Launched *into the* Hurricane

*Observations from
Small Unmanned
Aircraft*

Adapted from "Eye of the Storm: Observing Hurricanes with a Small Unmanned Aircraft System," by Joseph J. Cione (NOAA/AOML/Hurricane Research Division), George H. Bryan, Ronald Dobosy, Jun A. Zhang, Gijs de Boer, Altug Aksoy, Joshua B. Wadler, Evan A. Kalina, Brittany A. Dahl, Kelly Ryan, Jonathan Neuhaus, Ed Dumas, Frank D. Marks, Aaron M. Farber, Terry Hock, and Xiaomin Chen. Published in BAMS online February 2020. For the full citable article see DOI:10.1175/BAMS-D-19-0169.1.

In recent years, observations from unmanned aircraft systems (UAS) have contributed to atmospheric understanding as the technology has become increasingly affordable and reliable. Cheap, simple-to-operate small UAS (sUAS; less than 25 kg) are particularly useful in hazardous conditions, but within hurricanes, use of sUAS has been limited. One such aircraft, the Aerosonde, was launched and controlled from land, which limited its potential for tropical cyclone (TC) research and operations.

More recently, a new type of sUAS called the Coyote was deployed successfully in Hurricane Edouard (2014) from NOAA's WP-3 Orion aircraft. Launching the sUAS from the P-3 allows for improved sampling in an area of great interest—the TC planetary boundary layer (PBL; roughly the lowest 1 km in hurricanes)—and at high wind speeds (roughly greater than 30 m s^{-1}), without the need for long ferry times.

Such high-resolution measurements of winds and thermodynamic properties in strong hurricanes are rare below 2-km altitude and can provide insight into processes that influence hurricane intensity and intensity change. For example, these observations—collected in real time—can be used to quantify air–sea fluxes of latent and sensible heat as well as momentum, which have uncertain values but are a key to hurricane maximum intensity and intensification rate.

Turbulence processes in the PBL are also important for hurricane structure and intensification. Data collected by the Coyote can be used to evaluate hurricane forecasting tools, such as NOAA's Hurricane Weather

▲ (b) Author Kelly Ryan launching a Coyote from a NOAA P-3. (c) The drone has onboard autopilot, but the operator provides "waypoints" to fly toward.

Research and Forecasting (HWRF) system. sUAS platforms offer a unique opportunity to collect additional measurements within hurricanes that are needed to improve physical PBL parameterization.

Recent Coyote sUAS deployments in Hurricanes Maria (2017) and Michael (2018) include the first direct measurements of turbulence properties at low levels (below 150 m) in a hurricane eyewall. In some instances the data, relayed in near-real time, were noted in National Hurricane Center advisories. Our preliminary analyses of how sUAS data can be used to evaluate numerical models suggest opportunities for future work using these promising new observing platforms.

Coyote sUAS in Hurricanes

The Coyote, built and supported by Raytheon, is an air-launched sUAS developed for military applications and recently adapted for meteorological research. Its folding wings allow the Coyote to fit in a standard A-size sonobuoy launch canister for use with no modification to the NOAA P-3s. Initially launched in free fall, it quickly deploys a parachute. After ~15 s the cylinder stabilizes and the external canister is released; the Coyote's wings and stabilizers unfold. It then detaches from the parachute and the motor starts, leveling out the sUAS to begin operation. The Coyote in this work had a battery for ~1 h of endurance, although flights in highly turbulent environments and lost communications often lead to shorter missions. Like dropsondes,

the Coyote is not recovered at the end of a flight.

An advanced autopilot system controls the aircraft. With two-way radio, an operator aboard the P-3 monitors real-time meteorological information and can send waypoint and altitude commands to the Coyote for targeted sampling.

In 2017–18, 6 of the 7 successful Coyote flights in major Atlantic hurricanes were in Hurricane Maria east of the Bahamas as it slowly weakened from a category 3 to a category 2.

The seventh flight was in Hurricane Michael (2018) as it intensified from a category 3 to a category 4 in the northeast Gulf of Mexico.

Two specific types of these flights were "eyewall" and "inflow" missions. For the eyewall mission, the Coyote is launched in a hurricane's eye and then directed toward the eyewall for an eventual circumnavigation, in which the Coyote typically descends incrementally, making continuous measurements at various altitudes. Ascent, though possible, requires too much battery usage. The primary goal of this mission is to more accurately measure the extent of the maximum winds.

The inflow mission involves launching the Coyote in the maximum near-surface inflow—well outside of the inner core. The Coyote then flies radially inward to the eyewall where it can fly a pattern similar to the eyewall mission. Its primary purpose is to measure vertical fluxes of momentum, heat, and moisture in the hurricane boundary layer and to determine kinematic boundary layer properties such as near-surface inflow velocity.

The Coyote and the P-3 can communicate over a maximum of about 25 km. During an eyewall module, the P-3 typically crosses into and out of the hurricane eye and flies downwind just outside the eyewall to maintain relatively small horizontal separation from the Coyote. Initial Coyote flights in Hurricane Edouard had a limited communications range of ~10 km with the P-3. Beginning in 2017, a 350-MHz data link substantially improved the

range, allowing the P-3 to execute normal flight paths and also data collection from ~7% of data received during eyewall flights in Edouard to >90%, of data collection in the eyewall of Hurricane Maria.

The ability to change flight paths during a mission is crucial, as some TC characteristics (e.g., radius of maximum winds, storm asymmetry) can only be determined by using other P-3 instrumentation in real time. For Hurricane Maria, mission planning began after landfall in Puerto Rico. Maria was forecast to slowly reintensify, then become steady state. A clear, 40-nautical-mile-wide eye enabled the P-3 to maneuver safely while the sUAS executed both eyewall and inflow experiments. In Hurricane Michael, the Coyote measured eyewall conditions near the location of maximum winds during intensification. The eye was too small for the P-3 to circumnavigate, so the original flight plan was modified.

Turbulence within Hurricanes

The Coyote sUAS demonstrated its ability to fly on autopilot in 87-m s^{-1} winds. Its $>1\text{-Hz}$ measurements below 150 m within Hurricane Maria's eyewall are the first in situ measurements of this kind—at altitudes and wind speeds dangerous for manned aircraft. In Hurricane Michael, the tangential wind varied between 54 and 86 m s^{-1} , and averaged 72 m s^{-1} . With a 75% reduction to adjust these winds

*** The Coyote launch sequence.** (a) Release in a sonobuoy canister from a NOAA P-3. (b) A parachute slows descent. (c) The canister falls away and the Coyote wings and stabilizers deploy. The main wings and vertical stabilizers have no control surfaces; rather, elevons (i.e., combined elevator and aileron) are on the rear wings, controlled by the GPS-guided Piccolo autopilot system with internal accelerometers and gyros. (d) After the Coyote is in an operational configuration, the parachute releases. (e) The Coyote levels out after starting the electric pusher motor, which leaves minimally disturbed air for sampling at the nose. The cruising airspeed is 28 m s^{-1} . (f) The Coyote attains level flight and begins operations. When deployed, the Coyote's wingspan is 1.5 m and its length is 0.9 m. The 6-kg sUAS can carry up to 1.8 kg. Images were captured from a video courtesy of Raytheon Corporation.

HIGHS AND LOWS, for Coyote sUAS flights 2017–18

Longest flight: **40.9 min**; more than **90 km**

Lowest maintained altitude: **136 m MSL** (for **240 s**)

Most data points from one flight: **4,642**

Peak horizontal wind speed: **87.0 m s^{-1}** at **641 m MSL**

Peak downdraft: **-13.8 m s^{-1}** (at **126 m MSL**)

Peak updraft: **$+14.4\text{ m s}^{-1}$** (at **624 m MSL**)

a) Infrared satellite

b) Infrared satellite and flight tracks

from the 600-m level to the 10-m level, the maximum sustained wind of 54 m s^{-1} corresponds well with the NHC best track value of 56.6 m s^{-1} at this time.

Turbulence kinetic energy (TKE) is estimated from Flight 7 (Hurricane Michael) data. For one segment, TKE is an estimated $9 \text{ m}^2 \text{ s}^{-2}$, comparable to the largest values determined from X-band Doppler radar data in a previous TC. For a later segment, estimated TKE is much larger: $38 \text{ m}^2 \text{ s}^{-2}$. Note that this sUAS maintained nearly level flight in such conditions.

This flight showed updrafts and downdrafts exceeding 10 m s^{-1} within the hurricane boundary layer, consistent with previous measurements from other platforms. The Coyote moved from inflow to outflow conditions approximately 680 s into this flight as it gradually approached the hurricane eye.

There are a limited number of PBL turbulence measurements in hurricanes. In the CBLAST experiment, all of the P-3 flights were far from the hurricane center in tropical storm-force wind (10-m wind speed $< 33 \text{ m s}^{-1}$). Unusually low-level P-3 flights into major Hurricanes Allen (1980) and Hugo (1989) measured inner-core winds, including the eyewall, as low as 422 m.

A few sUAS measurements show similar flight-level winds as the CBLAST measurements (i.e., $\sim 40 \text{ m s}^{-1}$) and, encouragingly, exhibit similar turbulence momentum flux magnitude. Similarly, sUAS measurements compare well

*** Infrared satellite images of Hurricane Maria at 1927 UTC 23 Sep 2017 as Coyote flight 3 (white) and the NOAA P-3 (blue) fly near its center.**

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with P-3 measurements at higher flight-level wind speeds ($\sim 60 \text{ m s}^{-1}$) reported previously. These data show an overall increase in turbulence momentum flux downward from 400 m as expected for shear-dominated boundary layer turbulent flow.

In the future, we plan to examine the distribution of radial turbulence fluxes, which act to limit hurricane intensity. The few studies so far—like our preliminary calculations with Coyote data—show that radial momentum fluxes can have the same magnitude as vertical momentum fluxes in the eyewall.

Comparison with Simulations

The change from inflow to outflow during flight 7 requires explanation, as does the preliminary diagnosis showing that components (i.e., radial and tangential) of vertical turbulence momentum fluxes sometimes had the opposite sign compared to those in a simple shear-driven PBL.

To help place these high-frequency observations into better context of the overall hurricane structure, Coyote observations have been compared to a large-eddy simulation (LES) of an idealized hurricane. The simulation's tendency toward locally higher values of TKE in the inner half of the eyewall is consistent with observational studies. Near the end of flight 7, the sUAS was likely measuring from the outer edge toward the inner edge of the eyewall where the average radial velocity in the model changes from negative to positive, consistent with sUAS

observations. However, the sUAS may have encountered either a storm-motion induced asymmetry or a mesoscale vortex not present in the simulation. Nevertheless, the simulation can explain aspects of the sUAS data.

The LES demonstrates the complexity of turbulence in the boundary layer of eyewalls. The extreme turbulence of the eyewall is consistent with observations. Importantly, the LES output suggests, for example, future sUAS flights might proceed radially outward from the eyewall in simpler mesoscale flow and less TKE to enable more straightforward analysis of turbulence properties at less risk to small aircraft.

Data Impact on Forecast Models

The Coyote data provide a unique opportunity to conduct groundbreaking research in both the accuracy of numerical weather prediction (NWP) models and assimilation of observations. TDR on board the NOAA P-3 typically provides the greatest amount of data within a hurricane. However, the Coyote sUAS flights in Maria provided a similar amount of data. Even though the Coyote's aerial coverage is much more limited, they yield data within the eye where the tail Doppler Radar (TDR) cannot measure winds because precipitation is typically low.

The Coyote sUAS flights provided, by far, the greatest amount of thermodynamic observations (i.e., pressure, temperature, and humidity, collected and digitized by an International Met Systems XF system) compared to other instruments onboard or dropped from the plane. In every quadrant of Hurricane Maria, for example, Coyote sUAS flights provided at least an order (in some quadrants, two orders) of magnitude more thermodynamic observations than dropsondes. In summary, assimilating the large number of kinematic and thermodynamic sUAS observations could improve NWP models that can resolve relevant atmospheric features.

Aircraft observations have been crucial in previous physics improvements in the HWRF model, NOAA's primary operational modeling system for TC prediction. Safety concerns for manned aircraft make sUAS an attractive option for collecting data needed to evaluate the HWRF PBL scheme and to develop improvements. Retrospective forecasts of Hurricane Maria reveal that the 2017 operational HWRF configuration consistently produces 1–2°C

cooler and drier conditions than the sUAS observations at ~300–1,400 m above MSL. The cooler conditions are most pronounced at mid-PBL, suggesting that the modeled static stability is lower than observed.

These model biases have important implications for the representation of air–sea fluxes, lower boundary layer stability, and hurricane intensity change. HWRF model evaluation and development efforts using these sUAS data are ongoing. An important question is whether these thermodynamic biases in the eyewall also extend radially outward. If they are present throughout the storm, the radial gradients of temperature and moisture may be approximately correct, potentially reducing the impact of the biases.

To evaluate the ability of sUAS data to impact the analyzed structure of Hurricane Maria, data assimilation experiments were conducted with a system that assimilates inner-core observations at the vortex scale. One experiment assimilated horizontal wind, temperature, and specific humidity observations from Coyote flights, plus other available observations. To isolate the effects of the Coyote data, a second experiment excluded the sUAS observations.

The northeastern sections of the eyewall clearly demonstrate the effects of the sUAS data, with a shift in the maximum winds tens of kilometers away from the Coyote flight track, and an expansion of the region of strongest winds. The inflow flight (flight 2) sUAS

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In 2017–18, Coyote flights 1–4 and 7 were typical “stepped descent” flight patterns, while flights 5 and 6 were “glider” flights. * ▽

data act to decrease the winds nearly 200 km downstream. Further tests will see how the modified storm structure affects the HWRF forecasts.

Summary

The measurements of turbulence momentum flux by sUAS such as Coyote are encouragingly similar to previous measurements and provide confidence in their ability to collect reliable data in hurricane conditions. These data also allow for an evaluation of numerical models simulating hurricane boundary layers and can potentially lead to model improvements. The sUAS measurements can alter the distribution of winds in a simulated storm, thereby potentially reducing uncertainties associated with the initialization of forecasts for storm position, intensity, and structure.

At times, instrument challenges occurred. For example, thermodynamic data were unusable for roughly half of the missions. Because the aircraft are not recovered following each flight, the causes of these issues are unknown. New, improved instrument packages will include a multihole turbulence probe, improved thermodynamic and infrared sensors, and a laser or radar altimeter system to provide information on ocean waves and to more accurately measure the aircraft altitude.

In the future, sUAS might allow targeted observing of regions of hurricanes where numerical models have large uncertainty and direct measurements are rare. Meanwhile, efforts are underway to increase sUAS payload capacity, battery life, and transmission range so that the NOAA P-3 need not loiter nearby. ♣♣

≡ METADATA

BAMS: What would you like readers to learn from this article?

Joe Cione: *A potentially revolutionary platform is coming. It will be a targetable observing system able to sample a critical part of the storm that, to date, has been incredibly difficult and dangerous to routinely sample. We all live in the boundary layer and as far as the storm is concerned, this is where all the critical exchanges with the underlying surface occur (momentum, heat, and moisture).*

BAMS: How did you become interested in the topic of this article?

JC: *In my Ph.D. days, I was initially looking at boundary layer processes associated with explosive cyclogenesis of extratropical cyclones. Understanding this region has always been difficult, and the challenge drove me to study the rare cases when we were lucky enough to capture the interaction in sufficient detail. Unfortunately, these were usually rare instances when the TC “fortuitously” interacted with fixed buoy platforms. While the early part of my career concentrated on building composite “snapshots” of these rare interactions that gave us new critical insights into*

what “reality” actually looked like, I knew we needed more.

BAMS: But waiting for more storms to hit buoys wasn’t the answer?

JC: *To advance our understanding of this important environment we had to be able to target the near-surface boundary layer environment of the high wind TC. Enter small Unmanned Aircraft Systems (sUAS).*

BAMS: When did you get into this new technology?

JC: *My first work in this area dates back to the early part of this century. The highlight was with the first ever sUAS mission into a TC (Ophelia 2005) using the Aerosonde platform. This was followed by a second successful flight into Hurricane Noel (2007). Ultimately launching sUAS from land was replaced with what we have now—namely, an air-launched sUAS concept of operations that uses NOAA’s P-3s Hurricane Hunters as deployment vehicles.*

BAMS: How does such a small aircraft survive such a violent environment.

JC: *The way I like to explain it is that*

we do not fight Mother Nature. We go with the wind (mostly) where it will take us. A good analogy to use here would be to remember when you were a child and you threw a stick into a fast-moving stream. As you ran beside it to watch, the stick would invariably bounce around and go underwater, but it didn’t break, did it? Well, it’s a similar situation with these small aircraft. When we fly sUAS in the eyewall, we always go with the wind, and the altitude changes we make are only downward. Operating this way also allows us to conserve energy and minimize our flight time as a bonus.

BAMS: What was the biggest challenge you encountered while doing this work?

JC: *Convincing people it was worth the effort. As you might imagine, this took perseverance and patience from a lot of people inside and outside of NOAA. I started working on this back in 2003; 17 years later we are finally on the precipice of making these highly unique measurements routine. It has been a long and difficult road, but I can now finally see the signpost up ahead that says, “It was all worth it, well done!”*