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PUSH THE BOUNDA

RIES

The use of small unmanned aerial systems to provide boundary layer measurements is now within reach

The advent of the small unmanned aerial system (sUAS) for atmospheric research promises to provide new opportunities for meteorological measurements in the lowest levels of Earth's atmosphere. Potential applications of this technology are wide-ranging, including measuring profiles of temperature and relative humidity, remote sensing of small-scale surface features, performing storm damage assessment, and measuring wind and turbulence in the lowest levels of the boundary layer.

Although overcoming regulatory challenges can still be difficult, the operation of sUASs on a somewhat regular basis is now within reach of most institutions. Moreover, technology has coalesced in recent years to make this possible. Developments such as inexpensive multirotor aircraft, miniature global positioning systems integrated with inertial navigation systems (GPS/INS), autopilots that enable hands-off flight operation, and a new crop of miniature meteorological and remote sensing devices, have combined to provide the scientific community with unprecedented opportunities for innovative meteorological observations using sUASs.

Figure 1: **Test flight of the DJI S-1000 multirotor aircraft at Knox County Radio Control model flying field at Oak Ridge, Tennessee**

Multirotor sUASs are ideal for addressing the dynamics of land-atmosphere interactions in the lower boundary layer. These UASs are unique in that observations can be obtained both vertically and horizontally, producing accurate and repeatable low-cost measurements of the temperature and moisture fields. The diurnal development of the vertical temperature and humidity profiles in the boundary layer is linked to the aggregated sensible and latent heat fluxes at the land surface, thus enabling a better understanding of convective initiation. With the ability to profile temperature and relative humidity in the lower boundary layer while mapping the thermal land surface temperature with infrared cameras, these sUASs provide an inexpensive platform that can be used to link the dynamics of a developing boundary layer to observed changes in the heat and water fluxes at the land surface.

These systems are ideal for measuring profiles because they can hover at different elevations and provide a critical link between *in situ* measurement scales (meters) and satellite remote sensing scales (kilometers). UASs offer advantages over other methods (e.g. balloons, radiosondes and tall towers) for atmospheric profiling because they can capture the temporal and spatial heterogeneities of the boundary layer horizontally and vertically. Unlike balloons, they are also recoverable and reusable. Furthermore the flexibility, comparative low cost, and ease of UAS deployment overcomes many of the limitations of the temporal 'snapshot' provided by manned aircraft.

SMALL UAS TESTING

NOAA's Atmospheric Turbulence and Diffusion Division (NOAA/ATDD) in Oak Ridge, Tennessee, USA, has acquired a DJI S-1000 multirotor aircraft to test and evaluate as a meteorological measurement platform. It is operated with approval from both the Federal Aviation Administration (FAA) and NOAA's Aircraft Operations Center (NOAA/AOC) under visual flight rules (VFR), during daylight hours and within sight of the pilot.

The S-1000 and its accompanying suite of sensors are being tested at the Knox County Radio Control (KCRC) model flying field in Oak Ridge (Figure 1). The tests address the following questions: How can local data acquired by an sUAS be validated and used to better understand boundary layer

The VORTEX-SE field study

At the end of February 2016, research began on the latest Verification of the Origins of Rotation in Tornadoes EXperiment-Southeast (VORTEX-SE) project to collect data on tornadoes. The project, which will be held in northern Alabama throughout March and April, has been coordinated by NOAA's National Severe Storms Laboratory. The goal of the study is to understand how environmental factors in the southeastern United States affect the formation, intensity, structure and path of tornadoes, as well as determine the best methods for communicating forecast uncertainty to the public.

The VORTEX-SE field study will involve 40 physical and social science researchers from 20 research entities. They will deploy radars, weather balloons and a sUAS that will be flown by NOAA Air Resources Laboratory, Atmospheric Turbulence and Diffusion Division. The sUAS will be used to survey storm damage and provide key atmospheric data that can be used to understand how the land surface may play a role in tornadogenesis.

"In many ways, VORTEX-SE represents a new approach to tornado research in general," says Erik Rasmussen, VORTEX-SE project manager and research scientist for the University of Oklahoma's Cooperative Institute for Mesoscale Meteorological Studies working at the NOAA National Severe Storms Laboratory. "This is the first field observing campaign in the southeast US to begin to understand how the atmosphere can become locally favorable for tornadoes and how these changes can be better anticipated in the tornado forecast process."

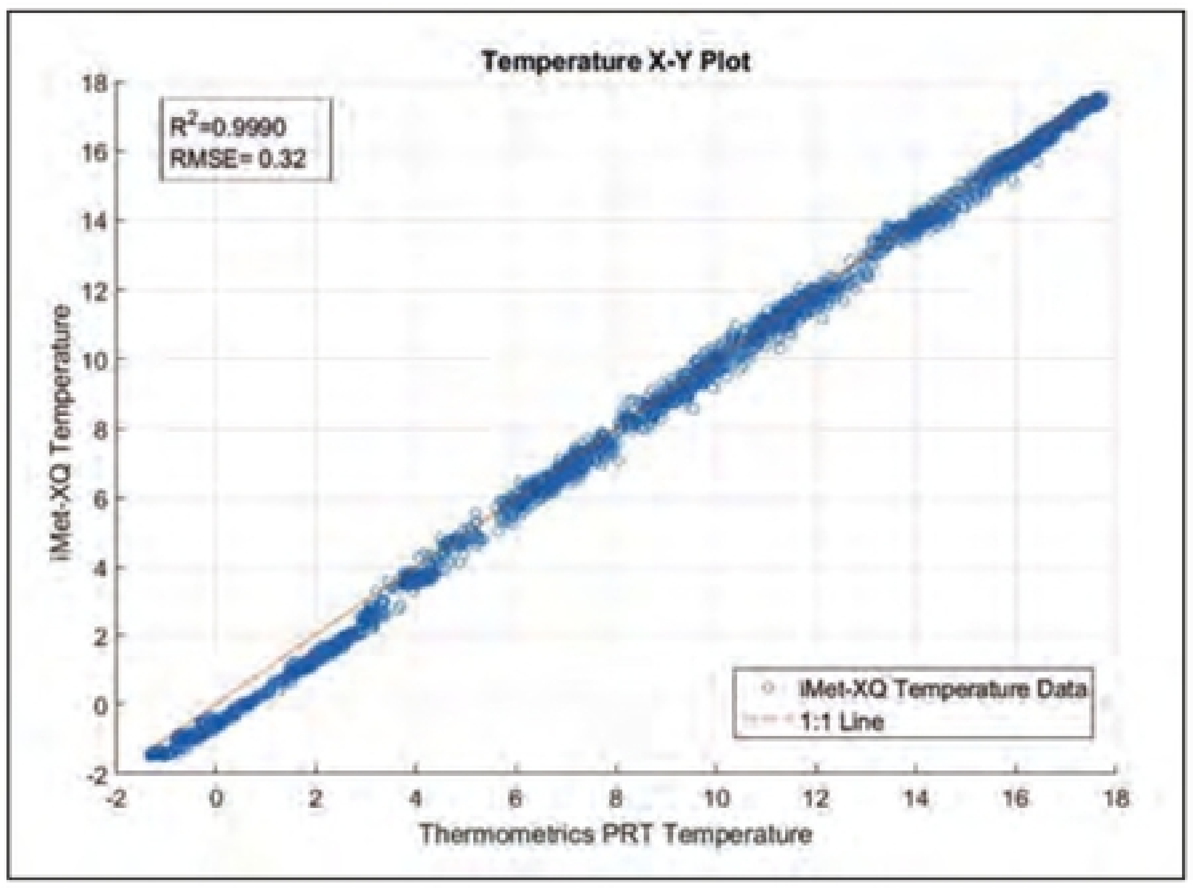

Figure 2: **Aspirated, filtered iMet-XQ temperature data versus Thermometrics platinum resistance thermometer**

evolution during the formation of severe storms? Can sUAS measurements be scaled to measure mesoscale atmospheric patterns and trends? What advances in concept of operation (CONOPS) requirements are necessary to feasibly operate sUAS as a meteorological diagnostic tool in the pre-storm/tornado environment for evaluation and experimental forecasting?

A meteorological tower has been installed at KCRC to provide instruments traceable to the National Institute of Standards and Technology (NIST) for comparison with instruments on the S-1000 including temperature, relative humidity and pressure. Data from each instrument is recorded every 10 seconds and transmitted to NOAA/ATDD every five minutes. The latest data is available at www.eddumas.com/kcrc. The tower is adjacent to a clear portion of the field, enabling the S-1000 to hover within a few meters of the tower sensors.

The S-1000 is fitted with four International Meteorological Systems iMet-XQ temperature, relative humidity and pressure sensors, as well as a FLIR infrared camera and a GoPro visible-light camera to document the surface below the vehicle in multiple wavelengths. The iMet-XQ sensors are self-contained units that include onboard GPS and log data at 1Hz. The FLIR Tau 2 camera uses a TeAx data storage module that records images at 7.5Hz.

The S-1000 has been used to make measurements while performing vertical profiles, horizontal transects and hovering flight under a variety of conditions at KCRC

The S-1000's A2 autopilot records the airframe's three-dimensional inertial data, which includes its position, velocity, acceleration, and pitch, roll and heading angles. This data is stored on board the vehicle and downloaded following the flight. The KCRC meteorological tower is used to make direct comparisons between the S-1000 instruments and NIST-traceable measurements. For example, the iMet-XQ temperature and relative humidity sensors have been compared with a Thermometrics platinum resistance thermometer (PRT) in the same environment. For this test, the iMet sensor was placed at the bottom of the aspirated shield so that its sensing elements were shielded from radiation and aspirated appropriately. An example of the iMet temperature data compared with the Thermometrics PRT is shown in Figure 2. The R2 value for this data set was 0.9990 and the root mean square error (RMSE) was 0.32.

The iMet-XQ sensors were then integrated onto the airframe and comparison flights were made next to the tower to quantify measurement errors that resulted from the installation and operation on the S-1000. During test flights it was found the measured air temperature sometimes depends on the attitude of the aircraft and the direction of the wind relative to the airframe. We believe this was due to airflow stagnation around the sensors. As a result, we placed the iMet sensors on the multirotor aircraft airframe in a location that minimizes this effect.

RESEARCH RESULTS

The S-1000 has been used to make measurements while performing vertical profiles, horizontal transects and hovering flight under a variety of conditions at KCRC. A total of 18 flights have been made at KCRC since October 2015.

NOAA/ATDD will use the S-1000 to support convective initiation research in the VORTEX Southeast (VORTEX SE) experiment in northern Alabama in the spring of 2016 (see *The VORTEX-SE field study*, above). Combined with flux towers, microwave radiometers, radiosonde balloons, space-based remote-sensing measurements, and *in situ* Doppler radar and lidar systems, the S-1000 will help bridge gaps in the remotely sensed and in-situ measurements by recording both *in situ* and high-resolution remotely sensed measurements within 120m of Earth's surface.

To prepare for VORTEX SE, a preliminary series of eight flights was made in late October 2015 at Auburn University's Tennessee Valley Research and Extension Center in Belle Mina, Alabama, to test several of the applications for small UASs, including the measurement of boundary layer profiles of temperature and relative humidity and the measurement of heat fluxes over a large area adjacent to an eddy covariance flux tower.

Measurements of boundary layer T/RH profiles were made simultaneously between the S-1000 and a Graw radiosonde a total of four times during the October deployment. Preliminary data shows good agreement between the profile systems. Figure 3 shows the difference between the iMet temperature and the Graw temperature for the four comparison flights in the left-hand panel and the difference between the iMet relative humidity and the Graw relative humidity in the right-hand panel. Note that the iMet sensor overestimates the temperature and underestimates the relative humidity relative to the Graw radiosonde.

Hurricane hunting with UAVs

NOAA is currently working with technology company Raytheon to use its enhanced Coyote UAS for hurricane tracking and modeling. The aim is to give researchers an unprecedented perspective from inside storms that build in the Atlantic Ocean. The Coyote is a small, expendable UAS that can be tube-launched from a host vehicle on the ground or in the air. It can perform surveillance imaging, targeting and real-time damage assessment.

A team of scientists will use the solution to monitor the track and intensity of storms. The team recently completed a successful calibration flight over Avon Park, Florida, USA, where a Coyote was launched from a P-3 hurricane hunter aircraft to prepare for deployment during the 2016 storm season. The Coyote UAS has been improved so that it can fly for up to one hour and 50 miles from the launch aircraft.

NOAA successfully deployed a Coyote from a hurricane hunter into the eye of hurricane Edouard in 2014, and the administration intends to expand the use of UAVs throughout future hurricane seasons.

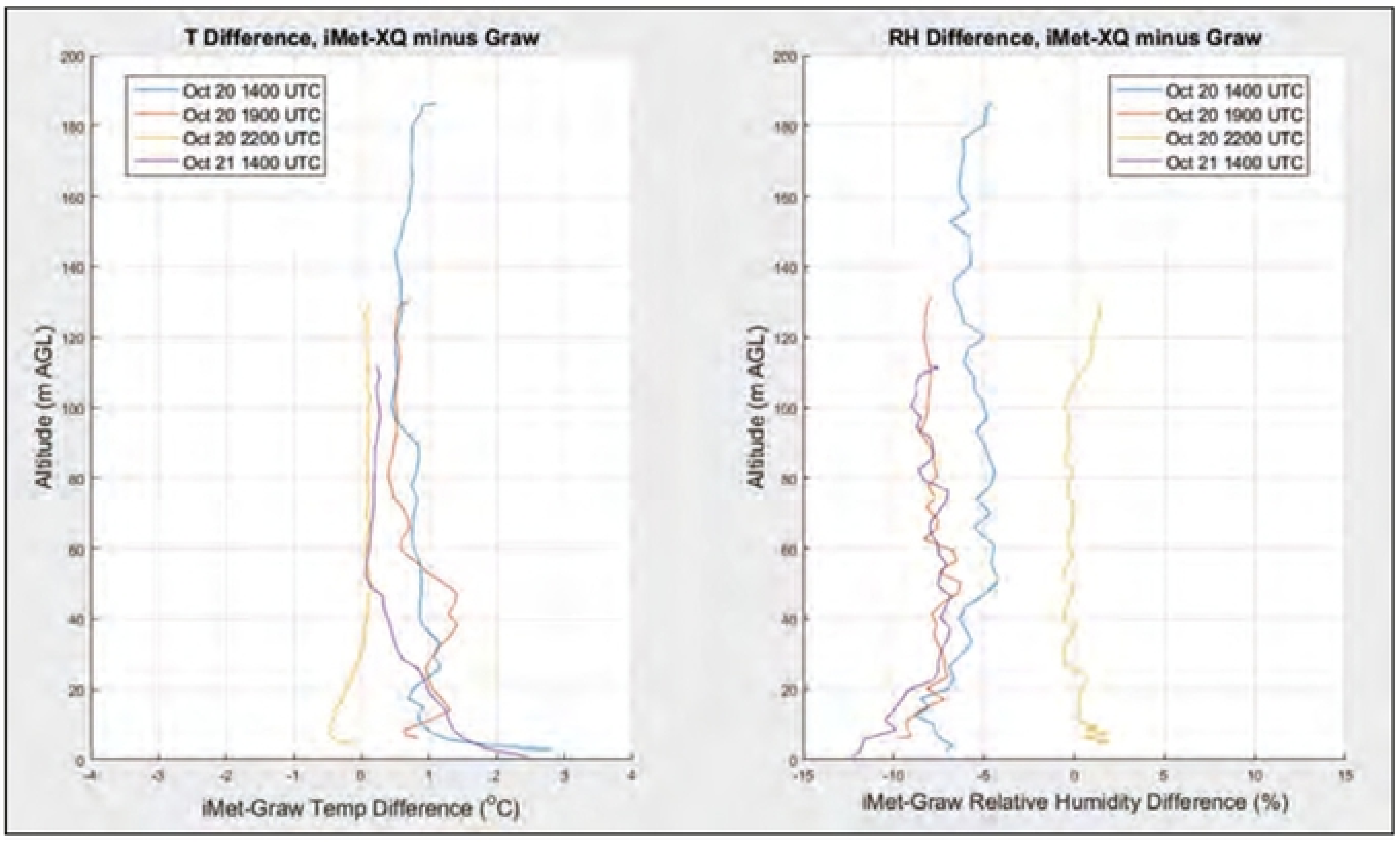

Figure 3: **Comparison of profiles between the iMet-XQ on the S-1000 and the Graw radiosonde**

An additional application of the UAS uses the thermal imager and air-temperature sensor on the S-1000 to measure and map heat fluxes (the rate at which the surface heats or cools the air) over a large area using a bulk method. This measurement technique was tested during the October 2015 deployment and relies on a flux tower to measure the standard deviation of the vertical wind speed and to provide a heat flux to derive a parameter (exchange coefficient) used to scale the fluxes determined by the DJI S-1000 multirotor aircraft.

Figure 4 shows the distribution of heat flux near sunset on October 20, 2015. The tower still showed weak heating of the air (22W/m^2) with a small vertical-wind standard deviation (0.25m/s). The S-1000 measured an air temperature of 20.5°C in hover 120m above the surface. In the blue regions of Figure 4, the surface is already cooler than this and is removing heat from the air. In the yellow areas, the surface is still heating the air. Ignoring the solar panel, there is still variation in heating and cooling (+20W/m^2 to -80W/m^2) over the image.

The potential and viability of the NOAA/ATDD multirotor aircraft for performing atmospheric research have been demonstrated. The ability of the UAS to record basic meteorological measurements in what is now a sparsely measured area of the atmosphere will contribute to fundamental boundary layer and mesoscale atmospheric research in the coming years. ∎

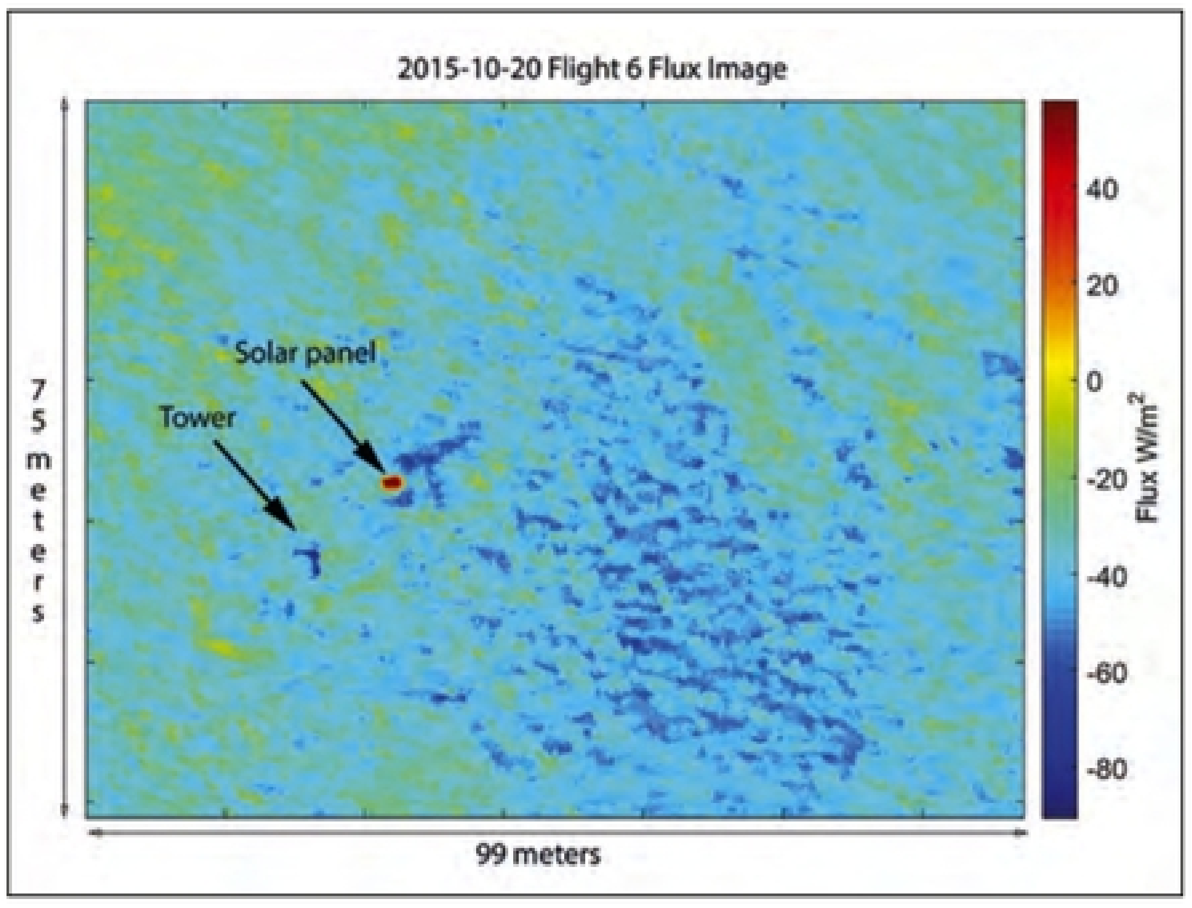

Figure 4: **Heat flux distribution estimated from the DJI S-1000 in Belle Mina, Alabama, in October 2015**