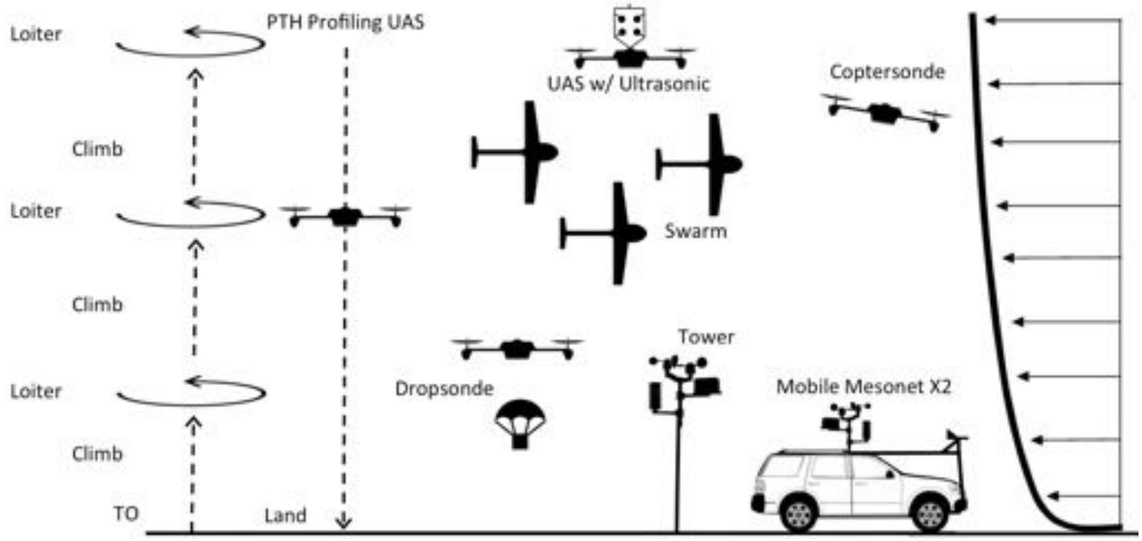

Figure 1: Mission concepts of operations conducted as part of the joint field campaign.

ing in situ and proximal sensing technologies for soil moisture monitoring [2]. The DOE ARM SGP site consists of in situ and remote-sensing instrument clusters arrayed across approximately 143,000 km^2 in north-central Oklahoma and is the largest and most extensive climate research field site in the world, making it an invaluable resource for CLOUD-MAP researchers. [?]. This site has a unique suite of atmospheric measurements useful for comparison with measurements from UAS platform sensors. In 2016, the CLOUD-MAP Year-1 campaign flight objectives focused on operations to collect thermodynamic, air chemistry, and wind data to compare with measurements from surface stations within the Oklahoma Mesonet and team-owned stationary and mobile sensor towers; see Figure ??. Mesonet measurements are available in general with an update time of 5 min [4, ?].

The 2016 campaign group photo includes 58 participants (see Figure 2a). OSU operated fixed-wing and vertical takeoff and landing (VTOL) platforms with a variety of sensors supporting multiple CLOUD-MAP tasks. OU flew VTOL platforms acquiring frequent repeated atmospheric measurements starting before dawn to capture the onset and development of the daily ABL cycle. UK flew three fixed-wing aircraft for chemical and atmospheric turbulence sensing, along with various rotorcraft supporting a focus on operations to measure soil conditions, to evaluate integration of spatially distributed data from moving sensor platforms, and for multi-vehicle UAS operations. Soil measurements were included to examine new remote sensing systems for early detection of water stress. UNL flew prescribed rotorcraft flight patterns to evaluate novel identification algorithms and dropsonde deployment and recovery systems, and also deployed a new tracker/scout vehicle equipped as a mobile mesonet as a reference system. The overall campaign leveraged the infrastructure of these sites to demonstrate the potential of extending the conventional surface Mesonet concept to include vertical profiling.

Flight totals for the campaign indicated an unexpectedly successful first year. The 2016 3-day total flight time exceeded 25 h for 241 total flights, comprised of 187 rotary and 54 fixed-wing flights. Indicating the increased capabilities in a year's span, the 2017 3-day

Figure 2: CLOUD-MAP flight campaign team participants and vehicles in (a) 2016 and (b) 2017.

flight numbers included more than 500 individual flights of a dozen different systems for cumulative total coordinated flight hours of approximately 70 h. The 2017 team with 71 participants is seen in Figure 2b.

Data evaluation, reduction and ABL characterization analyses are conducted by the various sub-task contributors (See Figure 3). Witte, for example, developed a fixed-wing sUAS sensing platform and data reduction to measure and characterize ABL turbulence and validated its performance in comparison to measurements from vertical profiles of a rotary-wing platform, and a portable tower-based sonic anemometer [5].

Temperature profile comparisons between fixed-wing and rotorcraft platforms were also possible. Potential temperature profiles were determined at nineteen times throughout the boundary-layer evolution on 28 June 2016. See Figure 3. Data from rotorcraft vertical profiles to 300 m and fixed-wing profiling circular trajectories at 20 m altitude intervals from 40 to 120 m coincided for ten measurement times [3]. Please note that the fixed wing aircraft observe a larger temperature variation but are also orbiting around a fixed point rather than taking measurements at a given horizontal position. Due to observed variations, questions may arise as the accuracy or "truth" of the data when compared to each other. While this has not been fully addressed by this study, data comparisons have been provided elsewhere in a first attempt to address this concern [17].

Persistent Atmospheric Monitoring During an Eclipse

During the total eclipse on October 21, 2017 the OSU, UNL, and UK teams conducted profiling and transect flights with a pressure, temperature, and humidity (PTH) and ultrasonic sensors mounted on rotary wing vehicles and multi-hole probes for turbulence measurements mounted on fixed wing vehicles. The OSU and UNL teams conducted profiles were conducted between Wilber, NE and Millian, NE while the UK team conducted profiles and transects at Hopkinsville, KY. Both sites were in the path of the totality. Flights were conducted before,

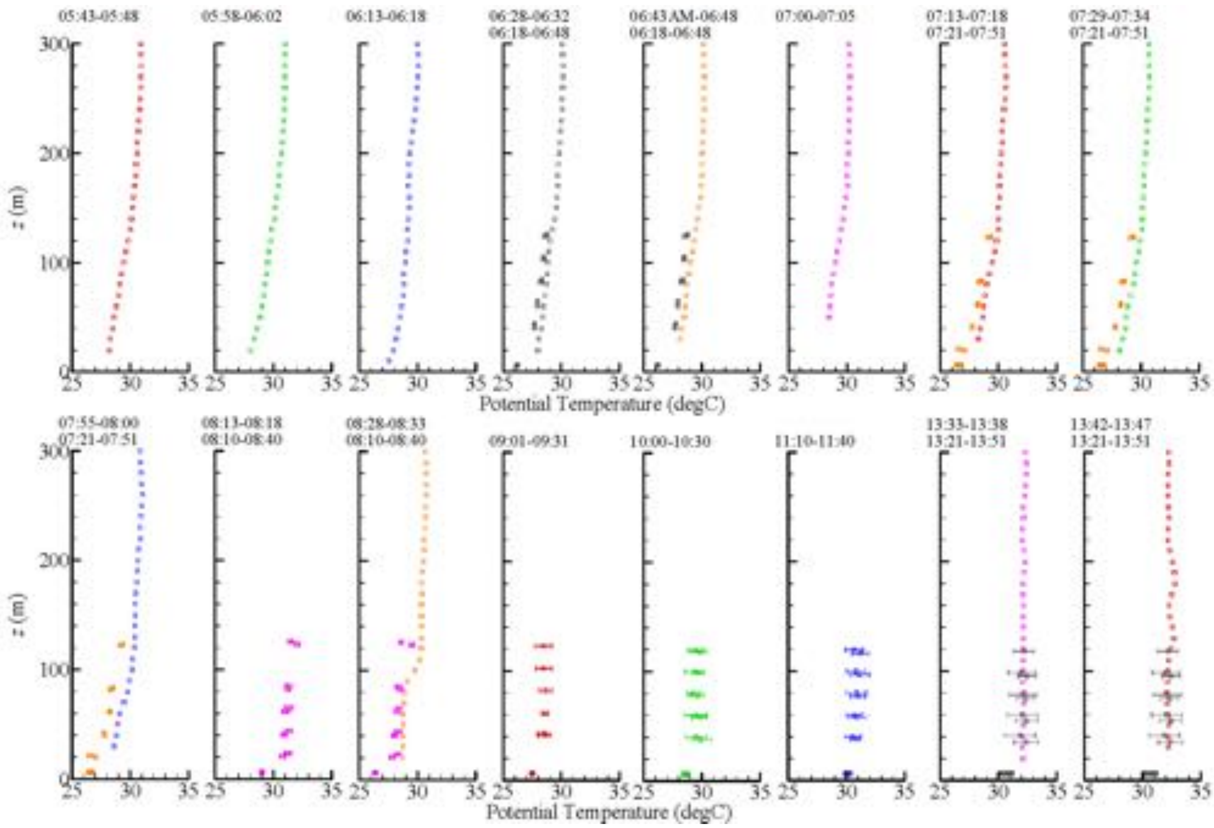

Figure 3: Comparison of potential temperature profiles measured by rotorcraft and fixed wing aircraft up to 300 m and 133 m, respectively. Times listed on top of each figure indicate flight time for rotorcraft, times below that indicate flight time of fixed wing aircraft. Points indicate measurement taken at a given altitude while error bars provide corresponding range of temperature variation. Profiles measured on June in Stillwater Oklahoma on 28 June 2016 from 05:43 a.m. to 17:20 p.m.

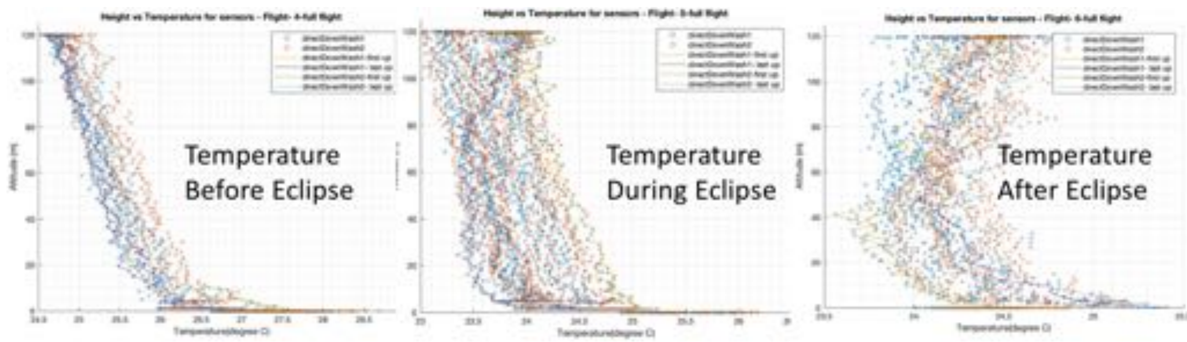

Figure 4: Temperature measurements taking before, during, and after the eclipse at the Wilber site.

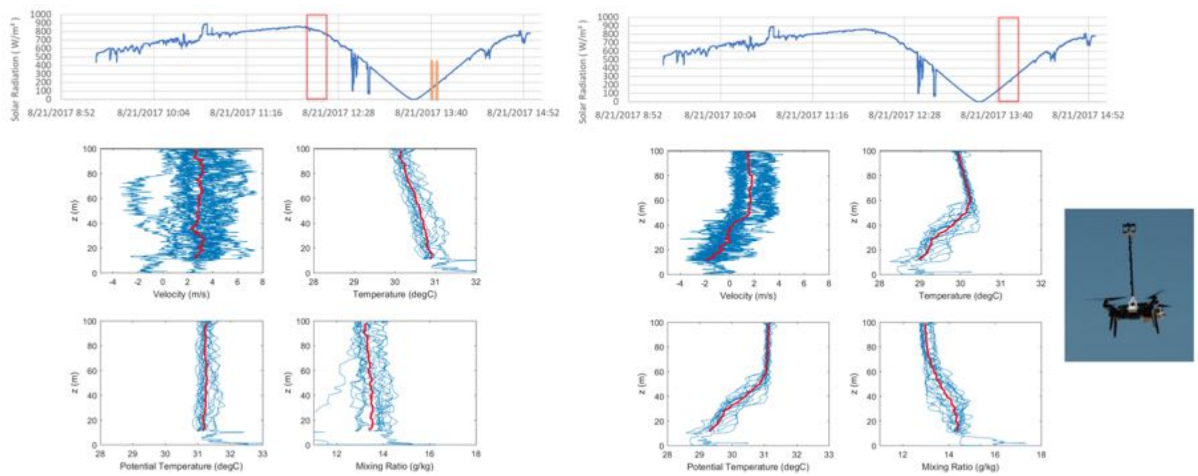

Figure 5: Profiles before and immediately after totality at the Hopkinsville site.

during, and after the eclipse with the goal of obtaining profiles from the ground to 400 ft AGL throughout the course of the day.

Figure 4 shows some of the temperature profile data collected during the day of the eclipse. Before the eclipse, there is a standard profile where temperature decreases with altitude as the ground is warmed by the sun during the day. During the eclipse, there is a wider variance as the temperature starts to drop rapidly. After the eclipse, there is an inversion where the temperature is cooler on the ground, similar to the types of inversions seen after sunset. Persistently collecting data can provide insights into the impact of these and other atmospheric events on the lower atmosphere.

1.2.2 Operational Considerations and Barriers to Adoption

A significant portion of this research has focused on barriers to successful unmanned technology adoption by weather services, meteorologists, and atmospheric scientists. This project addresses several key barriers, including system selection, observational confidence, tactical deployment, training, and dealing with the rapid evolution of technology and regulations. Recommendations from previous efforts provide guidelines for field scientists to use as they

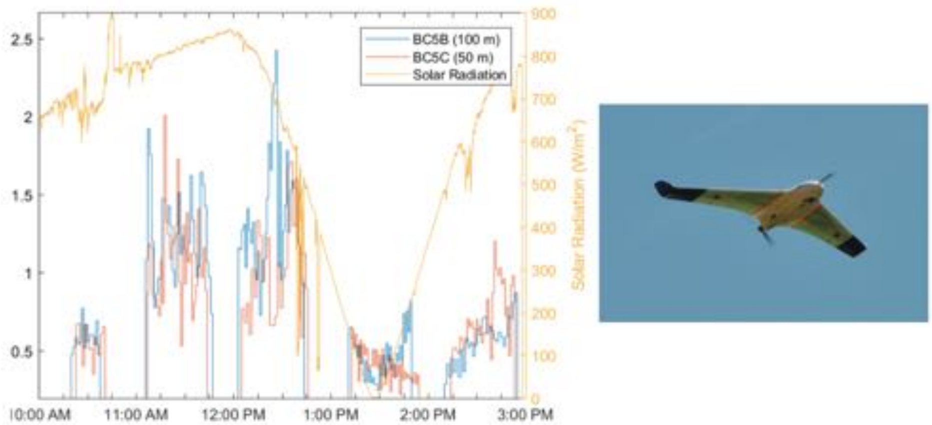

Figure 6: Turbulent kinetic energy from transects during the eclipse at the Hopkinsville site.

consider adopting sUAS into their operations, although the rapidly-changing technology and regulatory environment presents a challenge to research groups that do not have UAS operations managers on staff.

While many scientists have already started using sUAS, current technology may not yet be adequate for reliable scientific support. The limitations of current autonomous capabilities, ease of control and interface effectiveness, and lack of useful information provided to the research team in a timely manner all affect adoption.Barriers to large-scale use of sUAS stem from lack of sophistication, reliability, safety and flexibility as compared to currently fielded military systems that require large investments in capital and training unavailable to most researchers. Many emerging COTS systems have been developed from the hobbyist realm and do not have robust and well-engineered subsystems, making them unsuitable for widespread field applications and reliable, repeatable measurements. This is changing as the commercial sector expands, but as with any evolving technology, potential users will need solid information from unbiased sources.

The vast number of systems on the market today and the frequently inflated claims for system performance impact system selection and development of appropriate operations. It is imperative that realistic operational evaluations be conducted and accurate system requirements be established. By using simulations based on actual measurements of sUAS flight and sensor performance within real environments of winds, temperatures, precipitation, terrain, etc., the resulting outcomes will be reasonable representations of field performance. To ensure this, key outcomes have been tested in field conditions in live scenario exercise experiments. Additional considerations include night-time operation, precipitation effects, high- and low-temperature reliability, and deployment time.

Another barrier to sUAS adoption are the costs of purchasing systems and training personnel. These may be more than many researchers can justify without strong supporting evidence. Two items should be noted. The research discussed herein has been examining the range of existing (off-the-shelf) aircraft and sensors, and assess the capabilities/costs of several systems, from lower to higher priced. System prices are expected to fall over the coming years so more researchers should be able to afford them. Regardless, logistical footprints and associated costs are still high for even simple measurements, and higher if dedicated staff are required for operations management.

Finally, it is important to note the current issues with unmanned aircraft interfering with other aircraft operations, particularly in severe weather and other emergency response operations such as gas releases where airborne measurements may be of interest. The irresponsible flight of sUAS is a challenge across the aviation community with pilots, air traffic controllers and others noting close encounters on a frequent basis. While it is likely that there will be a collision in the near future, it is hoped the consequences will not be catastrophic. There are multiple research and development efforts underway to provide solutions for UAV operations in the National Airspace System (NAS), particularly as related to routine weather observations with sUAS.

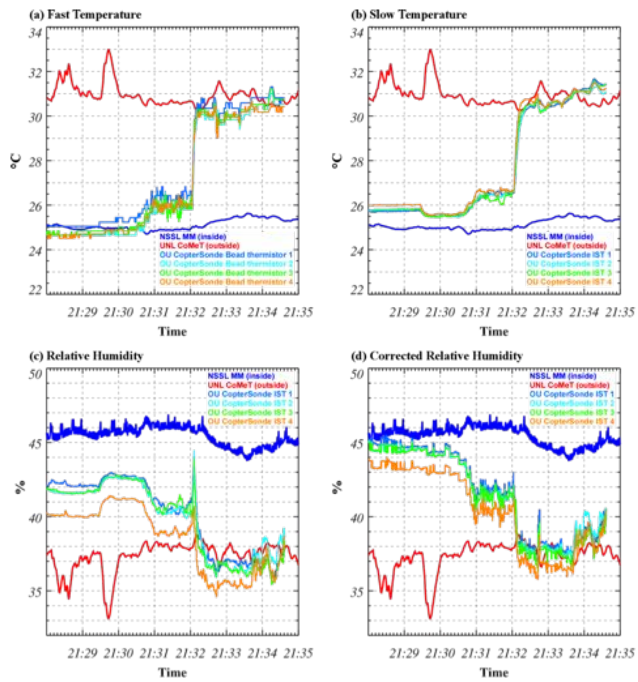

Figure 7: Calibration-validation experiment results.

1.2.3 Sensor Response

Calibration and validation of sensors mounted onboard sUAS is an important part of ensuring the robustness of the observations collected. While the required accuracy specifications will depend on the intended use of the observations, the methods adopted for calibration and validation (cal-val) should be universal. The focus of the cal-val exercises conducted as part of the 2017 CLOUD-MAP field campaign was on in situ sensors. Observation accuracy on mobile platforms will depend on sensor performance, sensor siting, platform motion/attitude, and the environment within which observations are collected. While several different sensors for a given measurement type (e.g., temperature) were tested, the aim of CLOUD-MAP cal-val exercises was not to provide guidance across the spectrum of sensors but was instead focused on evaluating accuracy as a function siting, platform motion/attitude, and environment.

Particular focus of CLOUD-MAP cal-val activities was on errors resulting from the temporal response of temperature and relative humidity sensors. These errors will depend on all three system characteristics and become particularly significant when data collection is directed towards phenomena characterized by rapid evolution of the measured quantity along the flow-relative trajectory of the platform. For the mesoscale to microscale boundary-layer phenomena that are often targeted by sUAS (e.g., convective thermals, well-mixed boundary layers, airmass boundaries), measurement response times need to be $\mathcal{O}(\infty)$ s or less. Sensors mounted where aspiration by environmental air is insufficient may experience significant errors due to slow sensor response. Moreover, if siting to maximize aspiration exposes sensors to external sources of radiation (e.g., insufficient solar shielding) or heat (e.g., engines, electronics), biases may emerge.

To maximize control over the environmental conditions that could expose errors resulting from sensor response issues, CLOUD-MAP cal-val exercises included the operation of sUAS systems across a thermodynamic shock with known quantities on either side. In these experiments, the shock was created by opening the overhead door of one of Oklahoma State Universitys air conditioned high bays in the middle of a summer day. The resulting shock was characterized by cooler (warmer) temperatures and lower (higher) moisture content, but higher (lower) relative humidity, within (outside of) the bay. Calibrated and validated mobile mesonet platforms were present on both sides of the shock to serve as references. In contrast to sensor oil baths which can be used to evaluate sensor performance, the experiments conducted enabled evaluation of the impact of siting and platform motion/attitude as well. The experiments were modeled off of those used by Waugh (2012) to evaluate sensor response characteristics associated with the U-tube sensor shield for mobile mesonets.

An example of temperature from a fast response sensor (Figure 8a) along with temperature (Figure 10b) and relative humidity (Figure 8c) from an iMet sensor package mounted on a University of Oklahoma CopterSonde multi-rotor sUAS flown across the shock illustrates the magnitude of the pseudo discontinuity. The results also illustrate the impact of sensor response errors on relative humidity: the spike in relative humidity (Figure 8c) is likely a consequence of the damped temperature response relative to the more rapid response of the sensor to changes in moisture content (Richardson et al. 1998). Thus, across a shock characterized by increasing temperature and increasing moisture but decreasing relative humidity, the slower temperature response yields an anomalously cool temperature and thus anomalously high relative humidity. Correcting the relative humidity following previous experiments not only removes the spike (Figure 8d) but also brings the relative humidity on either side of the shock into better agreement with the reference values (Richardson et al. 1998; Houston et al. 2016). Note that the decrease in relative humidity and increase in temperature between 21:31 and 21:32 is a consequence of rotor-driven mixing of the initially stratified air within the bay.

In this component of Tasks 2-1 and 3-7, the impact of sensor response and aircraft airspeed on the accuracy of in situ observations of the CBL and airmass boundaries are estimated using simulated aircraft flown within large eddy simulations. Both instantaneous errors (differences between observed temperature, which include the effects of sensor response and airspeed, and actual temperature) and errors in representation (differences between serial observations and representative snapshots of the atmospheric state) are considered.

Instantaneous errors should theoretically scale directly with the speed at which an aircraft passes across a gradient and with the sensor response time (τ), typically defined as the e-folding response. While errors stemming from "slow" sensors could be minimized in post-processing the aim of this work is to offer practical guidance on the configuration and operation of airborne systems that are required to maximize the accuracy of observations of boundary layer phenomena without substantial post processing.

Serial observations collected by in situ platforms are typically used to approximate the state of a phenomenon at a given time (a snapshot). However, this approximation degrades for phenomena that evolve over a timescale less than the observation period; a degradation that can occur even when sensors have near-zero response times. For an airborne platform, the accuracy of representation of a particular snapshot should scale directly with airspeed. In contrast, as noted above, the instantaneous accuracy should scale inversely with airspeed. Another aim of this work is to characterize the representation accuracy as a function of

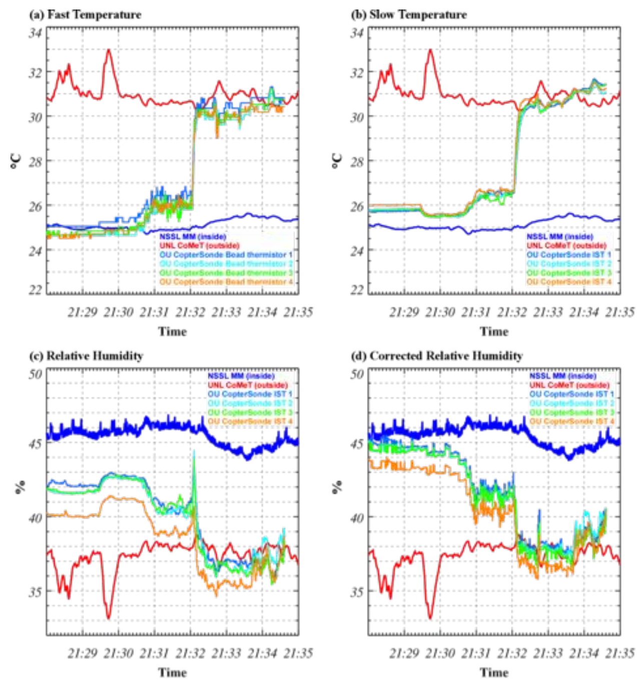

Figure 8: Calibration-validation experiment results.

aircraft airspeed.

Experiments for this work are conducted using simulated aircraft flown within large-eddy simulations. Experiments consider combinations of modeled sensor response as well as aircraft airspeed. Focus is directed towards two phenomena that are often the focus of targeted data collection by sUAS: the convective boundary layer (CBL; Figure 9) and airmass boundaries (Figure 10). Since the CBL is often observed using profiling by rotary wing aircraft, synthetic observations of the CBL are modeled using a simulated rotary wing aircraft. Similarly, since airmass boundaries are often observed using transects by fixed-wing aircraft synthetic observations of airmass boundaries are modeled using a simulated fixed-wing aircraft. Synthetic data assume a well-aspirated first-order sensor.

Instantaneous errors are found to scale directly with sensor response time and airspeed for both CBL (Figure 11) and airmass boundary (Figure 11) experiments. Errors tend to be larger for airmass boundary transects compared to the CBL profiles. Instantaneous errors for rotary-wing aircraft profiles in the CBL simulated for this work are attributable to the background lapse rate and not to turbulent temperature perturbations. For airmass boundary flights, representation accuracy is found to degrade with decreasing airspeed (Figure 11). This signal is most pronounced for flights that encounter the density current wake (e.g., the blue and red aircraft visualized in Figure 10). When representation errors also include instantaneous errors due to sensor response, instantaneous errors are found to be dominant for flights that remain below the turbulent wake. However, for flights that encounter the wake, sensor response times generally need to exceed 5 s before instantaneous errors become larger than errors in representation.

These results have been disseminated in the following article which has been accepted for peer-reviewed publication: Jacob, J., P.B. Chilson, A. Houston, and S. Smith, 2018:

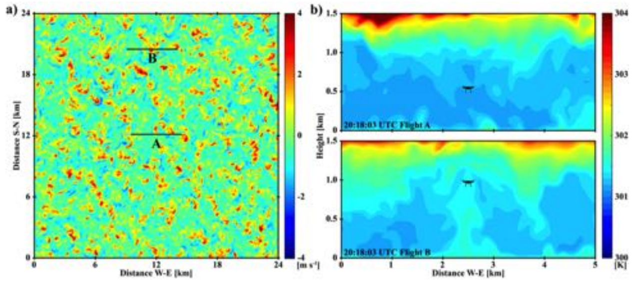

Figure 9: (a) Plan view of w in the CBL simulation at 20:18:03 UTC and z = 750 m (b) Vertical cross-sections of potential temperature (shaded every 0.1 K) along with rotary-wing aircraft positions for flights with an ascent rate of 1 m/s at the domain center (flight A) and in a thermal located 400 m west and 8500 m north of the domain center (flight B). The cross section locations are indicated by the W-E black lines in a. Flights are located at the center of the lines.

Considerations for Atmospheric Measurements with Small Unmanned Aircraft Systems as part of the CLOUD-MAP Flight Campaign. Atmosphere.

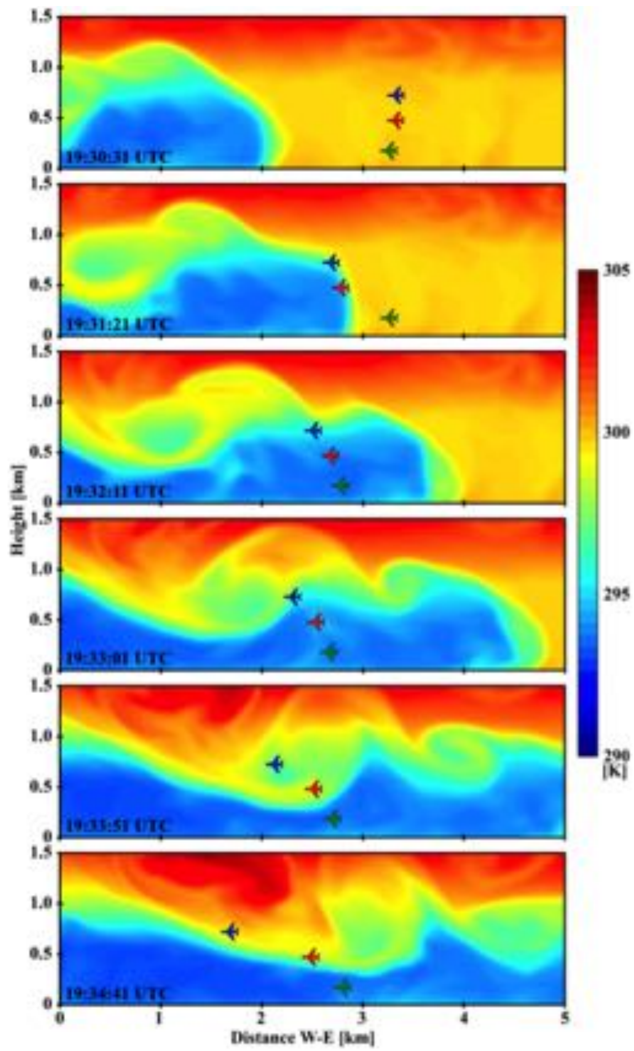

Figure 10: Vertical cross-sections of potential temperature (shaded every 0.1 K) for the air-mass boundary simulation along with fixed-wing aircraft positions for flights with a airspeed of 20 m/s, xb of 2000 m, and z of 175 m (green symbol), 475 m (red symbol), and 725 m (blue symbol). The subdomain shown in this figure is between 115,950 and 120,950 m from the western edge of the model domain.

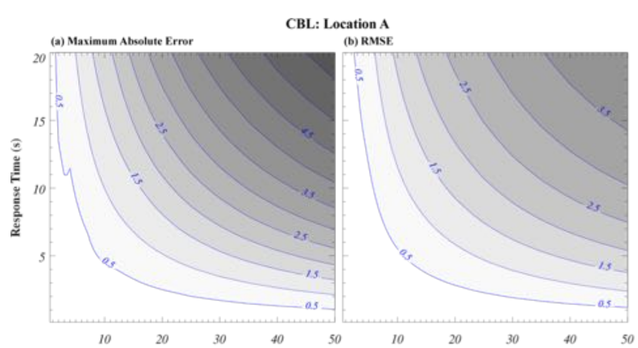

Figure 11: Instantaneous errors for rotary-wing aircraft flights in the CBL simulation contoured every 0.5 K: (a) maximum absolute error and (b) root mean square error (RMSE).

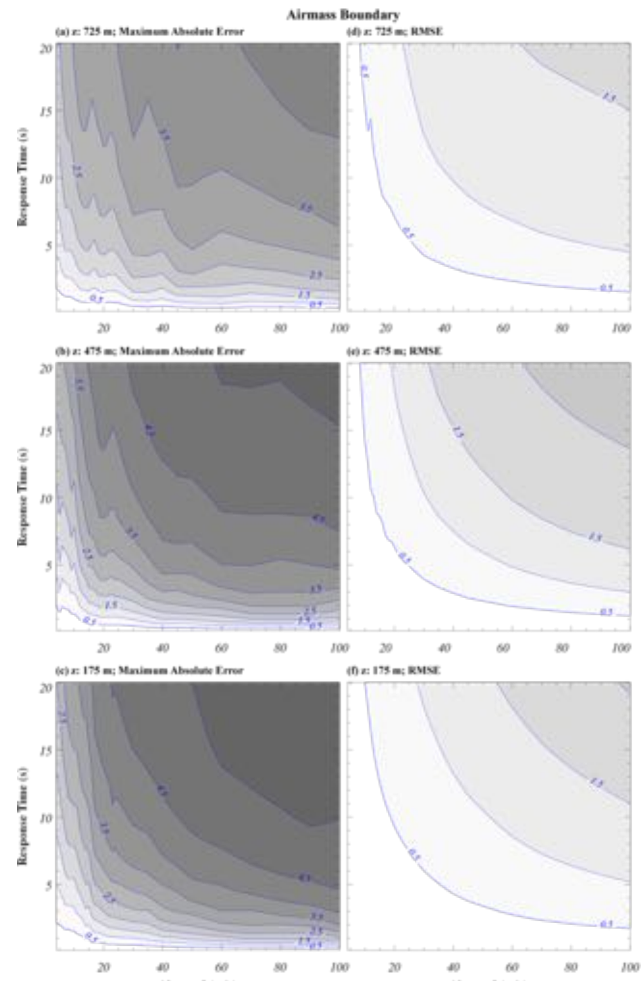

Figure 12: As in previous figure but for the airmass boundary flights at altitudes of (a,d) 725 m, (b,e) 475 m, and (c,f) 175 m.

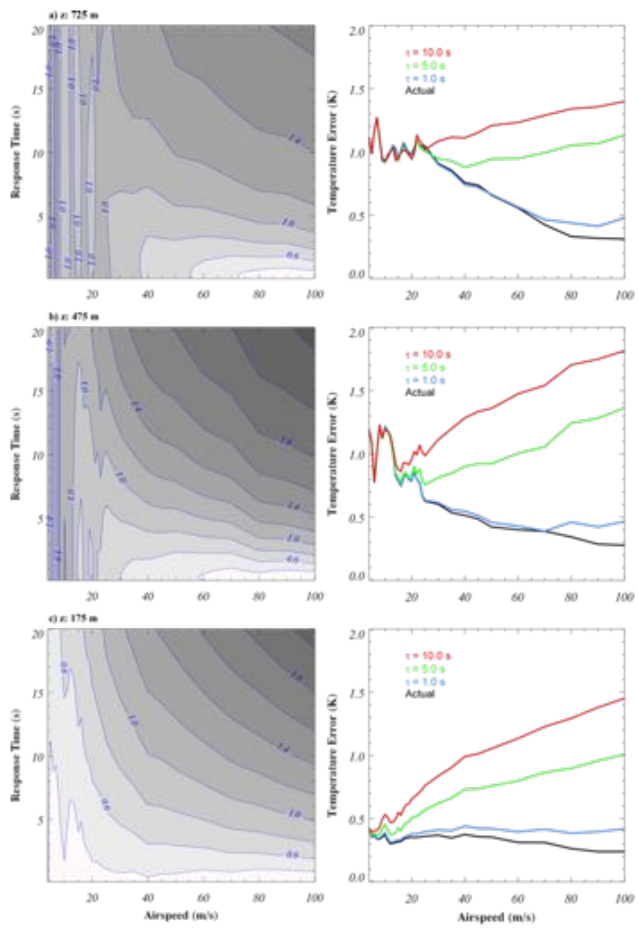

Figure 13: RMSE relative to representative snapshots for each flight for (a) z = 725 m, (b) z = 475 m , and (c) z = 175 m. Left panels: errors contoured every 0.2 K relative to airspeed and response time. Right panels: errors plotted as a function of airspeed for response times of 1 s, 5 s, and 10 s along with the errors for the actual data

CLOUD-MAP	Year 1 2015-2016	Year 2 2016-2017	Year 3 2017-2018	Year 4 2018-2019
Science	Science tasks	Science tasks, plus 2017 Total Eclipse	Science tasks, plus science question	Science tasks, plus science question
Technology	Sensors/platforms	Sensors/platforms, plus 3-5 formation	Sensors/platforms, plus >10 formation	Sensors/platforms, plus 3-5 adaptive flight control
Community Interaction	Perception focus groups, plus outreach	Perception, plus severe-weather risk, outreach, PR	Perception, plus risk, outreach, PR	Workshop and outreach
Team Science via Flight Campaigns	Complimentary	Multidisciplinary	Interdisciplinary	Transdisciplinary
	Flights: 241 Flight hours: 25	Flights: >500 Flight hours: >70		
Collaborative Publications	Multidisciplinary conference: 5	Multidisciplinary conference: 6	Multi-university conference: 1	
	Multi-university conference: 2	Multi-university conference: 2	Multidisciplinary, multi-university journal: 3	

Table 1: Summary of Annual CLOUD-MAP Goals and Results for Years 1 and 2.

1.3 Team Science

CLOUD-MAP research necessitates integration across disciplines, so it is also necessary to understand and incorporate approaches for successful transdisciplinary collaboration, referred to as team science, to increase the teams capacity to achieve its objectives [Salazar]. With more than 10 researchers working together, the CLOUD-MAP team is considered to be a "larger group" [NRC Team Science] so a framework for collaboration consistent with team science research was established including annual video and in-person team meetings and flight campaigns. An intentional research task structure defined smaller CLOUD-MAP collaboration subgroups, each involving researchers from multiple universities. Therefore, in addition to science and technology outcomes, growth of team science capacity was envisioned and is being evaluated.

Table 1 summarizes the envisioned 4-year progression of science, technology, community interaction, annual flight campaigns, and researcher collaboration. Science, technology, and community interaction growth can be seen in increasing numbers of archival publications and dissemination presentations. Campaign collaboration goals for each year are analogous to the final stages of Hardens experiential educational model that presents growth of interdisciplinary mastery through the combination of information with experience, and culminating with the following sequence: understanding complimentary ideas, multidisciplinary decision-making, recognizing interdisciplinary commonalities, and ultimately creating transdisciplinary meaning [Harden]. Collaboration can also be measured by co-authored conference presentations and archival publications.

Another approach for assessment of developing collaborations is a self-perception survey of research collaborations among the CLOUD-MAP faculty. The survey was completed in April 2016 (including before CLOUD-MAP), 2017, and 2018. Faculty researchers indicated which others on the team they had collaborated with during the previous year on research in general, proposals, conferences or journal papers. Thus, the survey represents perceived collaboration at that moment in time, not the actual that would be determined

Annual Summaries	Yr-0		Yr-1		Yr-2		Yr-3	
	Intra-	Inter-	Intra-	Inter-	Intra-	Inter-	Intra-	Inter-
Research	27	10	43	30	43	34	41	41
Journals	3	1	5	9	8	11	11	11
Conferences	8	1	11	6	9	21	21	27
Proposals	28	12	28	12	20	19	23	23
Totals	66	24	87	57	80	85	96	102

Table 2: CLOUD-MAP Collaborations Perceptions Survey Results

by counting paper co-author pairs or proposal co-PI pairs as is done in the NSF data portal results. Results of the CLOUD-MAP perceived-collaborations survey can be examined for a number of outcomes related to team science.

With 16 total faculty after one left the EPSCoR jurisdictions in the first year, the total number of collaborations possible is 960 over these four areas. In any one category of the four (research, journal papers, conferences, proposals), if all worked with all, the total collaborations would be 16*15 = 240. Each collaboration between a pair of faculty is represented twice, just as is done in the survey. Considering overall capacity, Table 2 shows that 90 total collaborations before CLOUD-MAP represented about 9% of the total capacity. Steady growth of research relationships increased both for inter-university collaborations and intra-university partnering, more than doubling collaborations to 198 by Year-3 (to over 20% of total capacity). Looking instead at a logical progression of collaboration-building, we see considerable impact of the CLOUD-MAP team science. We expect collaborations increases in research and proposals to lead those for conferences, and finally journal papers. Research collaboration in general increased from 15% to 34% of capacity by Year-3. Proposals collaboration increased from 17% to 19% of capacity. Conferences collaborations increased from 4% to 20% of capacity. Journal paper collaborations increased from 2% to 9% of capacity.

We can also look at the growth of relationships within and across universities - in each category - separated into intra-university collaborations versus inter-university collaborations. Before CLOUD-MAP, the majority of collaborations (73%) were intra-university. Even so, many of the CLOUD-MAP team at the same institution had not worked together so there was capacity to grow both internal as well as external partnering. Steady growth increased inter-university collaborations from 24 to over 100 (over 400% growth), along with increased intra-university partnering from 66 to 96 (150% increase). Insight into collaborations among and across disciplines is also possible with the survey results and will be developed in a future phase of these efforts.

Insight is gained into the progression of the CLOUD-MAP research network through biographs constructed from the survey research results. Figure 14 shows the evolution of the network from one connected primarily by the four institutional PIs (highlighted) through the project PI at OSU (circled in red). Before CLOUD-MAP, two researchers were not connected to any others. During Year-1, additional connections emerged to add to those before CLOUD-MAP and change the social network structure, although the institutional PIs remained as prominent connections within the network. Biographs for Year-2 and Year-3 show an evolving team, with the original structure almost lost and new leaders emerging at

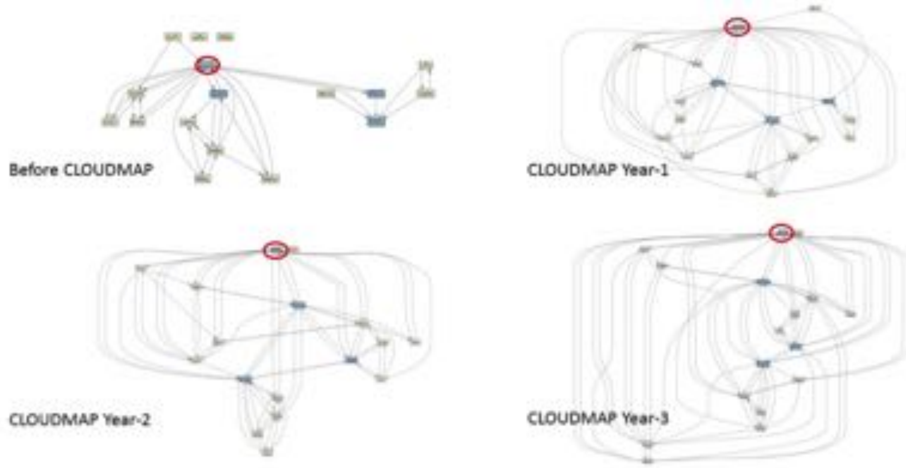

Figure 14: Biographs of self-perceived research collaboration connections in CLOUD-MAP.

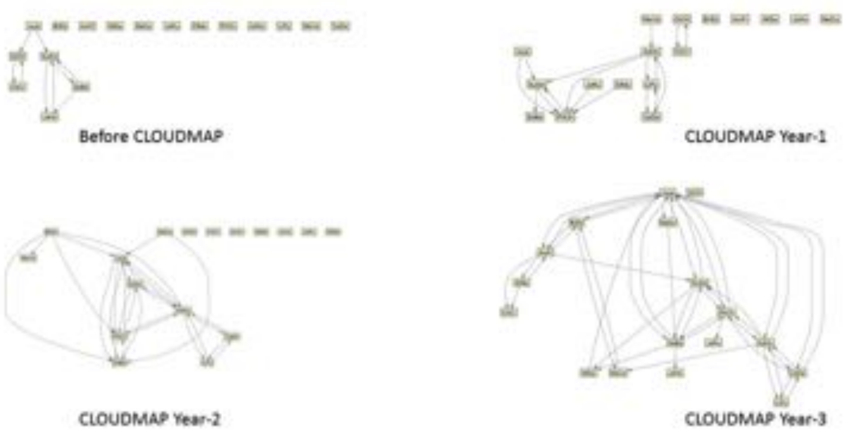

Figure 15: Biographs of self-perceived conference collaboration connections in CLOUD-MAP.

each institution. Biograph differences from one year to the next reveal emerging catalyzing connections indicating emerging leaders on the team.

Biographs of conference connections in Figure 15 show more dramatic team evolution to an integrated transdisciplinary research organization.

2 Additional Major Project Elements

2.1 Early Career Faculty Advancement and Interjurisdictional Collaborations

Early career faculty advancement has proceeded well, with ECE faculty participating at all levels within and without the project as indicated by the DOP results. To date, promotions to tenure have included 2 faculty obtaining tenure at the University of Kentucky, 2 at the University of Nebraska-Lincoln, and 1 at Oklahoma State University.

Table 3: Early career faculty promotions.

Year	**Early Career Faculty**	**Institution**
2016	Jesse Hoagg	University of Kentucky
	Carrick Detweiler	University of Nebraska-Lincoln
2017	Marcelo Guzman	University of Kentucky
	Matthew Van Den Broeke	University of Nebraska-Lincoln
2018	Chris Crick	Oklahoma State University

Collaborative proposals were highlighted elsewhere in the report indicating an increasing and high amount of research collaboration. Research collaboration, particularly interjurisdictional collaboration, among the project participants has been high exceeding expectations. Examining these numbers in more detail, before CLOUD-MAP , approximately 70% of the total faculty collaborations were intra-university. Even so, many of the CLOUD-MAP team had not worked together previously so there was capacity to grow internal collaborations as well as external ones. Collaborations between the team members has resulted in a substantial number of collaborative publications. A special submission for the journal *Atmosphere* was organized and edited by Prof. Marcelo Guzman of UK to highlight many aspects of this project, among others.

2.2 Public Outreach

The PIs have given both general and technical presentations and seminars discussing the details and broad benefits of the NSF sponsored program. These include but are not limited to the American Institute of Aeronautics and Astronautics, the American Meteorological Society, the Association of Unmanned Vehicle Systems International, the National Center for Atmospheric Research, the National Weather Service and the National Severe Storms Laboratory, Friends and Partners In Aviation Weather, NASA, and the FAA. There has been a growing interest in UAS related atmospheric monitoring by various news outlets. We have provided interviews with several of the local newspapers, magazines, and news stations. There has also been attention from more widely recognized news outlets such as Popular Science, PBS News Hour, Weather Channel, CBS News, Physics Today, and others.

2.3 NSF EPSCoR Specific Reporting Requirements

2.3.1 Diversity

The CLOUD-MAP team as a whole has been striving to recruit from underrepresented groups when selecting graduate and undergraduate students. Demographic information is collected by the team utilizing portions of the limited information provided by ILI Track-2 Data Outcomes Portal. However, due to some students under-reporting their information to ILI as well as those unwilling to disclose demographic data on the DOP, we have made an effort to gather this information through the students directly. This data is reported here for the current reporting period.

Over 105 recorded trainees have participated in the project over the current period with the majority of these students (over 80%) participating throughout the entire year. These trainees consist of primarily undergraduate and graduate students but also include K-12 (high school) students and post-doctoral researchers. The project has engaged undergraduate students at a substantial level with both integrated involvement in research projects (under direct mentorship of a graduate student) and with class-related and outreach projects. The number of undergraduate students actively involved in the project was so great that it exceeded the ability of the DOP to properly track the students working on the effort and required reprogramming on part of the DOP contractor. A small percentage also includes research staff, most of which transitioned from graduate student status to full-time employee during the project period. This is shown in Figure 16. Approximately 25% of the students participating in the project are female. This breakdown is shown in Figure 17. Racial and ethnic breakdown was harder to determine, since most students did not report that information on the DOP. Thus, best estimates were used based on information obtained by the universities. It is estimated that approximately 18% of participants are a member of an under-represented minority. The estimated racial and ethnic breakdown is shown in Figure 18.

At OSU, over 50 trainees have been involved on the project (46 recorded on the DOP plus many others that have not). This is roughly equally split between graduate and undergraduate students. Additionally, 6 high school students worked on the project. Approximately 25% of total trainees were female and 13% were under represented minorities (African American and Native American). At OU, the current makeup of undergraduate students consists of 5 women and 3 men across both meteorology and electrical and computer engineering. For the current graduate students, all 6 are men. Two postdocs have been hired in the area of UAS research, both are women. They are not paid from CLOUD-MAP directly, but the funds being used to support them were secured in part as a result of CLOUD-MAP. Two of the three faculty supported by OU are women and have provided a role model for the students. We should note that electrical engineering is a male dominated field. Although not as extreme, the majority of students in meteorology at OU are also male. The UK CLOUD-MAP team to date is comprised of 5 faculty, 2 staff, and 26 trainees. Five of the 26 trainees and one new staff member were added this year. A large number of new trainees is anticipated next year after expected graduations of graduate and undergraduate students. Four of the trainees are female; one is an underrepresented minority.

As discussed elsewhere, Objective 4 is focused on outreach activities, which includes

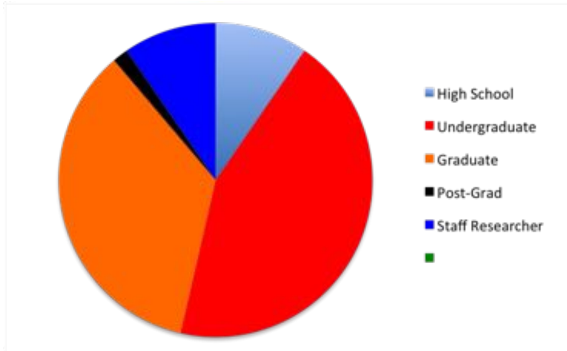

Figure 16: Student status.

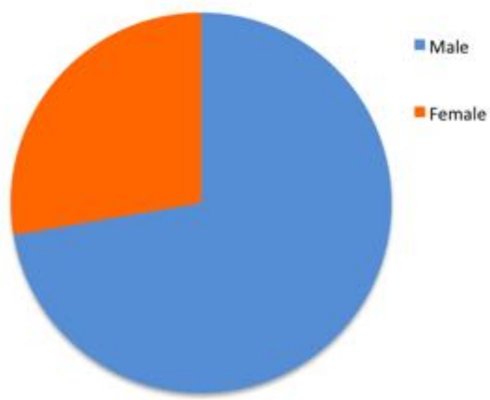

Figure 17: Gender breakdown.

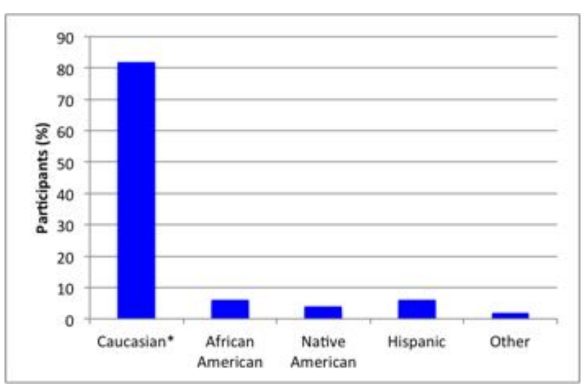

Figure 18: Racial and ethnic breakdown by university. *Includes undetermined or not reported.

K-12 STEM and diversity enhancement. We will build on current STEM activities in Oklahoma, Nebraska and Kentucky to develop national K-12 activities. This will also include community efforts to obtain a better understanding of public perceptions of UAS applications to assist policy development concerning the potential widespread application of UAS for atmospheric science. Since Oklahoma, Nebraska, and Kentucky serve large rural populations and both Oklahoma and Nebraska serve large Native American populations, the project teams are using the proposed research as a vehicle to serve these underrepresented groups working with Tribal Colleges to establish courses and programs to provide unique STEM related opportunities to underrepresented students. We use social media as one of our primary outreach mechanisms. In addition to our traditional web-site (cloud-map.org), this includes Facebook, YouTube and twitter posts and feeds to keep both team members and fans up-to-date with the progress of the program and will be used to promote STEM careers in atmospheric sciences, aviation, engineering, meteorology, and other related disciplines to K-12 students. Videos are being professionally developed to enhance the social media outreach efforts. Additionally, resources are aimed at encouraging undergraduate students to pursue graduate education.

2.3.2 Budget Status

Overall project budget is within expectations of planned expenditures, with a burn rate projected to expend the total budget by the end of the project for each of the core university partners. Expenditures as of March are at 50% of the total 4 year budget, allowing just over half for the remaining 18 months of the effort. Of the $5,995,869, $2,972,186.13 has been invoiced. Note that these numbers are only up-to-date as they are invoiced, so subcontracting universities (OU, UNL, and UK) typically lag expenditures by a quarter or more, so individual breakdowns are provided below. Invoice lags notwithstanding, this is still expected to be on track of a total burn due in part to the large expenditures expected as part of the 2018 summer flight campaign (additional travel and support). Summer expenditures typically increase with trainees added for flight testing and campaign travel, which will be a substantial portion of the 2017-18 budget.

For the remaining 2 years of the project, OSU has budgeted outside the MAE department $599,691 and has expended $316,334.47 leaving a remaining balance of $283,356.53. This includes $274,030.00 budgeted and $111,584.80 spent for Geology and $325,661.00 budgeted and $204,749.67 spent for Computer Science. The University of Oklahoma received $533,250 for years 1 and 2 of the CLOUD-MAP project and then $648,612 for years 3 and 4, or a total of $1,181,862. According to a budget report extending through 31 March 2018, $553,186 of that remains uncommitted; however, this number does not reflect several significant expenses. Therefore, by the end of July 2018, the total amount of uncommitted funds is estimated to be $324,414. UK expenditures are on track with total expenditures of $873,270 through March 2017 of the $1,400,000 total UK budget (62.4%). This total is through month 32 of 48 (66.7%) of the 4-year period of the project.

2.4 University Advancement

2.4.1 Oklahoma State University

Spurred by the NSF RII Track-2 FEC award, OSU established the Unmanned Systems Research Institute (USRI) in late 2015 with operations beginning in early 2016. The purpose of USRI is to bring together multidisciplinary research talent from across OSUs campuses to collaborate on the design, testing, evaluation and application of unmanned technologies to a wide variety of research problems. Building on its recognized expertise in developing a variety of applications for unmanned aerial vehicles, the USRI will apply this proficiency to design unmanned vehicles across a range of environmental conditions. Creating the institute is the latest example of OSU as a leading comprehensive research university. The NSF RII Track-2 FEC award highlightted the need for an interdisciplinary research organization.

USRI is initially housed at OSUs Richmond Hills Research Complex on the north side of Stillwater, however a new building devoted to to USRI is in the final planning stages, with construction scheduled for completion in spring 2018. The Unmanned Systems Innovation Laboratory (USIL) will house engineers and scientists at both the graduate and undergraduate level and be devoted to R&D in UAS. The OSU CLOUD-MAP operations will be housed here. The current design is shown in Figure 19. USRI includes facilities devoted to commercializing technologies developed through the institute. As part of USRI, this facility concentrates on focused UAS platform development and integration capability for government and commercial customers, including public and civilian aspects missions, to provide state-of-the-art research and development for UAS and manage a centralized venue for commercial, academic, and government entities to advance the overall UAS industrys operational and technical advancements. Specifically this facilitates

- UAS RDT&E - Providing relevant research topics for industry and academia
- Graduate student and faculty research support
- Full design/build/test capabilities for small vehicles and components of larger vehicles

The goal of this system is to reduce the environmental impact of oil and gas operations across the entire process range from extraction to production and is suitable for both research and industrial activities.

The overall goal of these collaborations is to develop and sustain a synergistic, interdisciplinary, campus-wide research and education program involving faculty, students, and staff that highlights multiple aspects of UAS. This multifaceted effort focuses on (1) development, design, and implementation of UAS, (2) legal operation and integration of UAS into the National Airspace System (NAS) as data collection devices, (3) use of UAS-captured data to analyze spatial processes and aid decision-making in a number of application areas, and (4) education and training to satisfy the growing number of professionals needed to support this emerging economic sector within and outside of Oklahoma. Our broad aim is to make OSU the leading university in the U.S. for UAS research and instruction. We seek to inspire, encourage, and develop the initial generations of UAS industry persons, academics, and entrepreneurs.

Team members from different disciplinary backgrounds bring a diverse array of expertise to the program. The project is supported by several on-campus entities, which help

Figure 19: USIL - Unmanned Systems Innovation Laboratory concept and view from construction site.

to ensure continued success: MAE houses aerodynamics and flight dynamics laboratories and has led efforts to obtain FAA clearance to fly under specified restrictions; OSU owns an airfield dedicated to UAS flight that provides a controlled, legal environment within which to operate UAS for flight testing, training, data collection, etc.; the Unmanned Systems Research Institute (USRI), directed by team member Jacob, offers certified UAS pilots, aircraft, and additional resources; GEOGs Center for Applications of Remote Sensing (CARS) has a full suite of hardware and software to process UAS-collected data; BAE has access to Agricultural Experiment Station land where flights have already occurred (e.g., monitoring prescribed burns) and is involved with the 120-station Oklahoma Mesonet where UAS prototype flights will occur.

Basic and applied research on UAS (e.g., the technology itself, use of the technology, and use of information gathered by the technology) remains in its infancy. The National Science Foundation (NSF, 2016) recently recognized the need for interdisciplinary research on UAS and allotted $35M for UAS projects. Team members have already secured funding from the NSF in several related research areas: (1) emergency management in wildfire response, (2) integration of UAS into the NAS, and (3) land cover dynamics from UAS-captured imagery. With respect to (1), since 2014 members of the team have submitted two $1.5M proposals to FEMA and one $2.8M proposal to NSF on using UAS for wildfire response and mitigation. These proposals include development of UAS for wildfire dynamics investigations as well as for emergency responder information and decision-making. Regarding (2), Aviation Education (AVED) is collaborating with USRI to establish a predictive UAS platform visibility model for pilots operating under visual meteorological conditions to detect and avoid midair collisions with manned aircraft. MAE is developing an experimental apparatus to evaluate the effects of a UAS platform collision with a general aviation aircraft structure. Geology (GEOG) is leading efforts surrounding (3) to use UAS-captured aerial imagery for accurate terrain modeling and land cover mapping.

A limited number of universities nationwide have established a formal UAS curriculum, and the team is working to develop a comprehensive, interdisciplinary UAS curriculum that will uniquely position OSU as a nationwide leader in UAS instruction. The curriculum will incorporate courses across departments and colleges to enable students to successfully compete for a variety of jobs in this emerging industry (e.g., UAS pilots, engineers, mapping specialists, etc.). The team is developing UAS-specific interdisciplinary (cross-listed) courses and outreach courses. The applied nature of the UAS project greatly supports OSUs land-grant mission. The UAS team works directly with state and federal agencies and state and local first responders on applications related to severe storm detection, forecasting, and warning, emergency management (i.e., wildfire monitoring, field operations, and preparation), agricultural monitoring, oil and gas monitoring (i.e., asset inspection), and natural resource management.

The team has successfully implemented several program offerings. MAE offers a UAS option for its MS and PhD degrees. AVED established a UAS Pilot Minor in 2015, providing students the ability to specialize in UAS flight operations. In 2016, GEOG introduced a BS in Geospatial Information Science that will incorporate UAS applications. MAE offers two graduate-level UAS courses (Unmanned Aerial Systems Design and Analysis and Unmanned Aerial Systems Propulsion) where students focus on UAS design. AVED offers an Unmanned Aircraft Pilot Laboratory for teaching UAS operational aspects. GEOG recently proposed Geospatial Applications for UAS to prepare students for processing and analyzing UAS-captured data. The team is working to build stronger interdisciplinary linkages between courses and round out degree options with specific topics. In addition, the team is developing outreach courses to train UAS- interested persons off-campus. Team members continue to hold workshops and participate in events such as GIS Day at the Capitol to foster positive perceptions of UAS. This collaborative effort is designed to provide the foundation for current and future UAS scholarship and education at OSU. Importantly, considering the interdisciplinary nature of the team effort, a plethora of other departments across campus are becoming involved in UAS projects in specific application areas (e.g., Plant and Soil Sciences, Horticulture) as well as the social aspects of UAS (e.g., Sociology, Psychology). In 2016, OSU recognized the team for *Interdisciplinary Synergies for Unmanned Aerial System Innovation & Advancement* with the OSU Presidents Cup Promoting Creative Interdisciplinarity.

The program has utilized undergraduate researchers in the lab at a large level employing them across all tasks. This includes both integrated involvement in research projects (under direct mentorship of a graduate student) and with class-related and outreach projects. An example of one of the projects is shown in Figure 20 where collaborative teams of undergraduate students are developing low-cost platforms for citizen science and third world applications. Regular meetings among all team members are held weekly for planning purposes and include presentations by student researchers and guest speakers.

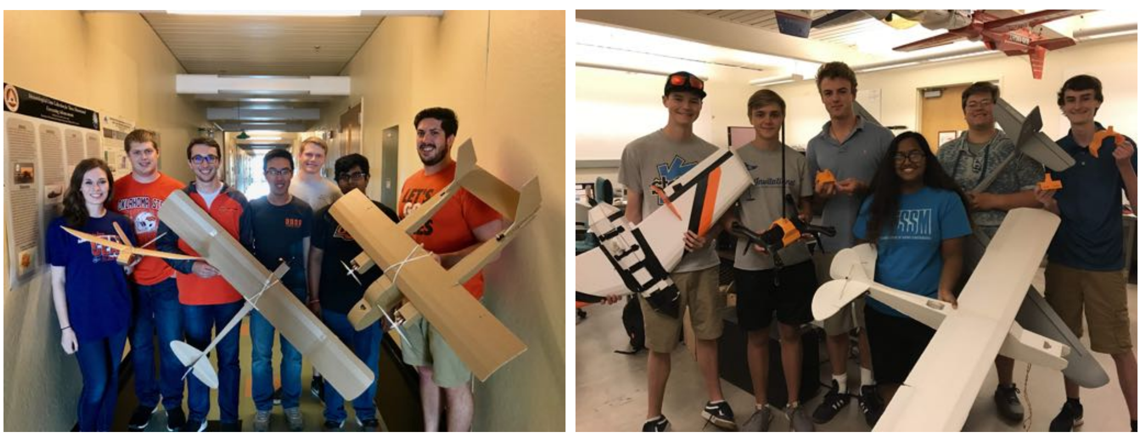

Figure 20: OSU undergraduate students (left) and high school students (right) developing low-cost platforms for citizen science and third world applications.

2.4.2 University of Oklahoma

<u>Overview</u>

The NSF RII Track-2 FEC award (CLOUD-MAP) has played a significant role in catalyzing activities involving atmospheric observations using UAS at OU. As we will show, this award has been a literal game changer for OU. As a result of CLOUDMAP, OU has hired 21 undergraduate research assistants (12 males and 9 females, 1 minority), 12 graduate research assistants (all males), and 2 postdoctoral researchers (both female). The breakdown of students by discipline is as follows: meteorology (15 undergraduate and 3 graduate), electrical and computer engineering (3 undergraduate and 6 graduate), aerospace and mechanical engineering (2 undergraduate and 1 graduate), and data science and analytics (1 graduate). This has provided the first research opportunity for most of the undergraduate students. The funding has also enabled the OU CLOUD-MAP team to purchase and develop vehicles and instrumentation to enable atmospheric research.

Through funding from NSF, OU has been able to significantly expand the scope of research involving UAS in general and for atmospheric studies in particular. The research in meteorology and atmospheric physics using UAS has created a “ripple effect” that has spread into such topics as investigations of radar antenna radiation patterns (radar engineering), studies of stream flows (fluvial geomorphology), how bees navigate in flight (zoology and animal behavior), and other areas.

Center for Autonomous Sensing and Sampling

Motivated in part by the grant, OU has created the Center for Autonomous Sensing and Sampling (CASS) and named the OU PI for CLOUD-MAP as the Director. CASS's mission is to explore, advance, and develop complete adaptive and autonomous sensing and sampling systems for use in the atmosphere, on the ground, and in the water, and to help facilitate the integration of this technology across various disciplines and institutions. To do so, CASS leverages the State's and University's strengths in aviation, atmospheric science, robotics, and remote sensing development to create innovative solutions to pressing societal needs and collaborate with industry to develop and transfer technology for commercial applications. The goal of CASS is to establish itself as a recognized global leader in research, education, and development involving autonomous sensing and sampling solutions to address science and technology driven needs, fostering an environment for trans-disciplinary applications of this technology, and helping to promote the effective transfer of knowledge and technology to academia, government, and industry.

The Center has been enjoying growth and maturity since it was created in 2016. CASS now supports six graduate students (two for only part of their studies) and one more will join in the summer. Currently CASS has two postdocs and just hired a full-time engineer. The Center is building up infrastructure as well. We have an established field site at OU Kessler Atmospheric and Ecological Field Station (KAEFS), which provides an excellent venue for atmospheric research. CASS is also creating a research lab near the OU Max Westheimer Airport, which will include a 200 ft x 240 ft x 35 ft netted enclosure for UAV testing and demonstration. The Center is also setting up office and laboratory space in the National Weather Center on the OU Research Campus.

CASS is expanding into a variety of research topics and reaching out to faculty across the OU campus to establish collaborations. The majority of topics in which CASS is involved focus on meteorology and electrical and computer engineering; however, as CASS becomes more established, additional potential connections should present themselves. On area in which CASS is looking to establish itself is in atmospheric chemisty

Environmental Profiling and Initiation of Convection

Through CLOUD-MAP, OU has also been able to strengthen its relations with NOAA in the area of sUAS for atmospheric monitoring. OU was already working closely with the National Severe Storms Laboratory (NSSL) and Storm Prediction Center (SPC); however, now new strategic partnerships are developing. NSSL, along with OU, the University of Colorado in

Boulder, and Meteomatics, a company in Switzerland that manufactures and operates small UAS for atmospheric monitoring, were awarded funding from the NOAA UAS Program Office to begin integrating UAS into operational weather forecasting. The official title of the proposal is “Three-Dimensional Profiling of the Severe-Weather Environment” but it is operating under the name of EPIC (Environmental Profiling and Initiation of Convection). The study is unique in that researchers are being directed by the National Weather Service, who is deciding when and where the UAS vehicles will be deployed.

An objective stated in the NOAA UAS Program Office request for proposals was to “evaluate options for UAS profiling of the lower atmosphere with applications for severe weather”. We proposed to: 1) develop small UAS (sUAS) capable of acquiring needed wind and thermodynamic profiles and transects of the ABL; 2) adapt and test miniaturized, high-precision, and fast-response atmospheric sensors for obtaining such measurements; 3) gain experience in collecting atmospheric measurements from a proven fixed-wing aircraft and two alternatives for VTOL (Vertically Take Off and Landing) UAS with sophisticated autopilot systems; and 4) conduct targeted short-duration experiments at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site in northern Oklahoma and a second site to be chosen in “real-time” from the Oklahoma Mesonet in coordination with the National Weather Service (NWS)-Norman Forecast Office. The SGP site offers a rich suite of instruments useful for comparison with UAS measurements radiosondes, interferometers, Raman lidar, radar wind profilers, and Doppler wind lidars. Our high “Technology Readiness Level (TRL)” UAS are evaluated as components of a composite observing system capable of vertically profiling the pre-convective environment using sensors that offer measurement precision commensurate with most operational rawinsonde systems. The sUAS data were transmitted to NWS forecasters in real-time in Spring/Summer 2017 for the purpose of evaluation in NWS operations. Our project has been to provide graduate students, and undergraduate students associated with the Chickasaw Nation, with opportunities to help validate the UAS measurements with soundings provided by the SGP site and also NSSL mobile ground-based surface and remote sensing systems at no cost to the project.

This project provides NSSL and NWS with a much-needed mobile observing system for monitoring rapidly evolving high-impact severe weather conditions not observed with current operational systems. By refining successful strategies and establishing new ones for monitoring the ABL using these airframes and sensor packages to meet NOAA requirements, quantifying measurement uncertainties, and presenting forecasters with these unique observations for evaluation, we are raising the TRL by one or more levels for each proposed sUAS being evaluated. The project addresses the goal of the Weather-Ready Nation in the NOAA/OAR Strategic Plan: “Society is prepared for and responds to weather-related events” and the subsidiary objective to “determine how we can improve forecasts, warnings, and decision support for high-impact weather events.”

The main field campaign covered two weeks in May 2017 with several IOPs. Here we focus on data collected on 11 May. One of the teams was deployed at the Marshall Oklahoma Mesonet site conducting profiles when a thunderstorm initiated to our southwest and quickly developed a mesocyclone and earned a severe warning. See Figure 21 for radar imagery. This system produced a tornado. Visually, as the storm was growing in strength, we observed an inflow “beaver tail” right above the observing site, indicating that air parcels at our location were being ingested into the storm. An examination of the wind data col-

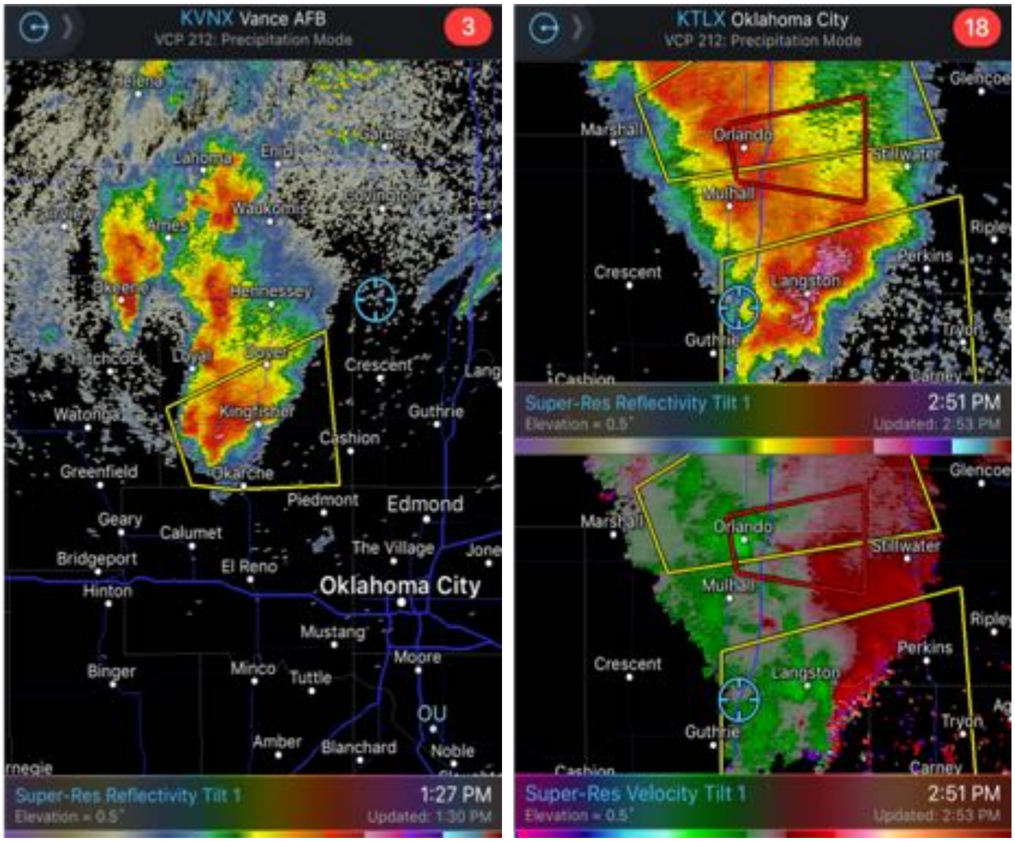

Figure 21: Images of the storm that developed during one of the EPIC IOPs. The left panel shows the reflectivity data at 1:27 PM local time (1827 UTC) The blue circle indicates the location of one EPIC observing sites (Marshall Mesonet Site) by the time of the image shown on the right panel (2:51 PM local time, 1951 UTC) the EPIC teams had terminated operations. Here the blue circle indicates the location of one of the project participants out observing the storm.

lected using our sUAS, we can see that indeed the conditions being sampled transitioned from ambient northwesterly flow and eventually veered towards inflow to the storm in just 90 minutes (see Figure 22). With this information being communicated back to forecasters in Norman in real time, this successfully demonstrated the utility of UAVs being deployed in near-storm environments.

Innovative Strategies for Observations in the Arctic Atmospheric Boundary Layer

Here we describe OUs participation in the Innovative Strategies for Observations in the Arctic Atmospheric Boundary Layer (ISOBAR) program. This is a multi-year research project supported by the Norwegian Research Council aimed at investigating stable arctic boundary layers using unmanned aircraft systems (UAS) in addition to other surface-based instruments. OU participated in the project the entire month of February by operating weather UAS on the island of Hailuoto, Finland, located at 65° North latitude just off the coast of Oulu. OU was selected to join the experiment based (in part) on account of technical development and operational experienced gained during CLOUD-MAP.

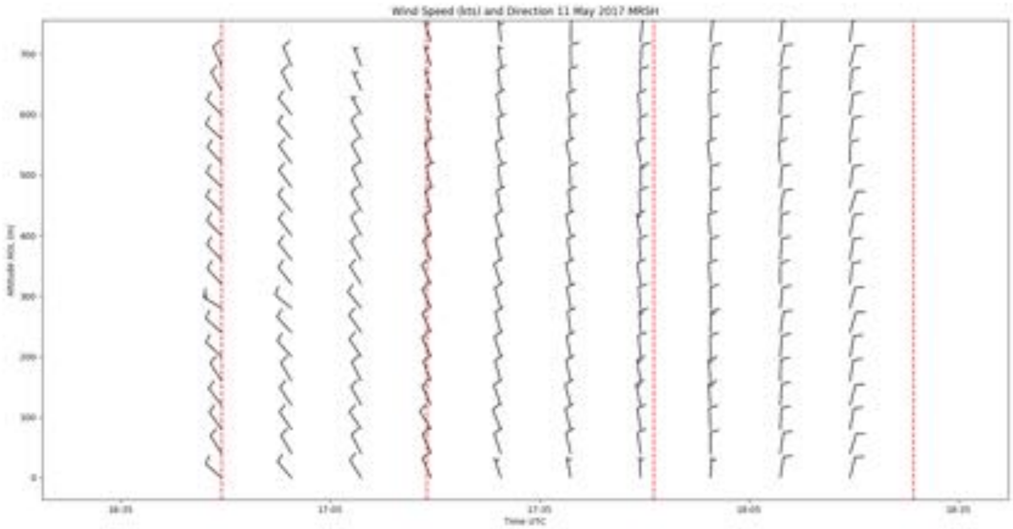

Figure 22: Plot of wind speed on 11 May 2017. The veering of the wind direction is indicative of the incoming storm. The vertical dashed red lines indicate when flights were made with the UAS. The plots of wind barbs with time and height are interpolations.

Teams from the University of Bergen (Norway), Finnish Meteorological Institute (Finland), University of Tbingen (Germany), University of Applied Science Ostwestfalen-Lippe (Germany), and the University of Oklahoma combined efforts for a 4-week long campaign. Deployed on the ice was a 10 m tower with sonic anemometers and thermodynamic sensors at multiple levels, as well as an eddy covariance flux station. There were two sodars, one vertically scanning and the other capturing horizontal winds. A Doppler wind lidar was also deployed halfway through the campaign. Participants were allowed to fly to 6500 feet AGL with no restrictions beyond line of sight or based on daylight hours. This allowed for continuous nighttime operations during intensive operations periods, which OU participated in. For more details about the project as a whole, see the ISOBAR blog at `https://isobar2018campaign.w.uib.no/campaign-plan/`.

OU employed four total UAVs, two fixed-wing and two rotary-wing. For thermodynamic profiling, a new generation of CopterSonde (designed and built by OU for EPIC) was deployed. These aircraft had a few design differences from one another, notably that one version made use of a ducted fan for sensor aspiration. Further testing is to be done to determine the true benefits of this setup, but preliminary results are very encouraging. On a whole, the OU CopterSondes flew close to 100 total missions, and broke several CASS records: highest altitudes flown (6000 ft, see Figure 23), nighttime flights, beyond visual line of sight, coldest temperatures, strongest inversions (see Figure 25), just to name a few. See Figures 23–26 for corresponding data and figures. While one of the CopterSondes did suffer a hard landing, it is still salvageable. The CopterSonde with the ducted fan performed without incident the entire campaign.

In addition to thermodynamic profiling, the University of Oklahoma brought along

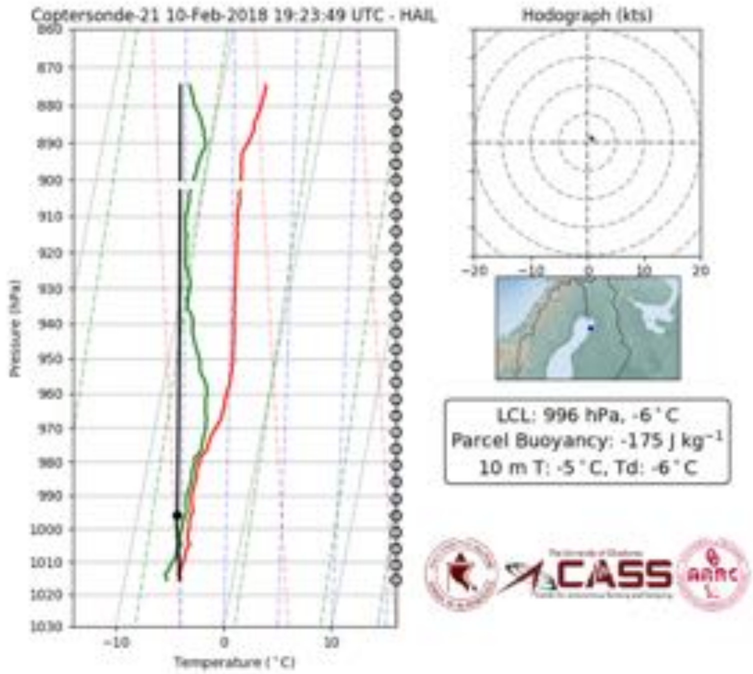

Figure 23: Coptersonde 2.1 sounding from CASS record highest altitude flight to 6000 ft (1800 m) during IOP 2 on 10 February 2018. Note: wind speeds are yet to be calibrated, so wind barbs on this and all figures are not representative.

two Tuffwing fixed-wing models. One was equipped with a specialized camera for photogrammetry missions, and the other equipped with a carbon dioxide gas analyzer. These both flew several missions successfully, however the photogrammetry Tuffwing suffered motor failure mid-flight due to water shorting out one of the magnetic coils. The rest of the aircraft and sensors are in okay condition; it has been determined that the fault was of the manufacturer.

Education and Outreach

There have been ample opportunities for the OU team to engage in education and outreach. During the 2017 Annual Meeting of the American Meteorological Society in January, a short course was offered, titled "Meteorological Observations, Instrumentation, and Data Assimilation". We presented one of the topics in the course called "Innovative Techniques: Unmanned Aerial Vehicles", which highlighted the value of UAS observations for meteorology and atmospheric physics. OU and the OU Max Westheimer Airport hosted the Aircraft Owner's and Operators Association "Fly In", which brought more than 300 pilots into the area. About 120 of the AOPA participants attended a day-long Weather Symposium at the National Weather Center. Chilson gave a presentation called "Improving Weather Forecasts with Unmanned Aircraft Systems". Several individuals expressed concerns about having more UAVs in the airspace, even to improve forecasts. After hearing about the level of risk mitigation and the scientists' willingness to work together with the FAA and the pilots, they

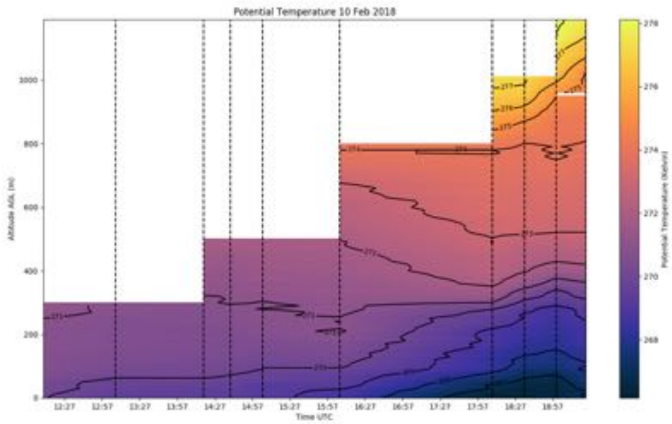

Figure 24: Time-height of potential temperature from IOP2. Hailuoto is situated at UTC+2. Stable boundary layer clearly present after sunset in early afternoon.

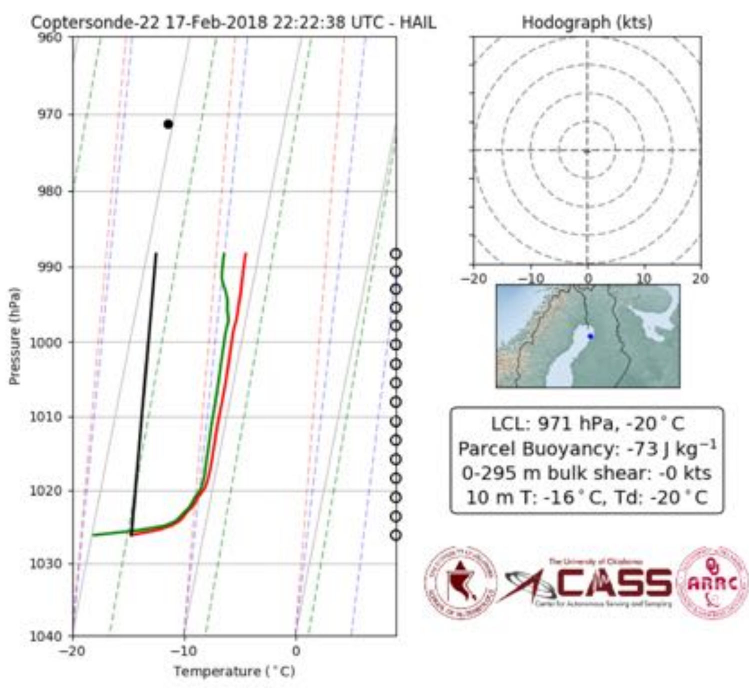

Figure 25: Sounding from IOP3 using CopterSonde 2.2 with the ducted fan. Impressive inversion close to 8 K in just 100 feet.

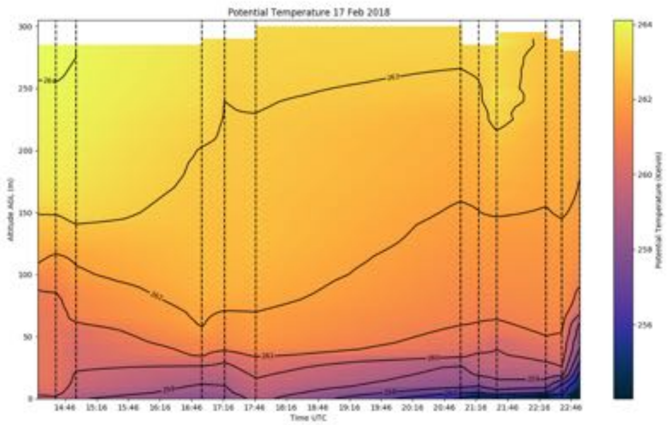

Figure 26: Time-height of potential temperature from IOP3.

came away excited about the prospects. In December of 2017, a group from OU visited the Boeing facility in Oklahoma to discuss how UAS can improve weather forecasts. This was received and the group was

2.4.3 University of Kentucky

Significant progress was made by all of the faculty and trainees in Year 3 of the UK CLOUD-MAP efforts. Task accomplishments and broader impacts are detailed in the task reports, however a few highlights are notable:

- UK's Dr. Marcelo Guzman edited a special issue of the journal Atmosphere focused on the development and application of UAS for atmospheric science. To date, three CLOUD-MAP team papers are published online as part of this special issue [Hemingway, Witte, Schuyler], with a fourth paper currently in edits after review.
- The 2017 Total Solar Eclipse offered a unique opportunity to measure response of the lower atmosphere to rapid changes in solar radiation. The path of the total eclipse through Kentucky included the site of maximum totality near Hopkinsville. The UK CLOUD-MAP team conducted UAS flight testing and complimentary measurements in Russellville, on the path of the total eclipse and 35 miles from maximum totality. More details of this unique opportunity are summarized below.
- Dr. Liz Pillar-Little graduated with her PhD from UK in Atmospheric Chemistry in 2017 and joined the University of Oklahoma CLOUD-MAP team as a Postdoc under OU institutional PI Phil Chilson. With her intimate knowledge of the capabilities of, and connections to, both programs, deeper transdisciplinary collaborations have been facilitated. For example, Phil Chilson led a large proposal effort involving collaborations among three researchers from UK, two from OSU, and several from OU that would not have been possible without connections and results from CLOUD-MAP. Liz Pillar-Littles connections through CLOUD-MAP were key to facilitating this complex proposal effort.

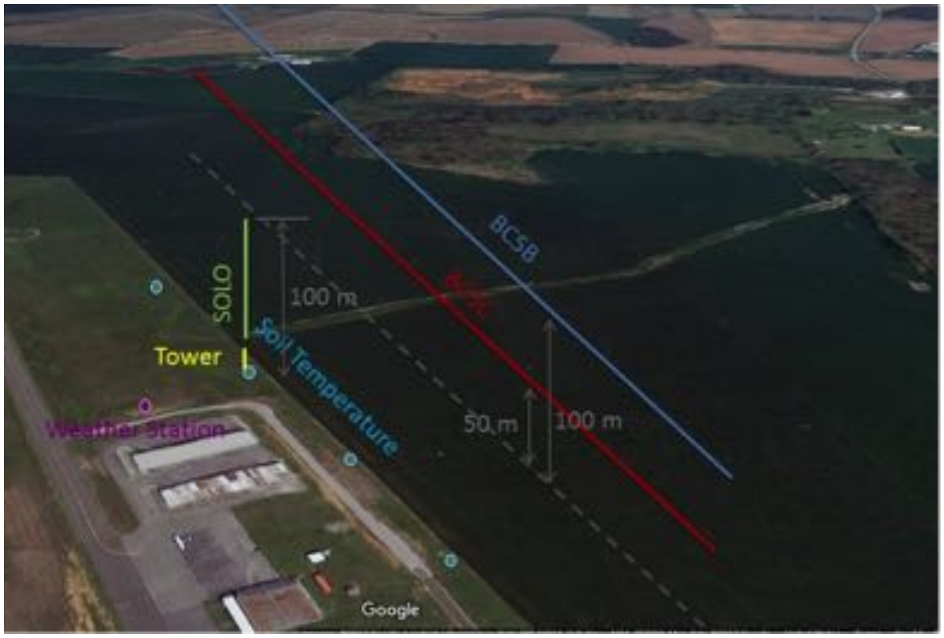

Figure 27: Fixed-wing transits at 50 m and 100 m altitudes, rotorcraft profiles, ground temperatures, solar radiation, and an instrumented tower recorded thermodynamic and kinetic variables of the atmospheric boundary layer.

- In Year 3, UK's flight testing and flight campaigns were characterized by high reliability performance and data acquisition success. The 2017 summer flight campaign in Oklahoma consisted of 39 fixed-wing flights (33.2 flight hours) in triples or pairs for turbulence transects and multi-unit control and 100 rotorcraft flights (23.8 hours) for profiling or remote ground testing. The 2017 solar eclipse flight campaign in Kentucky consisted of 10 fixed-wing flights (7.5 flight hours) and 30 rotorcraft flights (6.5 hours). Therefore, combined totals for 2017 were 179 flights (71 flight hours) demonstrating reliable performance of multiple sensing platforms.

On Monday, August 21, 2017, fifteen members of the UK CLOUD-MAP team conducted a flight campaign adjacent to the Russellville-Logan County Airport in Russellville, KY as illustrated in Fig. X for new insight into the evolution undergone by the atmospheric surface layer during the rapid decrease and increase of insolation which occurs during a solar eclipse.

Although these types of observations are not necessarily limited to UAVs, the use of these systems for these measurements enabled detailed measurements to be made up to 100 m in altitude of a transient phenomena, where a fixed ground station capable of making the same sort of measurements would have been cost prohibitive.

Most notably, these observations allow the subdivision of the evolution into six regimes of behavior, which depend on the boundary conditions at the surface. Whether a particular location will observe any, or all, of these regimes will depend on the time of year, time of day, and synoptic scale weather conditions at the time of the eclipse. During the measurement campaign reported here, the conditions were optimal for observing significant transient behavior, allowing us to confirm the formation of a stable layer.

Figure 28: UK CLOUD-MAP team at the summer and eclipse flight campaigns.

The existence of this layer results in observations made at ground level being very different from observations made at altitude. For example, this layer results in the calming of the wind and the cooling of the air are phenomena limited to the lowest 50 m of the atmospheric surface layer and associated with the suppression of mixing inducing convective eddies. Conversely, the properties of the turbulence above the stable layer are influenced by the elimination of production mechanisms, resulting in a rapid decay of the turbulence throughout the measurement domain. Thus, as the moon turns day into night, the atmospheric surface layer responds in kind and, for a 45 minute period, formed a shallow layer akin to the nocturnal layer that forms at night.

2.4.4 University of Nebraska-Lincoln

Research at UNL funded through CLOUD-MAP has contributed both directly and indirectly to research proposals and cross-jurisdictional collaborations that have been outlined elsewhere in the report. The focus of this summary is on broader programmatic benefits directly connected to the work supported by this project.

Research executed as part of Task 4-1 (Public Perception of Drones for Atmospheric Science) has involved three members of the Nebraska Public Policy Center (PPC): Dr. Lisa PytlikZillig, Ms. Janell Walther, and Mr. Jake Kawamoto. Their work has built capacity at PPC and facilitated additional work related to public engagement during technology development. For example, the NSF-funded National Robotics Initiative Fire-Drones project, on which Drs. Detweiler and PytlikZillig serve as co-PIs, now utilizes scales and methods fashioned off those developed through the Task 4-1 research. The CLOUD-MAP work has also buoyed a programmatic emphasis at the Nebraska Public Policy Center on the investigation of trust, from a focus on facets of trustworthiness, to take into account the interactive effects of different targets of trust.

CLOUD-MAP has influenced efforts at UNL to secure the resources necessary to construct a large indoor/outdoor flight training and evaluation facility. Not only does UNLs participation in CLOUD-MAP serve as leverage for this effort, but Dr. Detweiler (one of the leaders of the initiative) has gained valuable information through project field experiments hosted at similar facilities of partner institutions.

Finally, the fabrication of the second Integrated Mesonet and Tracker (IMeT-2), which is funded through an equipment allocation within the CLOUD-MAP award, has yielded a formal relationship between UNL and NOAA/NSSL. IMeTs fuse the capabilities of a UAS tracker vehicle, used to maintain compliance with FAA policies on UAS operation in the US National Airspace System, with the capabilities of a mobile mesonet. Like IMeT-1, IMeT-2 is a Ford Explorer with a dual moonroof (to enable the observer in the second row of seats to see the aircraft and airspace) and will have a full meteorological sensor suite forward mounted to avoid obstructing the view of the sky from within the vehicle. NSSL is supporting Dr. Sean Waugh's contributions to the fabrication of IMeT-2.

Part II

Research Report

3 Tasks Research Reports

Detailed discussion of individual program tasks are provided in this section.

3.1 Task 1-1: Mentorship

Collaborative proposals and publications were highlighted earlier in the report under research productivity in §??, with detailed numbers on proposal development and collaboration amongst the team. This is indicative of a highly successful faculty team at both the senior and early career levels. Early career faculty advancement has proceeded well, with ECE faculty participating at all levels within and without the project as indicated by the DOP results (shown elsewhere and in appendix). Promotions included faculty obtaining tenure at the University of Kentucky, the University of Nebraska-Lincoln, and Oklahoma State University.

Table 4: Early career faculty promotions.

Year	Early Career Faculty	Institution
2016	Jesse Hoagg	University of Kentucky
	Carrick Detweiler	University of Nebraska-Lincoln
2017	Marcelo Guzman	University of Kentucky
	Matthew Van Den Broeke	University of Nebraska-Lincoln
2018	Chris Crick	Oklahoma State University

To date, a significant number publications have been published or are pending publication, including journal articles, conference proceedings, and book chapters. A special submission for the journal *Atmosphere* was being organized and edited by Prof. Marcelo Guzman of UK to highlight many aspects of this project, among others.

Additional information is provided in the Team Science Development section.

3.2 Objective 2

Create and demonstrate UAS capabilities needed to support UAS operating in the extreme conditions typical in atmospheric sensing, including the sensing, control, planning, asset management, learning, control and communications technologies. Accordingly, develop test- beds and related analysis tools for better understanding of the atmosphere using small UAS and perform experiments to inform UAS capabilities and acquire data for atmospheric physics and improved weather forecasts and modeling.

There is a persistent and pressing need to collect better observations of the ABL. Having a better understanding of the kinematic and thermodynamic structure of the ABL, especially at small *mesoscale* time and space scales, impacts many areas of meteorology, such as improvements to: numerical weather prediction modeling through better ABL parameterization; our ability to forecast the development and evolution of severe storms and assessments of air quality in and around urban areas; the quality of information provided to the wind energy sector; and so forth. It has been clearly stated in such recent reports as those provided by the National Research Council and instrumentation workshops, that observing systems capable of providing detailed profiles of temperature, moisture, and winds within the ABL are needed to monitor the lower atmosphere and help determine the potential for severe weather development. [10, 11] Unfortunately, operationally available observations of ABL variability of the scope and across the scales needed by the meteorological community are currently not available. The foundational goal of this objective is on the development, evaluation and application of complete UAS system packages capable of acquiring needed meteorological and atmospheric data miniaturized, high-precision, and fast-response atmospheric sensors for wind and thermodynamic measurements along with measurements of air chemistry soil moisture, etc. relevant to climate science as a whole.

3.2.1 Task 2-1: Convection Initiation

Research Accomplishments The goals of this task are as follows:

1. Advance understanding of the mesoscale processes responsible for deep convection initiation (CI) and define the observable environmental conditions that regulate these processes.

2. Establish guidance for the system capabilities and deployment strategies required to maximize the impact of UAS on numerical weather prediction model skill.

3. Develop and test a system for coordinating multiple-UAS for a future CI-focused field campaign.

The research promises to advance the state of knowledge, integrate multi-disciplinary research conducted by atmospheric scientists and engineers, and transition research to operations and thereby directly benefit agencies such as the National Oceanic and Atmospheric Administration (NOAA).

The following are accomplishments achieved during the third year of this award.

Mesoscale Airmasses with High Equivalent Potential Temperature Recent UNL MS graduate, Wolfgang Hanft, undertook an observational and mesoscale modeling analysis on the formation and evolution MAHTEs. MAHTEs are airmasses formed through synoptic processes (e.g., large-scale advection) or mesoscale processes (e.g., thunderstorm outflow) and constitute the cooler/denser side of an airmass boundary but are characterized by mesoscale regions, typically near the boundary, for which the equivalent potential temperature (θ_e) and convective available potential energy (CAPE) are higher than the air mass on the warm side of the boundary. By virtue of their enhanced CAPE in proximity to airmass boundaries, MAHTEs are locations favorable for CI. Moreover, their spatial scale often falls below the resolution of the meteorological observing network. This work aims to make progress towards Goal 1.

(WRF-ARW) model. Surface transects were executed across a MAHTE which formed on 20 June 2016 along a weak synoptic cold front. Observations showed that the MAHTE was approximately 40 50 km wide with maximum e located 2-5 km on the cold side of the cold front and approximately 10 15 K higher than observations within the warm environment (see Figure for task 2-1 in the 2017 annual report). WRF simulations of this MAHTE showed that the most significant process driving MAHTE formation was cross-front differences in vertical θ_e advection. To quantify the impacts of differential vertical advection on the development of the MAHTE, volume-averaged vertical e advection was calculated within a volume with a 15 km by 15 km horizontal area and a depth extending from the lowest model grid point to a height of approximately 375 m. Within the warmer air mass, vertical mixing during the late morning and afternoon was stronger and deeper than on the cold side of the front (Figure 29a), resulting in a decrease of θ_e through advection in the warm air mass and insulation of moisture within the MAHTE (Figure 29b). This allowed largely unmitigated insolation-driven increases in e within the cold air. Surface moisture fluxes could not explain the cross-boundary differences in θ_e tendency and thus are an unlikely explanation of MAHTE formation. A conceptual model of the process for MAHTE formation is illustrated in Figure 3.

The role of vertical wind shear in airmass boundary evolution and CI occurrence. There are two complementary components to this research. The first component is led by Dr. Houston and focuses on the sensitivity of vortex formation along airmass boundaries to vertical shear. The objective of this component is to evaluate the sensitivity of micro-- to meso--scale vortices (herein simply referred to as mesoscale vortices) along airmass boundaries to low-level vertical shear. This broad class of vortices is intended to include both mesovortices and misocyclones, both of which are capable of producing locally destructive winds, particularly when associated with thunderstorms, but can also serve as the foci for CI. Therefore, understanding the environments associated with mesoscale vortex intensity has the potential to contribute to Goal 1 listed above.

In this work, idealized numerical model-based simulations of vortices along airmass boundaries are conducted to isolate the impact of low-level vertical shear on the strength of mesoscale vortices along airmass boundaries. Both 2D and 3D simulations have been conducted. The 2D simulations, although even more idealized then their 3D counterparts, have the benefit of limiting the theoretical mechanisms responsible for vortex formation.

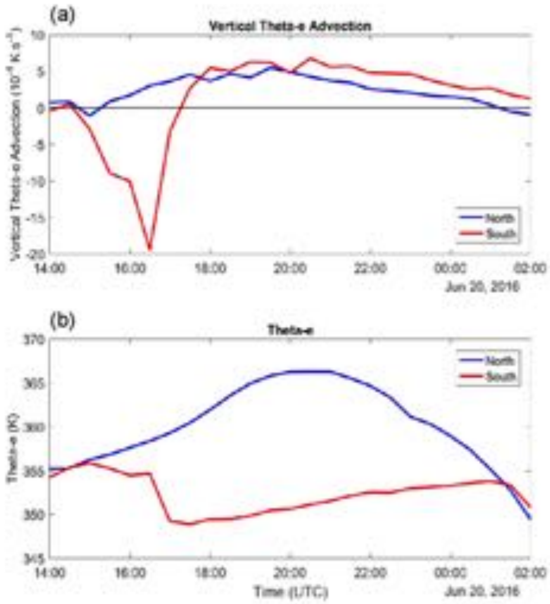

Figure 29: (a) Averaged vertical advection of equivalent potential temperature (10-4 K s-1) and (b) averaged 2-m θ_e (K).

Thus, they serve as a well-suited complement to the 3D simulations in an effort to not only determine associative relationships between vertical shear and mesoscale vortex strength but also expose possible reasons for the simulated differences.

Analysis of the 2D simulations is largely complete (analysis of 3D simulations is underway). Key results from the 2D simulations are as follows:

1. The magnitude of near-surface vertical vorticity (a proxy for vortex strength in 2D) scales directly with the magnitude of the boundary-normal vertical shear (Figure 31, Figure 32).

2. In general, the magnitude of near-surface vertical vorticity scales inversely with the magnitude of the boundary-parallel vertical shear (Figure 6).

3. The sensitivity of near-surface vertical vorticity to the boundary-parallel vertical shear depends on the temperature deficit in the airmass behind the boundary (Figure 33).

4. Despite microscale to mesoscale temporal scales, the Coriolis force is found to be a dominant contributor to the generation of near-surface vorticity.

5. Simulations with $dv/dz = 0$ and without the Coriolis force have no vertical vorticity (not shown).

6. For $dv/dz \neq 0$, when Coriolis is on vertical vorticity magnitude generally scales inversely with dv/dz (Figure 33b) but when Coriolis is off vertical vorticity magnitude generally scales directly with dv/dz (Figure 34).

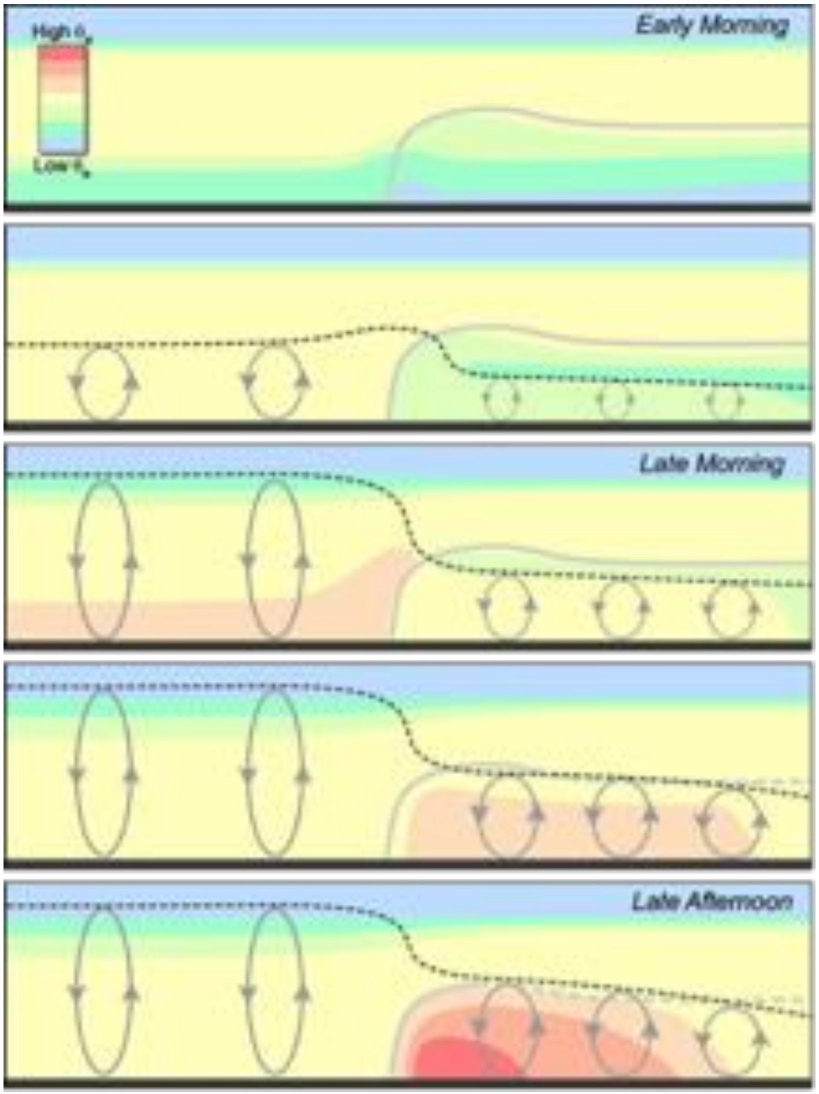

Figure 30: Conceptual illustration of the formation of the 20 June 2016 MAHTE. Panels represent the evolution of e in cross-section. The thick gray curves represent the cold front, the black broken curve represents the top of the CBL, and ellipses with arrows represent convective mixing.

The second component focuses on the sensitivity of CI occurrence along airmass boundaries to the boundary-parallel component of the vertical shear and is led by M.S. student Alexander Krull. This work aims to make progress toward Goal 1.

Thirty-five simulations have been completed in Cloud-Model 1 (CM1). These simulations are comprised of five differing boundary-parallel vertical shear environments and seven differing density current intensities. Although the primary interest is in the boundary-parallel vertical wind shear, previous work has indicated sensitivity of arimass boundary evolution and CI to the intensity of the density current which must be adequately addressed in this study. Density current propagation speed, vertical velocity, and passive fluid tracer transport are the basis of the analysis underway.

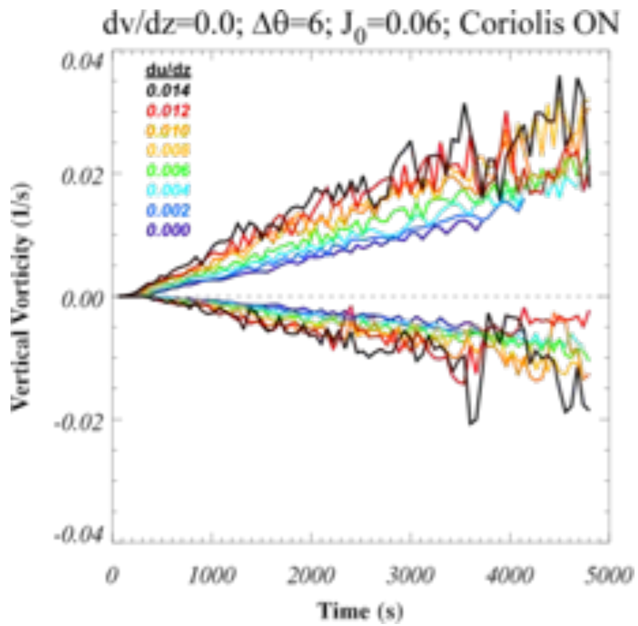

Figure 31: Time series of maximum vertical vorticity (upper traces) and minimum vertical vorticity (lower traces) as a function of boundary-normal vertical shear (du/dz).

Analysis reveals that boundary propagation speed and vertical velocity are correlated, with $r = 0.79$. This is consistent with other studies that have noted increases in propagation speed resulting in enhanced convergence, ultimately increasing the vertical motion along the leading edge of the density current. Propagation speed in these simulations is also found to be well correlated with density current strength (depth and density) with $r = 0.62$. Moreover, vertical velocity is well correlated with density current strength ($r = 0.81$). These results support the hypothesis that vertical velocity is causally connected to density current propagation speed.

The correlation between boundary-parallel vertical wind shear and propagation speed is found to be low: $r = -0.11$. Similarly, a low correlation is found between boundary-parallel wind shear and vertical velocity: $r = -0.04$. While these statistics suggest a weak relationship between boundary-parallel vertical wind shear and vertical velocity, this relationship is found to depend on the strength of the density current. Specifically, in the simulations with the two weakest density current intensities (theta perturbations of -4.0 K and -5.0 K), the environments with zero to weak boundary-parallel shear are found to have faster propagation speed and, by extension, stronger vertical velocity while the larger boundary-parallel shear support slower propagation speed and weaker vertical velocity (Figure 35). However, when the density current intensity is increased (-7.0 K and -8.0 K) environments with zero to weak boundary-parallel shear have generally slower propagation speed and vertical velocity and larger boundary-parallel shear environments support faster propagation speed and vertical velocity (Figure 36).

To further expose this sensitivity, simulations are divided into two groups: weak density currents and strong density currents. In the weak group, neither boundary propagation speed nor vertical velocity are well correlated with density current intensity. However, in the strong group, both propagation and vertical velocity are correlated with the density current

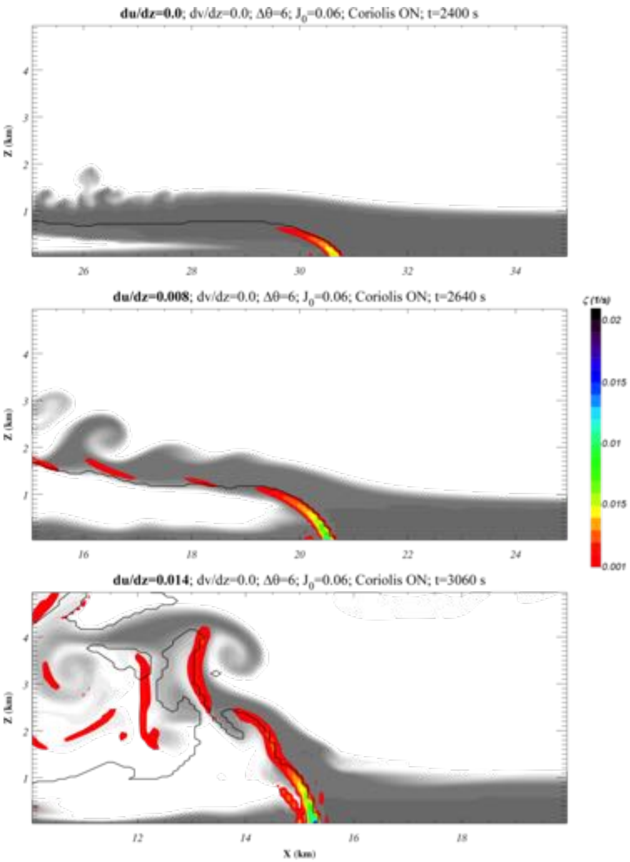

Figure 32: Cross-sections of tracer concentration (gray shading), gust front isochrones (black curve), and vertical vorticity (color shaded following key on right) for three different values of boundary-normal shear.

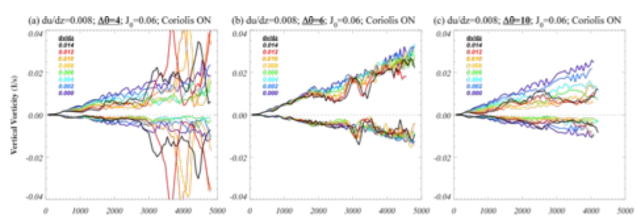

Figure 33: Time series of maximum vertical vorticity (upper traces) and minimum vertical vorticity (lower traces) as a function of boundary-parallel vertical shear (dv/dz) for cold block temperature deficits ($\Delta\theta$) of a) 4 K, b) 6 K, and c) 10 K.

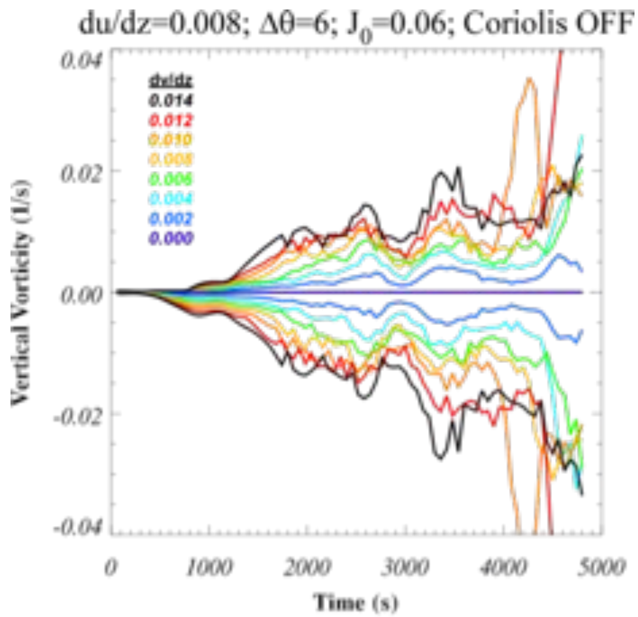

Figure 34: As in previous Figure but without Coriolis.

intensity, with $r = 0.33$ and $r = 0.65$, respectively. Therefore, it can be concluded that boundary-parallel vertical shear and density current intensity work independently to alter vertical velocity through boundary propagation speed. When density currents are weak, the vertical velocity responds more to the shear than to the density current intensity, yielding an inverse relationship to vertical velocity. When density currents are strong, the vertical velocity responds more to the density current intensity than to the vertical shear, yielding a modest but direct relationship to vertical velocity).

CI depends in part on the likelihood that parcels of air rising out of the lowest levels of the atmosphere reach the level of free convection. While this is a function of vertical velocity, vertical velocity represents instantaneous, not integrated, parcel displacement. The next stage of the analysis will focus on passive fluid tracers which capture the integrated ascent at an airmass boundary.

Sensor Response CI forecasts depend on accurate characterization of the thermodynamics and wind fields within the ABL. Numerical weather prediction (NWP) model guidance on PBL structure is prone to well-documented errors that could theoretically be mitigated with supplemental observations. UAS are well-suited to this task but large gradients in temperature and moisture associated with preexisting airmass boundaries (which often serve as the loci for CI), near-surface sources of potential energy (associated with spatially-variable surface fluxes), and top-of-the-PBL capping inversions, must be faithfully represented. As such, UAS-mounted instruments need sufficiently fast sensor responses. As part of our efforts to establish guidance for the system capabilities required to maximize the impact of UAS on NWP model skill (Goal 2 above), we developed experiments to evaluate sensor response in integrated systems. Further exploration of the importance of sensor response for characterizing the ABL is being conducted by addressing the question, what sensor response is required to represent key meteorological phenomena germane to the ac-

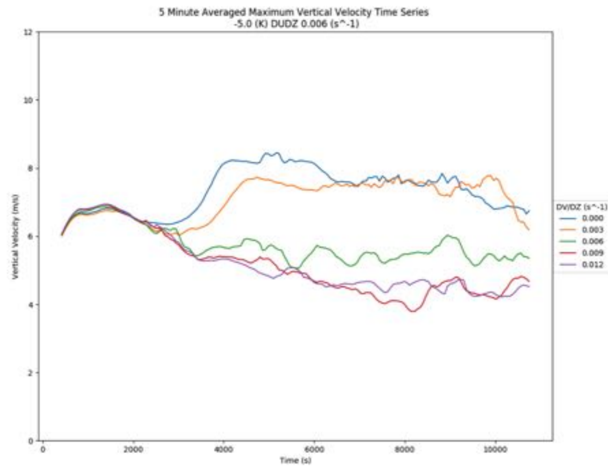

Figure 35: Vertical velocity along the leading edge of the density current with time with an intensity of -5.0 K. The weaker boundary-parallel shear environments have faster vertical velocities then the stronger boundary-parallel shear environments.

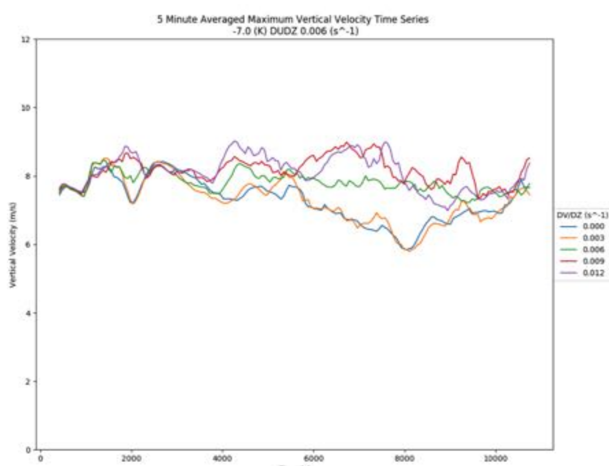

Figure 36: Vertical velocity along the leading edge of the density current with time with an intensity of -7.0 K. The weaker boundary-parallel shear environments have slower vertical velocities then the stronger boundary-parallel shear environments.

curate prediction of CI? Large-eddy simulations (LES) of a convective boundary layer and airmass boundary are being used for the simulation of SUAS data collection. Specifically, thermodynamic state variables developed using LES serve as the nature run for offline aircraft models that represent the flight of SUAS profiling the ABL and transecting airmass boundaries.

These issues were examined as part of a new task, 3-7.

Workforce Development The award is supported the training of UNL M.S. graduate Wolfgang Hanft and current M.S. student Alexander Krull.

This work was presented at the 17th Conference on Mesoscale Processes in July 2017 (Wolfgang won best student presentation at this conference) and has been conditionally accepted for peer-reviewed publication in Monthly Weather Review. Wolfgang Hanft graduated in December 2017.

This work has been presented at two conferences: 17th AMS Conf. on Mesoscale Processes, San Diego, CA. 2017 9th European Conference on Severe Storms, Pula, Croatia. 2017

This work has been presented at the 2018 Severe Storms and Doppler Radar Conference.

3.2.2 Task 2-2: Storm Microphysics

Research Accomplishments Research task 2-2 focuses on learning about storm-scale microphysics using UAS measurements. Research undertaken in this task will generate new datasets which will serve to demonstrate cloud physics measurements that can be obtained in real time using UAS. These datasets will be validated against polarimetric radar observations from the national Weather Surveillance Radar-1988 Doppler (WSR-88D) network, and methods will be developed to use UAS-based cloud physics measurements to derive estimates of variables that can serve as input to numerical models. Collaborators on this research task include Bailey (UK), Chilson (OU), Elbing (OSU), Houston (UNL), Jacob (OSU), and Ruyle (OU). Task 2-2 currently consists of three technical goals, described here:

- Gathering in-situ liquid drop distribution measurements in varying precipitation regimes, including young convective cells, stratiform precipitation, and supercell storms (including the rear and forward flank regions). Drop size distributions (DSDs) are very different in these different precipitation regimes, with some of the most novel mid-latitude DSDs occurring in supercell storms. A set of DSD measurements including several samples of several different precipitation regimes will be collected in the domain of a WSR-88D radar. DSD parameters can be derived independently from the local instrument and from the radar observations. We plan to compare our measurements with the radar-derived DSD characteristics, which will help to produce guidance on when a disdrometer may optimally be used to fill in DSD information at low levels, and how those data compare with radar-derived information under varying conditions.

- Retrieving representative values of the polarimetric radar variables at low levels in several precipitation regimes, as described above. A liquid water content (LWC) sensor will be used to estimate values of several radar variables in precipitation, including reflectivity factor (ZHH), differential reflectivity (ZDR), and specific differential phase (KDP) from regions of precipitation. These estimates will be compared with nearly collocated measurements from the WSR-88D network. Once validated, the LWC methodology may in certain precipitation regimes allow low-level fill-in of the radar variable fields, which are only collected by a radar at close proximity.

- Measuring condensation nucleus (CN) concentration from near-storm environments and storm inflow layers. The concentration of condensing particles in a storms inflow can strongly influence DSDs in convective updrafts. Such differences can result in changes to a storms outcomes (e.g., precipitation efficiency) and radar appearance (e.g., updraft depth). Thus, knowing the particle distribution in the convective environment may help nowcasters anticipate storm structure and know how to use radar variables optimally on a particular day.

Work toward these three technical goals has centered on obtaining appropriate sensors and getting the instrumentation ready for fieldwork, to begin in spring 2018. Specifically, toward each technical goal listed above:

- The optimal DSD sensor (disdrometer) was determined to be the OTT Parsivel disdrometer from OTT Hydromet, since it collects drop measurements over a large range of drop diameters with reasonably good spatial resolution of drop size. A disdrometer was obtained in fall 2017 with funding from the National Science Foundation (NSF). A base has been constructed for the sensor, to be used in field deployments. Two graduate students and an undergraduate designed and constructed the base. A mobile power supply was successfully developed for the disdrometer. Also, a method has been developed to write data output from the disdrometer to a file. This method works in Windows and Linux. For field deployments, the disdrometer will be connected to a Raspberry Pi miniature computer, which will be run via a small power supply. Pending this last step (making data output work on the Raspberry Pi), the entire system including instrumentation, power supply, and computer will be extremely mobile. This will facilitate ground-based field operations, and should make the transfer to an unmanned aircraft fairly simple if an appropriate aircraft is found. Initial outdoor test measurements are planned for mid-March 2018. Once initial test measurements are successful, we plan to conduct numerous field deployments through the 2018 warm season near (from 4.6-25.4 km away from) a WSR-88D radar; this distance allows the disdrometer measurements to be compared to radar measurements, which are at relatively low altitude but removed from ground clutter. Deployments during spring and early summer 2018 are likely to be centered around KOAX, the WSR-88D radar at Valley, Nebraska. Data collection efforts will eventually not need to be near a WSR-88D radar if sufficient test cases are obtained which are collected near a radar. In the future, it would be ideal to mount this instrument on a fixed-wing platform, and we continue to investigate potential options.

- Retrieving values of the polarimetric radar variables from precipitation can be achieved using liquid water content (LWC) sensors, which are sufficiently small to be airborne by unmanned aerial vehicles (UAVs). Using funding from NSF, in fall 2017 we obtained a sensor manufactured by Droplet Measurement Technologies which is sufficiently small and lightweight. Since the sensor arrived, we have been working on getting power to it (which turned out to not be trivial, requiring a special connector). But it appears that a workable mobile power supply has been developed. The instrument also came with a small specialized computer to store output during mobile operations, and we are currently working with the company to develop a power supply for it. Unfortunately, the company which supplied this instrument has not been willing to help us get the instrument set up, which has slowed our progress. Once this sensor is operational, the data collection plan is the same as for the disdrometer (noted above). We hope to collect initial test data during spring 2018, and to collect data in the field throughout the 2018 warm season.

- A CN counter has been obtained from TSI, Inc., in fall 2017. It was relatively easy to prepare for field operations, and includes an internal power supply (rechargeable AA batteries) and data storage. We have collected several test datasets around Lincoln, Nebraska, during spring 2018. A sample is shown below (Fig. 37). During spring and summer 2018, we plan to work in collaboration with the Nebraska Intelligent Mobile Unmanned Systems (NIMBUS) Lab at UNL to loft this instrument for the purpose of sampling CN concentration through a deeper portion of the boundary layer. Initial data collection with this instrument is not as constrained by distance from a radar, so it is anticipated that numerous measurements will be taken in the vicinity of convective clouds through the 2018 warm season. Cloud bases which are at least 15C are hypothesized to be necessary to see an aerosol effect in the polarimetric radar variables.

Additional work toward the project goals has included continuing research on how radar signatures vary in convective storms across a spectrum of environments characterized by different wind and moisture conditions. In the past year, the task lead published a paper describing how radar signatures vary across tornado life cycles, and submitted another paper describing radar differences between tornadic and nontornadic supercell storms.

Workforce Development Two Graduate Research Assistants have joined the research group of the task lead (Van Den Broeke) at the M.S. level starting in fall 2017. Two other M.S. students advised by the task lead are supporting CLOUD-MAP objectives by examining how radar signatures vary in convection across storm-scale environments. One undergraduate student is actively working on instrument preparation for fieldwork, supported by a UNL research program.

Leveraged Opportunities and Activities The technical goals of the Storm Microphysics task align well with some portions of the task leads research activities outside of this NSF project. He studies polarimetric radar signature variability in severe storms as a function of environment, and how this radar signature variability may be predictive of near-term future severe weather occurrence (currently focused mostly on tornadoes). He has published one manuscript in this area over the past year, and has submitted one additional

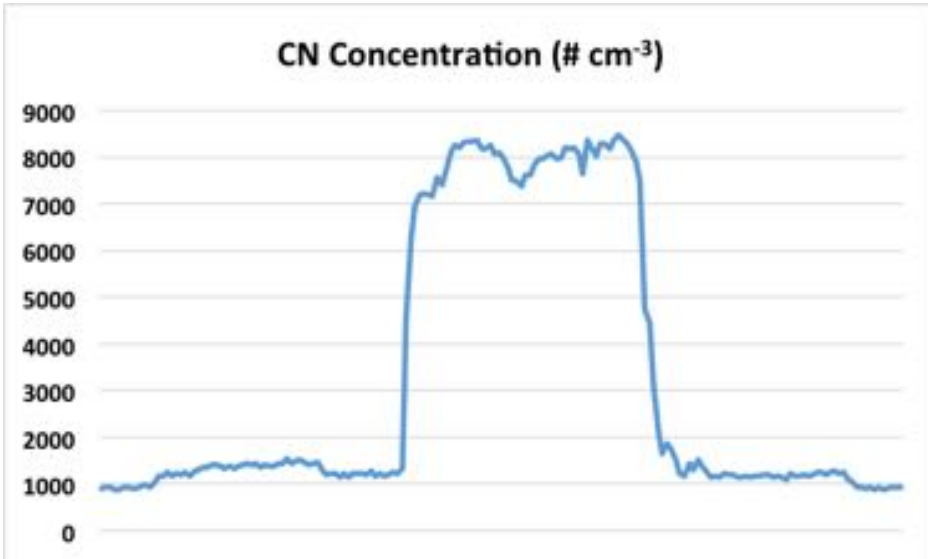

Figure 37: Concentration of condensation nuclei (cm-3) over a 3-minute period from 2044-2047 UTC on 18 February 2018 in Lincoln, Nebraska. Low, relatively steady values near the beginning and end of the time series were collected indoors; high and somewhat more variable values near the center of the time series were collected outdoors.

manuscript. These results are being leveraged into the development of hypotheses and research questions for this NSF project. The task lead also submitted a proposal related to this work, looking at environmental influences on tornadoes in linear convective modes (it was not funded). These efforts are anticipated to lead to new understanding which can be incorporated into the operational severe weather warning workflow.

The task lead is collaborating with the infrasound task of CLOUD-MAP by contributing polarimetric radar time series to compliment infrasound measurements. This work is expected to lead to several conference presentations, a manuscript, and a proposal in the coming year.

3.2.3 Task 2-3: Airborne Soil Hydrology

Research Accomplishments The overall objective of this task is to determine the feasibility of applying a novel remote sensing technology towards early detection of water stress in production agriculture. This objective is being addressed with two specific aims: (1) to develop a novel passive narrow-band single-pixel multispectral sensor for measuring visible and near-infrared (NIR) reflectance used to compute NDVI and NDWI and to determine its spectral response; (2) to test the hypothesis that the spatial patterns in land surface hydrological behavior are reflected in (a) low-altitude atmospheric humidity measurements and (b) NDWI measurements of bare soil, and that the pattern is related to the spatial variability in crop water supply as measured by NDVI/NDVI of the crop during the subsequent vegetative period.

Progress on the first specific aim is complete. Preliminary results from laboratory testing revealed that the index-based method proposed worked well on bare soils but was

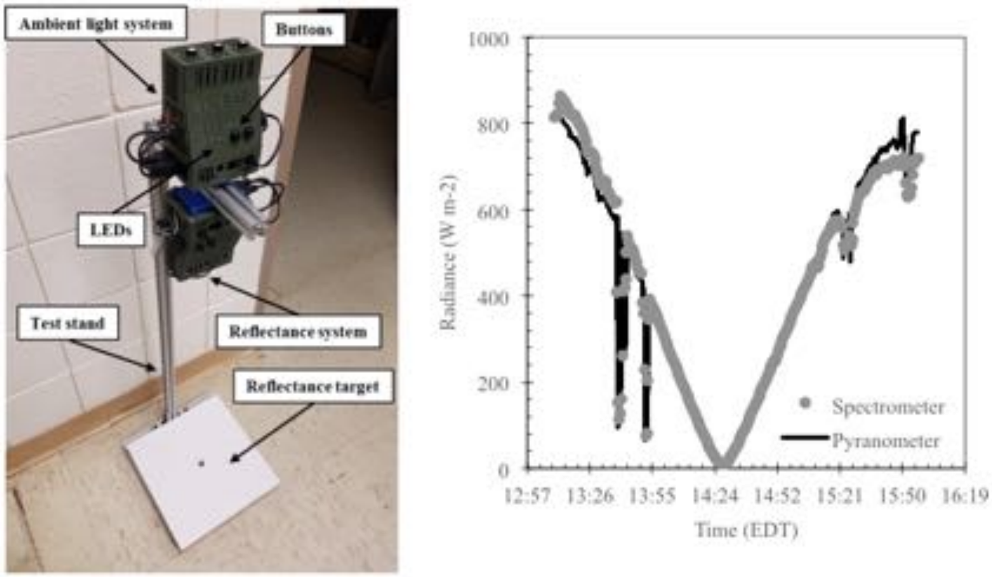

Figure 38: Reflectance and ambient light spectral measurement systems (left) and comparison between multiple ambient light measurement systems during the 2017 Great American Eclipse (right).

not satisfactory for crop residues.[35] (Hamidisepehr et. al, 2017). Consequently, a new analysis approach was developed [36] and a spectral measurement system for capturing a wide range of wavelengths was developed and tested [37] during this project year. The system was tested during the 2017 Great American Eclipse to demonstrate the ability to compensate passive spectral measurements for ambient light (Fig. 38).

Work planned for the next project year includes testing the classification accuracy of the system against a wider range of targets across and, subsequently, soil moisture samples across varying ambient light conditions. Modification of objective 1 will require the goals for objective 2b be slightly modified as well to reflect the change from index-based measurement to the machine learning approach using broad spectral data. We anticipate deploying the newly developed system during the 2018 CLOUD-MAP Flight Test Campaign held in collaboration with the 2018 ISARRA flight week.

Workforce Development Ali Hamidisepehr (Ph.D. Candidate, Biosystems and Agricultural Engineering, University of Kentucky) is the primary student working on this research project. He is being trained to develop, test, and integrate custom remote sensing UAS payloads.

Aaron Turner (Engineer Associate and Ph.D. Student, Biosystems and Agricultural Engineering, University of Kentucky) worked on developing MATLAB scripts for processing spectrometer reflectance data.

Christopher Good (M.S. Student, Biosystems and Agricultural Engineering, University of Kentucky) worked on sensor instrumentation using an embedded computer.

Surya Saket Dasika (M.S. Student, Biosystems and Agricultural Engineering, University of Kentucky) worked on a ground-based test fixture for sensor testing prior to UAS integration.

Luis Felipe Pampolini (M.S. Student, Biosystems and Agricultural Engineering, University of Kentucky) worked on spatial accuracy of UAS-based remote sensing measurements.

Leveraged Opportunities and Activities Several new projects have been funded resulting from this work including a USDA-NIFA National Robotics Initiative award relating to UAS, a USDA-NIFA Agricultural Foundation Research Initiative award relating to weather, and an internal equipment grant to purchase high-throughput soil sampling equipment.

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Hamidisepehr, A., Sama, M.P. 2018a. Moisture Content Classification of Soil and Stalk Residue Samples from Spectral Data using Machine Learning Algorithms. Transactions of the ASABE. Submitted 12/15/2017.

Hamidisepehr, A., Sama, M.P., Turner, A.P., Wendroth, O.O. 2017. A Method for Reflectance Index Wavelength Selection from Moisture Controlled Soil and Crop Residue Samples. Transactions of the ASABE. 60(5): 1479-1487.

3.2.4 Task 2-4: Local-Scale Spatiotemporal Climate Variations Measurements

Research Accomplishments The evolving objectives in this task are (1) establish CO_2 monitoring using UAS; and (2) identify local-scale characteristics of winter climate. Research accomplishments towards these objectives are described below.

CO_2 Monitoring CO_2 concentration monitoring by UAS can fill the critical gap of local, high resolution CO_2 concentrations in the boundary layer. These measurements are critical for providing constraints on local emissions and uptake of CO_2 by vegetation, agriculture, and human sources and for providing ground based validation of modeling experiments and satellite measurements, such as the NASA GeoCARB mission.

Tasks this year have continued the development and deployment of a robust CO_2 sampling system designed to be carried by small UAS. The response of commercially available near-infrared gas sensors (Senseair K30-FR) were thoroughly characterized on the benchtop to assess their capabilities and limitations. The purchase of a non-dispersive infrared (NDIR) CO_2 gas analyzer that corrects for water vapor (LI-COR 840A) as a ground station has enabled validation in the lab and in the field. Validation tests in the lab have shown agreements within 2-5 ppm. After optimizing airflow, placement, operating parameters, and shielding, the sensing units were integrated into a fixed wing (Tuffwing UAV Mapper) and a rotocraft (University of Oklahoma CopterSonde) for field deployment.

Observations have been made during weekly deployments at the Kessler Atmospheric and Ecological Research Farm (KAEFS) in Washington, Oklahoma over the course of several months to facilitate the examination of seasonal trends. An example of such data is shown in Figure 1. Data is collected in horizontal transects at 30m, 50m, 70m AGL with circling /grid patterns at each height for 3 - 5 min. The decrease in CO_2 with height is evident, with surface concentrations increasing as the sun rises. Moving forward, sensor optimization

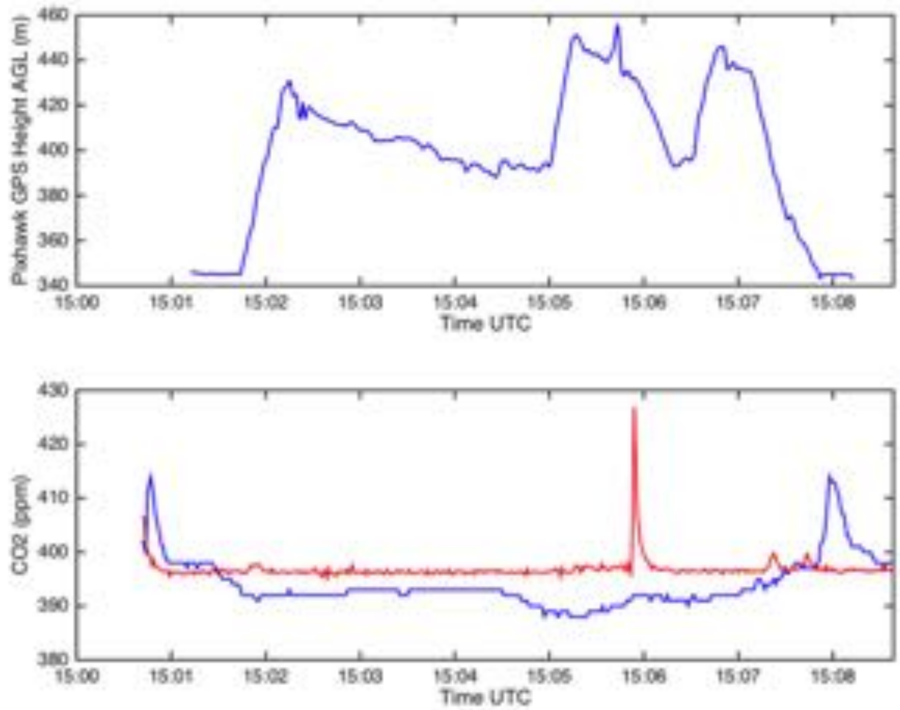

Figure 39: (Upper) Aircraft height AGL. (Lower) CO_2 measurements from the LICOR ground.

is ongoing, regular measurements are continuing in order to investigated horizontal and vertical profiles of CO_2, the diurnal cycle, and connections with the environment (land-use and precipitation).

Winter Weather Numerous studies have highlighted the challenges of forecasting the type of surface precipitation in winter weather.[38, 39] Vertical profiles of temperature and humidity are particularly important in determining precipitation type, especially characteristics such as the depth and magnitude of the freezing layer, the depth of the refreezing layer and the moisture amounts[40, 42, 41] (e.g. Bourgouin 2000, Theriault et al. 2010, Mullens et al. 2016). It is imperative that we obtain additional measurements of temperature and moisture locally and at high temporal resolution ahead of winter storms to aid forecasting of precipitation type. No evidence of UAS measurements of winter storms could be found during a literature review by undergraduate student Emily Lenhardt.

Due to burn bans during winter weather in Oklahoma in January 2018, no flights have been conducted prior to winter precipitation. In preparation for future flights, an analysis of the spatial and temporal characteristics of winter storms in Oklahoma is ongoing. Using the NCEI storm data database, five case studies have been identified and are being analyzed: 8-12 December 2007; 28-30 January 2010; 9-11 April 2013; 26-27 November 2015; 13-14 January 2017.

Using high resolution North American Regional Reanalysis (NARR) data, which has been shown to represent winter precipitation well (Mullens and McPherson 2017), categorical precipitation is shown in Fig. 39.[43] The sharp transition from rain to freezing precipita-

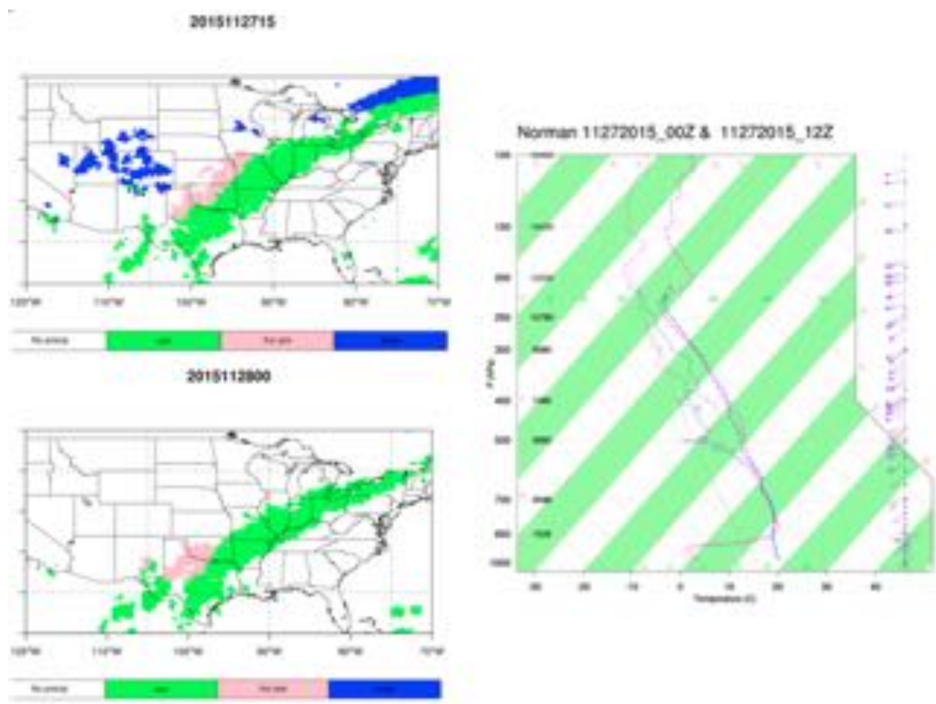

Figure 40: (top) Categorical precipitation type from NARR for the November 2015 case study. (bottom) Two soundings from Norman on 27 November at 00Z (blue) and 12Z (magenta) before and after the rain-freezing rain transition.

tion (including freezing rain and ice pellets) is evident across Oklahoma and Kansas and is approximately co-located with the freezing line at the surface.

To prepare for sampling with UAS in advance of storms, data from the Oklahoma Mesonet, local soundings, local weather reports, and NARR are being investigated for the case studies mentioned above. Fig. 40 shows two soundings from Norman pre- and post-freezing precipitation onset. The shallow (below 850 hPa) cooling near the surface of almost 20C is evident, with little change in temperature and dewpoint above that level. As sounding data is sparse in space and time, we suggest that UAS could play an important role in additional sampling of the boundary layer temperature and humidity profiles to help in predicting the onset of freezing precipitation.

Workforce Development Three undergraduate students have been actively involved in this task. Santiago Mazuera has developed the CO_2 sensor and plane integration and in conjunction with Myleigh Neill (graduated in May 2017) has performed numerous sensor tests. Emily Lenhardt has been undertaking a literature review of precipitation type in winter weather. MS student Daniel Tripp has been recruited to continue the winter weather work and is taking sUAS Pilot Training at OU.

Figure 41: Illustration of the overall analytical setup for task 2-5 displaying (A) an overhead view of the ground station for the DJI P3 and the gas sensing packages; (B) an underside view of the instrument bed below the DJI P3 with a gas sensing package attached; and (C) a top view of the Skywalker X8 with the gas sensing packages secured in the instrument bed.

3.2.5 Task 2-5: Airborne Sampling Systems

Research Accomplishments Considerable progress has been made in Task 2.5, which will enable us to collect datasets during the coming test flights in Kentucky and the ISARRA campaign in Colorado. Several lightweight devices capable of recording temperature, relative humidity, pressure, altitude, mixing ratios of methane, propane, butane, ammonia, carbon monoxide, carbon dioxide, and nitrogen dioxide were developed for deployment during operation of a Skywalker X8 and DJI Phantom 3 (DJI P3) unmanned aerial systems (UAS). In addition, several sensors for ozone and other hydrocarbons are considered.

Customized sensor packages for measurements of temperature, relative humidity, pressure, and mixing ratios several trace gases were deployed during flights with both UAS. A lightweight 3D printed frame (12 cm 6 cm 2 cm) held the sensor packages, and a 3D printed shield (12 cm 6 cm 1 cm) protected them from debris and damaging UV radiation while facilitating airflow over the sensors. The total weight (250 g including microcontroller, data logger, and battery) was minimized to meet the payload requirements for maximized flight times. The sensor package was installed on the hatch covering the instrument bed of the Skywalker and another package was secured beneath the DJI P3. Telemetry was collected with a Pixhawk Autopilot module and programmed with the ground station software Mission Planner. A VectorNav was used for GPS measurements. Flights were coordinated such that the Skywalker X8 flew horizontal profiles at a fixed altitude while the DJI P3 flew vertical profiles at a fixed location.

Several presentations have resulted from this work including a poster presentation at the 2017 Gordon Research Conference in Atmospheric Chemistry (Newry, ME) and a talk at

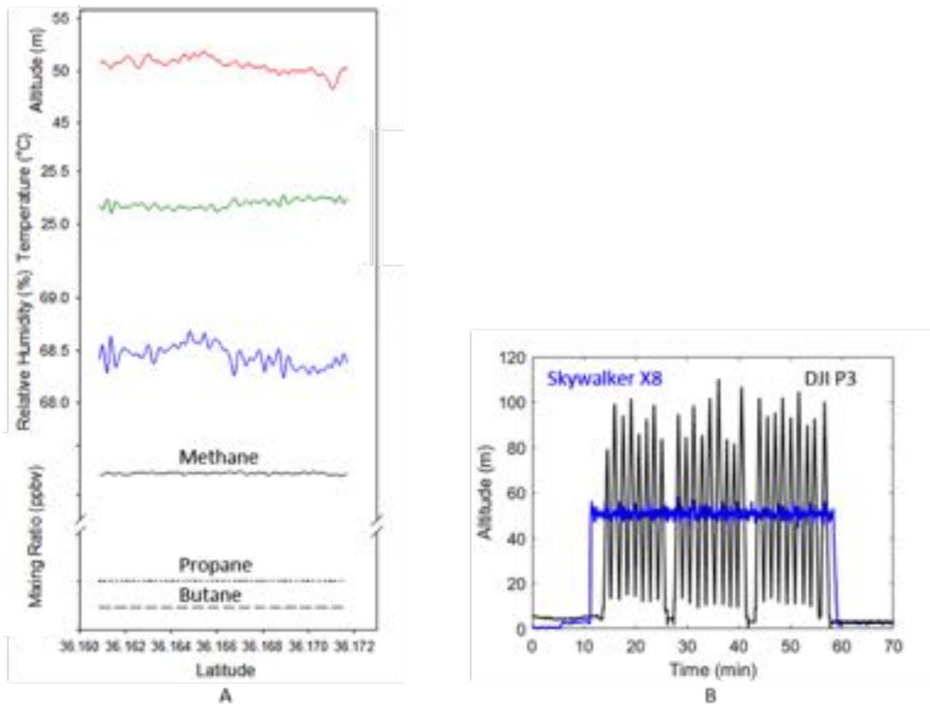

Figure 42: Example of data gathered during a flight with a Skywalker X8 and the gas sensor package during the second CLOUD MAP campaign in Oklahoma. Site name: Oklahoma State University Unmanned Aircraft Flight Station. Date: June 28, 2016. Start time: 7:06 am CST.

the 2017 AGU Fall Meeting (New Orleans, LA). The theoretical knowledge and experimental results are also part of two manuscripts, one published in a Special Issue of the peer-reviewed journal Atmosphere organized by the PI, and another in preparation. An example of the kind of data in preparation for the second manuscript is shown below.

The aim of flying robust, lightweight atmospheric sensors on UAS is to monitor air quality, investigate pollution sources, and determine real-world exposures to gases of concern near or at ground level. Measurements of this type will contribute a detailed inventory for the profile level of trace gases in the lower troposphere and reduce measurement uncertainty due to higher spatiotemporal resolutions. Data collected onboard UAS during all flights are paired with GPS data to build up chemical maps.

Workforce Development All the worked described above is performed by the participating PhD student. The interdisciplinary training received by the student is contributing to his professional development from direct interactions with the PI, co-PIs, and members of the UK mechanical engineering lab for this task. For example, skills such as computer programming, statistical analysis, computer-assisted design (CAD), and design-building electrical circuits have been acquired throughout this project. The nature of the interdisciplinary work has provided a well-rounded knowledge base in the sUAS field.

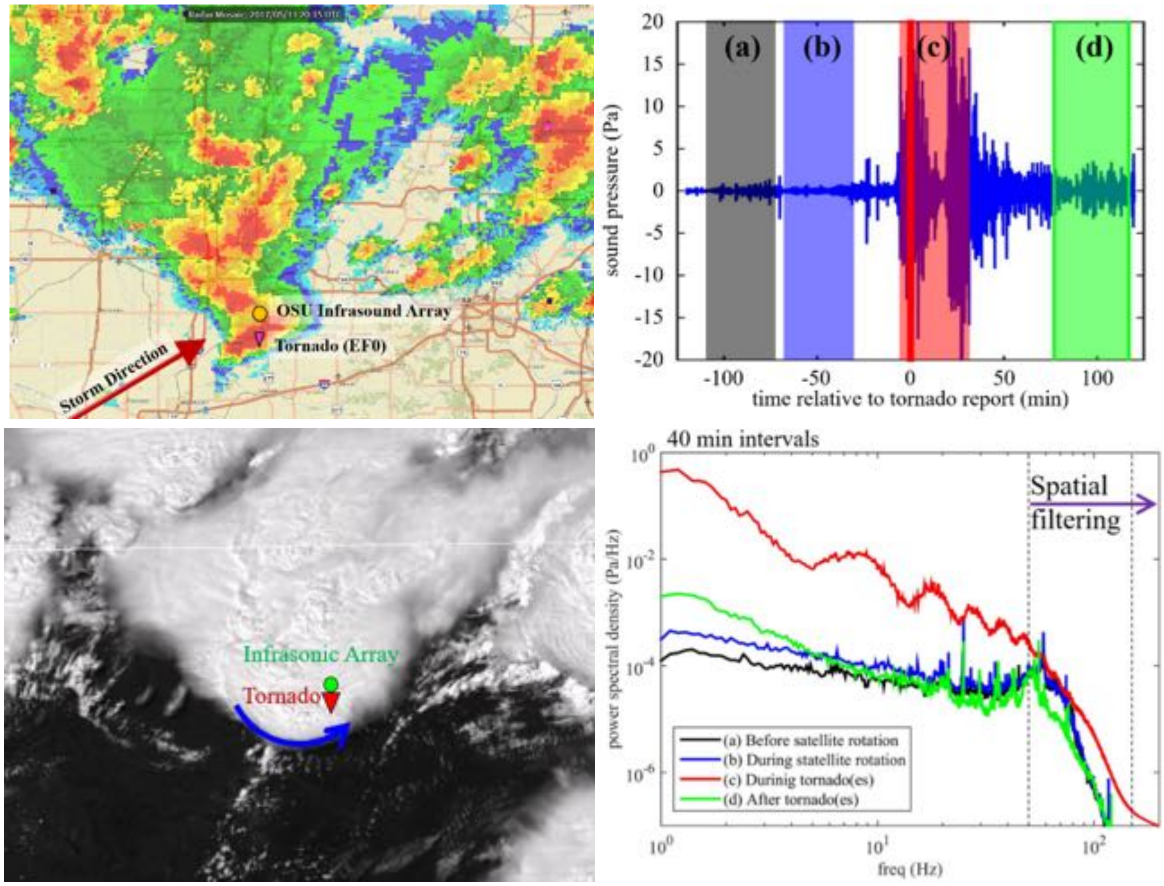

Figure 43: (top L) Radar image during tornado with infrasonic array and tornado marked. (top R) Four hour time trace of infrasound. (bottom L) NOAA GOES-16 image 50 minutes before tornadogenesis with the mesocyclone rotation denoted. (bottom R) Spectra from 40 minute windows corresponding to times specified in time trace.

3.2.6 Task 2-6: Atmospheric Infrasonic Sensing

Research Accomplishments During the 2017 field campaign the wires for microphones 2 and 3 were torn out of the ground by facility workers. This happened a second time later in the summer, which resulting in our team tearing all the ground-based wires out of the ground and rewiring microphones 2 and 3. This has significantly sets back on the planned improvements to the array, but we are currently operational and working to improve system fidelity before the heart of the 2018 tornado season. The primary activities that need to be performed are (i) perform a localization experiment using the pulsed combustion torch, (ii) do a sound pressure level check with a reference microphone, and (iii) create an automated event inspection code.

May 11, 2017 Perkins EF0 Tornado: On May 11, 2017 at 2013 UTC an EF0 tornado formed near Perkins, OK, which is located 19 km SSE of the OSU infrasonic array. The tornado path length and damage width were 0.16 km and 46 m (NOAA, 2017), respectively. There were reports of a possible second tornado, but it was never confirmed because the

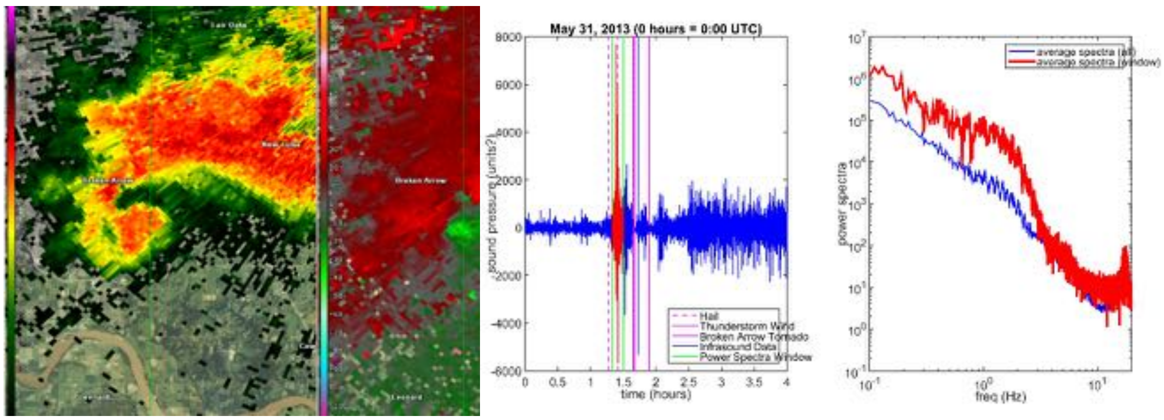

Figure 44: (left) Radar data from KINX Tulsa provided by Steven Piltz, Meteorologist-in-Charge at the NWS Tulsa Weather Forecast Office. (middle) Time trace during period of the tornado. (right) Spectra during hail.

storm was rain wrapped and low-level radar was unavailable. Approximately 50 minutes before tornadogenesis, significant mesocyclone rotation became apparent from satellite images (NOAA GOES-16; Fig. 43) and upper level radar data processed by Matthew Van Den Broeke (UNL). During this period there was no significant increase in the infrasound (Fig. 43 time b), which indicates that the infrasound is not associated with the large scale rotation. Then approximately 10 minutes before tornadogenesis the infrasound levels had a significant increase that was maintained through the life of the tornado. Note that 20 minutes after the tornado a nearly identical signal was received, which coincides with the unconfirmed rain-wrapped tornado. During both tornadoes (Fig. 43 time c) the spectra was significantly elevated with a fundamental frequency at 9 Hz. Following the work of Abdullah (1966) for a Rankine vortex with radial oscillations, this fundamental frequency corresponds to a 46 m diameter vortex. This matches the damage path width, though it should be noted that the predicted overtones from Abdullah (1966) do not match the current overtones. While it is unfortunate that radar was too far from this tornado to characterize the flow-field, it demonstrates the potential ability to use infrasound to characterize even weak tornadoes.

May 31, 2013 Broken Arrow EF2 Tornado: On May 31, 2013 from 0141 to 0154 UTC an EF2 tornado was on the ground near Broken Arrow, OK. This tornado had a path length of 5 miles and a damage path width of 450 yards. Approximately 3.5 miles north of the tornado, Steven Piltz (Meteorologist-in-Charge at the NWS Tulsa Weather Forecast Office) had a basic infrasonic microphone (INFRA20, Infiltec) recording. During the tornado there was a large burst, but the spectra could not be analyzed due to the short duration. It is difficult to interpret this since the microphone is really a pressure switch, which means there is some internal logic that is likely influencing the signal (particularly during rapid variation). However, of interest was that a strong signal was also present prior to the tornado during significant hail (1 to 2 inch). Infrasound sound from hail, updrafts, and inflows are important for interpreting tornadic infrasound.

Our current objective is to use available observations to determine the functional relationship (model) between the infrasound and the vortical flow-field. Our working model

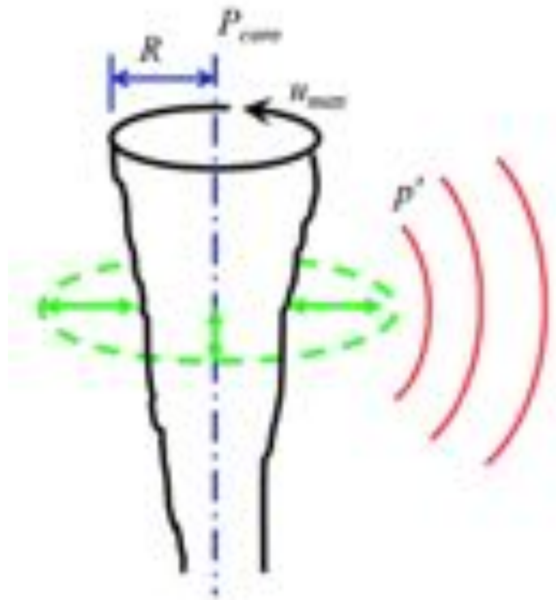

Figure 45: Sketch of the hypothesized physical model relating the acoustic production with flow-field properties.

is illustrated in Fig. 45 and assumes that the infrasound is produced from radial-modes-of-vibration (RMV) This is based on several previous observations (including the May 11th Perkins tornado). Assuming RMV and examining the terms in the wave equation above, we can make predictions about how the pressure fluctuations (p) associated with the propagating acoustic waves should scale with tornado properties. It suggests that $|p|$ should be directly proportional to the core pressure (p_{core}). Based on dimensional reasoning the frequency should scale with the ratio of the max wind speeds (u_{max}) to the tornado core radius (r_{core}), which is consistent with past observations. However, the unexpected outcome is that it also suggests that —p— should be directly proportional to the ratio of the storms convective velocity to the maximum wind speeds. The tornado infrasound observations (past, current, and future) will be used to test the validity of these predictions.

Summary of Intellectual Merit

Intellectual merit for this effort centers on the advancement of our fundamental identifying that fluid mechanisms responsible for infrasound from tornadoes. More specifically, we have measured infrasound from at least one tornado and are growing the database of available observations to test our working model of how they should be connected. Findings from this work have been presented in a conference paper, 6 technical presentations (4 regional; 2 national), and 1 M.S. thesis (Arnesha Threatt). In addition, we have been accepted to give 3 technical presentations and are currently preparing a manuscript on the May 11, 2017 Perkins tornado.

Summary of Broader Impacts

Broader Impacts from this task includes student exposure and involvement in research at all levels. This task has had 9 female engineers (7 undergraduate, 1 MS, 1 PhD) and 4 under-represented students (3 undergraduate, 1 MS). Undergraduate involvement has included a Wentz scholar, a Capstone Senior Design Project, two semester long course projects in Experimental Fluid Dynamics (MAE 4273), and research assistants. There has also been opportunities for high schoolers via hands-on demonstrations during National Laboratory Days and Dr. Elbings participation in OSUs Upward Bound program. Upward Bound provides low-income and/or first generation high school students interested in engineering the opportunity to job shadow Dr. Elbings team for 6-weeks.

Workforce Development This task has had four graduate students involved (2 PhD, 2 MS) with the two leaders being Arnesha Threat (MS) and Chris Petrin (PhD). This task has produced many opportunities for undergraduates to participate in research including 7 women and 2 African-Americans. Currently we have Jalen Golphin (presented a talk in Figure 4), Jared Hartzler, Katrine Hareland, Shelby Webb, and Logan King. Below I highlight a few of the students that have made significant contributions.

Leveraged Opportunities and Activities NOAA VORTEX-SE Grant Proposal Elbing and Matthew S. Van Den Broeke are currently writing a proposal to explore the fluid mechanism responsible for infrasonic production as well as identifying the infrasonic signatures from non-tornadic severe storms. This is a 2-year proposal that provides 3 total summer month of coverage for the PIs. In addition, it includes support for at least 2 graduate students.

NASA Oklahoma EPSCoR Implementation Grant: This grant will be submitted in May 2018 and focuses on the general subject of acoustic emissions from vortices. The objective will be to identify the fundamental properties of the acoustic emissions from low Mach number vortices including tornadoes and airplane wing tip vortices. This will continue the collaboration between Dr. Elbing and Dr. Qamar Shams at NASA Langley Research Center.

Steve Piltz (Meteorologist in Charge at U.S. National Weather Service) has agreed to collaborate on the VORTEX-SE Tornado Infrasound proposal. He will provide us with feedback/evaluation of the potential future benefits of the data they acquire as well as give direction for how it could be improved for use by operational weather forecasters.

3.2.7 Task 2-7: Multi-Scale GIS Correlation

Research Accomplishments The primary focus of this task is determining the appropriate measurement scales and requirements for capturing spatially and temporally distributed atmospheric variables via UAS in the ABL. While the processes shaping the atmosphere are governed by physical laws and are deterministic in nature, the many forces influencing the spatial and temporal variation of atmospheric properties, along with their nonlinear governing equations, make the behavior of these properties appear random. Therefore, it is impractical to use deterministic mathematical models to describe the spatial or temporal relationship between two sample points, which is needed to determine the structure. Instead, probabilistic approaches are needed to model the spatiotemporal behavior of atmospheric processes. In support of the CLOUD-MAP mission and the other science objectives, we are employing geostatistical modeling to uncover the statistical relationships of atmospheric variables relative to their location in space and time to determine the optimal spatiotemporal measurement scales to reliably capture the structure of atmospheric variables under different environmental and meteorological conditions. Our initial findings suggest that vertical scales of about 3 m for temperature and 1.5-2 m for relative humidity are appropriate for capturing their structure in both stable and mixed boundary layers. More datasets captured across varying environments and weather conditions are needed to validate the universality of these findings, but ultimately this information will contribute data collection standards for UAS thermodynamic measurements captured within the ABL.

We continue to build on our findings by capturing complementary datasets in diverse weather conditions and from the different climate zones in Oklahoma. Additionally, by flying adjacent to Mesonet sites, we are able to compute the Monin-Obukov length, which is an important scaling parameter for our estimates.

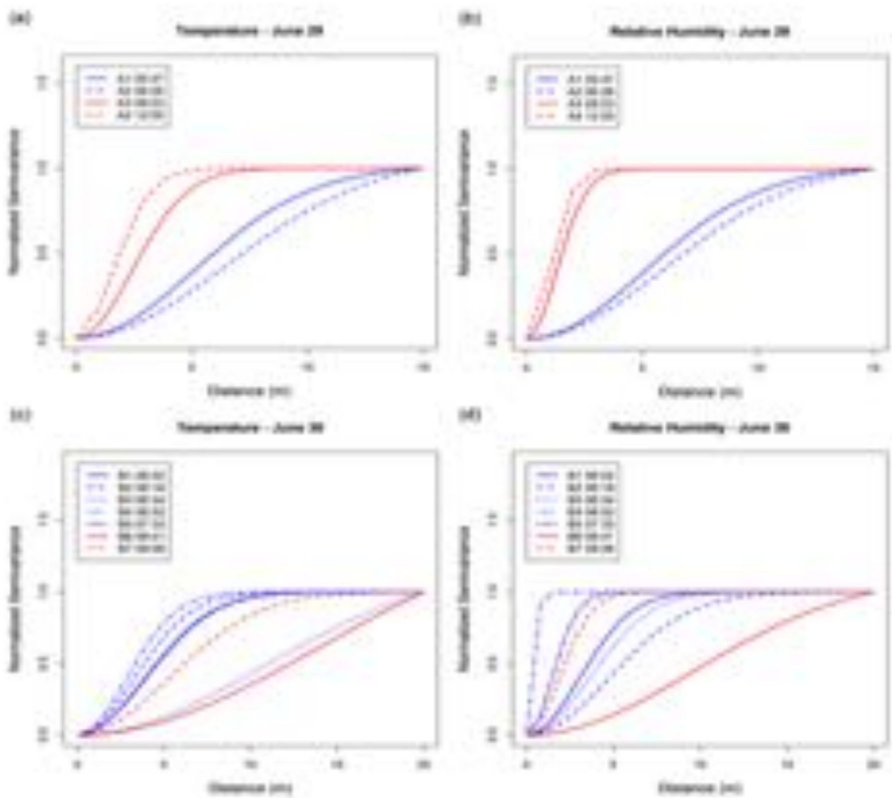

Figure 46: Standardized variograms for temperature and relative humidity captured during the 2016 summer flight campaign.

Workforce Development Trainee activities are ongoing and include GIS, remote sensing, and programming training for graduate and undergraduate students at Oklahoma State University. Task lead Frazier has been mentoring a female undergraduate student, who will participate in the summer 2018 field campaign as part of the Geography Undergraduate Mentors Program (GUMP). This student has also received a competitive departmental travel scholarship to support her participation in the field campaign. Outreach activities included engagement of high school students during the 2017 National Lab Day event held at Oklahoma State University. Manuscript writing mentorship and professional development activities (e.g., conference presentations) for graduate students are on-going.

Leveraged Opportunities and Activities Graduate student Benjamin Hemingway presented his work on Vertical sampling scales for atmospheric boundary layer measurements using small unmanned aircraft systems (sUAS) during the graduate student paper competition of the 2017 meeting of the Southwest Division of the American Association of Geographers (AAG) in October. His paper presentation was awarded first prize, which carried a stipend of $1,000 to support travel to the AAG annual meeting in April 2018 where he presented his work to a larger audience.

Task lead Frazier organized a five-session (25 paper) symposium on UAS for the AAG meeting in April 2018. She has been approached by the editor of the journal Drones (MDPI) to organize a special issue stemming from this symposium.

Collaborations related to this task (and other tasks) have been leveraged for multiple proposal submissions including:

- NSF Major Research Instrumentation (MRI): Development of PhenoScouts - Autonomous Field High Throughput Phenotyping System for Interdisciplinary Research and Training. (PI: V. Gopal Kakani OSU)
- NSF National Research Traineeship NRT: Unmanned Systems and Science (US2): Interdisciplinary Training for Leadership in Science, Engineering, and Policy. (PI: Michael Renfro - UKY).
- U.S. Geological Survey (USGS) National Competitive Grant (104g) Preproposal: Rapid Assessment Methods for Water Governance and Resource Management in Grassland Ecosystems. (PI: Peter Kedron - OSU)
- U.S. Department of Defense (DOD) Preproposal: Demonstration and Validation of Unmanned Aerial Vehicles to Assess and Monitor Natural Resources on Department of Defense Lands. (PI: Craig Davis - OSU)
- USDA National Institute for Food and Agriculture (NIFA) Participatory Approaches for Agroecosystem Resilience in times of Drought (ARID): An Example from the Southern High Plains (P.I. Amy Ganguli - NMSU).
- NASA EVS-3 4D Sampling and Modeling of the Earths Lower Atmosphere using Small Unmanned Aircraft Systems. (P.I. Phil Chilson OU)

3.3 Objective 3

Develop and demonstrate coordinated control and collaboration between autonomous air vehicles. The range, endurance and communication capabilities of SUAS is often less than desired for some of the applications described. By collaborating with mobile ground stations, the SUAS, both operating solo and in swarms, can relay communication, offload heavy computation, and potentially land to be refueled by the GCS.

Robust coordinated control of multiple SUAS is needed for routine operations in the NAS. There is a need to optimize control, coordination and communication and examine the resulting impact that these systems have for characterization of the data. The over arching goal of this objective is to explore a multi-platform approach for observing needed mesoscale atmospheric and meteorological observations with UAS and gain experience in deploying the platforms, collecting atmospheric measurements, and coordinating operations among different UAS teams.

3.3.1 Task 3-1: Cooperative Control of Small UAS Formations For Distributed Measurement

This task focuses on cooperative control of UAS for distributed sensing applications. For example, a coordinated group of air vehicles could be used in forest fire scenarios to measure wind velocities, which can then be used to predict how the fire will move. Similarly, coordinated air vehicles could provide distributed measurements for predicting airborne pollutant dispersion in a rapidly evolving emergency situation. In the agricultural industry, a coordinated group of air vehicles could conduct crop surveys on large farms.

In all of these applications, it is often desirable to have the vehicles fly in formations. For example, vehicles could travel together in a *flock* or *swarm*, where vehicles maintain desired separation distances, avoid collisions, and match velocities.

For some measurement applications, it is valuable to have formations that are capable of reconfiguring based on real-time sensor measurements. For example, considered a formation of vehicles measuring pollutant concentrations. Collectively, these vehicles could be used to estimate concentration gradients in real time. Then, the entire formation could be manipulated based on the real-time gradient estimates.

This task aims to develop, analyze, and demonstrate new methods of cooperative control for UAS formations—methods for flocking and swarming as well as methods for formations reconfiguration. We will develop these methods through a combination of mathematical analysis, numerical simulation, and experimentation.

Research Accomplishments Discrete-Time Flocking.

We developed a new *discrete-time formation* (DTF) control method [1–3] for coordinated control of multi-UAV systems. Most existing formation-control approaches are continuous-time formation (CTF) algorithms and do not account for sample-data effects, which can be significant for applications such as formation flying, where communication and sensing constraints limit the speed with relative position data can be obtained. In [1,2], we show that existing CTF methods do not perform well with slow-sample-rate feedback data. These algorithms can cause undesirable oscillations in the inter-vehicle distance and persistent corrective control forces, which can expend the UAV's energy supplies. In addition, these oscillations get worse with more vehicles and can result in formation instabilities. In the worst case, these oscillations could result in collisions with other vehicles or obstacles.

We also implemented DTF on indoor experiments with multiple rotorcraft. To implement DTF, each UAV's onboard controller requires a measurement of the relative positions and velocities of nearby vehicles. DTF uses this information to achieve: i) formation cohesion, and ii) collision avoidance. Formation cohesion causes UAVs that are too far away from one another to be attracted together, while collision avoidance causes UAVs that are too close together to be repelled from one another. We used a motion capture system (with six 1.3 mega-pixel cameras) to obtain real-time position and velocity estimates, which are then transmitted to each rotorcraft's onboard DTF controller. The sample rate for this experiment was only 18 Hz. As shown in Figure 47, the 3 rotorcraft form a triangle formation, and this formation travels in a desired circular trajectory. A video of this indoor flight experiment is available at: https://www.dropbox.com/s/whdzm8ysa7q3zg4/FlockingUAVs.mp4?dl=0. This experimental DTF research is published in [3].

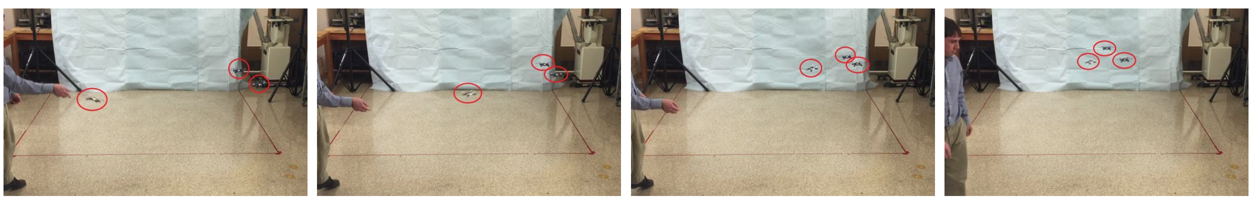

Figure 47: Indoor DTF experiments. The red circles highlight the UAVs. From left to right: a UAV is released to join the formation (left); the UAV autonomously joins the formation (center left and center right); the 3 UAVs maintain a triangle formation and follow a circular leader trajectory (right).

We also completed a flocking-and-destination-seeking control approach that allows vehicles not only to flock but also to leave the flock as they approach a desired destination. Our approach is not a leader-follower method and requires limited real-time information sharing. This decentralized method is beneficial for large formations. This work is published in [4].

Autonomous Quadrotor Collision Avoidance and Destination Seeking Using Vision Sensing

We developed and tested an integrated guidance and control method for autonomous collision avoidance and navigation in an unmapped environment that contains unknown obstacles. The algorithm was implemented on a custom quadrotor that uses onboard vision sensing (i.e., an Intel RealSense R200) to detect the positions of obstacles. This quadrotor is shown in Figure 48. We demonstrated autonomous collision avoidance and destination seeking in experiments, where the quadrotor navigates unknown GPS-denied environments. All feedback measurements are obtained from onboard sensors. A video of this indoor flight experiment in an unknown GPS-denied environment is available at: https://www.dropbox.com/s/vhxadsx0w1dasi7/AutonomousQuadVisionSensing.mov?dl=0. The new guidance and control algorithm uses a nonlinear inner-loop attitude controller; a nonlinear middle-loop velocity controller; and a potential-field-based outer-loop guidance algorithm for collision avoidance and destination seeking. This work has been submitted for

Figure 48: Front View of Fully Assembled Quadrotor. The Intel Realsense R200 is mounted to the front end.

publication in [4].

3.3.2 Autonomous Quadrotor Flocking Using Vision Sensing

We have made progress toward outdoor flocking experiments using vision sensing and DTF control. This work aims to combine our theoretical and experimental work on DTF with our experimental work on control using vision sensing. We aim to use a fleet of custom rotorcraft to perform flocking maneuvers, where the vehicles are in close formation (i.e., less than 0.5-m separation). The proposed outdoor experiments represent a significant step forward from our preliminary indoor experiments because a motion-capture system cannot be used outdoors in an unprepared environment to obtain feedback data. Instead, the outdoor experiments will rely on a combination of GPS and vision sensing. GPS alone is not accurate enough for close-formation flocking. Thus, each UAV will be equipped with several inexpensive off-the-shelf IR stereo cameras (i.e., Intel's RealSense) to supplement and improve the GPS-based estimates of relative positions and velocities of the UAVs.

3.3.3 Fixed-Wing Formation Flying Experiments

We have developed and implemented a relative-position formation-control method for fixed-wing UAVs. We have demonstrated this formation flying technique in experiments with fixed-wing UAVs. A video of this flight experiment is available at: https://www.dropbox.com/s/h0u34n4isrcjldd/FixedWingFormationFlying.mp4?dl=0. In the near future, we plan to implement a relative-position formation-control method on a group fixed-wing UAVs, and use the formation to obtain distributed measurements of atmospheric turbulence. This work is a collaboration with S. Bailey.

We also completed work on inner-loop control of fixed-wing UAVs in turbulent wind conditions. We performed single-vehicle outdoor flight experiments using a new altitude control approach, which will be beneficial for inner-loop control with multiple air vehicles. This work is published in [6].

3.3.4 Data-Driven Turbulent Flow Simulations

We developed a new data-driven adaptive computational model for simulating turbulent flow, where partial-but-incomplete measurement data is available. The model automatically adjusts the closure coefficients of the Reynolds-averaged Navier-Stokes (RANS) $k-\omega$ turbulence equations to improve agreement between the simulated flow and the measurements. We validated this data-driven adaptive RANS $k-\omega$ model on a variety of canonical flow geometries. This work is published in [7,8].

We are working toward combining our data-driven adaptive RANS model—a cyber system—with a group of autonomous fixed-wing UAVs—a physical system—to create a cyber-physical system capable of near-real-time flow-field prediction. We aim to use the fixed-wing UAVs to obtain physical flow-field measurements at discrete-but-time-varying locations. Then, the data-driven adaptive RANS model uses this measured data from the physical flow field to update the computational model and produce an accurate prediction of the flow field. This work is a collaboration with S. Bailey.

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3.3.5 Task 3-2: Integration of Spatially Distributed Data from Moving Sensor Platforms

Research Accomplishments In terms of broader impacts, obtaining time-dependent spatial distribution of a quantity ($\mathbf{x}$) can be extremely valuable for understanding the turbulent transport, dissipation, and diffusion processes of a quantity (ϕ, which can be mass, momentum or energy) and the role that the atmospheric properties play in those processes. Predicting the transport of heat, momentum, water vapor and pollutants due to this turbulence is a crucial part of many scientific disciplines such as meteorology, climatology, wind engineering and environmental science. Thus, increased understanding in this area will lead to improvements in many diverse and socially important scientific tasks including: modeling weather and climate patterns; prediction of structural loading; energy recovery in wind farms; or tracking pollutants in the atmosphere.

As far as intellectual merit is concerned, fixed-wing moving SUAS offer several advantages over small rotorcraft, including the ability to traverse a larger space during the 30 minute periods of quasi-statistical-stationarity. Most importantly for turbulence measurements, the sensitivity of pressure-based velocity probes increase with the square of velocity, making fixed-wing aircraft the most desirable option for low-cost wind measurement. However, measurements made using fixed-wing UAVs are neither fixed-point measurements, nor measurements of a spatial field, as both the position of the UAV and the flow field are time dependent. Thus, the measured quantity is $\phi(\mathbf{x}(t), t)$. Hence, the objective of this task is to identify approaches which allow the fixed wing UAV to obtain scientifically relevant, spatially distributed data. It is hoped that by using a unique combination of experimental tools and analysis techniques, the use of SUAS will fill a void in traditional atmospheric boundary layer turbulence research capabilities and contribute new understanding atmospheric boundary layer structure, organization and transport processes.

Progress to Date Years 1-2 have proven successful in development of systems and procedures. Two separate systems have been developed, a vertical profiling rotorcrraft and a horizontal profilling fixed-wing aircraft. Procedures and initial results for the fixed wing aircraft were published in an invited journal paper (Witte et al. 2017).

Three of fixed-wing airframes were operated simultaneously in the 2017 CLOUDMAP measurement campaign, simultaneously with the rotorcoraft profiler. Some of the achievements from this campaign were:

1. Flying 3 UAVs in formation for obtaining spatial statistics
2. Simultaneously flying a rotorcraft specifically for obtaining boundary layer profiles
3. Incorporating fast-response temperature probes onto the UAVs for measuring thermal transport, eddy fluxes
4. Airframe improvements: strengthening airframes, improving radio range, improving aircraft endurance, and improving internal system layouts
5. Improving instrumentation tower used to provide a reference and comparison point
6. Introducing autonomous takeoffs and landings for each flight, to minimize the risk of pilot error

7. Flying in windy conditions
8. Flying up to 1000 ft altitude

In addition, measurements were also conducted during the Aug. 21, 2017 solar eclipse. Results from this experiment has revealed numerous interesting phenomena supporting both conference presentations presented and additional journal and conference publications in preparation.

Workforce Development

One graduate student (male) is being co-advised with Dr. J. Hoagg developing the formation flying technology which is in development to applied to Task 3-2.

A new student (male) has taken over data acquisition and analysis tasks since Spring 2017. This student is also responsible for managing by 10 undergraduate students (7 male, 3 female) supporting the project. These undergraduates are largely responsible for maintaining the hardware and SUAS involved in this project and are learning skills in problem solving, engineering design, sensing and autonomy.

Leverages Opportunities and Activities

This project is closely related to NSF CAREER related research which has resulted in significantly greater productivity and efficiency solving technical challenges related to both projects. We also participated in University of Kentucky's Engineering Day (E-Day) in February of 2018 by hosting an open house in the UAV lab. This is an open house in which an estimated 6,000-9,000 kids (of all ages) tour the college of engineering. Students working on this NSF-funded research presented their project work to visitors, and gave visitors an opportunity to fly small quad-copters in an obstacle course contained within the lab's CNC enclosure.

In addition, we will be presenting modules for the Women in Engineering Summer Workshop Series targeting the recruitment of female high school students in engineering. This is just the second year that Mechanical Engineering will contribute a workshop for this program, and we will hold a glider design contest which will incorporate instruction in fluid mechanics fundamentals and wind tunnel testing into an optimization problem.

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3.3.6 Task 3-3/4: Tasks 3-3 and 3-4: Heterogenous Robot Control and Multi-agent UAS Simulators

Research Accomplishments *Distributed control as belief propagation in factor graphs*

We have developed a distributed algorithm based on loopy belief propagation within factor graphs that can be effectively used for coordinating within a team of heterogenous robots, while allowing occasional human input to affect the robots' task allocation. In an atmospheric physics deployment, a large number of different UAS with different capabilities and sensors may be employed, with limited numbers of human operators. Proper coverage requires a multi-robot deployment, and spatiotemporal data can change dynamically, requiring multiple sensors spread out in space to properly sample time-varying data. Assigning

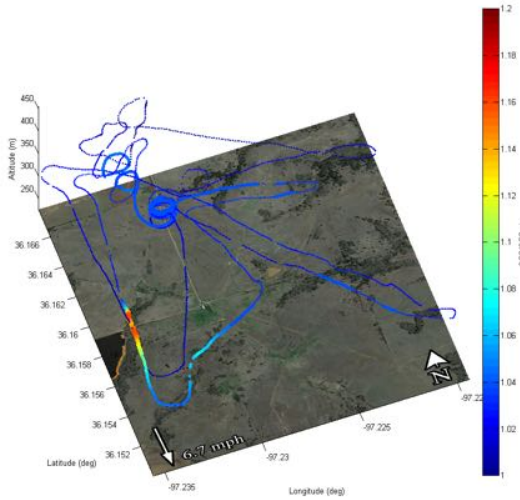

Figure 49: A simulated aircraft measures CO_2 concentration from a controlled release near Lake Carl Blackwell.

human operators to each UAS is not practical, as robot participants must coordinate closely with one another and make data-dependent decisions across the entire robot team in real time. We have addressed all of these problems using our factor graph algorithm. The application of our proposed algorithm is not limited to these particular tasks, but also can be generalized to many other tasks requiring heterogeneous multi-robot teams cooperating with human operators. The theoretical underpinnings of the approach were developed and described in the previous year's progress report.

In this reporting period, we have developed coordination functions which perform not only exploration and object avoidance, but which respond in real time to sensor data and incorporate human input. Our approach allows a human operator to exert an arbitrary amount of control over all of the agents that are indirectly or directly connected to the operator. If no human input is available (for example, if the human operator is task-saturated or does not have a connection to the agent), then the agent and the entire system function autonomously according to the robots own sensor data and communicated beliefs.

Weather-aware UAS simulation

We have extended the open-source flight simulator Flightgear[1] in order to develop a robotic simulation software suite which supports atmospheric physics phenomena such as turbulence, visibility, temperature, humidity, and the behavior of water vapor and gas plumes such as clouds, smoke, methane, and CO_2.

Figure 49 shows a simulated flight near Oklahoma State University, where an aircraft equipped with a CO_2 sensor is able to report data about a plume release. The gas concentration is injected into the simulation and is affected by wind and turbulence over time.

A paper detailing the simulation environment is under preparation for submission to

[1] http://home.flightgear.org/

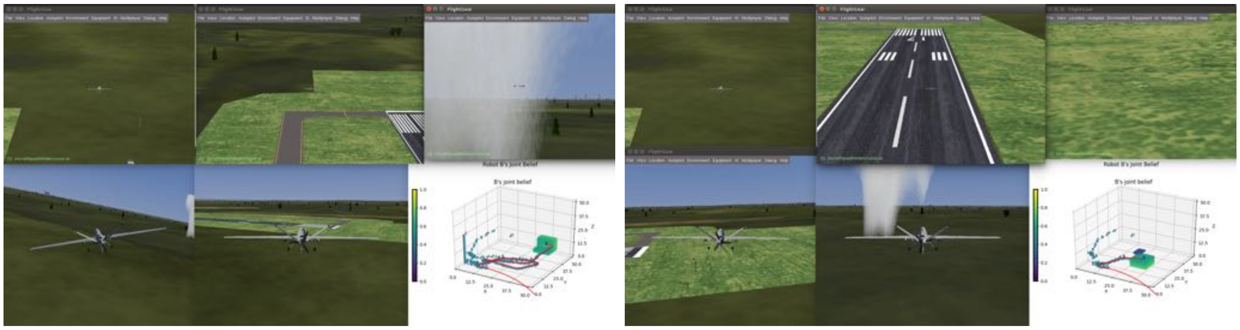

Figure 50: Snapshot of heterogeneous team exploration. For visibility we have hidden joint intention of all the robots except for B (a fixed-wing UAS). Quadrotors and fixed-wing aircraft coordinate together to explore, and are each captured in different picture elements. The lower-right element is the joint belief of B. (a) UAS B is moving towards the CO_2 plume. UAS A still exploring far from the plume. (b) UAS B already passed through the plume and sent intention for UAS which are interested in exploring area with high CO_2 density. UAS A is such a robot so it moves towards the plume. B's joint belief in lower-right sub figure also shows the trail of A's path.

Simulation.

Experimental results

Using our factor graph distributed algorithm, we can exploit the heterogeneous configuration of our robot team. Heterogeneous teams of robots can accomplish more complex tasks more quickly, and in distributed fashion. In this experiment, we demonstrate this using our simulator. The task for this experiment is to locate, survey and map a CO_2 plume within a given area. Our heterogeneous team consists of two similar fixed wing UAV and three quadrotors with slightly different sensory capabilities. All of these simulated UAVs are equipped with GPS, temperature and humidity sensors, but only the fixed-wing aircraft and one quadrotor are equipped with CO_2 sensors.

A fixed-wing aircraft is much faster than a quadrotor, but also far less maneuverable. A team of fixed-wing aircraft will quickly locate traces of CO_2, but they will not be able to carefully map its contours. On the other hand, while a maneuverable quadrotor is better equipped to perform the detailed survey, its slow speed makes the location of the plume difficult to find in the first place.

Figure 50 demonstrates the heterogenous team exploration. Experiments show that our approach is able to leverage the heterogenous capabilities of the team to map the contours of the plume phenomenon autonomously, and more quickly than a homogenous team can accomplish the same task.

We have conducted similar heterogenous team experiments in real world scenarios. In this case, one quadrotor aircraft is equipped with a temperature sensor, while the other can measure relative humidity. Figure 51 shows autonomously-developed temperature maps developed over a 64 m^3 cube of airspace, as the various systems coordinate with each other to explore interesting sensor gradients to which each has access. The robots are able to locate a temperature inversion at 45 meters above the ground.

We are also able to demonstrate seamless human intervention using our algorithm. In

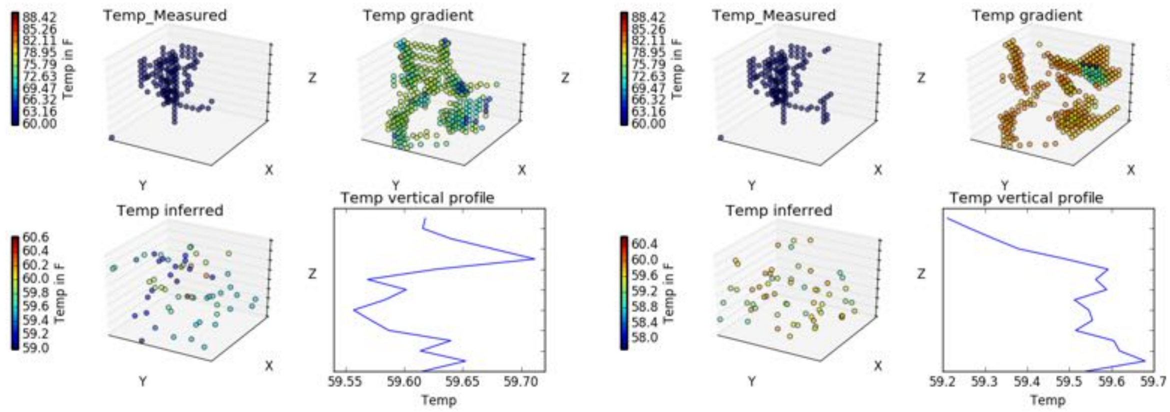

Figure 51: In each subfigure, upper left is measured temperature, upper right is the inferred temperature gradient, lower left is randomly sampled temperature predictions drawn from the inferred gradient, and lower right is a temperature vs altitude plot. The first figure is early in the exploration process, and the second is after additional exploration and mapping.

this particular instance, a human operator takes active control of one of the UAS, overriding the intentions developed by that robot. The robot, however, continues to communicate with the other team members, using the same loopy propagation framework. The other systems modify their intentions accordingly. Fig. ?? shows a human intentionally steering robot A toward its neighbor B. This induces robot B to evade, because of the influence of $\phi_{avoid\_collision}$. The human's intention is incorporated smoothly into the overall team behavior, without any explicit commands from the human to any other robot participant beyond the first.

These experiments have been submitted for publication at IROS.

Workforce Development

SM al Mahi (PhD student) is the primary contributor to the heterogenous robot control work. He has been working on the factor graph modeling and algorithm development.

Kyungho Nam (PhD student) is the primary contributor to the UAS simulation work. He has been working on all aspects of simulator design, implementation and development.

Neelesh Iddipilla (MS student) has been assisting in the simulation work, implementing comparison scenarios in currently-available state-of-the-art simulators such as Gazebo.

Leveraged Opportunities and Activities

This work has led to two other proposals, including a cyberphysical systems project to evaluate development and testing methodologies in the context of UAS for atmospheric physics, and the establishment of an REU site for robotics, machine learning and data analysis. This proposal has been funded.

3.3.7 Task 3-5: Robust Conformal Antennas for UAS Communication

Research Accomplishments Work on Task 3-5 has mostly focused on providing an antenna that can be conformally attached to plastic, fiberglass, or styrofoam SUAS of varying shapes to enable a robust data link. Additionally, we have worked to quantitatively measure the improvement of the developed antennas over more standard antenna designs. SUAS need

Figure 52: Experiment with two UAV robots A and B. (a) Robots take off. (b) Robots operating at safe distances from one another. (c) Human commands A to move toward B. (d) and (e) B moves to avoid collision with A. (f) A and B flying at safe distance again.

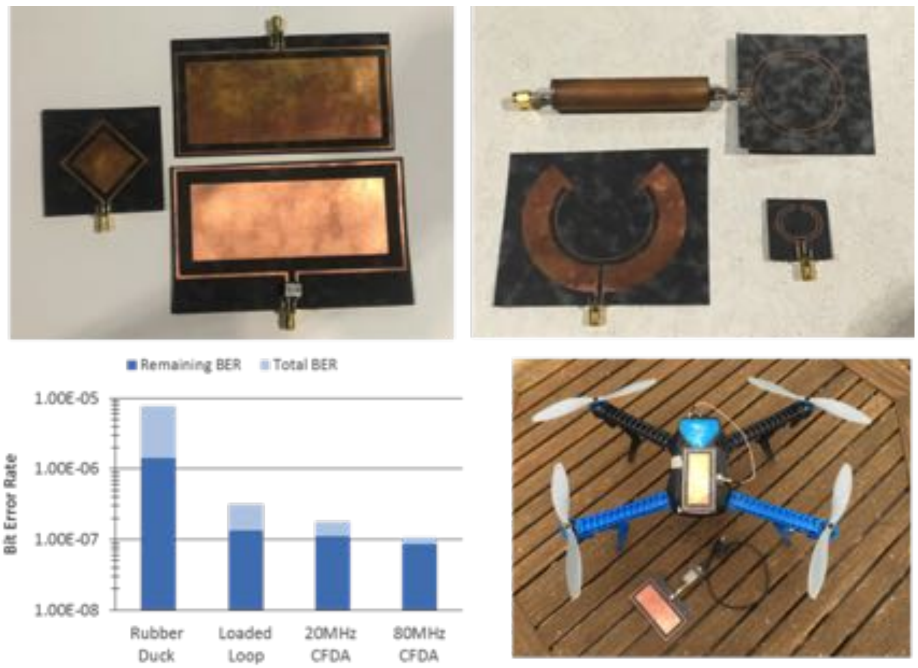

Figure 53: Depiction of antenna development progress with (a) showing the developed loaded loop antennas, (b) showing Curved Folded Dipole Antennas (CFDA), (c) showing the BER comparison of the developed antennas vs. standard antennas, and (d) showing the test setup for measurement of BER.

to maintain a constant communication link with the ground station, as they are remotely controlled and are continually taking measurements. The specific design goals that contribute to improved performance are creating as isotropic of a radiation pattern as possible, minimizing the antennas physical size with minimal degradation so that it may conform under significant form factor constraints, and minimizing the effect of the SUAS body structure as backing on the performance of a generalized conformal antenna solution. Additionally, a project in measuring a humidity gradient was investigated using a communication link between two antennas. This would allow for more detailed humidity information to be taken with shorter SUAS flight times.

Antenna Development Figure 53 shows the antenna development that has occurred over the last year. Two different types of antennas have been developed with design equations derived for each type of antenna to allow for simple scaling to the necessary operating frequency and bandwidth. As can also be seen in the figure, the developed antennas provide a much lower Bit Error Rate (BER) over a flight scenario, showing that the developed antennas will provide a much more robust communication link for SUAS. The extracted BER was obtained using the navigation software for SUAS. This software has a fixed modulation scheme and transmit power. The next section will describe work to obtain a standardized system for measuring BER with lower transmit powers (for longer battery life) and across different modulation schemes.

Figure 54: Depiction of the current transmission header based packet transmission model.

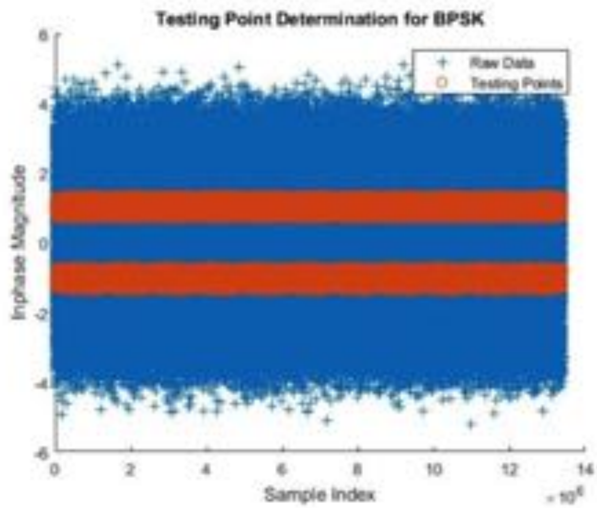

Figure 55: Testing point determination for an oversampled waveform in a noisy communication model.

Quantizing Improvement of Antennas We have worked to quantizing bit error rate for multiple encoding schemes, including but not limited to BPSK, QPSK, and QAM, to quantify the improvements in signal fidelity made by the quasi-isotropic antennas already designed for this investigation. Both curved folded dipole antennas (CFDA) and loaded loop antennas will be tested in comparison to the rubber duck antennas that originally came with the SUAS over a variety of maneuvers. This will allow for the correlation between flight patterns and communication performance to be measured for multiple antennas.

The preliminary stages of header based packet transmission and reception with BPSK between two FPGAs have been accomplished. After several attempts at clock synchronization were attempted, it has been decided to use real time data recording and perform bit error calculations as a post processing step. MATLAB code has been written to this effect to enable rapid location of the IQ testing points in an oversampled received data set.

Header free transmission will make it possible to collect real time flight data for postprocessing and bit error rate calculation. Additional MATLAB code will be written for the automated calculation of bit error rate for large data sets.

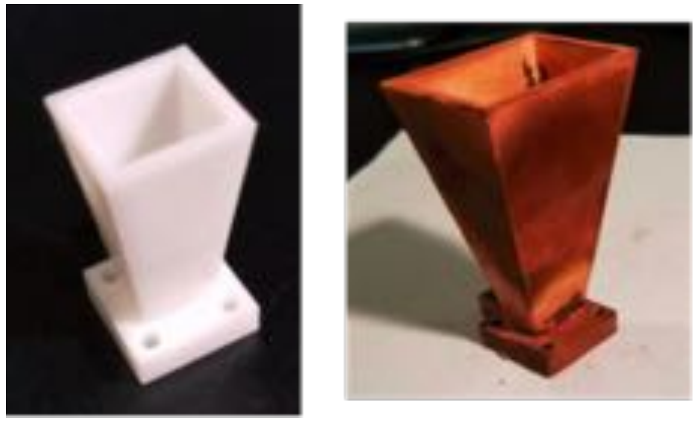

Figure 56: 3-D Printed horn antennas, before plating (left) and after plating (right).

Humidity Gradient Measurement Investigation There are two radar frequency bands of interest for this experiment, K band and Ka band. K band, from 18 to 26.5GHz, contains 22.235GHz which is known to be the typical water absorption band [1]. Ka band, from 26.5 to 40GHz, contains the 30 to 36GHz region well known to have high scattering [2]. For the experiment, horn antennas have been 3-D printed using a Formlabs resin printer and then copper plated.

For the setup, two of each antenna, K and Ka, will be on mounted on the roof of the Radar Innovations Lab at the University of Oklahoma and a reflector will be placed on the roof of an adjacent building (National Weather Center) which is approximately 1000 ft away. A high frequency network analyzer will be used to measure the magnitude and phase of the monostatic reflection at both K and Ka band. Although the distance is not long, calculations indicate that the noise floor of our equipment be low enough to detect both phase and attenuation changes due humidity changes. Measurements will be taken at various humidity levels and the results will be compared to humidity measurements taken at the same time and location.

Workforce Development This funding supported two graduate students (Taylor Poydence and Garrett Robinson) and an undergraduate student, (Hope Schneider). Both Taylor and Garrett were undergraduate research assistants for me before beginning graduate school and this project helped to transition them into graduate studies. Taylor successfully defended his masters thesis in December of 2017 and is now working at L3 Mustang Radar in Dallas Texas as an antenna designer. Garrett has successfully transitioned onto the project and is set to graduate in December of 2018. He will be interning this summer at Raytheon in Dallas Texas as an antenna engineer. Hope Schneider will graduate with her bachelors degree in electrical engineering in May of 2018 and will begin work immediately afterward as an applications engineering for Texas Instruments.

Structure-Independent Conformal Quasi-Isotropic Antenna for Small Unmanned Aerial System Applications (Taylor Poydence Masters Thesis)

T.A. Poydence and J.E. Ruyle, "Structure-Independent, Conformal, Quasi-Isotropic Antennas for Small Unmanned Aerial Systems," in Proc. 2017 Antenna Applications Symposium, Allerton Park, Monticello, IL, Sept. 2017.

References [1] Richards, Mark A., and James A. Scheer. Principles of Modern Radar. SciTech Pub., 2014.

[2] Melnikov, V., et al. Potentials of Frequency Agile Ka and W Band Cloud Radars. 2011 IEEE RadarCon (RADAR), 2011, doi:10.1109/radar.2011.5960572.

3.3.8 Task 3-6: Persistant Monitoring

Research Accomplishments This task aims to improve the ability to precisely obtain atmospheric sensor data over longer periods of time or spacial areas through the development of novel hardware and software systems deployed on UASs. Specifically, this task is investigating dropping sensors connected to a parachute (also known as a dropsonde) from a UAS and then autonomously recovering the parachute with another UAS to ease immediate or later reuse. In addition, this task is investigating other long-term monitoring approaches, such as deploying low-altitude balloons with sensors and developing algorithms to optimize their altitude for sensing while minimizing the number of control inputs. Finally, this task also investigated using a UAS to persistently monitor the lower atmosphere during an eclipse.

Parachute Tracking and Catching Sensors suspended by parachutes, also known as dropsondes [?], are often used for atmospheric profiling, yet they are rarely recovered since they often land in inaccessible locations. In practice, this limits the sensor payloads to inexpensive sensors such as temperature and humidity. We have developed a system for quickly and autonomously tracking and then capturing parachutes in-air using a multi-rotor UAS. Parachute-suspended payloads often have loosely modeled dynamics, which makes their tracking and estimation difficult. The overall design of the system must therefore account for the physical capabilities of the UAS and the limits on an end-effector that traps the parachute. Additionally, interception methods need to have greater considerations for the safety of the vehicle when the target is in close proximity, and these are aggravated by the erratic motion of the parachute.

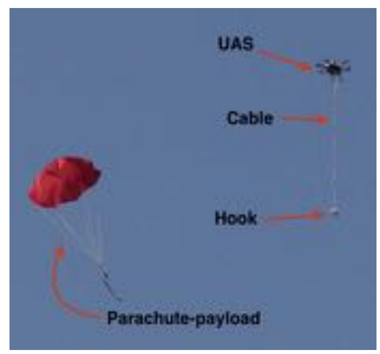

Figure 57: A multirotor UAS chasing the parachute through its descent.

Our proposed approach formulates the UAS mission first as a target identification and following problem, and then as an aerial interception problem. The design is generic, and does not require a special type of parachute or UAS, nor additional sensors and communication with the payload. The UAS is only augmented with an onboard computer, two color cameras and a passive hook to trap the parachute, as shown in Figure 57.

We performed simulations to develop evaluate a range of parameters including parachute types, speeds, impact of wind, length of cables, and other factors. Based on the results of the simulations, we developed and deployed the system in the field to determine the efficacy of our proposed method. Figure 58 shows a sequence of images from a successful catch and Table 5 summarizes the results of ten trials. In ten runs on two different days, five were successfully, four were near misses, and one resulted in a failure. The successful captures took on average 40 seconds. We also analyzed other factors that impacted performance and believe that small changes, such as better yaw control, will result in more successful captures.

Figure 58: Four snapshots from a successful mission. The successive images show the UAS approaching the parachute from a distance, positioning itself before the maneuver, swooping towards the parachute, and finally trapping it in the hook.

We aim to test the refined approach in the coming year.

Balloon Altitude Control

Weather balloons are a cheap sensing tool when used in atmospheric sciences. They have been shown to provide satisfactory results when compared to expensive aircraft sensing equipment [?]. While research has been conducted to add different sensors and manage payloads on a balloon [?], there is often no or limited control over the movement of the balloon. Having a balloon maintain a constant altitude or a constant sensor value as it drifts horizontally could improve persistent monitoring of the atmosphere, yet maintaining altitude is a challenging problem. Of particular interest is controlling the altitude of the balloon at lower altitudes to complement UAS sensing.

We propose using a balloon that has limited control over its altitude. This could be through periodic inflating using onboard helium tanks or dropping weights to increase altitude and releasing helium or pumping it back into a tank to reduce altitude. Regardless, due to power and resource constraints, the balloon has a limited number of times that it can adjust its altitude. In addition, we assume that the balloon has limited or no knowledge of the, for instance, temperature front it is following. Hence, it must make decisions in real-time based on the sensed data. Further, it must balance a move it takes now with the fact that moving now will reduce the number of times it can move in the future. So, the balloon needs to decide at what time and when to react to changes to result in the most beneficial and close to

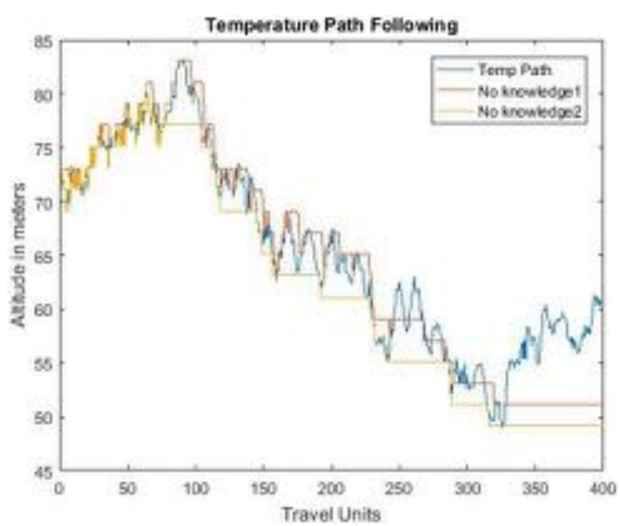

Figure 59: A temperature path with two no knowledge algorithms following it with a limited number of altitude adjustments.

Table 5: Summary of results and factors involved in the parachute catches.

Runs	Result	Run time	Interception triggered	#phase changes	Last ϕ, θ	Miss cause
1	Success	22.7s	18.7s	1	56%, 16%	-
2	Success	62.3s	58.3s	12	15%, 14%	-
3	Success	63.1s	59.1s	13	49%, 59%	-
4	Success	14.5s	10.5s	6	21%, 16%	-
5	Success	23.6s	–	11	81%, 08%	-
6	Miss	41s	36.9s	2	38%, 88%	Relative orientation
7	Miss	32.0s	28.0s	3	20%, 63%	Relative orientation
8	Miss	35.3s	31.3s	9	62%, 24%	Relative orientation
9	Miss	53.3s	49.3s	3	26%, 89%	High v_p
10	Fail	12.3s	–	4	22%, 91%	Unsafe pose

an optimal path to follow. We consider such a solution a no knowledge solution.

We are developing algorithms to optimize the altitude of the balloon based on our prior work on decision making with limited information [**?**]. Our preliminary experiments results show promising results. Figure 59, shows preliminary results of a no knowledge algorithm, that only reads the temperature at each point after reaching it. We generate a temperature front and the balloon can perform a limited number of moves in one axis, we assume 50 moves up and 80 moves down. The total length of the path is 400 moving units. The balloon attempts to follow the front and stay on, or as close to, the temperature path. In these preliminary results, the algorithm can be tuned to match balance minimizing the error versus reserving moves for later adjustments. We are currently analyzing the performance of the algorithms and we aim to implement this on an actual balloon for field deployments this coming year.

Workforce Development

During this period, three graduate students worked on parts of this task, participated in the summer flight campaign, and eclipse flights. The students are seeking degrees in Computer Science, Computer Engineering, and Mechanical Engineering. The students have been directly involved in meetings with researchers from atmospheric sciences and public policy, which has broadened their experiences and training. This work has resulted in one publication [?] and three submissions [?, ?, ?].

References

3.3.9 Task 3-7: Sensor Integration

PI: Dr. Phillip Chilson, co-PIs: Dr. Sean Bailey, Dr. Carrick Detweiler, Dr. Adam Houston, and Dr. Jamey Jacob
Graduate Students: Antonio Segales (Ph.D., ECE) and Brian Greene (M.S., Meteorology)

Research Accomplishments
This is a new task for CLOUD-MAP with a focus on the effective integration of sensors onto UAS platforms. Although a new task, the activity captured under the topic has been on-going from the beginning of grant. Therefore, this update will will be longer than those for the other tasks. In the interest of brevity, only a few of the sensor integration activities are highlighted here.

Multi-hole probes
Multi-hole probes are designed to determine the magnitude and direction of the local air velocity vector. Specifically, on aircraft, they provide the angle of attack and side-slip angles typically denoted by α and β respectively. The five-hole probe is made up of a cylindrical body with one hole along the centerline and four holes evenly spaced cylindrically around an angled tip. Therefore, if the flow of the fluid is not aligned with the center of the probe, each hole will read a different pressure which, through calibration, can be used to estimate α, β and the velocity magnitude. When coupled with accurate aircraft kinematic information, these probes can provide a relatively high data rate wind velocity vector, useful for extracting turbulence statistics. As part of this work, five-hole probes have been manufactured by University of Kentucky team members and integrated on fixed-wing aircraft including designing and construction of a custom circuit board to provide a compact layout for all five pressure transducers with optional inputs for 1st order RC low-pass filters.

Before flight, each five-hole probe was calibrated using a 0.3 m $\times$ 0.3 m wind tunnel. The calibration followed standard calibration techniques outlined by [?]. After the data is acquired from the calibration, the required coefficients were determined a posteriori so that the wind direction and magnitude can accurately be calculated from the pressure at each of the five holes of the probe.

An additional calibration was conducted to determine the frequency response of the five-hole probe. This was performed by subjecting the measurement tip of the probe to a step change in pressure while measuring the voltage output of the transducers. The results showed a slightly underdamped response, with a corresponding frequency response of 60 Hz. At the typical cruise speed of the aircraft used in this study, this frequency response translates to a spatial measurement resolution of approximately 0.28 m.

Interference effects between the airframe and five-hole probe were mitigated by placing the probe measurement volume 18 cm in front of the nose of the aircraft. This location was selected following scale-model tests of the aircraft in which dye was injected into a water

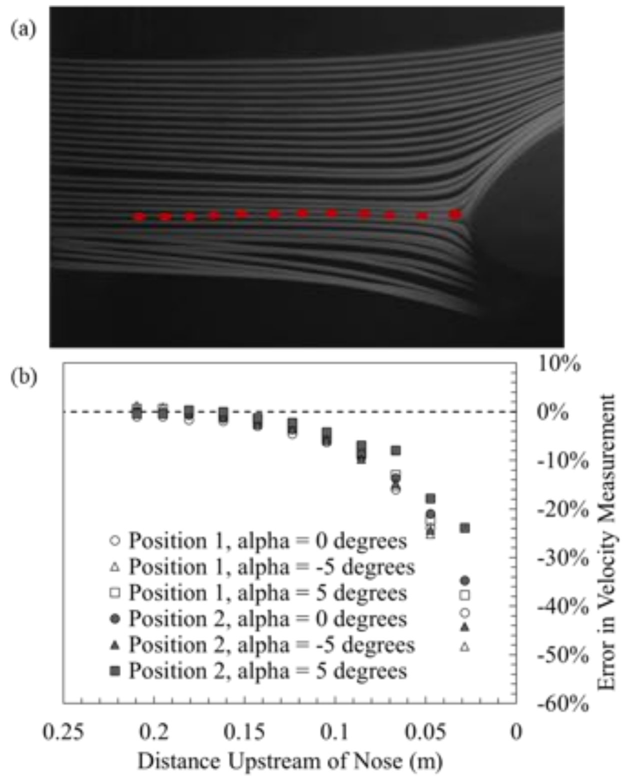

Figure 60: Results investigation of airframe influence on flow field: (a) scale-model flow visualization; and (b) full-scale wind tunnel comparison of measured velocity to true velocity. Red dots on (a) correspond to streamwise measurement locations in (b).

tunnel containing a model of the Skywalker X8 airframe and examining the deflection of the dye around the airframe. This water tunnel flow visualization, shown in Figure 60(a) was coupled with a full-scale wind tunnel test in which a Pitot-static tube was positioned at various streamwise positions upstream of the aircraft nose and used to measure the local velocity magnitude. For the wind tunnel tests, two vertical positions were tested, corresponding to the position of the position of the Pitot-static tube (position 1) and five-hole probe (position 2). Vertical position 1 was located at the leading edge of the aircraft and vertical position 2 was 1.5 cm above it. The difference between the velocity measured at these locations and the actual wind tunnel velocity are presented in Figure 60(b). From Figure 60(a) the streamline deflection was limited to a region very near the airframe (less than 5 cm) and the flow deceleration was limited to the 16 cm upstream of the nose of the aircraft.

Thermodynamic probes

Another objective was to establish an optimal location to mount pressure, temperature, humidity (PTH) sensor on a rotary-wing UAS body for accurate data collection. The primary requirements were: sensors need to be aspirated, sensor must avoid direct sunlight, and the readings represent the actual property of the surrounding air mass. Aspiration can be direct or indirect. While direct aspiration would be sensor mounted right underneath the propeller, indirect aspiration would be when air is drawn from/to the propeller area through a tubing and sensor probe is mounted inside the tubing. OU and UNL have both participated in this investigation. Here we report on both groups' efforts.

At OU, we conducted a series of measurements in a controlled environment to ascertain the best location to mount thermodynamic sensors, with the emphasis being on the temperature measurements. In an effort to characterize ideal locations for sensor placement, a series of experiments were conducted in the homogeneous environment of an indoor chamber with a pedestal-mounted rotary-wing UAS. A suite of thermistors along with a wind probe were mounted inside of a solar shield, which was affixed to a linear actuator arm. The actuator arm was configured such that the sensors within the solar shield would travel underneath the platform into and out of the propeller wash. The actuator arm was displaced horizontally underneath the platform while the motors were throttled to 50 percent, yielding a time series of temperature and wind speed which could be compared to temperatures being collected in the ambient environment. Results indicate that temperatures may be biased on the order of 0.5–1.0°C and vary appreciably without aspiration, sensors placed close to the tips of the rotors may experience biases due to frictional and compressional heating as a result of turbulent fluctuations, and sensors in proximity to motors may experience biases approaching 1°C. From these trials, it has been determined that sensor placement underneath a propeller on an rotary-wing UAS a distance of one quarter the length of the propeller from the tip is most likely to be minimally impacted from influences of turbulence and motor, compressional, and frictional heating while still maintaining adequate airflow. When opting to use rotor wash as a means for sensor aspiration, the user must be cognizant of these potential sources of platform-induced heating when determining sensor location.

The overall goal of the experiment was to find locations on a rotary-wing UAS where temperature readings are most representative of the environment. With this in mind, data collected at multiple locations on the rotary-wing UAS needed to be examined to determine where the sensors experience influence or bias relative to ambient air. To achieve this, the thermistors were placed on a linear actuator arm capable of moving the sensors horizontally directly underneath two of the motor mounts, as depicted in Figure 61. Tempeature probes from the NOAA National Severe Storms Laboratory (NSSL) were used as a reference. The sensor tested on the vehicle were from International Met Systems (iMet). A Thermo Systems Inc. (TSI) hot-wire anemometer was used to gather precise velocity measurements as close as possible to the temperature sensor location.

Temperature and velocity are plotted versus relative time as the sensors moved along the linear actuator arm during the first experiment in Figure 62. To account for the longer response function of the NSSL probes and to make more appropriate comparisons, a moving boxcar average of the iMet temperatures was applied to 10 seconds before each analysis point; wind speeds displayed are the raw output. Furthermore, the hot-wire anemometer had not been calibrated prior to this experiment, and thus values displayed may not be absolute; however, confidence in relative precision is still high.

In figure 62, the background temperature is shown by the NSSL 109 probe (dotted black) and the iMet sensor (solid black). The rotary-wing UAS temperatures are shown by the iMet sensor (solid blue), while the reference temperature of the NSSL 109 is shown in solid red. The figure also shows the air velocity at the rotary-wing UAS sensor location (solid orange), showing clear signs of passing through the rotor wash of the propellers as the linear actuator moves from one side of the rotary-wing UAS to the other. This is indicated

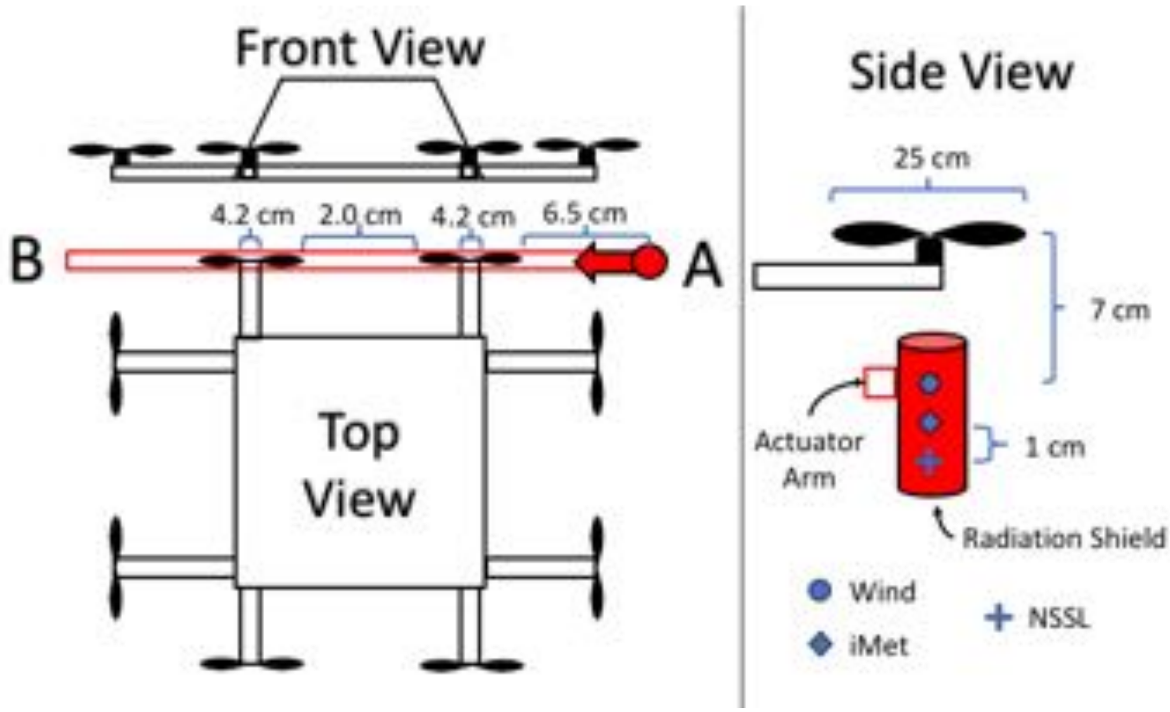

Figure 61: Setup schematic and dimensions of the rotary-wing UAS used in this study (drawing not to scale). In front and top view, the linear actuator arm is represented by the red rectangle outline, and the sensor package as red circle. The arm was displaced from point A to point B, directly underneath the motor mounts and one pair of propellers as seen in the top-down and side views.

by peaks in the velocity as the hot-wire approached 17 m s^{-1} flow rates, before decreasing to near zero directly underneath the motor. A second minimum was encountered between the two propellers, before a similar pattern was observed while the sensors passed under the second propeller. A gradual increase of 0.5°C was observed by both background temperature sensors over the course of the 35 minute experiment, likely attributable to the mechanical mixing of the chamber environment.

This velocity pattern demonstrates that when considering sensor location for adequate airflow, directly under the motors or between the two propellers is not a viable option. While the first conclusion might be obvious, a relative minima in the flow velocity was not expected between the propellers. In addition to the velocity structure, Figure 62 shows that differences do exist between the various sensors, and that a steady increase in temperature on all sensors was measured over the duration of the experiment.

A full description can be found in [?]. Of the locations tested, the optimal position for measuring environmental temperatures while hovering or ascending with a rotary-wing UAS is in a solar shield about 5–10 cm below the propeller and one third the length of the propeller from the tip. This location provides ample aspiration while avoiding the warm air streams from the motor and propeller tips. Other locations above or below the UAS run the risk of encountering stagnation in flow, which can exaggerate the effects of self-heating and generally decouple the sensor from the environment. Furthermore, proximity to external

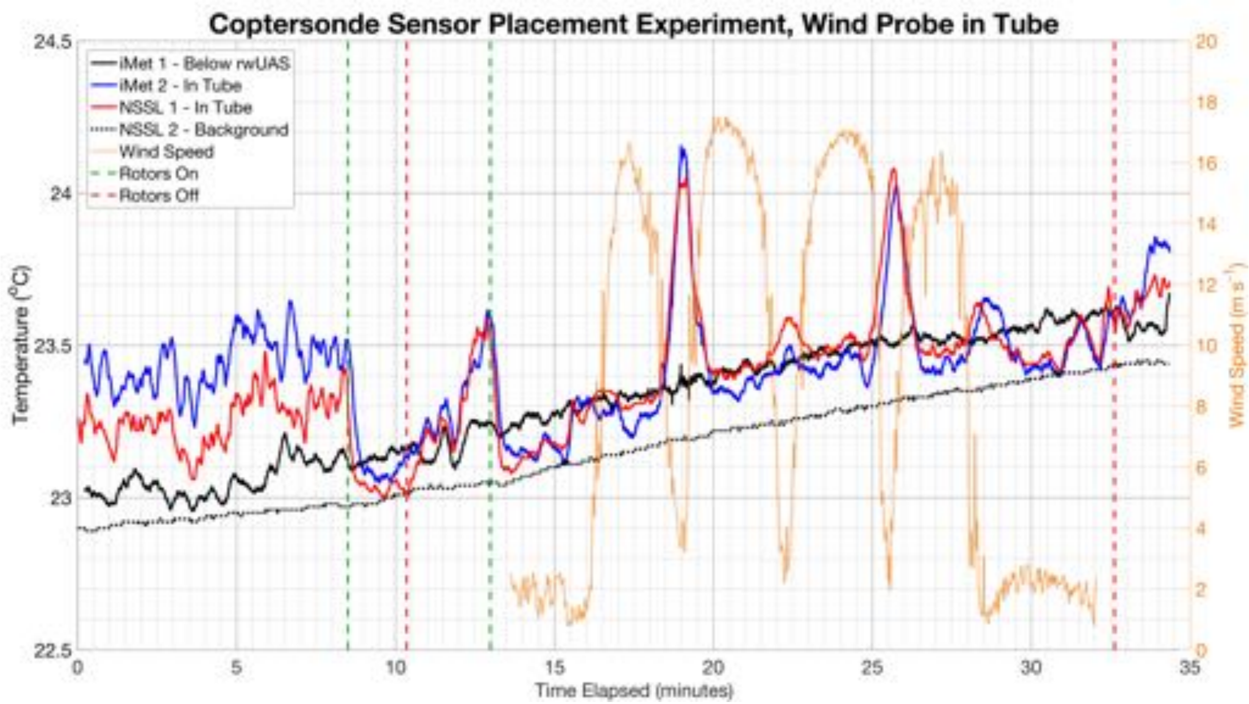

Figure 62: Experiment 1 - temperature and wind speed vs. relative time, entire time series. Temperature response to aspiration noticeable between minutes 8.3–10.3. Compressional heating off tip of propeller at minute 15.5 just as wind speed picks up. Rise in temperature underneath motor mount at minute 19. Small rise in temperature between two propellers at minute 22.3 due to hot wire anemometer in stagnant air. Same pattern reflected for second half due to symmetry of setup.

heat sources such as batteries or the rotary motors are also capable of introducing artificially warmed air streams. By following these general guidelines, it is of the authors' opinions that rotary-wing UAS are capable of obtaining trustworthy atmospheric measurements across a variety of applications.

At UNL, we tested two indirectly aspirated sensor mountings (one indirect down wash, one indirect up wash), and one direct downwash. The first, shown in Figure 63, placed the sensor in a tube to protect the sensor from sun and other environmental factors, while being indirectly aspirated from the downwash of propellers. The second, also placed the sensor in a tube, but was indirectly aspirated by placing the inlet to the tube above the propeller, with the goal of providing a more consistent and laminar flow than the turbulent downwash. The final placement was directly below the propeller without any housing and was directly aspirated. We conducted a number of experiments to characterize the sensors.

Figures 64 - 66 show temperature profiles collected (at STILLWATER, OK (6/29/17)) during three ascent and descent flights where the UAS was at different orientation with respect to atmospheric wind direction. Our finding was that the indirect tubing readings were affected by orientation of the vehicle with respect to the air flow direction. We had to keep the rotors on for a few minutes before each flight to flush the air out of the tubes to get rid of the residual heat inside the tubing. Even after that, the tubes possibly were retaining

Figure 63: UAS with direct and indirect downwash PTH sensors

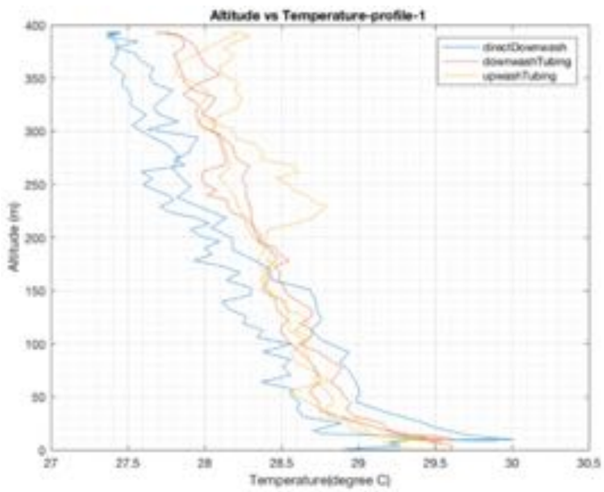

Figure 64: Indirect tubings parallel to the flow (0 degree). Exit air of downwash tube/ inlet air of upwash tube in same direction as atmospheric airflow

heats for a long time, which further affected the readings. Preliminary conclusion was that the indirect tubing mounting was not as effective/responsive as the direct mounting sensor. We are currently refining and testing new configurations based on the findings from these tests.

Workforce Development All the worked described above has been performed by participating graduate and undergraduate students under the supervision of the project PI and co-PIs. The students worked in an interdisciplinary environment involving meteorology, atmospheric science, electrical and computer engineering, aerospace and mechanical engineering, computer science, data science and analytics, and chemistry. This has had a significant impact on the students ability to approach and solve problems and work through real-world tasks.

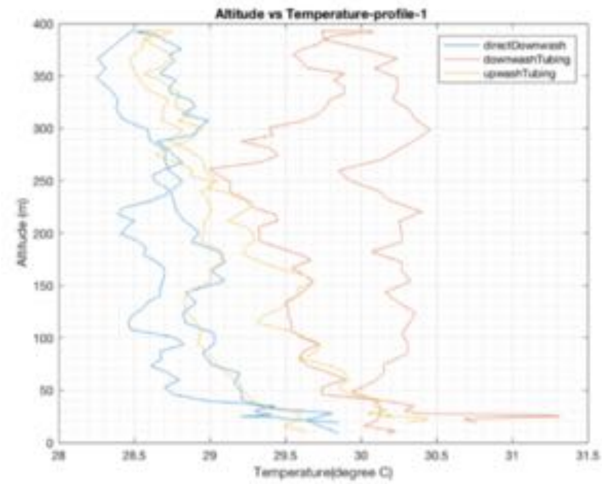

Figure 65: Indirect tubings reverse to the flow (180 degree). Exit air of downwash tube/ inlet air of upwash tube in opposite direction as atmospheric airflow

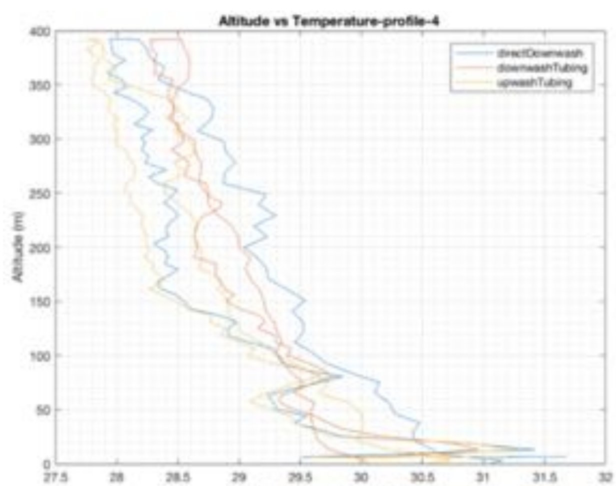

Figure 66: All the tubings are at an angle (270 degree). Exit air of downwash tube/ inlet air of upwash tube is at an angle with atmospheric airflow

3.4 Objective 4

Develop and conduct UAS themed outreach in support of NSF's technology education and workforce development. We will build on current STEM activities in Oklahoma, Nebraska and Kentucky to develop national K-12 activities. This will also include community efforts to obtain a better understanding of public perceptions of UAS applications to assist policy development concerning the potential widespread application of UAS for atmospheric science.

Primary outcomes of this objective include in the wider sense education of the public on the use of UAS and in an academic emphasis to facilitate the broader application of UAS for atmospheric science. This will include seminars for faculty from EPSCoR states who are interested in learning how to integrate UAS into research in the atmospheric sciences. We also wish to facilitate the application of UAS in secondary education pedagogy, specifically working with experts in K-12 education (PLTW) to develop examples of how UAS can be used in the classroom to illustrate basic atmospheric science and engineering principles. For example, atmospheric profiling using UAS can illustrate the dependence of temperature and pressure on height and how this evolves throughout the day; the aircraft itself can be the focus of discussions concerning remote command and control and basic aeronautics; by incorporating simple onboard autopilots, students could use basic computer coding principles to design flight paths.

3.4.1 Task 4-1: Public Perception

Research Accomplishments The specific goals of this task are to: 1) Determine key issues that are likely to arise among the public related to the use of UASs for atmospheric measurement and other applications; and 2) Determine the impact of different forms of RRI and responsivity on public trust. The approach used in this task merges social science methods with technology development to better close the loop between public perception and technology development. This will impact not only the other tasks in this project, but will result in findings that will inform best practices for technology development in a wide range of fields.

We have made significant progress in assessing the public perception of UASs operated in a variety of contexts.

Since last year, our primary activities have included:

1. Writing up and submitting for publication the results of the mixed-method study that was developed and deployed regionally and nationally in 2015 (qualitative results now under consideration at Science Communication, see Walther et al., submitted);

2. Writing up and disseminating results from a longitudinal national survey experiment (conducted in fall of 2014, 2015 and 2016) exploring how the views of various publics are impacted by factors such as the terminology used to describe UASs, who is using the UAS, the purpose of the UAS, and level of UAS autonomy (now published in IEEE Technology & Society Magazine; see PytlikZillig, Duncan, et al., 2018);

3. Analyzing and presenting the results of a nationwide survey experiment specifically focused on comparing the impacts of identified key variables, including rural/non-rural

use of UASs, use for noble versus non-noble purposes, and use by public versus private actors (initial results presented at AMS in PytlikZillig et al., 2018); and

4. Finishing the analyses of the NWS interviews (i.e., with employees from the National Weather Service) concerning the data needs that might be met by the CLOUD-MAP UASs (data is collected, results have been reported at two conferences, see Houston et al., 2017; Walther et al., 2018).

Next, we will discuss each of these efforts in more detail, including describing findings not included in last years report.

Mixed-Method Study As reported last year, our study used a convergent design mixed methods approach where we merged the results of quantitative (survey) and qualitative (focus group) data to provide a more complete understanding of various perspectives on drone technology and how people formed their perspectives.

As a reminder: Stage 1 of the study employed a 30-minute quantitative recruitment survey involving 159 participants recruited through Amazons Mechanical Turk (for a nationwide sample) and via Craigs List ads targeted to oversample persons from the three states involved in the drones development tasks. The survey sample came from 36 different states and was approximately 64% female, with a mean age of 41 (SD=12 years), and 70% reporting white, 7% black/African American, 2% Asian, 2% American or Alaskan native, and 6% Spanish, Hispanic or Latino/a.

Participants in the recruitment survey reported their general attitudes and affects toward drones and support for drones under different specific conditions (scenarios). Specifically, participants were randomly assigned to read about use of UASs for weather research or tornado forecasting followed by another other (non-weather) scenario. Because we were interested in how perceptions of use of UASs for weather purposes compared to perceptions of UASs for other purposes, for the second scenario, participants were randomly assigned to read about use of UASs for infrastructure inspection, prescribed fires, video and movie making, package delivery, agriculture, and water sampling. Specific to each scenario, participants were asked to rate their perceptions of the trustworthiness and untrustworthiness of drone users, drone regulators; and of the technology.

In Stage 2, to gain insight into the survey responses, we next conducted eight 90-minute focus groups with a sub-sample of the 30 of the respondents to the survey. Focus group participants were given a $50 Amazon gift card for their participation. CLOUD-MAP members with expertise in drone development and use of drones for weather research and prediction were present at the focus groups to answer questions that arose and to hear for themselves public reactions and recommendations. We varied the scenarios that we asked participants in the groups to read and respond to in the focus groups as shown in Table 1. All groups discussed a weather-related and non-weather related scenario, with order of discussion counterbalanced. If there was time for discussion of a third scenario, we used the commercial delivery scenario as the 3rd because it appeared to result in the greatest diversity of responses and to have the greatest contrast with the weather scenarios. During the focus groups, we used a semi-structured protocol and specifically asked participants to report their reactions to the scenarios; to discuss their hopes, concerns, and recommendations related to use of UASs in different situations; and to share their thoughts, if any, regarding UAS autonomy in different situations.

Table 6: Scenarios by focus group.

Focus group	Tornado	Weather	Commercial Delivery	Water Sampling	Wildfires	Agriculture	Video Production	Infrastructure inspection
1	1st		2nd					
2		1st			2nd			
3	2nd		3rd			1st		
4		1st					2nd	
5	2nd		3rd	1st				
6		2nd	3rd					1st
7		2nd	1st					
8	1st		3rd				2nd	

We reported some of the key findings from our mixed-method last report. Additional analyses of the qualitative data conducte this year (see Walther et al., submitted) revealed:

- How people make sense of drones: Analysis of focus group transcripts indicated people make sense of drone technology by considering: 1) personal experiences, (2) media representations, (3) comparisons between technologies, and (4) the trustworthiness (or distrustworthiness) of the users, regulators, and the drone technology itself. It did not seem that participants used vastly different sense-making processes to understand weather drones compared to other drones. Participants relayed their interpretations of use through their location or personal knowledge, experiences with various technologies, media portrayals of technology (fictional or news representations), and a balance of trust in different targets.

- Purpose-specific benefits: People seem to see drones as especially useful for information gathering, increasing safety, and increasing services. However, the specific nature of information, safety, and service benefits varies by drone purposes as shown in the table below.

- Cross-purpose concerns: The concerns raised by our participants were found to be more general and less-specific to the particular use of the drone. For example, privacy was a concern across purposes and the qualitative nature of the concern did not change much across those purposes (even though it may have been more of a concern or less of a concern across situations). On the other hand, participants in the focus groups, as they explored the tension between the perceived benefits and concerns, tended to offer alternative perspectives that countered their concernsespecially when discussing drones used for “noble” purposes (e.g., for weather forecasting or prescribed fires or agricultural purposes).

Table 7: Examples of purpose-specific benefits in the identified major categories.

	Information gathering	Safety	Service efficiency, access, quality
Weather	Real time information relating to wind, temperature, between ground level and satellite level	Storm chasers could be further away from danger. Notify public sooner of impending storms	Decreased need to drive to the storms, respond to storms more quickly
Fire	Observe where the fire is, which way fire is going, where the hotspots are, at the same time as getting wind speed, weather information	Keep fire fighters out of way of danger Notify public of danger sooner thereby saving lives	Aerial views without needing manned helicopters
Agriculture	Watch herds, observe fields and crops	**	Fewer personnel required if drones are used
Water sampling	Sample water sources for pollution	Identify potentially harmful water quality	Access remote and hard-to-access water sources
Infrastructure	Observe bridges, aerial views of roads	Identify dangerous infrastructure Personnel safer if sending drone to observe	Less personnel required
Delivery	Multi-purpose drones could gather weather information during deliveries	Deliver to unsafe neighborhoods Keep delivery drivers off the road	Potentially quicker deliveries
Videos/Movies	**	**	More attractive, cheaper, video captured

***No exemplars available.*

Longitudinal National Survey Experiment As noted in our prior report, we began a longitudinal national survey experiment just prior to receiving this award and, given the relevance of that data to project goals, conducted additional analyses and extended the project by collecting an additional wave of data from two separate samples in 2016. Specifically, in 2016 we extended the longitudinal survey by (a) administering it again at a larger scale (two samples instead of one, ns = approximately 2000 each), (b) including a nationally representative sample in addition to the Mturk sample for comparison of findings across samples, and (c) including assessments of perceptions of trustworthiness/ distrustworthiness of a larger set of targets (users, regulators, and the UAVs themselves).

Findings from analyses of these data and of the main effects of varied factors have been presented at conferences (PytlikZillig et al., 2016; PytlikZillig et al., 2017) and most recently in IEEE Technology & Society Magazine (PytlikZillig et al., 2018). This year we have focused on analyses and publication of the results, but did not obtain another wave of data. Some of the additional findings from these data (not included in last years report) include:

- Results indicating how the nationally representative (NR) sample differed from our prior MTurk samples. For example,
  - NR sample was significantly older and varied in age, as well as more racially/ethnically diverse, more conservative leaning, and had more pilots in the sample.

  - NR sample was less likely to say they had heard of the technologies and expressed both more trusting and distrusting attitudes toward UASs thanthe MTurk respondents.
  - NR sample was less trusting and more distrusting of regulators than MTurk respondents
  - NR sample also indicated greater subjective knowledge, but less objective knowledge than MTurk respondents

- Despite the above differences, a number of results were common for both the MTurk and NR samples in 2016. Such results included:
  - The term drone(s) was most familiar and associated with the shortest time horizons for usage across purposes.
  - Terminology was not associated with different levels of support or trust in users of the technologies.
  - There was a trend for more trust in companies using the technologies than for the government
  - There was the most support for use of drones for environmental purposes
  - Autonomy of the technologies did not have much effect on support and trust factors.
  - Prevention framing tended to relate to more support than promotion framing, although not always significantly so.

Over the next year we will continue to analyze the data and disseminate the results.

Nationwide survey experiment Having identified some potentially key issues as a result of activites 1 and 2, we sought to conduct a more controlled experimental study of those factors in a nationally representative sample. Our goals in this study were to better understand and quantify the individual and combined effects of three key factors while holding other factors constant. From the focus groups (see activity 1), it appeared that use of UAVs (1) in rural versus non-rural places, (2) for noble of non-noble causes, and (3) by different actors, played important roles in peoples opinions and support for UAV use.

Our end goal is to determine if there adjustments to technology design that might off-set observed effects (e.g., eliminate decreased support for non-noble purposes). As a preliminary step toward that goal, we created a survey experiment to quantify the effects of these three factors. We piloted (n=300, Nov 2016) and administered the survey experiment to a nationally representative sample (n = 2100, Feb 2017). Analyses of the data revealed a number of interesting results, many of which we reported at AMS 2018.

For example, people rated concerns for privacy and safety as the greatest of their concerns, but drones used for weather purposes resulted in lower ratings of the relevance of privacy concerns. People also rated concern about the drones being a nuisance lower when weather drones were the topic than when movie or delivery drones were the topical focus, as shown below

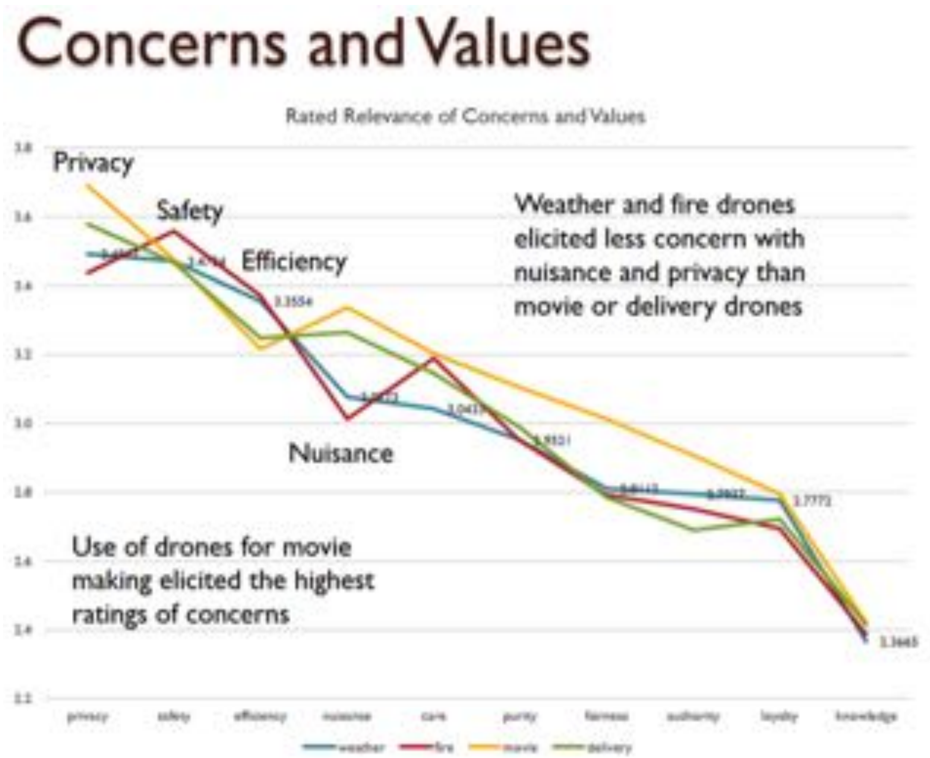

Figure 67: Concerns and values.

It was interesting, however, that people were more concerned with weather drones being a nuisance when used in rural areas than if depicted as being used in urban areas, as shown below.

In addition, weather drones were highly supported by respondents compared to drones used for movie and delivery purposes, and especially highly supported when used in rural areas. Overall, people supported rural use of drones more than urban use, as shown below.

We also looked at the relative importance of trustworthiness judgements for predicting public support and, across all drone purposes, found that trust in the drones (the technology) accounted for more variance in support for drone use than did trust in regulators or users, as shown below.

Finally, we also found that trust in the technology could compensate for low trust in drone users. That is, if people viewed drones as trustworthy, viewing the users as distrustworthy did not have much of any negative effect on their support for drone use, as shown below

Our next steps are to publish the findings in a peer reviewed publication and to conduct another experiment to examine how and if UAV design features and regulations might moderate the impact of the known effects.

Nationwide survey experiment In last year's report we noted that we were seeking the views of a unique group of stakeholders (National Weather Service employees) to obtain their views of weather drones and to better understand their data and data presen-

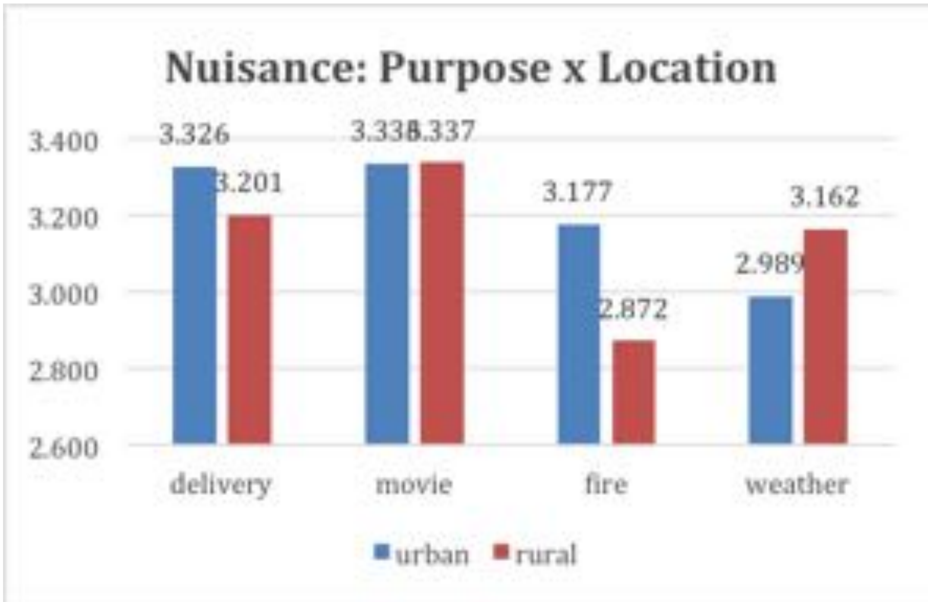

Figure 68: Nuisance survey results.

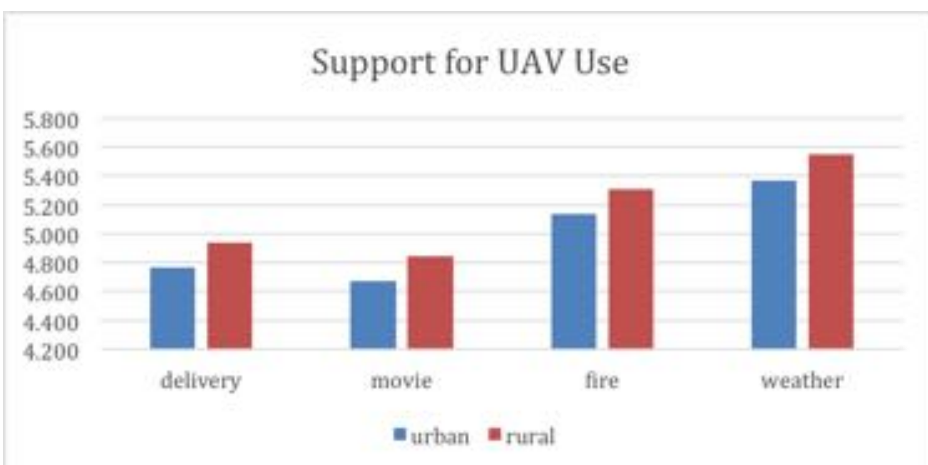

Figure 69: Support for UAV use.

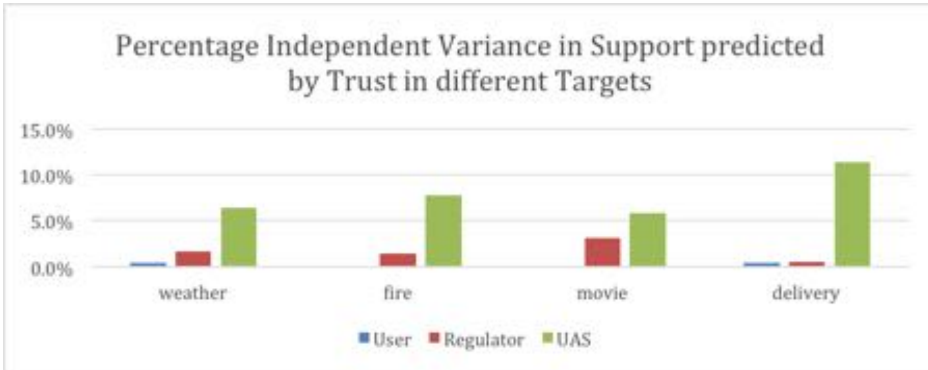

Figure 70: Trust predictions.

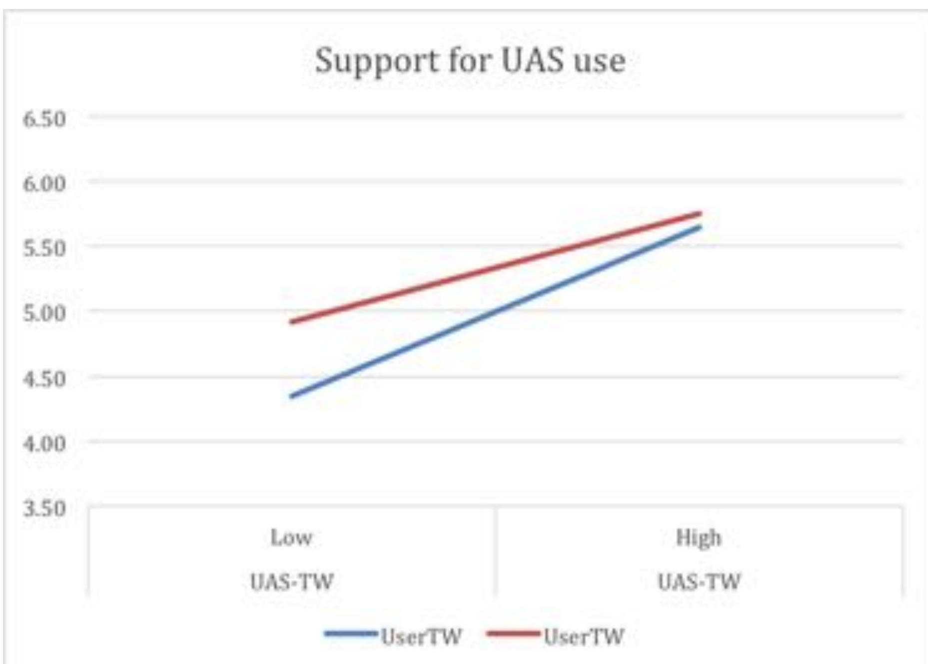

Figure 71: Trust predictions.

tation needs, with the goal of responsively developing UAVs that might meet those needs. Participants completing the pre-survey included NWS employees from the Central NWS region (12) and the Southern NWS region (2). A total of 10 participants also took part in the focus groups or interviews. The key findings from this study are:

- Address gaps in forecasting and meteorology (between 5,000 12,000 feet). Weather scientists were optimistic that drone technology could assist in filling current data gaps, such as the gap between ground and radar measurement. Data for a variety of forecasts is needed, for not only severe storms and tornado formation, but also for drought, winter precipitation (type and amount), ice jam inspection, and flood (e.g., river height assessment). Participants noted that
- Use visuals collected via drone to enhance forecasting and share with audiences. While public respondents did not want a camera, weather scientists indicated that cameras on drones would be helpful to validate forecasts, provide visual inspection of damage, and aid in sharing forecasts with the public.
- Collaborate via drones during severe weather events (e.g., damage assessments, plume movement, evacuation monitoring). NWS participants suggested sharing data and collaborating information via drone technology with others, such as emergency managers, research organizations, and governmental entities. NWS participants did not want to fly or navigate the drones themselves but were interested in receiving data informed by drone technology.

The findings are being developed into a formal report for public dissemination.

Workforce Development This task has involved workforce developments at a number of levels. First, the team on this task involves an Assistant Professor (Dr. Detweiler), a Research Associate Professor (Dr. PytlikZillig), and an Associate Professor (Dr. Houston). They have all been actively involved in the development and deployment of the studies, which has also led to a number of mentoring opportunities.

Second, this year, two students were involved in this work. Janell Walther is a PhD student pursuing a degree in communication and has been working closely with Dr. PytlikZillig and the rest of the team in conducting and analyzing the focus groups and interviews. Jake Kawamoto (undergraduate in political science) also continued to work on the project in 2017 and to gain experience conducting research and analyzing and presenting social science qualitative and quantitative data as a result of this project.

As mentioned earlier (see reference list), this work also has been disseminated in talks both locally and nationally each year of the project, providing presentation and communication training opportunities for students.

Leveraged Opportunities and Activities As mentioned above, this task has leveraged a prior longitudinal survey of attitudes toward UAVs. It also has leveraged many of the other tasks to define atmospheric science scenarios, such as convection initiation (Task 2-1), and also potential technological advances, such as the ability to use swarms (Task 3-1). These

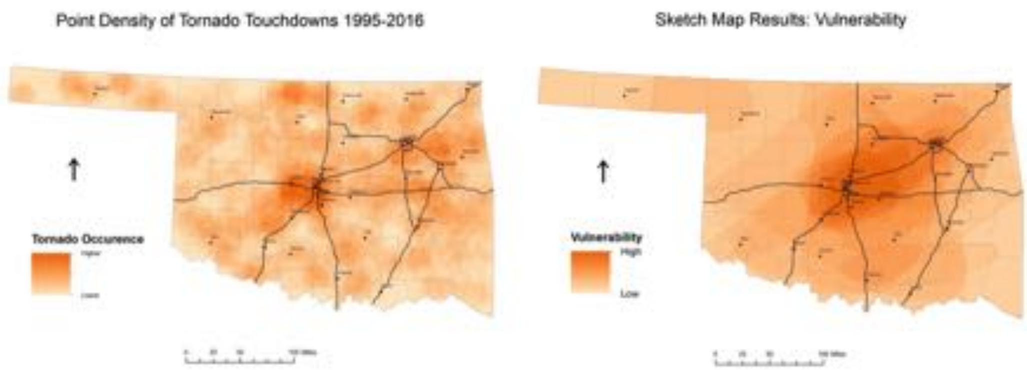

Figure 72: Real (left) and perceived (right) tornado risk in Oklahoma. Point density of tornado touchdowns produced through kernel density mapping. Sketch maps compiled from user input.

scenarios are used as part of the surveys and focus groups to assess public perception on different types of applications and technologies. This task will likely have a significant impact on all other tasks as the results will help inform how the technology should be developed and deployed to alleviate concerns by the public and policy makers.

3.4.2 Task 4-3: Rapid Dissemination of Risk Information

Research Accomplishments Progress on these technical goals of this task included a pilot study to map the spatial variation of tornado risk perceptions throughout the state of Oklahoma. To capture participants perceptions of tornadoes in Oklahoma a qualitative data collection technique known as sketch mapping was used. Sketch mapping allows participants to create visual representations of how they perceive a threat (i.e., tornadoes) in geographic space. The measurements are not precise, but they do allow for qualitative analysis of geographic phenomena (real or perceived). Spatial locations of documented tornado touchdowns occurring between 1995 and 2016 were mapped and compared to the digitized sketch maps created by participants (Figure below). Respondents noted several perceived vulnerable areas including the Oklahoma City metro area and the I-44 corridor to Tulsa, which correspond to higher tornado densities, but there are more true hotspots than respondents perceived. We also found that participants born outside of Oklahoma were more concerned about property damage than native Oklahomans, but indicated they were less likely to seek shelter during a storm. We received Institutional Review Board (IRB) approval for this study through OSU and intend to expand the number of participants in a full scale study scheduled for Fall 2018.

Workforce Development Trainee activities are ongoing and include training in geospatial and geovisualization techniques for one PhD student in the Department of Geography at Oklahoma State University. Additionally, that student is being trained in mixed methodological techniques, human subjects research, manuscript preparation, and professional development (e.g., conference presentations).

Leveraged Opportunities and Activities Collaborations related to this task have been leveraged for the following grant proposals:

- OAR NOAA VORTEX-SE Terrain Impact and Evaluation on the Atmospheric Boundary Layer and Convective Events with UAS (P.I. Jamey Jacob OSU)

Part III
Supporting Information

4 Products

4.1 Product Summary

A product summary as reported by the Data Outcomes Portal is shown in Table 8. Due to the nature of the reporting process and system, this is not necessarily up-to-date nor comprehensive, but does provide an accurate representation of activities and efforts undertaken by the CLOUD-MAP team. A full list of publications is provided in the following section, but proposals details are only provided on the DOP site.

Table 8: Product summary as reported by Data Outcomes Portal

All Proposals	
Total Submitted:	69
Total $ Submitted:	$81,140,797
Total Funded:	28
Total $ Funded:	$9,216,678
Funding Rate:	41%
NSF Proposals	
Total Submitted:	25
Total $ Submitted:	$34,411,175
Total Funded:	8
Total $ Funded:	$3,068,054
Funding Rate:	32%
Publications	
Total Journal Articles - Print:	18
Total Journal Articles - Electronic Only:	1
Total Conference Proceedings:	40
Total Book Chapters:	1
Total Books:	2

4.2 Products

An alphabetized comprehensive list of publications and presentations is provided below.

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Avery, A. and Jacob, J. Optimal Search Patterns for Low Altitude Icing Conditions with Unmanned Aircraft, AIAA 2017-1375, AIAA Information Systems-AIAA Infotech at Aerospace, 2017.

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Chilson, P., Jacob, J., Smith, S. and Houston, A., CLOUD-MAP: Advancing Meteorology and Atmospheric Physics through Unmanned Aerial Systems, American institute of Aeronautic and Astronautics Convention, Washington, D.C., June 2016.

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