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TRACER-Uncrewed Aircraft System (TRACER-UAS) Field Campaign Report

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Acronyms and Abbreviations

ABL	atmospheric boundary layer
AGL	above ground level
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
CBL	convective boundary layer
CLAMPS	Collaborative Lower Atmospheric Mobile Profiling System
CSAPR	C-Band Scanning ARM Precipitation Radar
DOE	U.S. Department of Energy
IOP	intensive operational period
NEXRAD	Next-Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NWR	National Wildlife Refuge
POPS	printed optical particle sensor
SB	sea breeze
SGP	Southern Great Plains
SPARC	Space Science and Engineering Center Portable Atmospheric Research Center
sUAS	small uncrewed aircraft system
TBS	tethered balloon system
TRACER	Tracking Aerosol Convection Interactions Experiment
UAS	uncrewed aircraft system
UCB	University of Colorado-Boulder
UH	University of Houston
UO	University of Oklahoma
UTC	Coordinated Universal Time

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1.0 Summary

Convective processes drive the development of clouds across a variety of scales, thereby playing a central role in governing weather and climate globally. These processes help to set the stage for circulations that redistribute heat and moisture throughout the lower atmosphere, and simultaneously develop storms that supply precipitation to regions that depend on such rain events for supporting a variety of societal needs. At the same time, extreme precipitation events can result in localized flooding of low-lying areas, posing hazards to transportation and regional inhabitants, and potentially damaging structures and infrastructure. As a result, there is an inherent need to better understand the drivers and modulators of clouds and precipitation and leverage such understanding to make projections of how these important systems may evolve with a changing climate. With nearly three billion of Earth's human inhabitants living within 200 km of a shoreline, development of such understanding is particularly important in coastal regimes.

Central drivers of convective cloud development and life cycle in coastal environments include synoptic forcing, local meso- and microscale circulation regimes, microphysical evolution, and aerosol properties. Atmospheric boundary layer (ABL) development and its evolution can help drive the formation and organization of convective clouds, which then impart their own controls through dynamic processes related to latent heating and cooling (including cold-pool formation and propagation), three-dimensional radiative effects, and background environmental conditions (Fan et al. 2016). Such clouds have been contributing to record precipitation events in southeast Texas in recent years, relative to the last several decades of data from regional precipitation gauges (Fagnant et al. 2020). The greater Houston urban area has experienced particularly large increases in the frequency of extreme rainfall events, with enhanced intensity of extreme events (stretching of distribution tails) having potentially significant implications for watershed floodplain planning and mapping in greater Houston and Harris County. While the most extreme precipitation events were associated with tropical cyclones (e.g., Tropical Storm Allison and Hurricane Harvey; Blood 2014, Kao et al. 2019), strong thunderstorms can also deliver large amounts of precipitation over the area over relatively short periods.

To better understand the complicated web of processes governing convective cloud life cycle and aerosol-convection interactions, the U.S. Department of Energy (DOE)'s Atmospheric Radiation Measurement (ARM) user facility supported deployment of various advanced atmospheric measurement systems to the greater Houston area from 1 October 2021 to 30 September 2022 as part of the TRacking Aerosol Convection interactions ExpeRiment (TRACER). Houston was selected as a study area because isolated convection and a variety of aerosol conditions are common in this region (Wang et al. 2022). This one-year AMF deployment featured a four-month intensive operational period (IOP) during summer 2022 (1 June-30 September). The ARM instrumentation was deployed at three sites along an east-west transect from La Porte, Texas to an ancillary site in a less-polluted, rural region southwest of downtown Houston (Figure 1).

Figure 1. Map of the instrumented sites during the DOE TRACER experiment. This includes the different ARM sites and the National Weather Service Next-Generation Weather Radar (NEXRAD; orange diamonds); two sites featuring deployments of additional boundary-layer profiling systems (Collaborative Lower Atmospheric Mobile Profiling System [CLAMPS]; University of Houston [UH] Coastal Center and Aldine, blue circles) and the University of Wisconsin's Space Science and Engineering Center Portable Atmospheric Research Center [SPARC]; orange, collocated with the C-Band Scanning ARM Precipitation Radar [CSAPR]); and the TRACER-Uncrewed Aircraft Systems (UAS) operations sites (UH Coastal Center and Lemon/McCormack Reservoirs) during the IOP in the summer of 2022 (background map from Wang et al. 2022).

At the La Porte site, which is located near the Houston ship channel in an area that experiences significant polluted conditions, the first ARM Mobile Facility (AMF1), was deployed. AMF1 instruments included a vertically pointing Ka-band radar and a scanning dual-frequency Ka- and X-band radar to measure properties of cloud and precipitation particles. High-frequency radiosondes (weather balloons) were launched to monitor quickly evolving thermodynamic and kinematic conditions near convective cells. An instrumentation suite for aerosols collected measurements of their cloud-nucleating properties, radiative properties, composition, and size distribution, as well as information on key trace gasses. During the IOP, the ARM tethered balloon system (TBS) operated at the ancillary site. The second-generation ARM CSAPR) operated near Pearland, Texas, roughly half-way between the Laporte and ancillary site.

As part of the TRACER IOP period, teams from the University of Colorado-Boulder (UCB) and University of Oklahoma (UO) collaborated to deploy small uncrewed aircraft systems (sUAS) to collect measurements of the lower atmosphere. This collaboration included staggered deployments with the UCB fixed-wing RAAVEN sUAS (see de Boer et al. 2022 and Cleary et al. 2022 for more details on the RAAVEN) and the UO CopterSonde (Segales et al. 2020), a rotary-wing UAS. Both platforms were cleared by the U.S. Federal Aviation Administration to conduct flight operations up to 2000 feet (~610 m) above ground level. A diagram illustrating the general plan for deploying UAS during TRACER is shown in Figure 2.

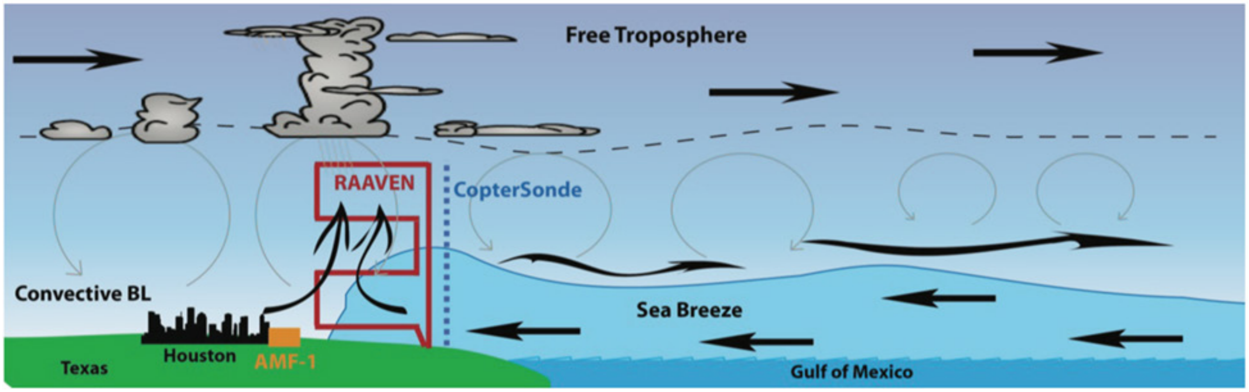

Figure 2. An illustration of the general sampling pattern to be undertaken during the TRACER-IOP field campaign by the two UAS platforms.

For TRACER, the RAAVEN was equipped with a flux payload, providing high-resolution (100 Hz) measurements of horizontal and vertical wind; fast-response temperature, pressure, and humidity information; and information on surface and sky infrared brightness temperature (to detect cloud and surface temperature gradients). Additionally, RAAVEN was instrumented with a Handix Scientific/NOAA Chemical Sciences Laboratory printed optical particle sensor (POPS), which provided high-temporal-resolution observations of the aerosol size distribution between 150 and 2500 nm. Each platform deployed for approximately two weeks per month, with an intentional stagger between the two platforms to offer roughly three weeks of flight coverage per month between June 1 and September 30, and some limited overlap between the two platforms. Data were collected at two primary sites in the sampling region, including at the University of Houston Coastal Center and near the Brazoria National Wildlife Refuge (NWR) southwest of Houston (blue rectangles in the southern portion of Figure 1). Flights conducted by the two platforms at the Brazoria NWR were separated by approximately 1.5 miles horizontally, offering limited insight into spatial gradients in this location.

Data from these two platforms provide ABL profile observations at unprecedented temporal and spatial resolutions in this coastal urban environment. The RAAVEN was generally operated three times daily, with targeted launch times of 9:00, 11:30, and 14:00 local time. These times offered perspectives on the developing ABL in the morning, sometimes including insights into elevated stable layers and low-level jets, the morning convective boundary layer (CBL), and the afternoon sea breeze (SB) layer (when present). RAAVEN flights were conducted with a repeated flight pattern that included an initial profile up to the maximum allowable flight altitude (2000 feet or 500 feet below cloud base), a series of 9-minute legs to capture statistics at several different altitudes (600 m, 400 m, 250 m, 150 m, 100 m, 50 m, 20 m) and a second profile at the end of the flight (if sufficient battery power remained). The CopterSonde was operated at a 30-minute frequency, collecting regular profiles of temperature, pressure, humidity, and winds between the surface and 2000 feet. During events of interest, this cadence was increased to 15-minute windows, providing very high-resolution insight into evolving atmospheric structure and its variability.

In addition to the activities conducted in the greater Houston area, the TRACER-UAS team conducted pre-deployment evaluation flights at the ARM Southern Great Plains (SGP) observatory in Oklahoma. These flights were aimed at ensuring that the two UAS platforms to be deployed to Houston both provided high-quality, consistent data that could be used to support atmospheric research efforts as part of TRACER. In the spring of 2021, the UCB and UO teams spent nearly a week (2-8 April) conducting flight activities alongside ARM radiosondes and the ARM 60-meter tower at SGP. The SGP flight activity is discussed in detail in de Boer et al. 2023.

2.0 Results

The UCB RAAVEN conducted 131 flights over 47 days during the TRACER-IOP period around Houston, collecting 187 flight hours of scientific data, and 251 total profiles. The OU CopterSonde completed 546 total flights over 33 days, totaling 56 flight hours and 544 individual profiles. These flights occurred during daylight hours and covered altitudes between the surface and 2000 feet AGL (see Figure 3).

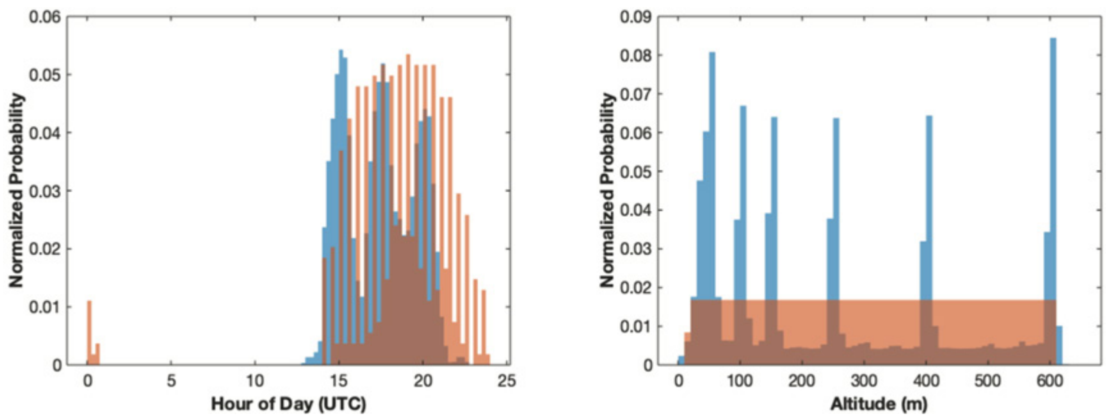

Figure 3. Normalized histograms showing the times of day (left) and altitudes (right) sampled by the two UAS platforms. RAAVEN flight data are represented in blue, and CopterSonde data are shown in red.

Initial screening of the data reveals numerous cases with coastal circulations, local convective initiation, and interesting boundary-layer features such as strong nocturnal low-level jets. A summary of project statistics is provided in Table 1.

Table 1. Overall flight statistics for the TRACER-UAS field campaign.

	UCB RAAVEN	OU CopterSonde
Total flight days during the TRACER IOP	47	33
Total flights (flight hours) during the TRACER IOP	131 (187)	546 (56)
Number of profiles during the TRACER IOP	251	544
Days with bay breeze (BB) or gulf/sea breeze (SB) circulations detected	17	15
Cases with local convection initiation due to BB/SB	TBD	5
Nocturnal low-level jet with $ULLJ$ > 10 m/s	5	10
Total flights (flight hours) during the SGP intercomparison	15 (18.3)	43 (6.2)

Over the course of the campaign, the two platforms sampled a variety of atmospheric conditions. Figure 4 provides histograms illustrating the range of temperature, humidity, and wind conditions sampled by the two UAS platforms. While these distributions are generally similar, it is important to note that the platforms did not fly on exactly the same days. Therefore, there are some differences between the observations. Notably, the RAAVEN sampled later into September, which included colder mornings, as visible in the left edge of the temperature distribution. Additionally, the different sampling patterns executed by the two platforms, with the CopterSonde conducting routine up/down profiling, and the RAAVEN also including fixed-altitude legs to collect statistics on atmospheric variability, show up in these histograms from the two platforms, which take slightly different shapes.

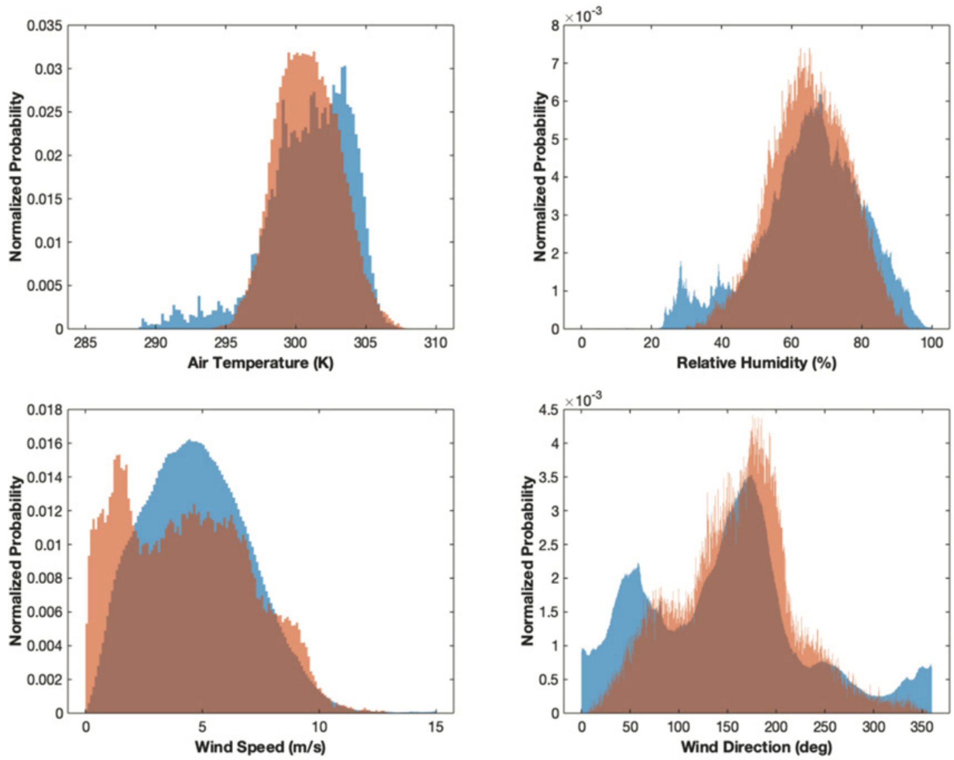

Figure 4. Histograms showing the range of temperature, humidity, and wind conditions sampled by the RAAVEN and Coptersonde during TRACER-UAS. The RAAVEN observations are represented in blue, and the Coptersonde observations are represented in red.

As an example of the richness of the UAS data set, Figure 5 shows an example of data from the UCB RAAVEN for 25 July 2022. In this particular case, the Gulf of Mexico sea breeze likely played a role in the initiation of convective cells based on radar data. On this day, convection initiates in a quiescent environment with no surrounding synoptic-scale boundaries or prior convection. As the gulf breeze reaches the coastline, a convective cell develops close to the shoreline southwest of Houston. This cell dissipates, but new convection arises again a couple of hours later as the gulf breeze front reaches downtown Houston. With the passage of the gulf breeze front, wind speed increased at the UH Coastal Center. Looking at the details of Figure 5, the top five panels show time-height cross-sections of several variables, demonstrating their evolution over the daytime hours. On this particular day, four RAAVEN flights were conducted because the second flight had to be cut short due to intense precipitation associated with the convective cell that formed around 17:00 UTC. There are several notable features, including a shift in wind speed and direction associated with the passage of the gulf breeze front, a general drying of the atmosphere after the passage of the precipitating cell, a decrease in particle concentration from the onboard aerosol spectrometer after the passage of the precipitation, and general reductions in ABL growth with the passage of the SB. The sixth panel from the top shows the sky infrared brightness temperature, with spikes indicating the presence of clouds overhead of the RAAVEN. Finally, the bottom three panels show examples of additional insight that can be gained from the RAAVEN, including the horizontal velocity variance, the vertical velocity distributions, and the aerosol particle size distribution between 150 and 2500 nm. These show a clear increase in turbulence, a broadening of the vertical velocity distribution, and a decrease in the total number of particles (and specifically of the smaller aerosols) for the later flights relative to the earlier flights.

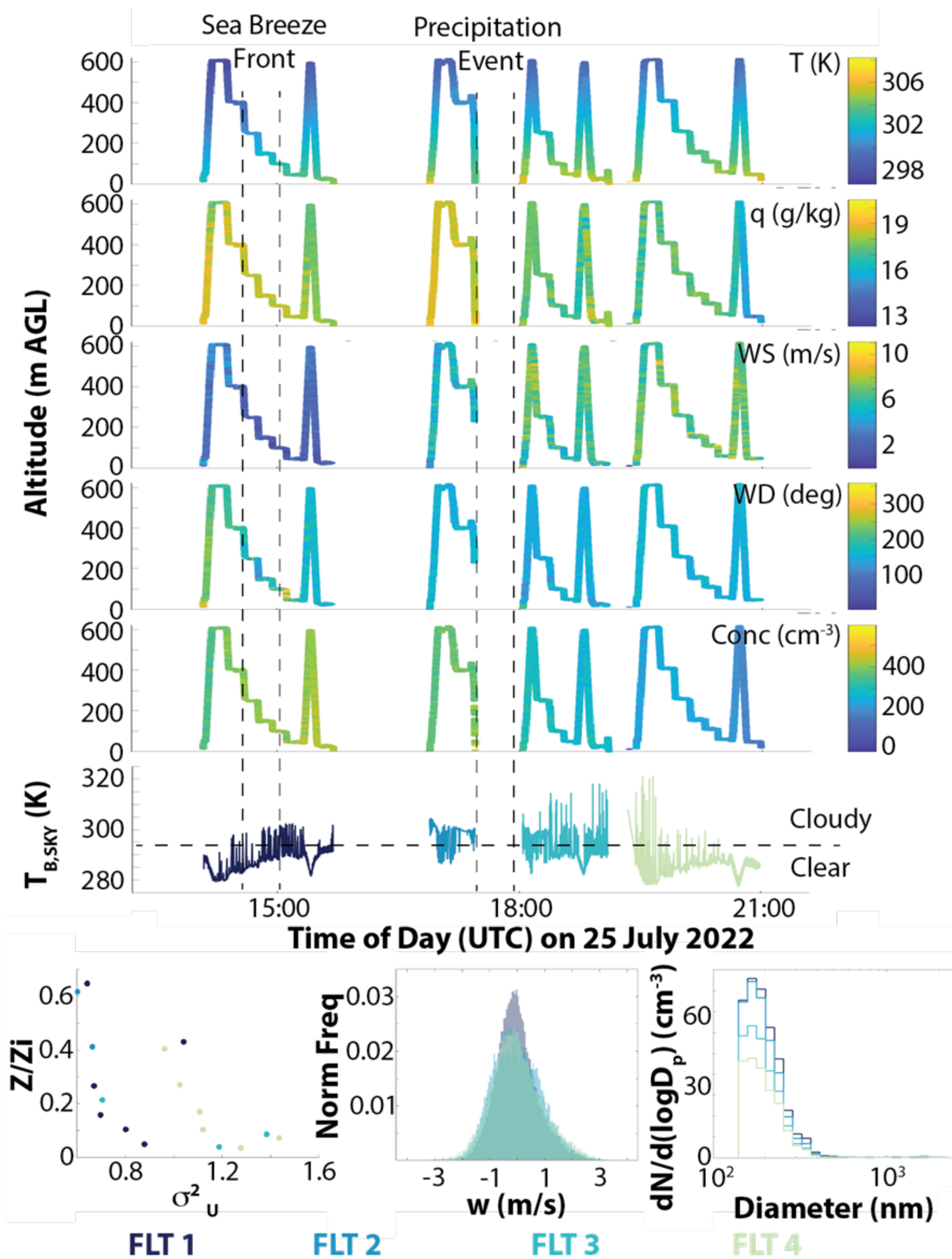

Figure 5. An example of RAAVEN data collected on 25 July, 2022. The figure includes detailed information on (from top to bottom) temperature, humidity, wind speed, wind direction, aerosol particle concentration, sky infrared brightness temperature, and wind.

Seen in Figure 6, data from the CopterSonde illustrates the ABL evolution as a function of the morning transition as well as the SB passage. The morning began with very weak flow and rich moisture near the surface. Around 15:00 UTC, moisture begins to be transported vertically with buoyant mixing and the transition to a convective boundary layer. At 18:45 UTC, southeasterly flow accelerates, coinciding with an increase in water vapor throughout the layer. While moisture remains higher than pre-SB passage, there is a decline in overall water vapor through the remainder of flights. The cooling from the SB is most noticeable in the potential temperature but is overall a small change. Although the SB is rather weak with less than 5 m s^{-1} winds, the moisture advection is distinct, leading to a 2.5 g kg^{-1} increase in 15 min.

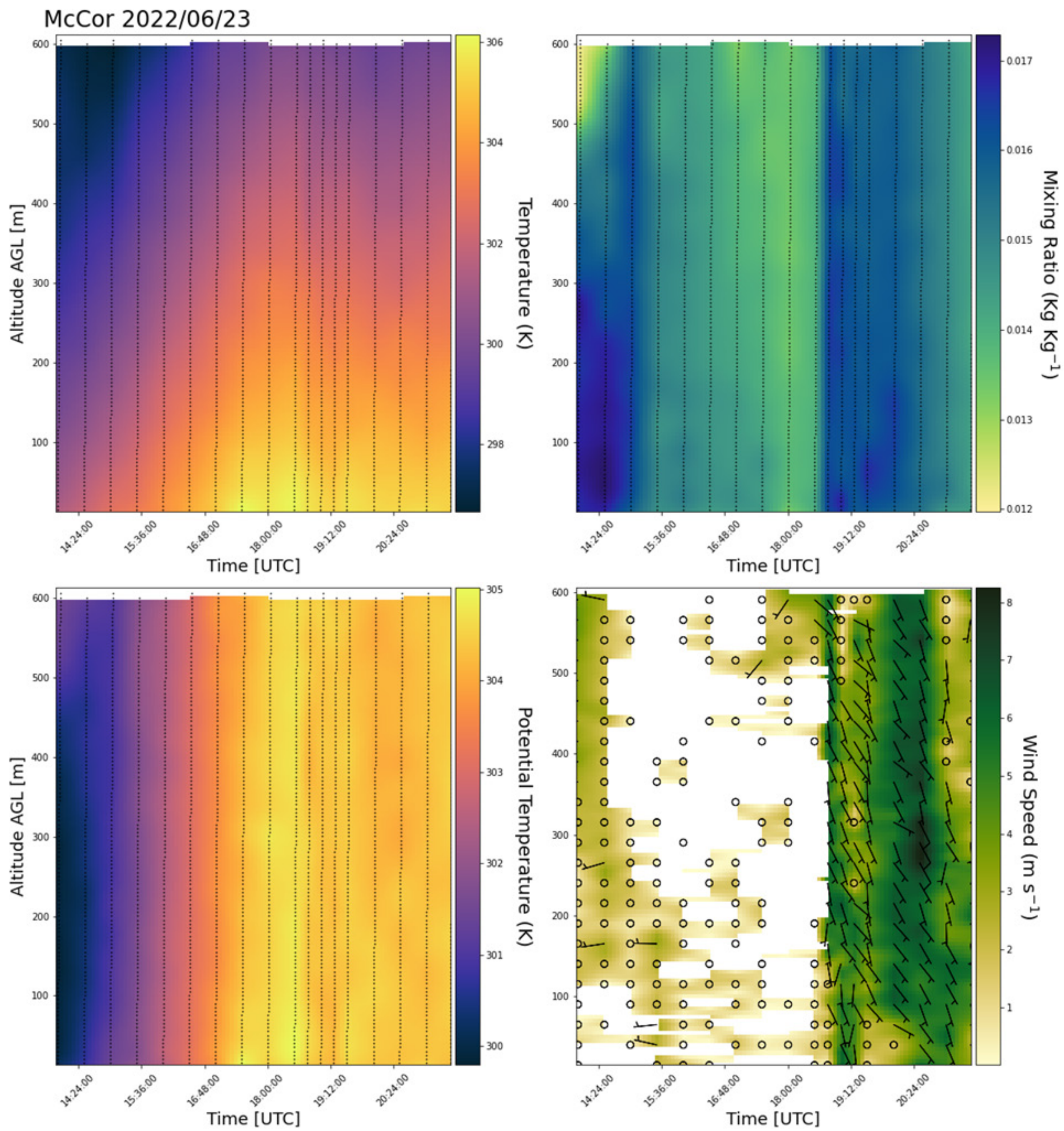

Figure 6. An example of data collected by the OU CopterSonde on 23 June, 2022. The figure includes temperature, water vapor mixing ratio, potential temperature, wind speed, and direction (from top left to bottom right).

Detailed analysis of this rich data set will help to improve our fundamental understanding of processes governing evolution of the atmospheric boundary layer and convective storms in coastal Texas, including the influences of the sea breeze, urban heat island, and aerosols. Some specific research directions that the TRACER-UAS data should be able to help to inform include:

- Classification of the ABL structure during the TRACER IOP based on synoptic conditions, gulf breeze and bay breeze circulations, and convective storm evolution.
- Investigation of the evolution of the gulf and bay breeze circulations across the greater Houston area to identify how they change the ABL structure, including turbulence and fluxes.
- Classification of Houston urban heat island intensity and its spatial evolution across the greater Houston area and investigation into its role in modulating ABL processes.
- Investigation of the relationships between aerosol properties and synoptic weather conditions, ABL vertical structure, and local circulation regimes.
- Identification of the relative roles of synoptic conditions, local circulations and related changes in the ABL structure and aerosol properties on development and convective storm intensification in the greater Houston area.

Finally, TRACER-UAS included a targeted effort, conducted at the ARM SGP facility, to document the performance of different small UAS platforms used broadly for atmospheric science experiments. Such efforts represent a key step towards widespread adoption of small UAS in atmospheric science, including in field campaigns designed to advance process-level understanding like TRACER. The platforms evaluated as part of this effort included two fixed-wing systems (including the UCB RAAVEN) and three rotary-wing systems (including the OU CopterSonde), and include both custom systems developed in university settings and commercially available aircraft. The evaluations themselves included comparisons between sUAS observations and those from radiosondes launched at the same location as the sUAS operations and an instrumented 60-meter tower on site, and intercomparison between different platforms.

These efforts show that all platforms provide reasonable measurements of atmospheric state (see Figure 7). The absolute values of mean temperature biases over these flights ranged from 0.24 to 1.88 K with standard deviations between 0.1 and 0.7 K. Absolute values of air pressure mean biases ranged from -3.58 to -0.57 hPa, with standard deviations ranging from 0.23 to 1.33 hPa. Absolute values of mean mixing ratio biases ranged between 0.03 to 0.61 g kg^{-1} with standard deviations between 0.17 and 0.45 g kg^{-1}. When combined with pressure and temperature measurements, this resulted in mean absolute value relative humidity biases between 1.62 and 5.34% (standard deviations between 1.37 and 5.82 %). For the platforms reporting wind estimates, mean absolute value wind speed biases ranged between 0.07 and 0.7 m s^{-1}, with standard deviations between 0.73 and 2.14 m s^{-1}, and mean absolute value wind direction biases ranged from 1.15 to 6.3 degrees (standard deviations 6.45 to 14.75 degrees). These values were derived over several hundred (360-1360) points of comparison per platform. Comparisons to the tall tower showed similar results, though there were some challenges related to maintaining the tower altitude over extended time periods, and it is possible that some of the biases in the tower comparison were the result of small altitude offsets.

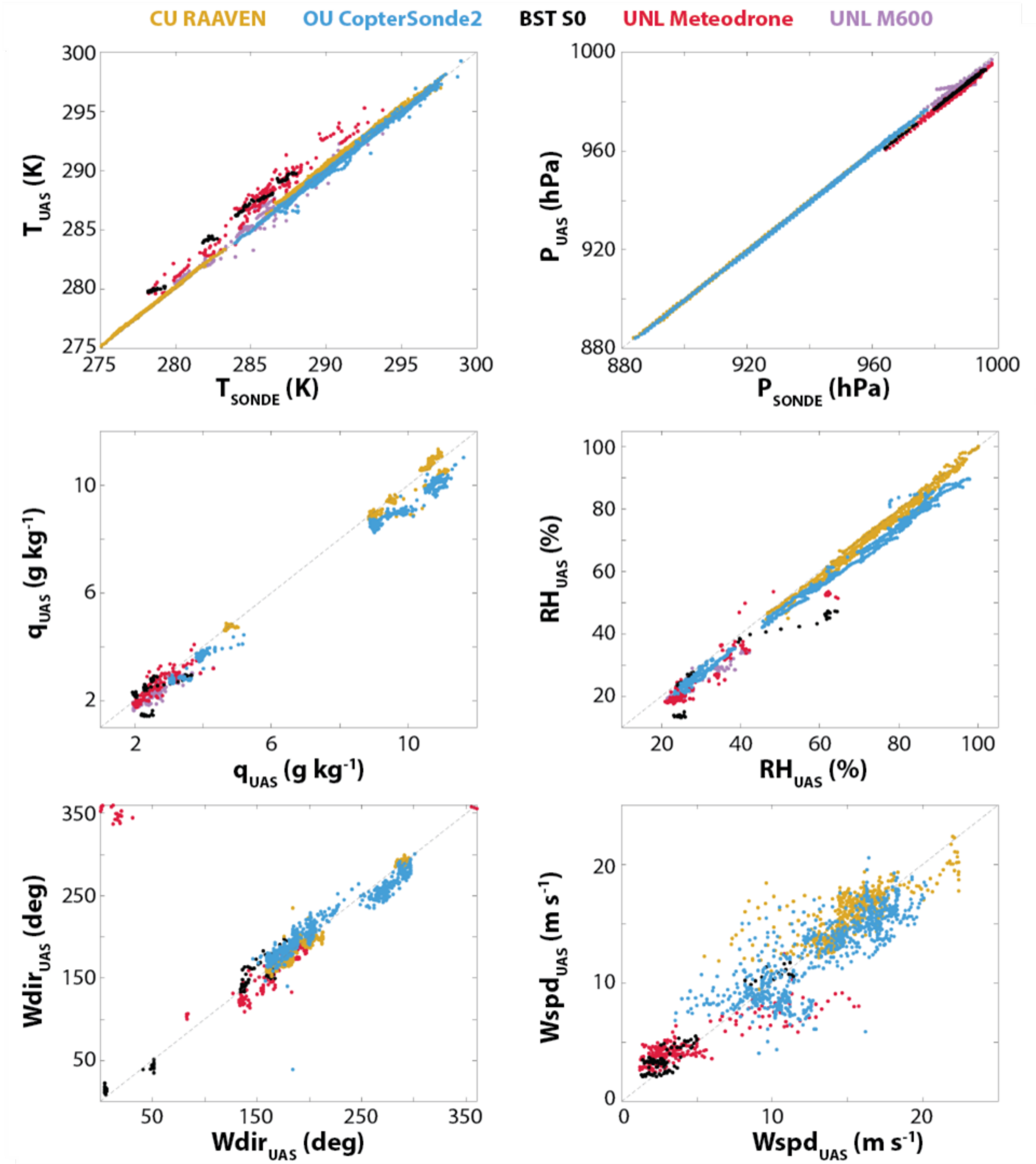

Figure 7. Results of comparisons between different small UAS platforms and radiosondes launched at the ARM SGP facility as part of TRACER-UAS (from de Boer et al. 2023).

In addition to these evaluations, the SGP intercomparison effort provided some of the first detailed comparisons of turbulent fluxes of heat and momentum calculated through eddy dissipation techniques for platforms that provide high-resolution data of the vertical velocities (see Figure 8). These evaluations revealed that at least one of the platforms (UCB RAAVEN) provided reasonable estimates of momentum and heat fluxes and their variability over time, relative to the ARM tower. Comparisons of the co-spectra derived from these flight legs generally show comparable spectral power to that derived from the sonic anemometer on the tower across different sampling frequencies, though there was a bit more noise in the sUAS spectra than the tower. The cause of this elevated noise is a continued subject of investigation.

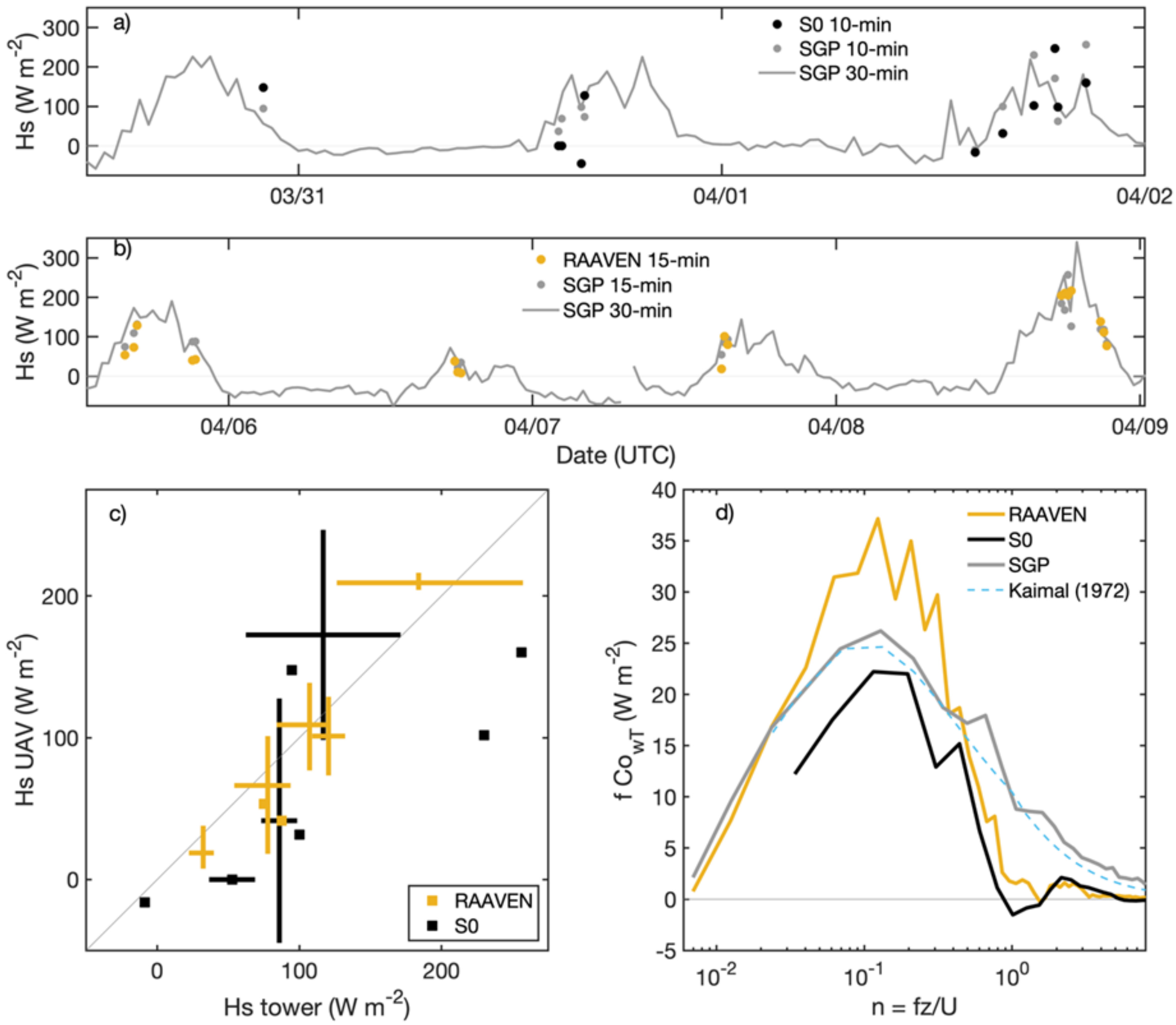

Figure 8. Comparisons of sensible heat fluxes measured by the UCB RAAVEN, the Black Swift Technologies S0, and the ARM SGP tower (from de Boer et al. 2023).

Ultimately, we believe that this intercomparison activity was worthwhile and informative, and supported the notion that sUAS are a research-ready observational capability that should continue to be considered for future field campaigns targeting atmospheric phenomena. Additionally, we believe that such intercomparisons are valuable and should be supported, wherever possible, in connection with funded field projects to ensure that the sUAS to be operated are providing reasonable information. This also requires investment in infrastructure for such intercomparison. In this case, we leveraged sensors deployed as part of routine operations at the ARM SGP facility, though it would be beneficial to have several such sites distributed across the country and world to foster additional verification efforts.

3.0 Publications and References

3.1 Project Publications to Date

de Boer, G, B Butterworth, J Elston, A Houston, E Pillar-Little, B Argrow, T Bell, P Chilson, C Choate, B Greene, A Islam, R Martz, M Rhodes, D Rico, M Stachura, F Lappin, S Whyte, and M Wilson. 2023. "Evaluation and Intercomparison of Small Uncrewed Aircraft Systems Used for Atmospheric Research." *Atmospheric and Oceanic Technology*, submitted.

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3.2 Project Data Sets to Date

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3.3 Project Presentations to Date

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