Boundary Layer Measurements Over Land Use/Cover Discontinuities Using a Small UAS

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Surface features such as vegetation, land use, soil type, and terrain are known to influence lower atmospheric characteristics; however, the specific influence of these features on the development and modification of larger atmospheric processes is difficult to quantify. This is primarily a result of the difficulty in obtaining requisite observations of low-level atmospheric properties for direct diagnosis of meteorological conditions. Fortunately, advances in low-cost instrumentation and small unmanned aerial vehicles (UAV) has led to the possibility of near-real-time monitoring of the atmospheric boundary layer. Such information gives meteorologists invaluable information for a variety of applications, including research into land-atmosphere interactions, verification of NWP model output, and assessment of local-scale convective boundaries. This study utilizes a variety of low-cost UAVs along with a simple meteorological sensor package (which together comprise an unmanned aerial system (UAS)) to measure lower-atmospheric (<250 meter) temperature, humidity, and pressure along known land surface boundaries. Flights were conducted over the Grand Bay National Estuarine Research Reserve (NERR) and an agricultural research area in east-central Mississippi to quantify the variability in horizontal and vertical temperature and moisture patterns due to the land use/cover discontinuities. The results of this research show small-scale spatial variations in lower atmosphere features (namely temperature and moisture fields), which along with analysis of surface characteristics, indicate definite relationships between land surface type. However, it was found that flight patterns (i.e., path and speed), UAV type (i.e., fixed wing vs. rotary), and sensor characteristics (i.e., lag and resolution) played critical roles in the ability to quantify specific changes in meteorological conditions.

I. Introduction

DUE to the rapidly varying nature of the atmosphere with respect to both time and space, the viability of predictions and diagnostics of meteorological processes is inherently dependent on the availability and timeliness of measurements throughout the entire troposphere. When dealing with local-scale thermodynamically driven convective events, measurements in the lower few kilometers of the troposphere (a.k.a., planetary boundary layer (PBL)) are even more critical as small variations in surface and lower-atmospheric characteristics (such as temperature, humidity, and wind speed) play a key role in the generation and evolution of atmospheric instability and subsequent convection. The ability to diagnose and predict the distribution and intensity of these convective processes is critical, as the spatial and temporal frequency and intensity of convective systems plays a large role in

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patterns of precipitation and low-level winds, which have direct impacts on applications related to such disciplines as water resources and aviation.

Although surface features such as vegetation, land use, soil type, and terrain are known to influence lower atmospheric characteristics, the specific influence of these features on the development and modification of larger atmospheric processes is difficult to quantify. This is primarily a result of the difficulty in obtaining requisite observations of low-level atmospheric properties for direct diagnosis of meteorological conditions. Often numerical weather prediction (NWP) models are utilized to downscale or interpolate available atmospheric observations using known physical processes along with statistical and physical parameterizations; however, the inherent accuracy of such models is heavily determined by the amount and accuracy of data assimilated into them. This is especially true regarding mesoscale (~1-100-km in scale) convective atmospheric processes; therefore, lower-atmospheric observations are critical for improved understanding and forecasting of such events.

Current atmospheric observation methods rely on expensive and/or inefficient equipment, such as atmospheric profilers and weather balloons (a.k.a., radiosondes). Although proven, these methods are severely limited with respect to flexibility and mobility - profilers offer a high temporal frequency of wind observations at a set location, while weather balloons allow for measurement of a range of parameters at low temporal frequency. Recent advances in low-cost instrumentation and small unmanned aerial vehicles (UAV), which together are often referred to as unmanned aerial systems (UAS), has led to the possibility of near-real-time monitoring of the atmospheric boundary layer.

UAVs and UASs have been used in military applications since World War I, with their primary applications focusing on surface reconnaissance and target acquisition[1]. The continued success of UAVs for this purpose has led to extensive development of related technologies for civilian applications of environmental surveying and monitoring. For example, UAS imagery was used to define environmental impacts caused by the MORAKOT typhoon[2], which is invaluable for emergency response and rescue missions. In addition, UAV-based sensors were used to generate high-resolution digital elevation models (DEMs) for assessment of a dam break flood scenario in support of hydrological modeling efforts and the development of decision-making and evacuation plans[3]. UAS platforms have also been used for detection and mitigation of forest fires[4, 5], where the ability to fly in areas deemed unsafe for manned flight allowed for rapid estimation of burnt areas and more efficient and effective fire-fighting plans.

It is only relatively recently that UASs have been used for atmospheric boundary layer research due to their sensor flexibility, relatively low-cost, and rapid deployment capabilities. Early work by Ref. 6 paved the way for UAS applications in meteorology; however, advancements in sensor size and UAV performance have now made lower atmospheric research using small UAVs more widespread[7-10]. UASs have a distinct advantage over other aircraft in that they can be quickly deployed into environments considered unsafe for manned flight due to hazardous meteorological conditions[11]. Ref. 12 showed the initial results of using UASs within tropical cyclones for assessment of near-surface atmospheric characteristics, where Coyote UAS platforms were released from hurricane hunter aircraft within Hurricane Edouard. The Tempest UAS was used in the VORTEX2 experiment, where UAVs were successfully launched into supercell thunderstorms for measurement of near and in-storm meteorological characteristics[13,14].

The information provided by UASs gives meteorologists invaluable information for a variety of applications, including research into land-atmosphere interactions, verification of NWP model output, and assessment of local-scale convective boundaries. This information can be used to improve local-scale weather prediction, especially over areas with distinct spatial variations in land use/cover. Such features are most noted along land-water boundaries (i.e., sea/land breeze, lake breeze), urban-rural interfaces (i.e., urban heat island), and in agricultural areas where vegetation type and irrigation can influence atmospheric characteristics such as temperature and moisture. The UAS platforms offer a rapid, cost-effective means to observe weather patterns and features in the lower atmosphere, and show tremendous promise and potential for atmospheric research.

For this study, a low-cost UAS involving a Windsond© meteorological sensor package along with either a fixed-wing or rotor-based UAV was used to measure lower-atmospheric (<250 meter) temperature, humidity, and pressure along known land surface boundaries. Flights were conducted over the Grand Bay National Estuarine Research Reserve (NERR) in southern Mississippi and an agricultural test field on the Mississippi State University campus to quantify the variability in horizontal and vertical temperature and moisture patterns due to land use/cover interfaces. Such information is useful for the prediction of local-scale convective boundaries (i.e., sea and land breezes), although it is hypothesized that other boundaries smaller than coastal sea breezes can be generated and modified due to variations in boundary layer properties.

The objectives of this research are two-fold. First is to test the efficacy of low-cost UASs in the monitoring of PBL characteristics, including the development of viable flight strategies and instrumentation platforms for effective observations. Second is to utilize the collected data to quantify the influence of surface conditions on the generation and/or evolution of lower-atmospheric convective features, especially along land use/cover boundaries.

II. Experimental Design

This study involved two independent sets of flights of small UASs over a coastal location and over an agricultural region, both of which are characterized by substantial land use/cover boundaries and the propensity for convective initiation. The flights utilized different UAS platforms and measurement strategies, although the same meteorological sensor equipment was used in all instances. The following sections describe the UAS configuration, designated flight path, and surface characteristics for each mission.

A. Grand Bay National Estuarine Research Reserve

The first set of flights took place on November 20 and 23, 2015, within the Grand Bay National Estuarine Research Reserve (NERR) along the Gulf Coast of Mississippi (Fig. 1). This location was chosen because of its proximity to the ocean to the east and south, and the variations in land cover (grassland, marsh, and urban). The flight on November 20, 2015 was focused on measurement of temperature, pressure, and moisture characteristics related to the land/water interface, while the flight on November 23, 2015 was focused on the land/water interface along with the natural/urban land cover interface.

Figure 1. Overview of UAS flights over Grand Bay National Estuarine Research Reserve (NERR) on November 20 and 23, 2015. North is towards the top of the image.

Each flight was conducted using a fixed-wing Altavian Nova Block 3 UAV with a Windsond sensor attached to the upper section of the fuselage. The Windsond sensor is originally a sonde meant for use in balloon applications; therefore, it was modified for this flight by being removed from its original case and placed directly in the instrument space on the UAV with only the temperature-humidity probe and antennae within the air stream.

The UAS was flown using a north-south oriented series of transects, roughly parallel to the land/water interface to the east. The flights were conducted at an altitude of ~800 ft (244 m), which was the maximum altitude allowed under the existing FAA Certificate of Authorization (CoA). This flight pattern generated a relatively constant field of measurements over the region of interest, which allowed for an assessment of the spatially varying energy and moisture characteristics of the PBL in relation to the changes in surface features.

Both of the Grand Bay NERR flights took place in the late morning, with the November 20 flight lasting from 10:46–11:34 LST and the November 23 flight lasting from 10:55-11:51 LST. On November 20 there was a synoptic high pressure to the north over Kentucky, which propagated southwards until it was over southern Mississippi on November 23, leading to clear skies above the PBL and scattered cumulus clouds in the lower levels. Surface wind speeds on both days remained at roughly 5-10 miles hour^{-1} (2.2-4.8 m s^{-1}), with approximate surface temperatures and relative humidities of 23°C (73°F) and 44%, respectively, on November 20 and 17°C (63°F) and 26%, respectively, on November 23.

B. Mississippi State University Agricultural Research Farm

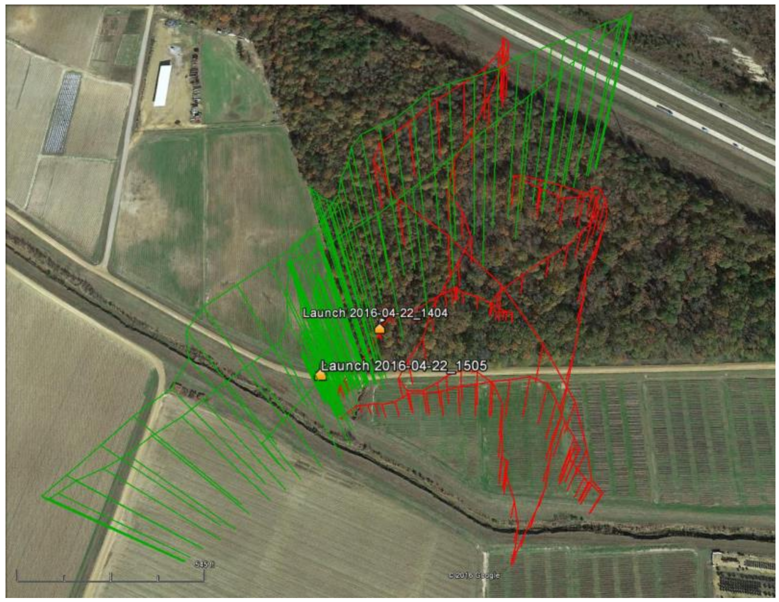

Figure 2. Overview of UAS flights over agricultural research farm on Mississippi State University campus on April 22, 2016. North is towards the top of the image.

The second set of flights took place on April 22, 2016 over an agricultural research farm (a.k.a., North Farm) on the campus of Mississippi State University (MSU; Fig. 2). This location is routinely flown by research teams for precision agriculture applications, and the CoA allowed for a maximum operating altitude of 1000 ft (305 m). The specific area used for this research was on the edge of the farm where the cultivated area was adjacent to a section of mature (though spatially limited) hardwood forest.

A total of two flights were conducted using a custom-built eight motor rotary-wing UAV, with the flights following a straight path with roughly equal distances over the forested and cultivated areas. As with the flights over the Grand Bay NERR, the Windsond sensor package was used for obtaining measurements. The sensor was placed along the top edge of the UAV, with the temperature-humidity probe and antennae placed in the wind stream but directed towards the center of the UAV. This setup was intended to minimize the influence of propeller wash on the readings.

Except for the vertically-oriented flight, the UAS was generally flown at constant altitudes beginning at ~200 ft (61 m), with additional flights every 100 ft (30 m) up to 800 ft (244 m).

Meteorological conditions for the flights were relatively benign, with low-level cumulus building through the afternoon. Surface wind speeds were 10+ miles hour^{-1} (4.5+ m s^{-1}) from the west (~270°) with an approximate temperature of 25°C (77°F) and a relative humidity of 45%, as recorded by a nearby surface recording gauge. These conditions varied slightly during the course of the flights, which took place over a roughly one hour period (14:04 and 15:05 LST).

III. Observational Results

A. Grand Bay National Estuarine Research Reserve (NERR)

The November 20, 2015 flight over the Grand Bay NERR showed a clear indication of north-south oriented variations in all observed meteorological variables (pressure, temperature, and relative humidity; Fig. 3). The boundary between land and water along the coast is visible, where there is a relatively sharp pressure and temperature gradient. This is reasonable, such that the surface temperature should be lower over water and higher over land due to the differences in specific heat, which is the precursor to the onset of a sea breeze boundary. The resulting variation in pressure is what drives the process; therefore, it is expected that the pressure difference exists along the same line as the temperature gradient.

What is most noticeable in the observation fields is the larger north-south oriented pressure and temperature gradient along the west of center of the flight path, where pressure increases substantially (relative to the mean values) and temperature decreases. There is also an increase in relative humidity over the same area, although the variations are relatively small and not as spatially coherent. As seen in Fig. 1, this change occurs over a surface discontinuity associated with land cover, where the vegetation is replaced by an open marshy area. The decrease in temperature indicates that the marshy area leads to a definite change in the surface heat flux, leading to a modification of the lower PBL nearly equal in magnitude to the ocean-land interface to the east and south.

The same general north-south oriented gradients in pressure, temperature, and relative humidity also exist during the November 23, 2015 flight; however, the overall magnitude of the measured values (as well as the resulting

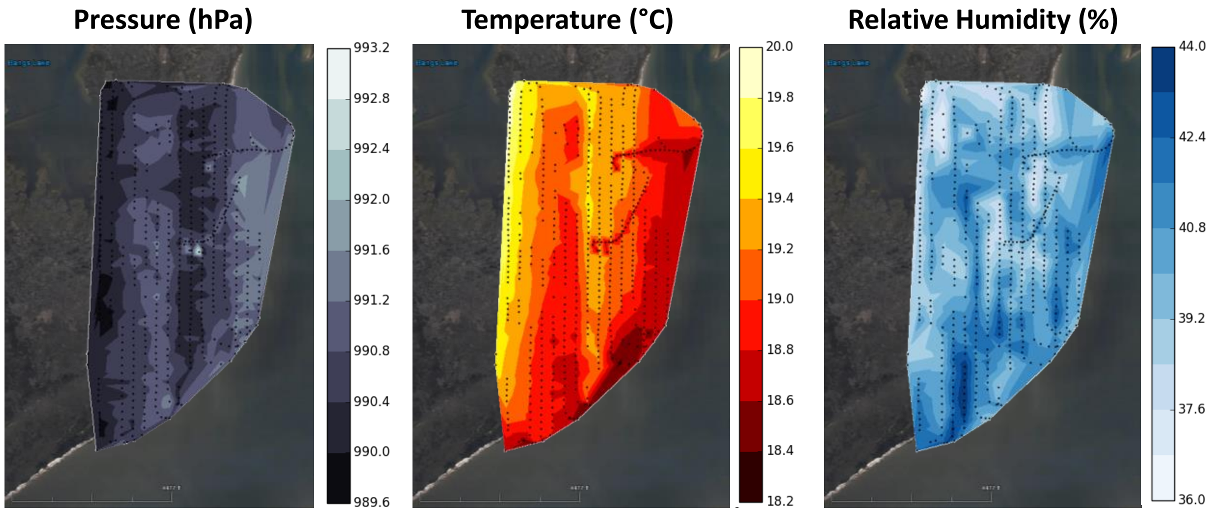

Figure 3. UAS-measured pressure, temperature, and relative humidity at 225m AGL altitude over the November 20, 2015 test flight over Grand Bay NERR test flight. Black points represent UAS observation locations.

gradients) is lower compared to the observations from November 20 (Fig. 4). This is likely a result of increased cloudiness and the onset of lower surface temperatures and relative humidity, which is related to the changes in the synoptic-scale weather patterns (described previously). It is interesting to note that there is no noticeable change in the lower PBL characteristics in relation to the urbanized area to the west of the study area, which should have led to an increase in temperature due to the higher albedo and lower specific heat of that surface type (i.e., concrete, asphalt, etc.). The primary reason for this lack of influence is likely the prevailing northeasterly wind during the study period, which effectively mixed the potentially warmer surface air to the southwest, away from the UAV flight path.

It should be noted that the orientation of the gradients on both days could be related to the orientation of the flight paths. Justification of this possibility can be seen in the local-scale east-west gradients that appear on a local-scale when the UAV has reached cruising altitude but is en route to the start of the sampling run. This is most apparent in the northeast of Fig. 3 and the southwest of Fig. 4. Analysis of this characteristic can only be done with further flight testing, and is left as a topic for future research.

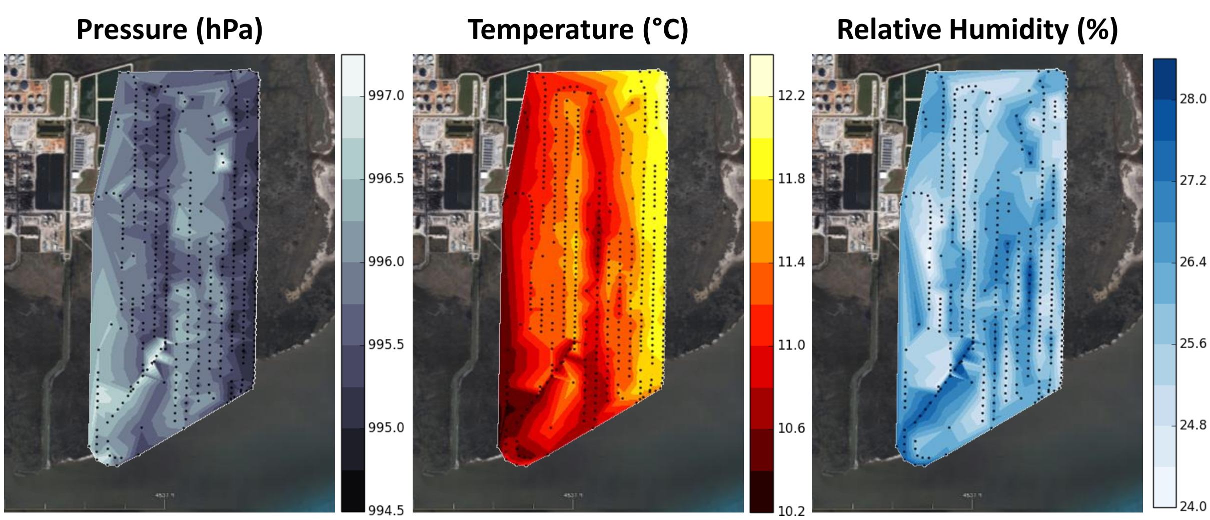

Figure 4. UAS-measured pressure, temperature, and relative humidity at 225m AGL altitude over the November 23, 2015 test flight over Grand Bay NERR test flight. Black points represent UAS observation locations.

B. Mississippi State University Agricultural Research Farm

The UAS flights over the MSU agricultural research farm (a.k.a., North Farm) on April 22, 2016 were conducted in a different manner than those over the Grand Bay NERR, such that they were meant to test the differences in pressure, temperature, and relative humidity between a cultivated area and a forested area along a selected path. The primary reason for the different flight strategy is the expected flight duration, such that the X8 octocopter used for these flights only has a 7-10 minute flight time (as opposed to 60-90 minutes for the Altavian Nova Block 3). As a result, although studies using rotary-wing UAVs do allow for additional flexibility in study location since they can be deployed within a smaller clearing, the resulting flight time is usually much shorter and the study design must change accordingly. This is something that must be taken into account when assessing the operational utility of UAVs for boundary layer observations.

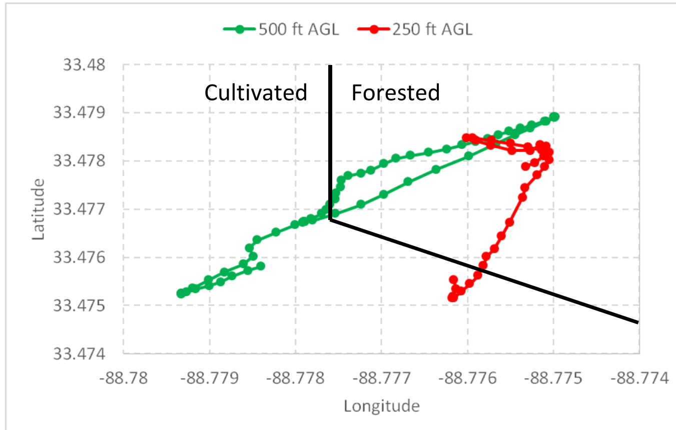

Figure 5. Observation points associated with 250 ft (red) and 500 ft (green) AGL flight paths, conducted on April 22, 2016 at MSU research farm. The colors correspond to the flight paths shown in Fig. 2. Black lines denote approximate boundary of cultivated-forested land cover boundary.

Although data were collected at a variety of altitudes during the two flights on April 22, 2016, the only two continuous and relatively linear paths were at roughly 250 ft (76 m) AGL and 500 ft (152) m AGL. To remove any influences of altitude on the meteorological measurements, and also for the sake of brevity, only these two altitudes were included for analysis. Fig. 5 shows the paths of these flights, along with the relative location of the crop-forest boundary (Fig. 2), as reference for the quantitive analysis of the meteorological variables relative to this boundary. The data from these flights were separated into measurements taken over the cultivated area (a.k.a., crop) and those taken over the forested area (a.k.a., forest). Due to the unequal number of data points over the two land cover types (cultivated and forested), as well as the limited sample sizes, the data were resampled using a bootstrap approach with 10,000 replicates. Using this approach, the datasets can be considered statistically significantly different ($p < 0.05$) if the median of one dataset falls outside the range of the $5^{th}/95^{th}$ percentile of the second dataset.

Based on the results of the bootstrap resampled meteorological data over the two test flights (Fig. 6), the temperature between the crop and forest land cover types at the 250 ft AGL flight level is the only variable that shows statistically significant differences ($p < 0.05$). However, although it is expected that the temperature would be lower over the forested landscape due to the increased latent heat flux such that energy is used for evapotranspiration instead of changing surface temperature, the opposite is true. This could be a result of several factors, both statistical and natural, although likely causes could be the much shorter flight path over the cultivated land for the 250 ft AGL flight (Fig. 5), or mixing of higher temperature near-surface air over the forest due to the extended fetch and moderately strong westerly winds over the cultivated fields. It is difficult to verify either of these statements since pressure and relative humidity do not show any significant differences ($p < 0.05$).

For the data at the 500 ft AGL flight level, none of the measured variables show any statistically significant differences ($p < 0.05$); however, pressure and relative humidity show the largest differences in data ranges, while temperature shows little difference in the overall ranges. This pattern is hypothesized to hold true at some distance above the surface, such that the influence of surface features decreases with height until atmospheric conditions become more related to synoptic-scale conditions than surface characteristics. Despite this hypothesis, though, the height at which surface features no longer play a role in defining atmospheric conditions is not clearly defined, especially due to the influence of a myriad of other variables (i.e., turbulent mixing, variations in solar radiation, UAS equipment sensitivity, etc.). Based on the moderate low-level wind speeds recorded on April 22 at the test location, it is expected that any changes in atmospheric conditions related to land cover type would be dampened through turbulent mixing within the PBL; however, further justification of this fact requires additional observations.

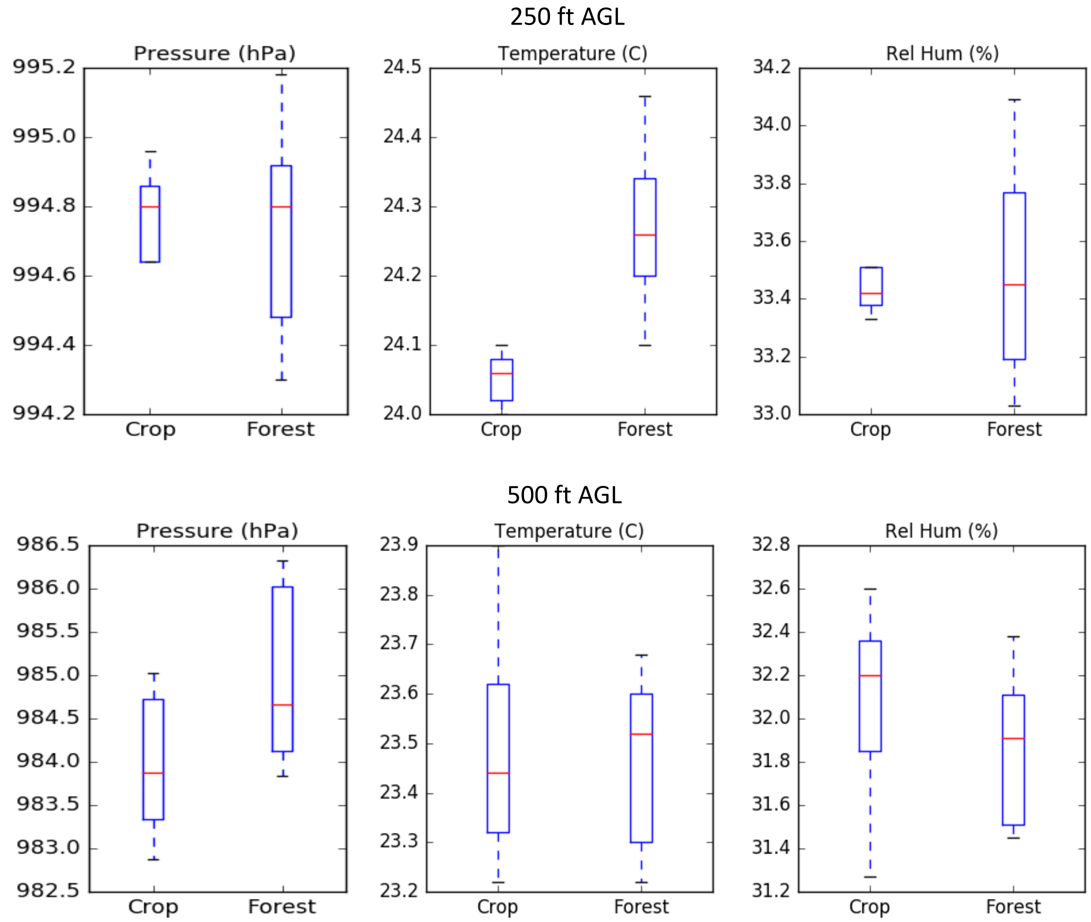

Figure 6. Box and whisker plots of bootstrap resampled meteorological data over crop and forest land covers measured at 250 ft and 500 ft AGL UAS flights over MSU research farm. The median of each plot is donated by the horizontal red line, the limits of the box are the 25th/75th percentiles, and the whiskers denote the 5th/95th percentiles.

IV. Conclusion

The relationship between surface land cover characteristics and lower atmospheric conditions, especially within the planetary boundary layer (PBL), is generally defined through the surface energy and moisture fluxes; however, specific influences are difficult to quantify due to limitations in rapid spatial and temporal sampling of related atmospheric variables. This study utilizes small unmanned aerial systems (UASs) as a means for sampling lower PBL features (i.e., pressure, temperature, and relative humidity) in relation to varying land use/cover types in both a coastal and an agricultural setting.

Sampling in the coastal location involved measurements in the Grand Bay National Estuarine Research Reserve (NERR) using a fixed-wing UAS flying a north-south oriented path at 800 ft AGL on November 20 and 23, 2015. Results indicated that the UAS was able to define temperature and pressure boundaries associated with the land-ocean interface, as well as variations associated with a marshy area. In both cases, temperature was lower over the water surface, which is reasonable and expected given the higher latent heat fluxes over those surface types. Despite the measurement of these boundaries, data patterns associated with the UAS flight path showed that there were biases in the measurement associated with the specific flight path and sensors used in the experimental design. Unfortunately the only way to quantify these biases is to compare the results of additional flight, which is the next step in this research.

Sampling in the agricultural environment was done over a research farm on the Mississippi State University (MSU) campus – specifically along a boundary between cultivated and forested land. Such a location allowed for an assessment of the meteorological changes associated with varying land cover type. For these tests, which took place on April 22, 2016, a rotary-wing UAS was utilized to conduct straight-line, constant-altitude (250 ft and 500 ft AGL) flights across the land cover interface. The resulting data were then statistically analyzed after a bootstrap resampling procedure to define differences in pressure, temperature, and relative humidity at a 95% confidence interval. Results indicate that the only statistically significant difference ($p < 0.05$) occurred in the temperature field at 250 ft AGL, while all other variables at all levels showed no difference. Despite the recorded difference in temperature, though, it is difficult to conclude that the result was based on natural variations instead of statistical bias associated with unequal spatial sampling.

Although the results of this research are limited, they provide a good description of where and how additional PBL measurements using small UASs can be beneficial over a variety of landscapes and flight strategies. Many studies of the PBL utilizing UASs focus on changes in atmospheric characteristics with altitude at a specific location, such as what is found using a balloon-mounted radiosonde. Although interesting and potentially useful, UASs offer a unique measurement platform that can be used in conjunction with (instead of in place of) existing balloon radiosondes to gain a better understanding of local PBL variations, and with the right equipment and flight permissions, variations within the entire troposphere.

Using the information from this study, the next logical research goal is to repeat the experiments and gather additional data for comparison. Since the amount of data available for analysis is relatively small, the focus on future research efforts should be maximum sampling and data acquisition. However, these sampling efforts should be based on defined flight strategies and statistical analysis procedures for maximum scientific benefit. This will maximize the amount of useful data obtained through the UAS missions, and allow for specific research questions to be answered in relation to surface-atmosphere interactions and influences.

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