J1.2 **DEVELOPMENT OF UAV-DEPLOYED AIR-LAUNCHED DRIFTERS FOR ABOVEGROUND THERMODYNAMIC MEASUREMENTS IN SUPERCELLS**

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1. INTRODUCTION

Tornadoes are one of the most common and destructive forms of extreme weather in the United States. From 2008 to 2017, the United States experienced an average of 1,213 tornadoes per year (Storm Prediction Center, 2018b). In 2017 alone, 1,429 confirmed tornadoes (Storm Prediction Center, 2018a) resulted in 35 deaths, 516 injuries, and 649.18 million dollars in damages (National Weather Service, 2018). The deadliest and most destructive tornadoes occur in supercells. In the presence of the rear-flank downdraft (RFD), it is possible for the supercell mesocyclone to develop into a sustained tornado. However, not all supercells produce tornadoes. It has been observed that tornadoes occur in 20 percent of supercells (National Severe Storms Laboratory, 2018). Therefore, a complete picture of the inner workings of supercells and the mechanics that lead to tornadogenesis are vital in accurately predicting when and where a supercell tornado will form. A better understanding of supercell tornadoes can help to inform future research and increase tornado warning lead times.

Remote sensing systems such as weather radar do not provide thermodynamic data in the RFD. In-situ measurements at the surface have been provided by mobile mesonets (e.g., Houston et al., 2012; Waugh, 2012; Straka et al., 1996) and have shown promising results when used alongside radar data. A major benefit of the mobile mesonet (MM) is that, when an appropriate road network is available, the MM can move with the storm to target regions of interest, as the supercell evolves. However, even with increased mobility the risk for placing a manned MM beneath the most dangerous parts of the supercell can be unacceptable.

With the advent of Unmanned Aircraft 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 (Houston, 2012). 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.

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.

1.1 *Superpressure Balloons as Pseudo-Lagrangian Drifters*

Pseudo-lagrangian drifters have been used for decades to sample Earth's atmosphere (Businger, 1996). 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 (Businger, 1996). 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 (Businger, 1996). The advent of miniaturized sensors has led to the reintroduction of PLDs for meteorological measurements (Manobianco, 2008) 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. (2018) 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

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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 (Lin, 2007). The RFD is characterized by a downdraft that wraps around the mesocyclone. 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 under sampled 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.

2. DESIGN

2.1 *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, entrainment into the RFD is expected, 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, using the 1976 standard atmosphere for density.

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

Figure 1: Pseudo-lagrangian drifters. Photo credit: Roger Laurence, University of Colorado.

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 is a microsonde developed 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 micro controller (MCU); and a 915 Hz, 100 mW transmitter. There is a difference of 23.4 g between the actual ALD weight, including the microsonde, and the maximum payload weight capability. This difference can be used to reach a higher altitude, ballast weight can be added, or a smaller ALD balloon can be used. Smaller, cylindrical balloon options are being explored to decrease 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 uses a 4-channel radio and a high-gain antenna to simultaneously communicate with up to four microsondes per channel, in total communications with a maximum of 16 microsondes.

The microsonde is powered by a 1.5V lithium AAA battery. At room temperatures, this battery can power the microsonde for approximately nine hours. However, one of the strengths of lithium batteries is that they continue to perform reasonably well at sub-freezing 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.

2.2 *Mistral Small UAS*

The Mistral sUAS is a fixed-wing, long-endurance, battery-powered sUAS developed in the CU Boulder IRISS program. For the NSF-sponsored Severe-storm Targeted Observation and Robotic Monitoring (STORM) project, the Mistral was outfitted with a system to fill and deploy the ALD balloons.

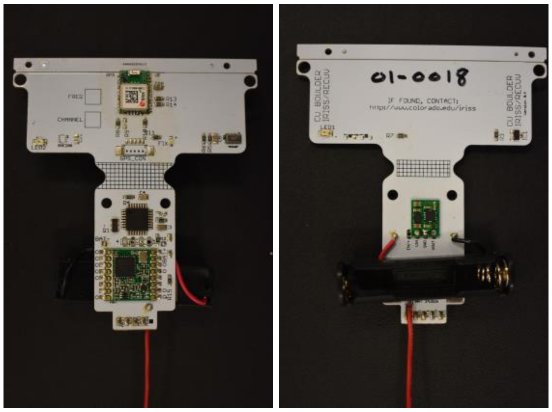

Figure 2: Close-up of the microsonde sensing system. Onboard the microsonde are PTH sensors, a GPS, MCU, and transmitter. The sensor board is powered by a 1.5V lithium battery (not pictured).

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 interfering with the Mistral control surface. Inflation is initiated from the ground station when the Mistral reaches the desired target altitude and region. 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 the ALDs are released, the Mistral can fly to a safe location for recovery.

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 square km) 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.

3 RESULTS

3.1 *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 (Keeler, 2017), 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 parameterzation, 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 4 shows the results of running the simulation 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 and high-altitude releases, the ALDs appear to pass just over 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 the

Figure 3: ALD in the storage position behind the fueslage of the Mistral before flight. Photo credit: Cole Kenny, IRISS.

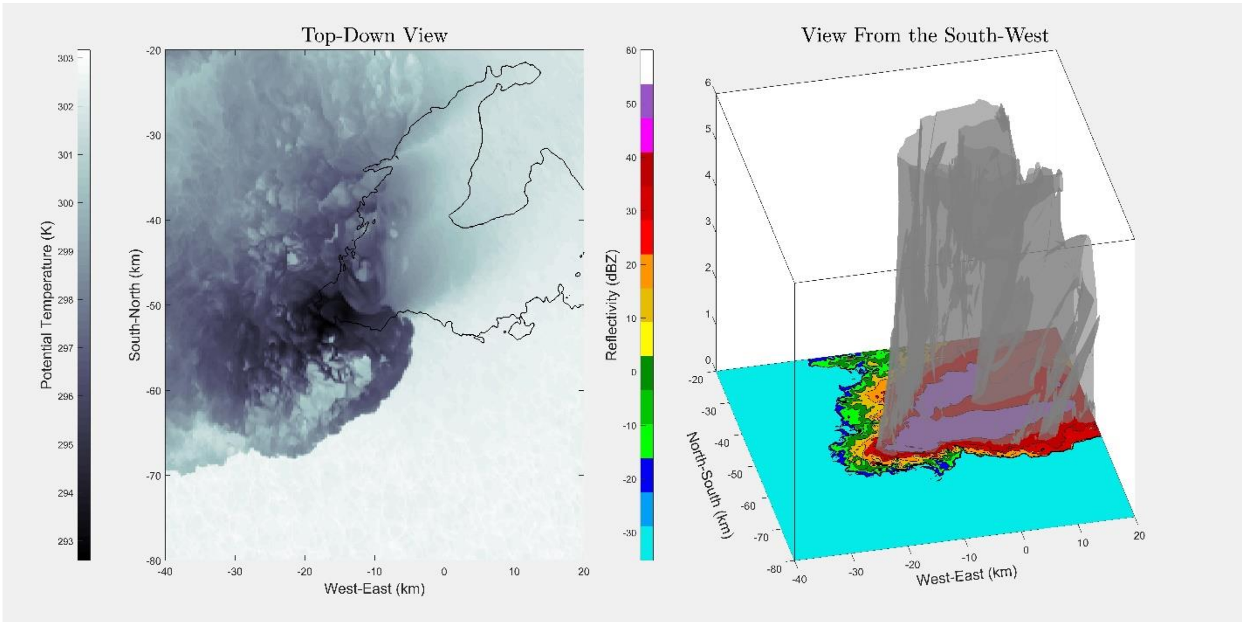

Figure 4: Supercell simulation data used to calculate ALD trajectories. To the left, the black outline corresponds to 45 dBZ reflectivity of the storm, overlaid onto a two-dimensional view of the potential temperature of the supercell at the lowest altitude of the simulation. To the right, the same 45 dBZ surface is projected onto the estimated reflectivity of the supercell simulation at the lowest altitude of the simulation.

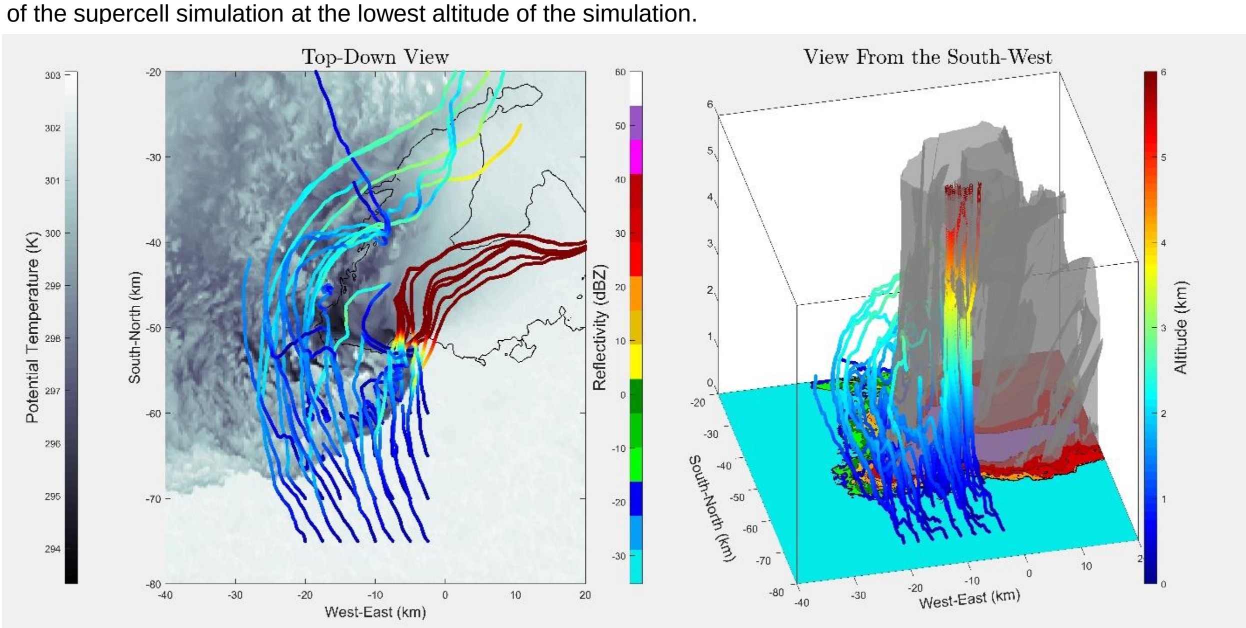

Figure 5: Simulation of drifters released into a north-east moving supercell. ALDs were released approximately 2.5 km apart in both the East-West and North-South directions at an altitude of 225 meters. The colors of the trajectories correspond to the altitude of the ALDs in both plots.

expectation that there are release points upwind of the gust front where the ALD will rise above the horizontal outflow boundary where it will become entrained into the RFD.

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

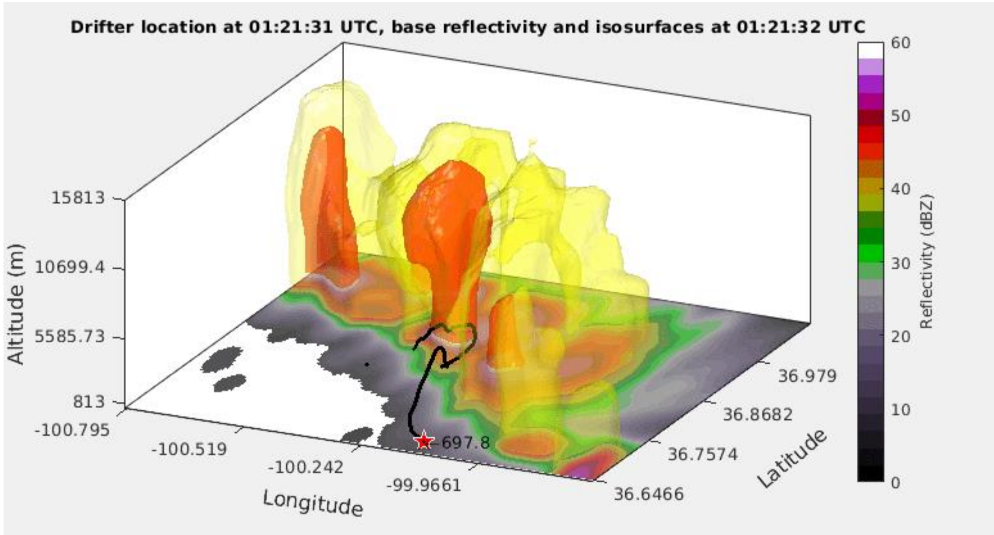

Figure 6: The PLD path, shown in black, overlaid on Nexrad data shows the PLD moving through the supercell.

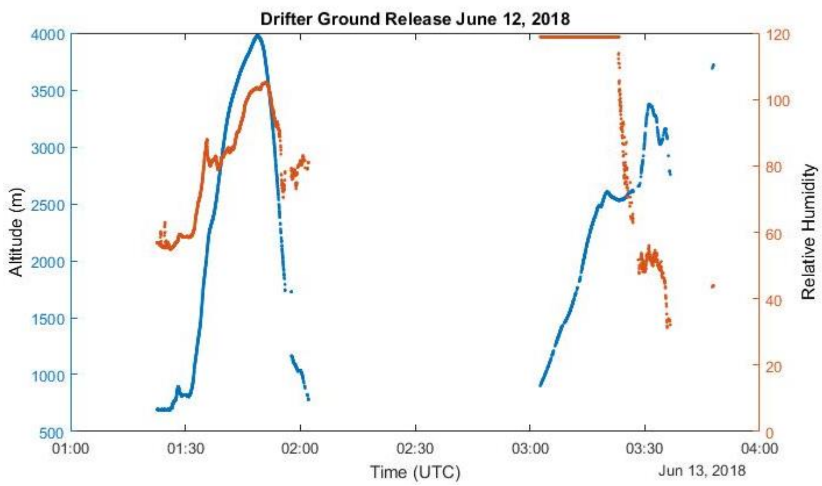

Figure 7: Altitude and relative humidity data suggest the drifter could have been forced down due to the presence of precipitation in the supercell.

3.2 *Initial Field 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. It appears that the PLD ascended 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. The PLD could have been forced down due to the presence of a down-draft 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 7 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.

3.3 *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.

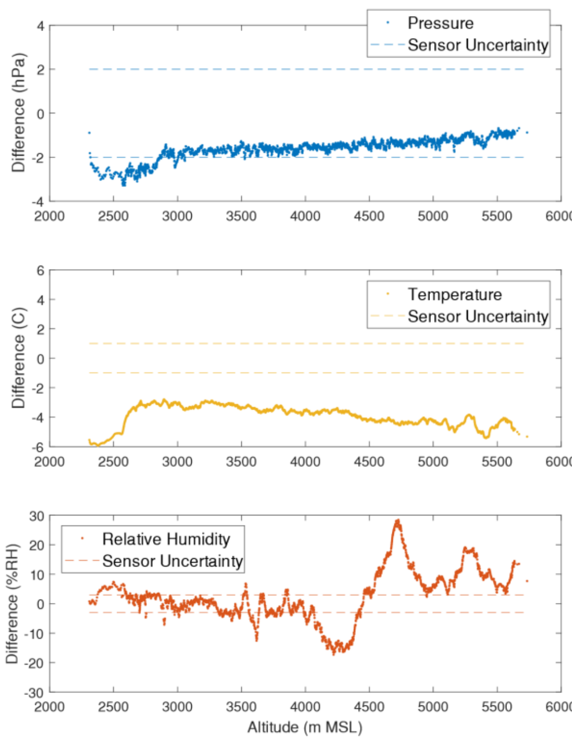

Figure 8: Comparison between Vaisala RS92 radiosonde on the NSSL weather balloon and the microsonde on a ground released PLD. Dashed lines give the expected sensor uncertainty.

Results from the comparison between the microsonde and RS92-SGP shown in Figure 8. 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 expected sensor accuracy. The difference can, in part, be attributed to the fact that the NSSL weather balloons ascended at a faster rate 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. However, there is still an apparent bias 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 further contributed 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 9. 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 measurements. Therefore, work is underway to increase airflow over the sensors to achieve proper aspiration.

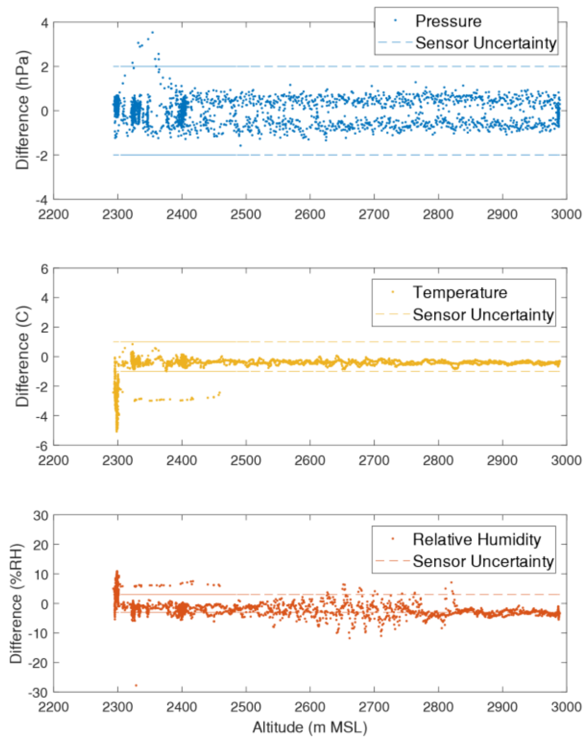

Figure 9: Comparison between microsonde flown alongside a Vaisala RS92 on board the Talon sUAS. Dashed lines give the expected sensor uncertainty.

4. CONCLUSION

The Air-Launched Drifter system is designed to place pseudo-lagrangian drifters into the rear-flank downdraft of tornadic supercells to perform thermo-dynamic 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 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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REFERENCES

Businger, S., Chiswell, S., and Ulmer, W., 1996, Balloons as a lagrangian measurement platform for atmospheric research. *Journal of Geophysical Research*.

Houston, A. L., Argrow, B., Elston, J., Lahowetz, J., Frew, E. W., and Kennedy, P. C., 2012, The Collaborative Colorado-Nebraska Unmanned Aircraft System Experiment. *Bulletin of the American Meteorological Society*.

Keeler, J. M., and Houston, A. L., Eds., 2017, Impact of UAS Data on Supercell Evolution in an Observing System Simulation Experiment, *28th Conference on Weather Analysis and Forecasting, 24th Conference on Numerical Weather Prediction*, American Meteorological Society.

Lin, Y.-L., 2007, Mesoscale Dynamics. *Cambridge University Press*.

Manobianco, J., Dreher, J., Adams, M., Buza, M., Evans, R., and Case, J., 2008, How nanotechnology can revolutionize meteorological observing with lagrangian drifters. *Bulletin of the American Meteorological Society*, 1105–1109.

Markowski, P. M., Richardson, Y. P., Richardson, S. J., and Peterson, A., 2018, Aboveground thermodynamic observations in convective storms from balloon borne probes acting as pseudo-lagrangian drifters. *Bulletin of the American Meteorological Society 99*, 711–724.

National Weather Service, 2018, Summary of Natural Hazard Statistics for 2017 in the United States, http://www.nws.noaa.gov/om/hazstats/sum17.pdf

National Severe Storms Laboratory, 2018, Severe Weather 101: Tornado Types, http://www.nssl.noaa.gov/education/svrwx101/tornadoes/types/

Storm Prediction Center, 2018a, Monthly and Annual U.S. Tornado Summaries, https://www.spc.noaa.gov/climo/online/monthly/newm.html

Storm Prediction Center, 2018b, Storm Prediction Center WCM Page, https://www.spc.noaa.gov/wcm

Straka, J.M., Rasmussen, E.M., and Fredrickson, S.E., 1996, A Mobile Mesonet for Finescale Meteorological Observations. *Journal of Atmospheric and Oceanic Technology 13*, 921–936.

TE Connectivity. MS8607-02BA01, 2015.

u-blox. CAM-M8, 2016.

Waugh, S. M., 2012, The U-Tube: An Improved Aspirated Temperature System for Mobile Meteorological Observations, Especially in Severe Weather. PhD thesis, University of Oklahoma.