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DEVELOPMENT OF UAV-DEPLOYED AIR-LAUNCHED DRIFTERS FOR ABOVEGROUND THERMODYNAMIC MEASUREMENTS IN SUPERCELLS

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Abstract

Above-ground thermodynamic and wind measurements in supercells are challenging for both ground-based and airborne sensing systems. Outflow winds behind the rear-flank downdraft (RFD) make the RFD particularly difficult to access with balloon-borne sensors launched from the ground. A goal of the NSF National Robotics Initiative project "Severe-storm Targeted Observation and Robotic Monitoring" (STORM) is to develop new in situ atmospheric sensing applications through targeted observations. STORM is a three-year collaboration of researchers from the University of Colorado Boulder, University of Nebraska-Lincoln, Texas Tech University, University of Minnesota, and Texas AM University. This paper describes the development and deployment of the Mistral small UAS (sUAS) with an integrated air-launched drifter (ALD) deployment system. Simulation results are shown for balloons released into the wind field of a high-resolution supercell simulation to target potential ALD release points favorable for entrainment into the RFD. Results from Mistral airborne-release tests are shown, along with results from a ground-release test during a supercell intercept in the Oklahoma Panhandle on 12 June 2018, where position and meteorological data were delivered from the supercell for a duration of 2 hours and from a distance of greater than 100 km.

1. INTRODUCTION

Currently, there is a lack of direct thermodynamic measurements for use in the validation of supercell models and simulations. Radar is the most widely used method to measure and predict weather patterns and severe storms like supercells. The structure of a supercell is illustrated by the presence of hail and rain, outlined through radar by reflectivity measurements. Doppler radar can also measure wind velocity fields, shedding light onto how different regions of the storm interact and produce the structures characteristic of supercells.

However, as integral as radar measurements have become, they are unable to measure the forces that produce winds and their accelerations. To calculate the forces, thermodynamic properties of the storm are needed. Studying thermodynamic properties within supercells is crucial in understanding tornado formation. Without thermodynamic measurements, only half of the supercell story is understood.

Radar is not the only tool used to study supercells. In situ measurements taken from mobile mesonets have had promising results when used alongside radar data [7] [10]. Mobile mesonets have been able to accurately record thermodynamic measurements from both fixed and mobile locations [7], allowing for data collection around some of the relatively less severe portions of the storm. One of the biggest benefits of the mobile mesonet is that it is able to move with the storm, adapting as the supercell changes course heading or speed. However, even with increased mobility it is impossible to safely position manned mobile mesonets inside the dangerous parts of the supercell.

With the advent of Unmanned Aerial Systems (UAS), portions of the storm have been sampled that were otherwise inaccessible. UAS have allowed for temperature, pressure, and humidity measurements to be taken around and within vertical portions of supercells [2]. Facilitating the development of UAS has been a high priority in both the meteorological and engineering fields, in part driven by the advantage UAS pose in measuring within supercells. Due to these technological advances, small UAS (sUAS) have been able to get even closer to critical parts of the storm than ever before.

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However, operating sUAS within supercell environments necessitates the ability to fly in dangerous conditions where rain, hail, and strong aerodynamic forces are present. These conditions risk the safety and operations of the aircraft as well as the ability to conduct accurate measurements of the supercell. Therefore, direct measurements of the more severe portions of the supercell from sUAS are dangerous and ill-advised. It can be surmised that other methods for sampling above-ground portions of supercells are needed.

2. SUPERPRESSURE BALLOONS AS PSEUDO-LAGRANGIAN DRIFTERS

Pseudo-lagrangian drifters have been used for decades to sample Earth's atmosphere [1]. A "true" Lagrangian drifter has zero mass and perfectly tracks a fluid parcel as it moves through the atmosphere. In reality it is impossible to create a mass- and drag-less Lagrangian-drifter, therefore the term pseudo-lagrangian drifter is used to describe this form of atmospheric measurement.

Early atmospheric pseudo-lagrangian drifters (PLDs) took the form of large, helium filled, superpressure balloons that functioned as high altitude observation platforms [1]. Unlike typical weather balloons, superpressure balloons are made of materials with minimal elasticity to maintain a relatively constant volume once fully inflated, enabling the balloon to maintain a fixed density altitude. This property makes superpressure balloons useful for measuring pressure variations and wind fields. Early PLDs were close to three meters in diameter and were used to measure oceanic wind currents [1]. The advent of miniaturized sensors has led to the reintroduction of PLDs for meteorological measurements [5] with a commensurate reduction in the size of the balloon required to reach a specific altitude.

During the Rivers of Vorticity in Supercells (RiVorS) project in May 2017, Markowski et al. [6] used ground-launched PLDs for thermodynamic measurements in supercells. Using ground-level inflow, the team was able to successfully target the supercell forward flank region. While the project had considerable success, the possible areas of the storm that can be targeted with this system is limited by the ground-level inflows and outflows. Furthermore, latex balloons compromise some of the lagrangian aspects that can be leveraged to study the wind patterns within the supercell.

The rear-flank downdraft (RFD) is one of the regions of the supercell targeted for in-situ measurements to study tornadogenesis [4]. The RFD is characterized by a downdraft that wraps around the mesocylone. At the ground level, a strong gust from marks the boundary of the RFD outflow that pushes the air entrained by the RFD outwards from the southwest portion of the hook echo for an east-moving supercell.

Outflows following the RFD gust front make ground-release of PLDs impractical since balloons will be carried away from the storm. Consequently, the RFD is a severely undersampled portion of supercell storms. However, supercell models indicate that air is entrained into the RFD at some altitudes above the ground. We expect PLDs to be entrained into the RFD if released at the appropriate altitude and distance from the storm. The motivation for the development of the air-launched drifter deployment system is to release PLDs to target supercell regions that cannot be accessed by ground release. Throughout this paper the term PLD will be used to refer to this type of atmospheric measurement system in general, specifically those that are ground released. In contrast, air-launched drifters (ALDs) are atmospheric PLDs that are released from UAS.

3. DRIFTER DESIGN

The balloon envelope for the air-launched drifter (ALD) is comprised of 0.03-mm thick polyethylene foil, a durable, lightweight material with properties that minimize the loss of helium lift gas through effusion. The ALDs are designed to float at a maximum altitude of about 3 km MSL. At and below this altitude, inflows to the RFD are present, making it the ideal altitude target. By adding ballast to the drifter or decreasing the ALD balloon volume, the drifter altitude can be controlled before release. A 125 liter balloon lifting a 92 g payload will reach a maximum drift altitude at 3 km MSL.

The sensor payload is connected to the bottom of the balloon with a 30 cm offset. The offset provides distance to mitigate signal interference with the balloon while still maintaining a semi lagrangian scheme.

The sensor payload, termed microsonde, is a sensing system in development at the University of Colorado's Integrated Remote and In Situ Sensing Program (IRISS). The microsonde consists of pressure, temperature, and humidity sensors sampling at 1 Hz; GPS to measure position, course, and speed; a

(a) PLD with attached microsonde.

(b) Ground release of a PLD near Boulder, CO.

Figure 1: Psuedo-lagrangian drifters. Photo credit: Roger Laurence, CU.

micro controller (MCU); and a 915 Hz, 20 dB transmitter. Table 1 summarizes component accuracy and range values while Table 2 displays the weight distribution of the microsonde. The weight breakdown of the entire ALD is shown in Table 3. As can be seen, there is a difference of 23.4 grams between the actual ALD weight and maximum payload weight. This difference can be used to reach a higher altitude, ballast weight can be added, or a smaller ALD balloon can be used. Options into smaller, cylindrical balloons are being explored to make use of this to decrease some of the forces the ALD balloon experiences during the fill process.

While it is economically beneficial to recover the drifters after deployment, it cannot be assumed that this is possible. Therefore, on-board data storage is impractical and would take up a large portion of the limited mass budget available. Instead, the data is relayed to a ground station through the transmitter. The ground station is comprised of a high gain antenna and a MCU. The current configuration allows for each ground station to collect data from four microsondes. The limiting factor on the number of ground stations available is the number of separate radio channels the ground stations can tuned to to. With four channels, the total number of available microsondes is limited to 16.

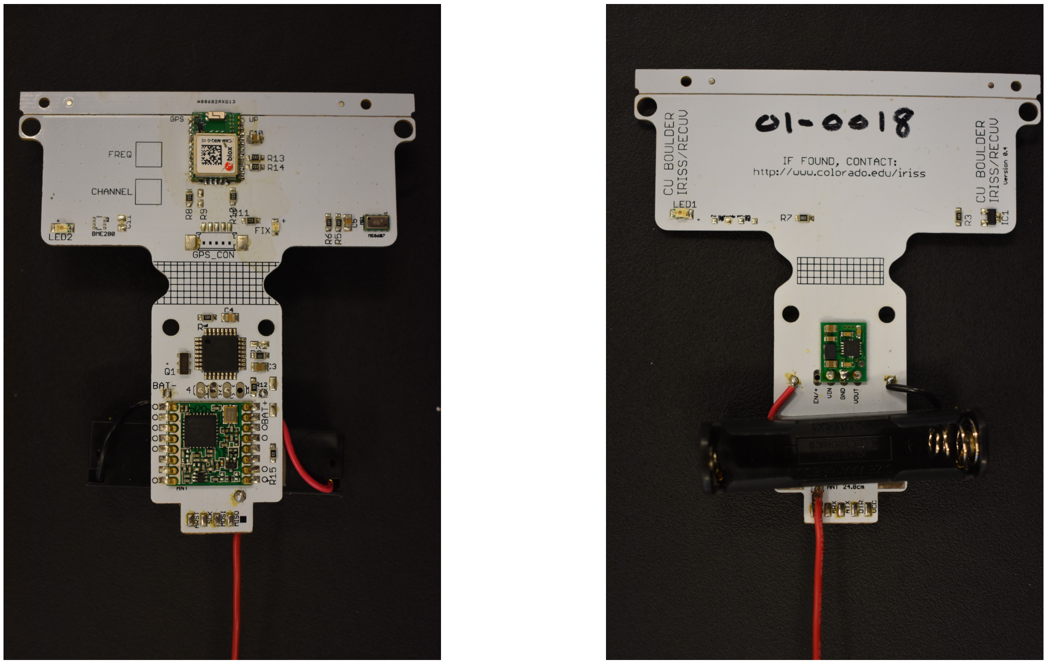
The microsonde is powered by a 1.5 volt lithium AAA battery. At room temperatures, this battery is able to power the microsonde for approximately nine hours. However, one of the strengths of lithium batteries is that they continue to perform reasonably well at subfreezing temperatures. Therefore, while the battery life decreases as the microsonde reaches higher altitudes and cooler temperatures present in supercells, it is still able to collect data over the mission time of an hour.

4. ALD TRAJECTORY SIMULATIONS

To assess the feasibility of deploying ALDs from a sUAS to be entrained into the RFD, simulations of possible ALD trajectories were performed. A high-resolution supercell nature run simulation was created using CM1 [3], a three-dimensional, nonhydrostatic, non-linear, time-dependent, numerical atmospheric model. The nature run simulation was initialized in an environment that contained realistic boundary-layer convection and included radiative parameterization, thermal and moisture surface flux, and a semi-slip surface boundary condition.

Simulated supercell data are provided in a fixed reference frame. At 16 gigabytes per time frame, the nature run data file is large enough to make repeated simulations computationally expensive. Therefore, to save on computation time, a single supercell frame is used to explore ALD trajectories. The mission concept of operations is to collect data from the drifters for a short period of time relative to the lifetime of the supercell, approximately 30 minutes to one hour. Future studies will employ time-dependent storm data to explore ALD trajectories.

Figure 3 shows the results of running the simulation



(a) Front side of the microsonde.

(b) Rear side of the microsonde.

Figure 2: Closeup of the microsonde sensing system. Onboard the microsonde are PTH sensors, a GPS, MCU, and transmitter. The sensor board is powered by a 1.5V AAA Lithium battery (not pictured).

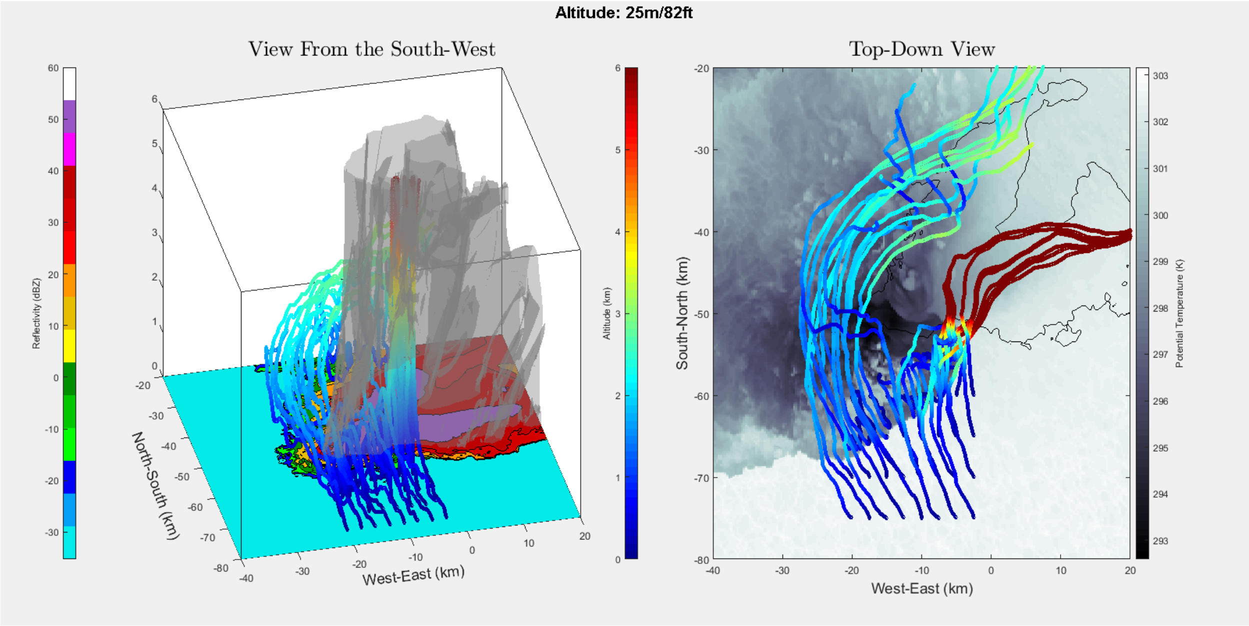
Table 1: PTH Sensor and GPS Specifications

PTH Sensor MS8607 [8]			
	Max. Operating Range	Accuracy @ 25°C	Resolution
Pressure	10-2000 mbar	±2 mbar	0.016 mbar
Temperature	-40-80°C	±1°C	0.01°C
Relative Humidity	0-100%	±3%	0.01%

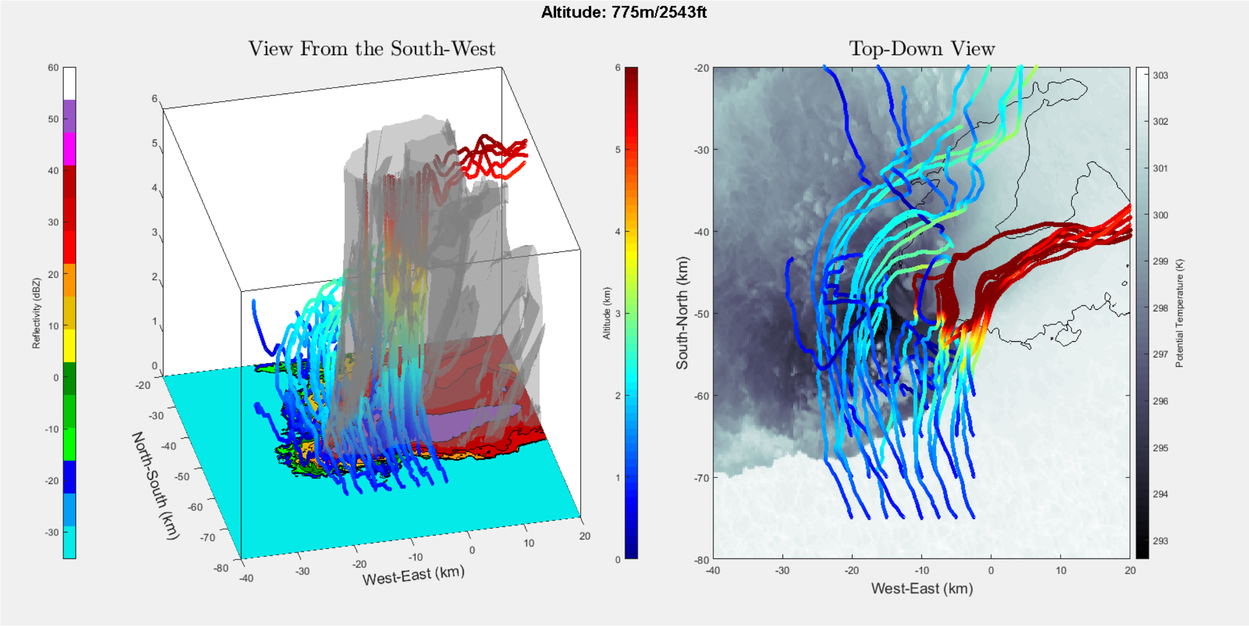
GPS Module ublox CAM-M8Q [9]		
Horizontal Position Accuracy	Max. Navigation Update Rate	Sensitivity
2.5 m	10 Hz	-166 dBm

at different release altitudes. The plots give the trajectories of a theoretical drifter released at 2.5 kilometer horizontal intervals to the south of the storm. From these results, it appears that the ALDs are most likely to be entrained when they are released at the edge or just inside of the rear-flank gust front. For both the low-altitude and high-altitude releases, the ALDs appear to pass just over the top of the gust front before being turned around and pushed back out through the gust-front. It is believed that this location will produce the most helpful data for studying the RFD. When the ALD is released too far south or west of the RFD, the ALD is pushed up and over the RFD into the updraft. These results support what is known about rear flank gust front dynamics. If the ALD is released too far south of the gust front, the balloon is pushed up and over the front, into the upper parts of the storm. However, if the ALD is released close enough, it will become entrained into the RFD instead.

From the simulation results, it appears that ALDs can be deployed for in situ measurements in the descending portion of the RFD. However, there is some sensitivity to where the ALDs are released. At lower altitudes, if they are released too far to the southwest of the gust front, they are more likely to be pushed out around the outer portion of the storm. However, at higher altitudes it becomes more likely that they will be pushed upwards into the updraft and away from the RFD. However, these results give an initial region for ALD release. It is expected that a combination of knowledge gained from these sim-



(a) Simulated releases at 25 meters above ground level, the lowest altitude of the supercell simulation.



(b) Simulated releases at 775 meters above ground level, the altitude closest to the COA ceiling.

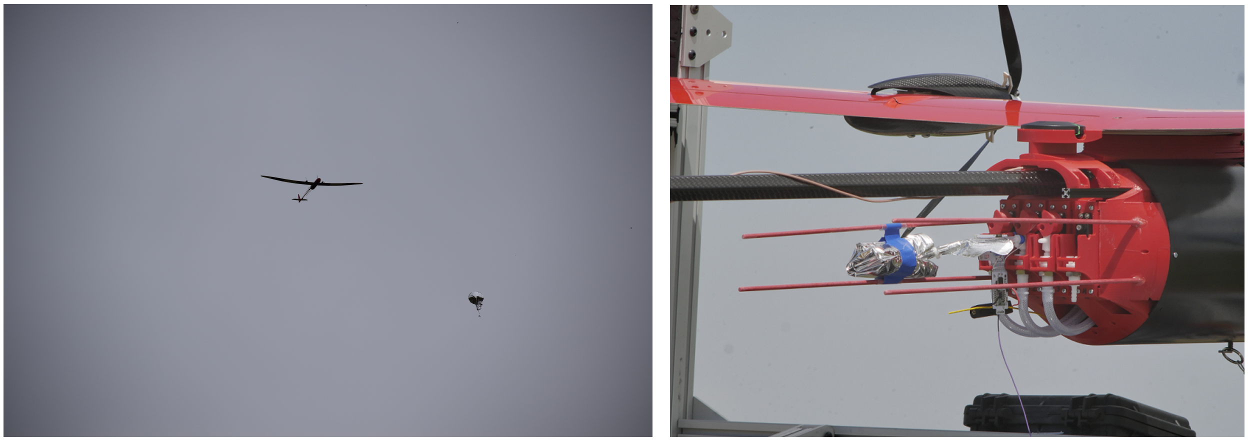
Figure 3: Simulation of drifters released into a north-east moving supercell. Drifters were released approximately 2.5 km apart in both the East-West and North-South directions. The colors of the trajectories correspond to the altitude of the drifters in both plots. On the left, a three-dimensional view of the ALD trajectory with respect to the 45 dBZ outline, a rough indicator of precipitation within the supercell, are plotted above the nature run reflectivity. To the right are the same trajectories plotted at the altitude of release as well as the 45 dBZ outline in black.

Table 2: Microsonde Weight Distribution

Battery & Battery Holder	10.5g
PCB	6g
Radio	2g
GPS	0.5g
Microcontroller	∼ 0g
PTH Sensor	∼ 0g
Miscellaneous Parts	1g
Total:	**20g**

Table 3: ALD Weight Distribution

Microsonde	20.0g
Mylar Balloon	48.0g
Connectors	0.6g
Total:	**68.6g**



(a) ALD after release from the Mistral. Photo Credit: Roger Laurence, CU

(b) ALD in the storage position behind the fuselage of the Mistral before flight. Photo credit: Cole Kenny, IRISS.

Figure 4: Images taken of the Mistral equipped to release ALD's.

ulations as well as field experience will enable release strategies for reliable penetration of the ALDs into the RFD.

5. MISTRAL sUAS

The Mistral sUAS is a fixed-wing, long-endurance, battery-powered sUAS developed in the CU Boulder IRISS program. For Project STORM, the Mistral was outfitted with a system to fill and deploy the ALD balloons.

A 1.5 liter, high-pressure tank with a maximum pressure rating of 31 MPa is used to fill the ALD balloons in-flight. The current system has capacity to fill three balloons in-flight.

The helium tank is located in the Mistral fuselage forward of the center of gravity (CG). Tubing connects the helium tank to the unfilled ALD balloons, which are located aft of the Mistral CG. The ALD balloons are folded along stabilizing rods that run along the length of the aircraft towards the tail boom. The folds in the balloon envelope enable a controlled filling process without interference with the Mistral control surface. Inflation is initiated from the ground station when the Mistral reaches the desired target altitude and region, inflation is initiated through a command given by the ground station. The balloon inflation generally takes about 60 seconds, with the balloon inflated downwind of the CG to maintain a pitch up moment during the fill process.

The Mistral outfitted for ALD release has the capability of performing a fill and release of three ALDs. Once all the desired ALDs are released, the Mistral can fly to a safe location for recovery. The depleted helium tank can then be swapped for a full one, three new ALDs would be placed on the Mistral, and the Mistral batteries would be changed for fully charged ones. This whole process could be done in approximately 15 minutes.

A FAA blanket certificate of authorization (COA) enables the Mistral to fly up to an altitude of 500 ft (150 m) AGL in the United States. Other COAs that cover about 500,000 sq. mi. (1.3M km^2) of the Great Plains have a 2,500 ft (760 m) AGL ceiling. The

CU team is currently discussing with FAA a maneuver that will enable the Mistral to briefly ”pop-up” to 5,000 ft (1.5 km) to release the ALDs at a higher altitude above the supercell outflow, and to increase the probability that the ALDs will ascend to the target equilibrium altitude before being entrained into the RFD. These were the release points explored in the simulations of Sect. 4.

6. MICROSONDE CHARACTERIZATION TESTS

Characterization tests of the microsondes were carried out during the Lower Atmospheric Process Studies at Elevation - a Remotely-Piloted Aircraft Team Experiment (LAPSE-RATE) in the San Luis Valley near Alamosa, Colorado during the week of July 14, 2018. In one test, PLDs were ground released next to a Vaisala RS92-SGP attached to a NSSL weather balloon. In another test, a microsonde was flown next to a Vaisala RS92 on a Talon fixed-wing sUAS .

Results from the comparison between the microsonde and RS92-SGP shown in Figure 5(a). At lower altitudes, the differences between the two sensors fall closely to within the quoted sensor accuracy bounds. However, at increasing altitudes, readings from the two relative humidity sensors differ at magnitudes much larger than the the expected sensor accuracy. The difference can, in part, be attributed to the fact that the NSSL weather balloons ascended much quicker than the PLD. Immediately following release, the weather balloon and PLD followed similar trajectories. However, after a few minutes the weather balloon and PLD were measuring very different parcels of air. This could contribute to the large discrepancies that were seen between the two relative humidity sensors at higher altitudes. The pressure and temperature differences appear to be less sensitive to the path differences between the weather balloon and the PLD. Figure 5(a) also shows an apparentbias between the two measurement systems. The tests were conducted during a sunny week in July, therefore it is believed that radiative heating of the microsonde is likely contributing to the sensor bias. A new version of microsonde is currently in development that will include sensor shielding from external and internal heat sources.

Results from the comparison between the microsonde and RS92 are given in Figure 5(b). In this case, the differences between sensors were larger at low altitudes, before the Talon UAS was in flight. Once the Talon took became airborne, the differences between the sensors dramatically decreased. This confirms the expectation that proper aspiration of the microsonde sensors is necessary for accurate measurements, particularly for the relative humidity measurments. Therefore, work is underway to increase airflow over the sensors to achieve proper aspiration.

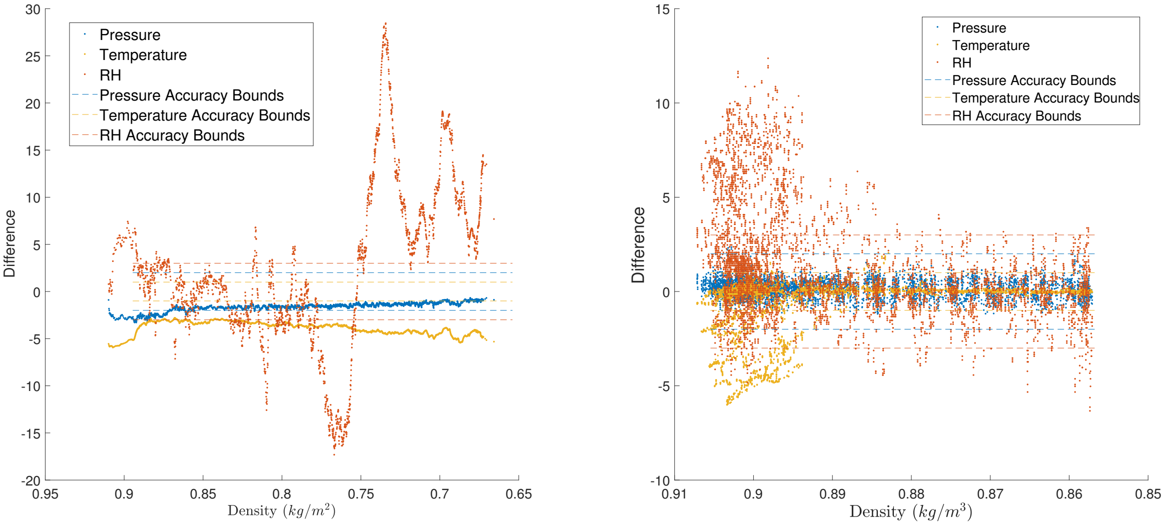
7. INITIAL TEST RESULTS

During the 2018 Project STORM deployment, a PLD was ground released into a supercell near Gate, Oklahoma. The PLD path through the supercell can be seen in Figure 6(a). It appears that the PLD increased to a maximum altitude of 3.5 km MSL about 30 minutes after release before dropping or being forced to the ground the radio link to the PLD was temporarily lost. It is believed that the PLD could have been forced down due to the presence of a downdraft or due to the weight of precipitation. The second theory is supported by the data reported by the relative humidity sensor when contact was regained with the PLD after about one hour. In Figure 6(b), it can be seen that when communication was reestablished, the relative humidity sensor was saturated. However, after the supercell passed, it is believed that a combination of a decrease in precipitation and increase in temperature allowed for favorable enough conditions that the PLD was able to ascend. It was seen that as the PLD ascended, it turned towards the south as the storm moved to the south. During the balloon flight, the communication range between the microsonde and the ground station exceeded 100 km over a time of two hours.

8. CONCLUSION AND FUTURE RESEARCH

The Air-Launched Drifter system is designed to place pseudo-Lagrangian drifters into the rear-flank downdraft of tornadic supercells to perform thermodynamic measurements of the RFD. Pseudo-lagrangian drifters offer a unique solution to sample the RFD safely and remotely. While ground-released pseudo-lagrangian drifters have had promising success in measuring portions of the forward-flank downdraft, it is believed that the airborne lagrangian drifter system enables balloon release points for entrainment into the RFD and other parts of the supercell not readily accessible with ground launches.

High-resolution supercell simulation data were used to explore the feasibility and guide the concept of operations for an ALD system. It was found that by



(a) Comparison between Vaisala RS92 radiosonde on the NSSL weather balloon and the microsonde on a ground released PLD.

(b) Comparison between microsonde flown alongside a Vaisala RS92 on board the Talon sUAS.

Figure 5: Vaisala RS92 and microsonde comparisons.

releasing the ALD from the south and southeast of an easterly-moving supercell results in the greatest likelihood of entrainment into the RFD. While these simulations are important for understanding the supercell structure and possible ALD trajectories, field deployments will be required to better understand how to successfully entrain the ALDs into the RFD. Furthermore, the supercell simulation data used a single frame at a fixed time in the supercell simulation to compute the trajectories. Future research will focus on using the time-dependent data from the nature to compute balloon trajectories.

The first successful deployment of an ALD occurred in August 2018. Further testing and refinement of the inflation and release systems are expected to produce a reliable system by spring 2019.

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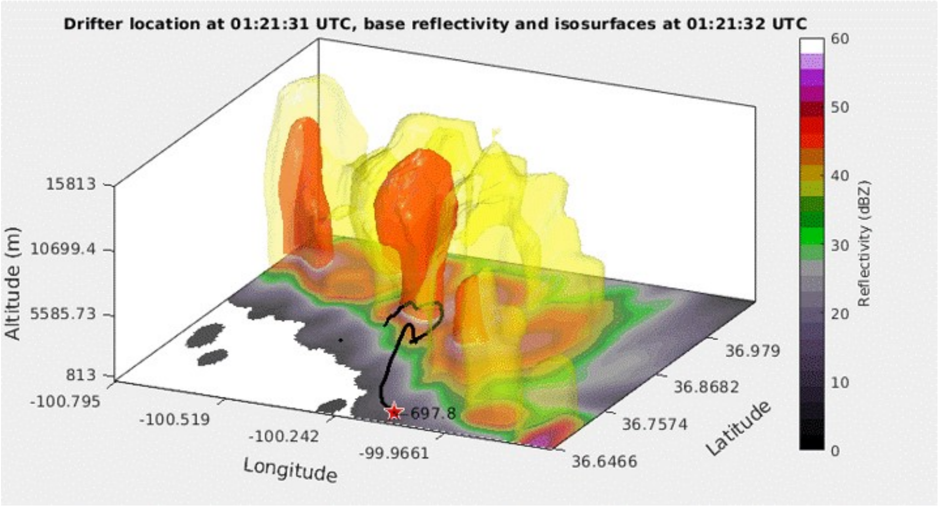
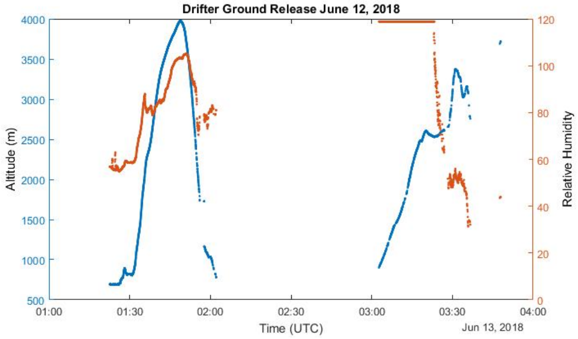


(a) The PLD path, shown in black, overlayed on Nexrad radar data shows the drifter moving through the supercell.



(b) Altitude and relative humidity data suggest the drifter could have been forced down due to the prescence of precipitation in the supercell.

Figure 6: Drifter data from the ground release done on June 13, 2018 in the Oklahoma panhandle. The drifter was ground-released to the south of a convective storm and proceeded to move to the north-west.

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