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Considerations for Atmospheric Measurements with Small Unmanned Aircraft Systems

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Abstract: This paper discusses results of the CLOUD-MAP (Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics) project dedicated to developing, fielding, and evaluating integrated small unmanned aircraft systems (sUAS) for enhanced atmospheric physics measurements. The project 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 are being used to validate sensor performance while integrated into various sUAS platforms. This paper focuses on aspects related to atmospheric sampling of thermodynamic parameters with sUAS, specifically sensor integration and calibration/validation, particularly as it relates to boundary layer profiling. Validation of sensor output is performed by comparing measurements with known values, including instrumented towers, radiosondes, and other validated sUAS platforms. Experiments to determine the impact of sensor location and vehicle operation have been performed, with sensor aspiration a major factor. Measurements are robust provided that instrument packages are properly mounted in locations that provide adequate air flow and proper solar shielding.

Keywords: atmospheric boundary layer; unmanned aircraft; meteorological observation

1. Introduction

The availability of high-quality atmospheric measurements over extended spatial and temporal domains provides unquestionable value to meteorological studies. In recent reports from the National Research Council and instrumentation workshops it was stated that observing systems capable of providing detailed profiles of temperature, moisture, and winds within the atmospheric boundary layer (ABL) are needed to monitor the lower atmosphere and help determine the potential for severe weather development [1,2]. Despite the need for such data, these measurements are not necessarily easy to acquire, especially in the ABL. Remote sensing instruments on satellites or in situ probes carried by balloons or manned aircraft are typically relied upon to meet this need. Figure 1 shows an altitude-time depiction of daily ABL evolution (after [3,4]), with the addition of twice-a-day weather balloons to 30.5 km and Mesonet towers at 10 m. An alternative to these approaches is the acquisition of atmospheric data through the use of highly capable unmanned aircraft systems (UAS), such as multirotor vertical profiles to low or high altitudes in the ABL, and longer-flight fixed-wing UAS flights following various trajectories. In addition to providing better understanding of physical processes, these systems can provide better initialization data for numerical weather prediction (NWP) models, reducing the level of uncertainty and need for ensemble simulations [5,6]. However while promising, these technologies need to be developed, matured, and validated [7].

A multidisciplinary team of researchers at four universities, Oklahoma State University (OSU), the University of Oklahoma (OU), the University of Nebraska-Lincoln (UNL), and the University of Kentucky (UK), were among those who recognized the emerging opportunity of deploying sUAS for atmospheric boundary layer studies, along with the potential benefit of understanding severe storm formation among other compelling problems in atmospheric science. Operating under the project name of CLOUD-MAP (Collaboration Leading Operational UAS Development for Meteorology and Atmospheric Physics), this team of researchers consists of atmospheric scientists, meteorologists, engineers, computer scientists, geographers, and chemists, capable of developing the advanced sensing and imaging, robust autonomous navigation, enhanced data communication, and data management capabilities required to develop and demonstrate the potential role of sUAS in atmospheric research.

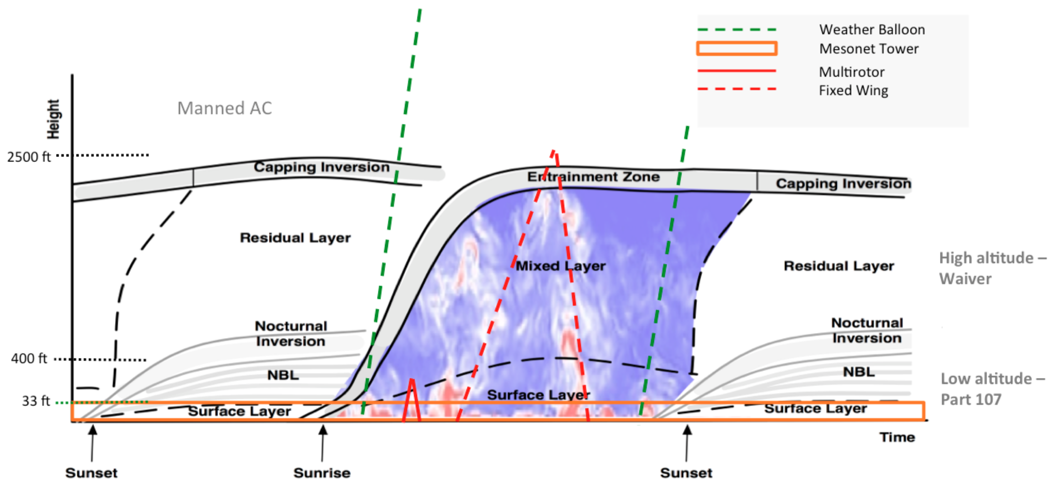

Figure 1. Time-height depiction of structure of the atmospheric boundary layer over one diurnal cycle. Corresponding traces of various in situ sensor platforms are also shown, along with notations of typical FAA operations authorizations.

CLOUD-MAP Multidisciplinary Collaborative Research

The primary technical goal is to develop highly reliable and robust platforms that can routinely perform regular atmospheric measurements in a variety of weather conditions, including day or night operation and during hazardous weather. Waivers or Certificates of Authorization (COAs) are necessary for these operations as required by the FAA; all operations discussed in this study were conducted in accordance with current FAA regulations. In particular, observations and data collection will focus on the atmospheric boundary layer. The importance of accurate data in this region is well understood (e.g., [8]). Due to the complex interactions with terrain and sources of energy, the ABL region is a major factor in the development of many meteorological phenomena, not the least of which include phenomena such as convection initiation and tornado-genesis. The project leverages key expertise across the institutions, including unmanned aircraft systems, atmospheric measurement, robotics and autonomous control, and weather analysis and modeling. Each of these areas is critical for the research to succeed. Basic questions being addressed include: How can local data acquired by sUAS be used to better understand larger weather phenomena? Can sUAS be used to measure large-scale patterns and trends found in the atmosphere? What advancements in operational requirements are necessary to provide routine capabilities and confidence to use sUAS as a meteorological diagnostic tool? How are these measurements best integrated into current and future forecasting models? The interdisciplinary and inter-institutional team was assembled based on these questions and project goals.

The nature of this research challenge necessitated integration across disciplines, so it was also necessary to understand and incorporate approaches for successful cross-disciplinary collaborative research, referred to as team science, to increase the team's capacity to achieve its objectives [9]. With more than 10 researchers working together, the CLOUD-MAP team is considered to be a "larger group" [10] so a framework for collaboration was established including annual team flight campaigns and an intentional research task structure comprised of 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 will be evaluated.

Table 2 summarizes the envisioned four-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 Harden's experiential educational model that presents growth of interdisciplinary mastery through the combination of information with experience, and culminating with the following: understanding complimentary ideas, multidisciplinary decision-making, recognizing interdisciplinary commonalities, and ultimately creating trans-disciplinary meaning [11]. Collaboration can also be measured by co-authored archival publications.

Table 1. Summary of Annual CLOUD-MAP Goals and Results.

CLOUD-MAP	Year 1 2015–2016	Year 2 2016–2017	Year 3 2017–2018	Year 4 2019–2019
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 Development	Complimentary	Multidisciplinary	Interdisciplinary	Transdisciplinary
	Flights: 241 Flight hours: 25	Flights: >500 Flight hours: >70		
Collaboration Publications	Multidisciplinary conference: 5	Multidisciplinary conference: 6	Multi-university conference: 1	
	Multi-university conference: 2	Multi-university conference: 2	Multidisciplinary, multi-university journal: 3	

Members of the CLOUD-MAP team had prior experience designing, building, and flight-testing sUAS platforms, as well as in the development of sensors, algorithms, and communication systems. These were matured and integrated into more complex systems and swarms. Different sensor suites and multiple platform types including custom built and commercial off-the-shelf models of both rotary-wing aircraft and fixed-wing platforms are seen in Figure 2, which depicts several of the sUAS platforms. Details can be found on the CLOUD-MAP web-site (www.cloud-map.org). These systems are equipped with high-precision and fast-response atmospheric sensors to focus on the observation of boundary layer thermodynamic (viz., pressure, temperature, and humidity (PTH)) and kinematic (viz., wind speed, direction, and turbulence levels) parameters necessary for models. How to best utilize data to determine atmospheric stability indices and the likelihood for development of severe weather then becomes the next question. Atmospheric sensors adapted for use on sUAS rotary-wing platforms that fly vertical profiling trajectories are often different than those used on fixed-wing aircraft. Both are compared as to their suitability for carrying a variety of sensors for the study of ABL properties. Because various properties of the atmosphere are being sensed, the UAS aircraft, its movements, out-gassing, thermal profile, rotor down wash, wake, and other properties have the potential to affect sensor data. This study has objectives to determine the proper aircraft, sensor position, and sensor suite to use in further research with the ultimate goal of being able to use a heterogeneous system of autonomous vehicles to map critical features of the ABL through both space and time, allowing for a better understanding of this critical set of related atmospheric phenomena.

Figure 2. Representative systems developed as part of the CLOUD-MAP project.

Four specific objectives are being addressed in CLOUD-MAP related to program governance, atmospheric measurement and sensing, unmanned systems development and operations, and public policy. In particular, they are listed as (1) Develop a strong mentoring program and intellectual center of gravity in the area of UAS for weather, and develop joint efforts for future funding; (2) Create and demonstrate UAS capabilities needed to support UAS operating in conditions that may be present in atmospheric sensing , including the sensing, planning, asset management, learning, control and communications technologies; (3) Develop and demonstrate coordinated control and collaboration between autonomous air vehicles; and (4) Conduct UAS-themed outreach in support of NSF's technology education and workforce development. These objectives have been developed to flow from one to another and are further broken down into targeted tasks. For the most part, each targeted task is led by a researcher, who is responsible for successfully organizing and implementing the research. An executive committee consisting of the lead investigator from each institution is facilitating collaborations within and between institutional researchers. However, some tasks are overarching and extend across all aspects of the CLOUD-MAP effort. This includes the issues discussed herein.

This paper focuses on aspects related to atmospheric sampling of thermodynamic parameters with sUAS, boundary layer profiling, specifically sensor integration and calibration/validation.

2. CLOUD-MAP Flight Campaign

2.1. 2016 and 2017 CLOUD-MAP Flight Campaign Overview

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 are shown in Figures 2 and 3, respectively. In some cases, custom vehicle solutions, such as OU's CopterSonde and OSU's MARIA, proved the best option [12]. 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 emerging in situ and proximal sensing technologies for soil moisture monitoring [13]. 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 [14]. 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 4. Mesonet measurements are available in general with an update time of 5 min [15,16].

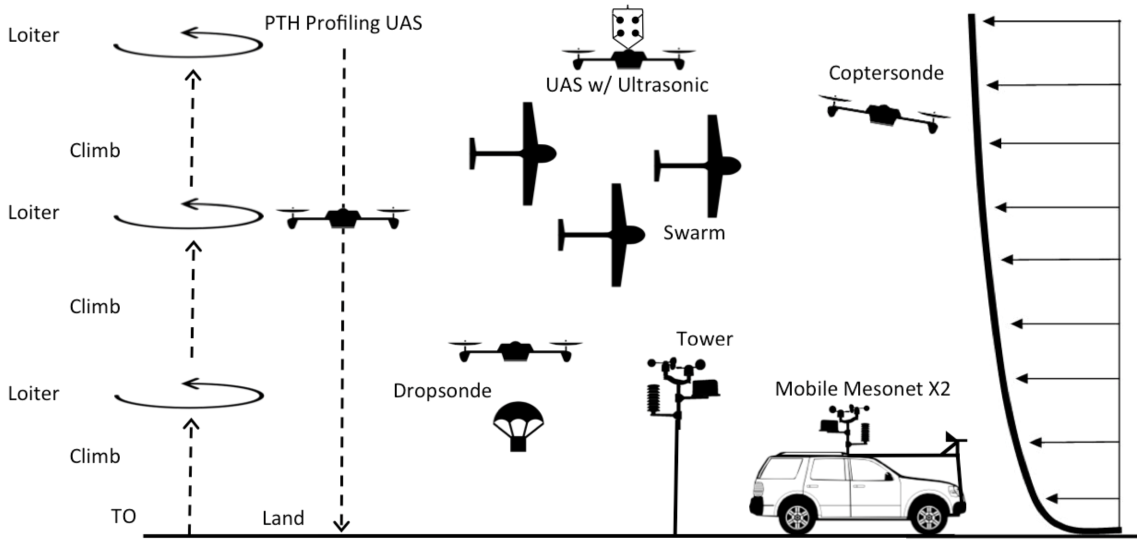

Figure 3. Mission concepts of operations conducted as part of the joint field campaign.

Figure 4. CLOUD-MAP Year 1 flight campaign operations.

The 2016 campaign group photo includes 58 participants (see Figure 5a). 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.

(**a**)

(**b**)

Figure 5. CLOUD-MAP CLOUD-MAP flight campaign team participants and vehicles in (**a**) 2016 and (**b**) 2017.

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 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 5b.

Data evaluation, reduction and ABL characterization analyses are conducted by the various sub-task contributors (See Figure 6). 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 [17].

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 6. 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 [18]. 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 [19].

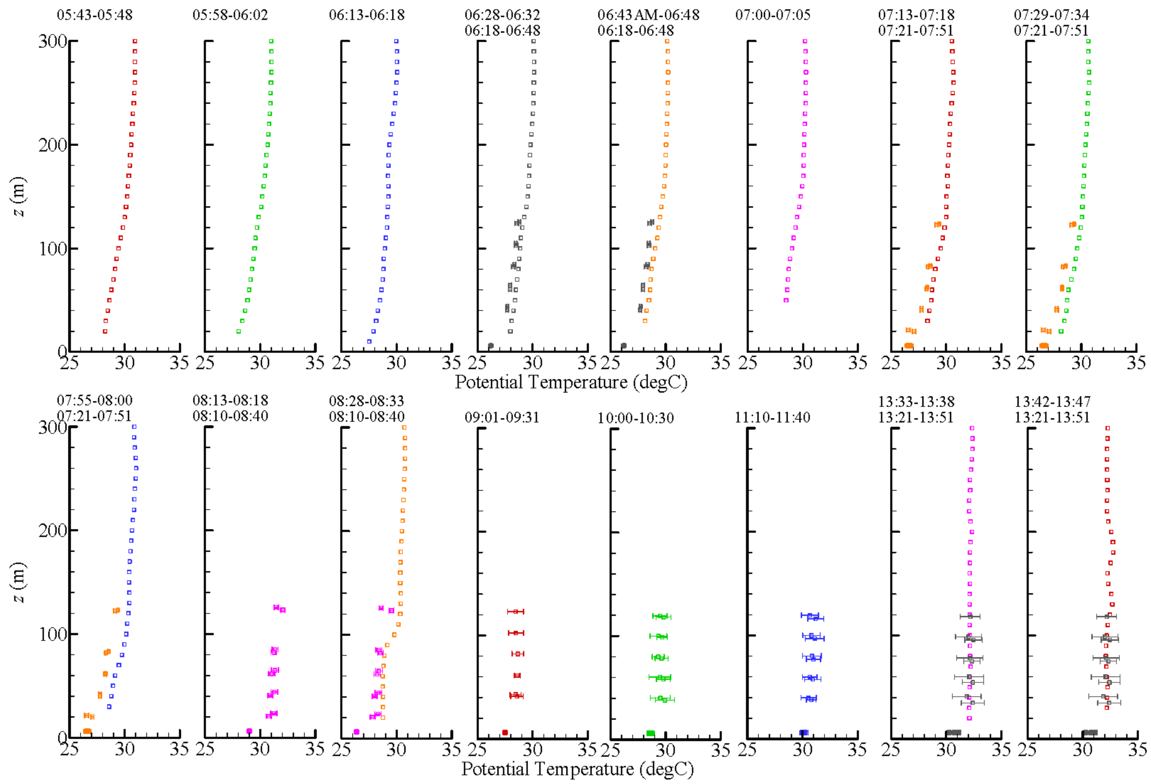

Figure 6. Comparison of potential temperature profiles measured by rotorcraft and fixed wing aircraft up to 300 m and 133 m, respectively. Times listed on top of each figure indicate flight time for rotorcraft, times below that indicate flight time of fixed wing aircraft. Points indicate measurement 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. [18].

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 consider adopting sUAS into their operations [20], 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 [21]. 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.

3. Sensor Integration, Calibration, and Validation

3.1. Determining Required 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 CLOUD-MAP field campaigns 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.

The importance of sensor response for characterizing the ABL is considered by addressing the question, "what sensor response is required to represent key meteorological phenomena germane to the accurate prediction of important atmospheric phenomena, such as convection initiation (CI)"? Large-eddy simulations (LES) of a convective boundary layer and airmass boundary (Figure 7) were developed using Cloud Model 1 (CM1) for the simulation of sUAS data collection [22]. CM1 is a three-dimensional, non-hydrostatic, non-linear, time-dependent numerical model designed for idealized studies of atmospheric phenomena and can be used to generate simulated data useful in UAS sensor evaluation [23,24]. 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 and resulting horizontal and vertical inhomogeneities. This allows experimenters to evaluate the surface inhomogeneity effects and resulting advection, as was done in the BLLAST experiments, for example [25]. The experiment parameter space also includes air speed (ascent/descent rates) for fixed-wing and rotary-wing aircraft since the large gradients that characterize these phenomena might be better represented at lower air speed (ascent/descent rates). However, when instantaneous representation of a rapidly evolving phenomenon is required, slower air speeds may ultimately degrade the accuracy of in situ observations.

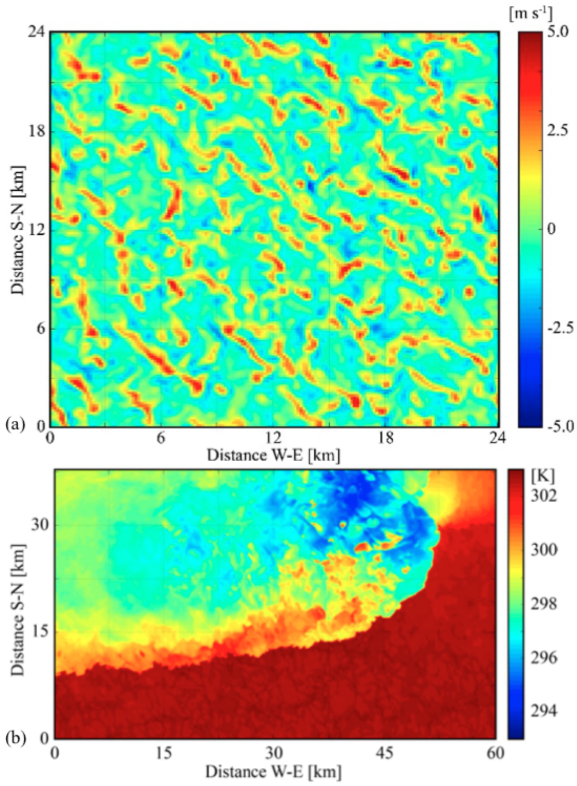

Figure 7. LES solution of a convective boundary layer (**a**) and airmass boundary (**b**).

Once data are available from UAS deployments, these data will be assimilated into NWP models along with all other available weather data to determine the extent of improvement to the model forecasts and the longevity of the impact with a focus on high impact weather events depending on the season and location. These types of modeling studies are known as Observing Simulation Experiments (OSEs). Likewise, Observational System Simulation Experiments (OSSEs) are used to assess the impacts of possible measurements on NWP forecasts before the measurements are available [26]. Using OSSEs, forecasters will be able to investigate the optimal observational requirements and impact for a UAS deployment. The design could include such parameters as number and spatial distribution of weather UAS observations, cadence of the measurements, maximum height of operations, and vertical sampling resolution, for example. Additionally, knowledge of the spatial scales over which a given phenomenon is correlated can provide insight into coherent structures within the flow, which in turn can provide insight into how we can most efficiently sample the environment. However, the forces influencing the spatial variation of a particular atmospheric property combined with the non-linearity of the governing equations coupled with the sensor response give erroneous results. Variogram analysis has shown to provide insight into the distance over which spatial autocorrelation dissipates and coherence vanishes, providing a measure of the optimal spatial separation between measurements and observations of horizontal inhomogeneities. Results suggest that the multiple scale domains present in the ABL can be resolved using sUAS [19].

3.2. Observed Sensor Response

ABL measurements and convection initiation (CI) forecasts depend on accurate characterization of the thermodynamics and wind fields within the ABL. NWP model insight on ABL 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-ABL capping inversions, must be faithfully represented. As such, UAS-mounted instruments need sufficiently fast sensor responses, as shown in Table 2 [21].

Table 2. Desired meteorological sensor specifications for meteorological observations.

Meteorological Variables and Accuracies		**Sensor Response Time**	
Temperature	±0.2 °C	Time	<5 s (Preferably < 1 s)
Relative Humidity	±5.0%	**Operational Environmental Conditions**	
Pressure	±1.0 hPa	Temperature	−30–40 °C
Wind Speed	±0.5 m/s	Relative Humidity	0–100%
Wind Direction	±5 Degrees Azimuth	Wind Speed	0–45 m/s

One example of the impact of platform motion on measurement accuracy was exposed through CLOUD-MAP cal-val activities, and is shown in Figure 8 where an early-morning boundary layer profile is captured using a COTS sensor (iMet XQ) mounted on a 3DR Solo multi-rotor sUAS [27]. Note the variations in the observations are primarily due to sensor aspiration issues since the aspiration changes upon ascent and descent and the sensor response time is not fast enough to pick up the changing values in temperature and humidity. This illustrates issues related to not only sensor integration and calibration but of operational deployment as well as calibration not only of the sensors themselves but of the fully integrated sUAS as well. These results have informed changes to sensor placement that were inspirations for the cal-val activities discussed below [28].

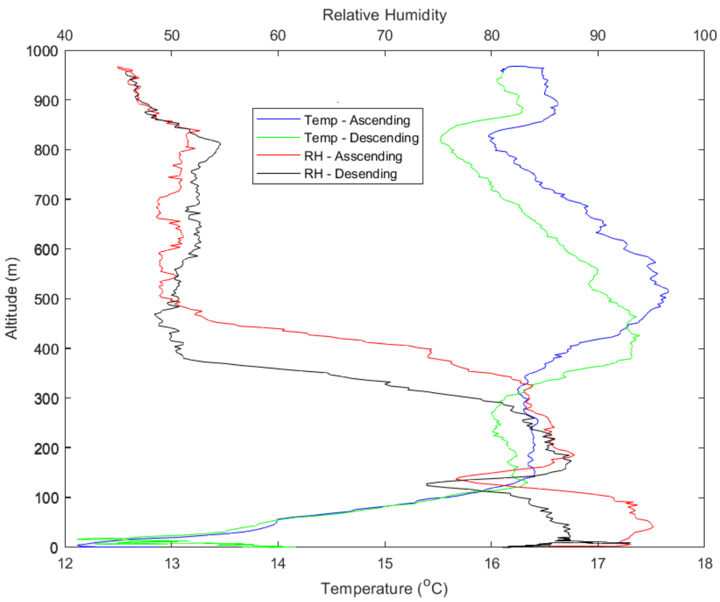

Figure 8. Sample profile to 1000 m showing impact of sensor placement and vehicle ascent/descent rate on observation confidence at the Marena mesonet on the morning of 18 April 2017.

As part of our efforts to establish guidance for the system capabilities required to maximize the impact of UAS on modeling efforts, we developed a simple experiment for execution during the summer 2017 CLOUD-MAP field deployment in Oklahoma. Specific aims of this experiment include (i) evaluation of the sensor response characteristics of a broad suite of temperature and humidity sensors; and (ii) evaluation of the robustness of several aspirating strategies on rotary-wing aircraft. The experiments were conducted in the OSU Unmanned Systems Research Institute high bay in Stillwater, OK. Pseudo-step-function changes in temperature and moisture were created by moving instruments (both on and off parent platforms) from inside the climate-controlled bay to the ambient environment outside. A similar experiment design has been adopted in the past but this is the first time that UAS-borne instruments were to be tested in this manner.

Two sets of tests were conducted. The first set of tests (toward aim (i) listed above) involve the placement of many sensors on a single cart that will be moved across the temperature/humidity change. This test will enable valuable benchmark intercomparisons of all instruments involved. The second set of tests involve full flight tests of rotary-wing sUAS across the step-change.

A 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 micro-scale 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 on the order of 1 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.

Additional flights executed during CLOUD-MAP cal-val activities aimed to test the impact of platform orientation on measurement accuracy. These experiments involved a temperature/RH sensor housing mounted above the rotor of a University of Nebraska multi-rotor sUAS (shown in Figures 2). Sensors within the housing are aspirated via flow generated by the pressure difference induced between the inlet and exhaust of the housing. Vertical profiles across a well-mixed boundary layer manifested a difference between observations from the sensor within the housing (upwash sensor) and a sensor mounted within the downwash and outside of a housing (direct downwash). This difference depended on whether the housing inlet was pointed downwind (Figure 9a) or upwind (Figure 9b). Differences for the downwind-pointing inlet are consistent with insufficient aspiration of the upwash sensor (within the housing): temperatures at the top of ascending profiles are too warm and at the bottom of descending profiles are too cold (Figure 9a)). In contrast, the upwind-directed inlet produced no apparent aspiration issues, though the direct downwash sensor appeared to experience some solar exposure (Figure 9b).

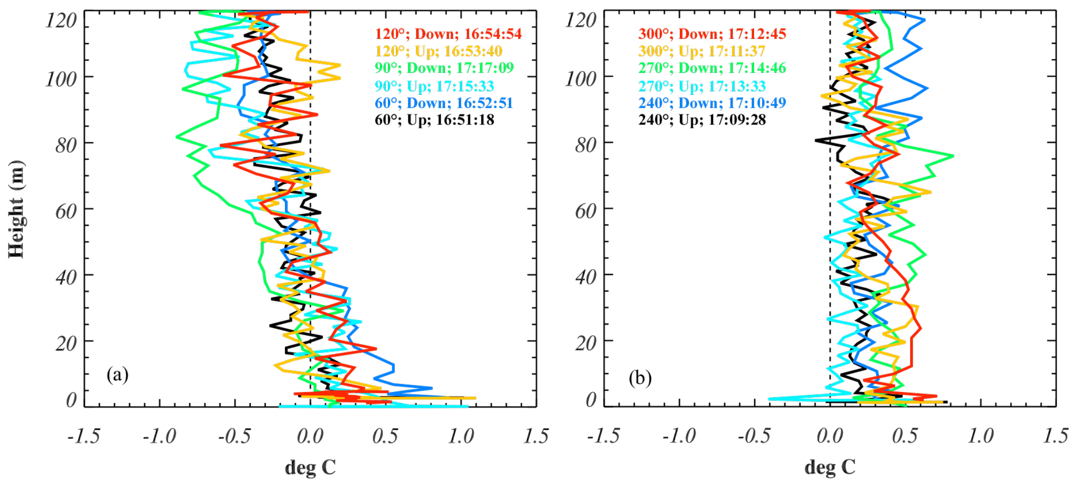

Figure 9. Difference between the test cases with (**a**) downwind and (**b**) upwind inlet orientations.

To afford more control of the environmental conditions that could expose errors resulting from sensor response issues, CLOUD-MAP cal-val exercises also included the operation of sUAS systems across a thermodynamic "shock" with known quantities on either side (Figure 10). In these experiments, the shock was created by opening the overhead door of one of Oklahoma State University's air conditioned high bays in the middle of a summer day. The resulting shock was characterized by a sudden change in temperature and moisture content over a small distance of less than 1 m, which translated to less than 1 s of sensor measurement time. 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 enabled evaluation of the impact of sensor siting and platform motion/attitude as well. The experiments were modeled off of those used previously to evaluate sensor response characteristics associated with the u-tube sensor shield for mobile mesonets [29].

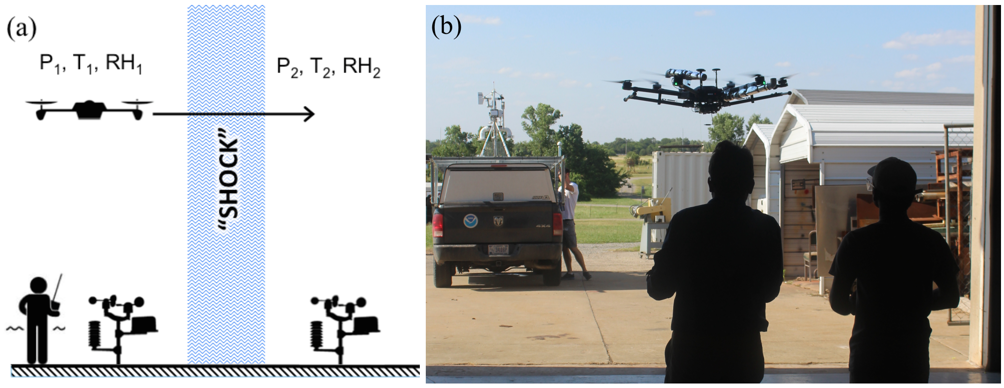

Figure 10. Validation experiment (**a**) arrangement and (**b**) sample test. Upstream and downstream conditions were carefully monitored and the thermodynamic shock created by rapidly opening the door prior to system test.

Multiple transits across the shock were performed during the exercise with the sUAS approximately 1–2 m off of the ground. An example of temperature from a fast response sensor (Figure 11a) along with temperature (Figure 11b) and relative humidity (Figure 11c) from an iMet sensor package mounted on a 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 11c) is likely a consequence of the damped temperature response relative to the more rapid response of the sensor to changes in moisture content [30]. 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 11d) but also brings the relative humidity on either side of the shock into better agreement with the reference values [31]. Please note that the decrease in relative humidity and increase in temperature between 21:31 p.m. and 21:32 p.m. is a consequence of rotor-driven mixing of the initially stratified air within the bay.

Additionally, tests were conducted at the University of Oklahoma in a controlled chamber to evaluate the optimal placement of temperature sensors on a rotary-wing aircraft, namely the OU CopterSonde. Typically, thermistors require aspiration to make representative measurements of the atmosphere. A collection of thermistors along with a wind probe were mounted to a linear actuator arm. The actuator arm was configured such that the sensors 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%, 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, 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 a rotary wing sUAS a distance of one quarter the length of the propeller from the tip is most likely to be minimally impacted from influences of motor, compressional, and frictional heating while still maintaining adequate airflow [28].

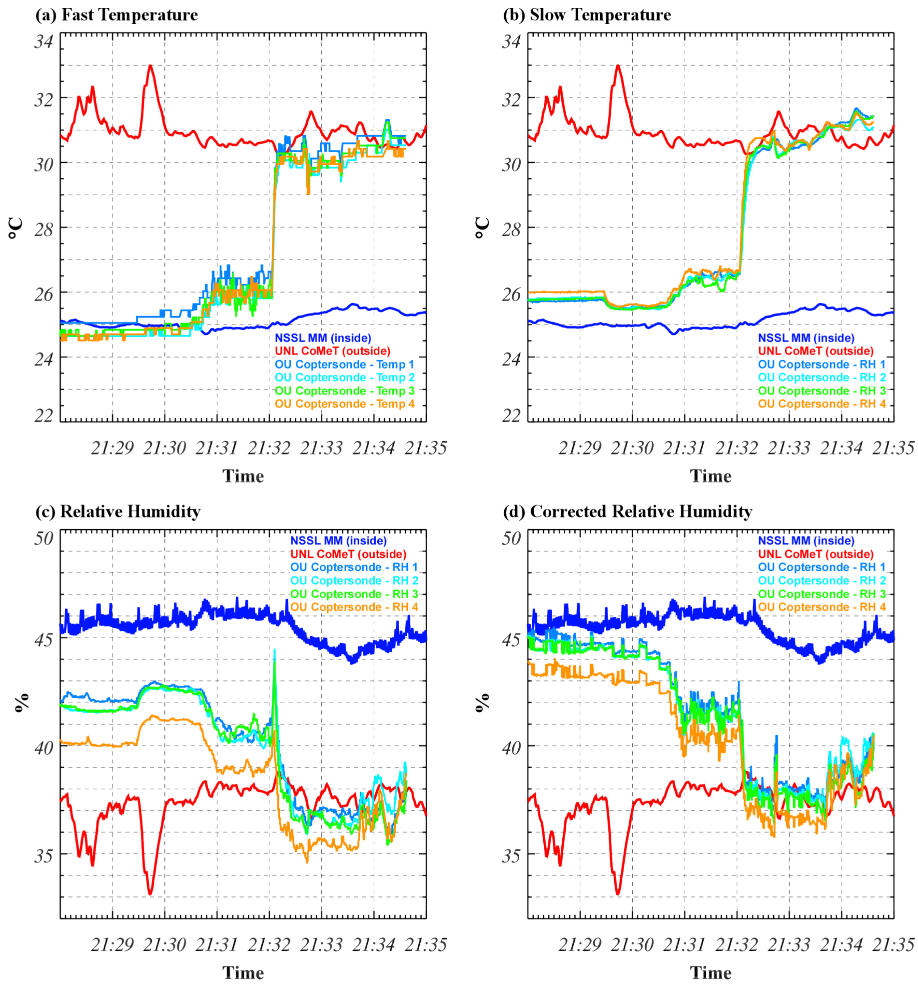

Figure 11. Calibration-validation experiment results. Reference conditions are denoted in blue.

4. Conclusions

sUAS are quickly becoming a viable option for routine and accurate observations in the ABL, albeit with caveats. The aim of flying robust, lightweight atmospheric sensors on UAS to monitor atmospheric conditions including PTH and wind speed, air quality, investigate pollution sources, and determine real-world exposures to gases of concern near or at ground level has been demonstrated as a primary goal of the CLOUD-MAP flight campaigns. Measurements of this type can contribute a detailed inventory for the profile level of thermodynamic and kinematic parameters, trace gases in the lower troposphere. Data collected onboard UAS during all flights are paired with GPS data to build up maps of conditions in the ABL.

A wide range of atmospheric science applications can benefit from sUAS. Several these applications serve as the focus of the seven CLOUD-MAP science themes. Under each theme, end-to-end research is being executed that advances basic understanding, identifies open questions and testable hypotheses that emerge from this basic research, defines the sUAS design required to answer these open questions, and begins to evaluate the concept of operations necessary to use sUAS to enable discovery. One example of this end-to-end approach can be illustrated by the convection initiation (CI) component of CLOUD-MAP. In this component, basic research is underway to understand the multi-scale interactions that lead to the initiation of deep convection. For example, CLOUD-MAP-supported research has revealed that, in the vicinity of airmass boundaries, meso-beta-scale diurnal modification of the ABL can manifest in meso-gamma-scale regions that are thermodynamically favorable for CI [32]. Moreover, even absent diurnal evolution to the ABL, the vertical profile of winds (even when exhibiting mesoscale homogeneity) can interact with airmass boundaries to produce micro-alpha- to meso-gamma-scale heterogeneities that can be kinematically favorable for CI [33]. These results, along with a growing body of primary research on CI highlight the need for high-fidelity observations of the "rapidly" evolving thermodynamic and kinematic fields around airmass boundaries. The configuration of sUAS required to realize these high-fidelity observations of ABL both with and without airmass boundaries has been the focus of additional work supported by CLOUD-MAP [34]. Further work has explored how sensor placement on multi-rotor aircraft impacts measurement accuracy [35]. With a clearer picture of open questions and required system configuration, plans are underway to evaluate the concept of operations for field research focused on CI, e.g., Lower Atmospheric Process Studies at Elevation—a Remotely-piloted Aircraft Team Experiment—LAPSE-RATE – a field campaign scheduled for July 2018 in Colorado coordinated by the International Society for Atmospheric Research Using Remotely-Piloted Aircraft (ISARRA). ding of the environmental conditions that support or inhibit CI along with optimized system configuration are leading to an improved concept of operations for the distributed and targeted surveillance of the atmosphere for improved CI prediction.

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