Proposal Title: **Employing Small Unmanned Aircraft Systems to Improve Situational Awareness and Operational Physical Routines Used to Predict Tropical Cyclone Structure and Intensity**

A Proposal Submitted to

NOAA Funding Opportunity: *NOAA-OAR-WPO-2021-2006592*

Competition Area: Observations

Principal Investigator:
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Proposed period: **2 years (August 1, 2021 – July 31, 2023)**

Requested budget: 1st Year: $299,182; 2nd Year: $299,173; Total budget: $598,355

	Year 1	**Year 2**	**Total**
U. Miami	**$288,415** (including the indirect cost of $59,514)	**$288,176** (including the indirect cost of $59,465)	**$576,591** (including the indirect cost of $118,979)
HRD/AOML/NOAA	**$10,767** (field travel)	**$10,997** (field travel)	**$21,764** (field travel)
Total Project Cost	**$299,182**	**$299,173**	**$598,355**

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***Principal Investigator*:** Dr. Jun A. Zhang, University of Miami
***Co-Principal Investigator*:** Dr. Joseph J. Cione, HRD/AOML/NOAA
***NOAA Collaborators*:** Dr. Brian C. Zachry, NHC/NCEP/NOAA
Dr. Avichal Mehra, EMC/NCEP/NOAA
Mr. Mark Rogers, AOC/OMAO/NOAA

ABSTRACT

The primary objective of this proposal is to evaluate and assess the benefits of using NOAA P-3 aircraft-deployed, low-altitude small unmanned aircraft systems (sUAS) to improve operational situational awareness for Tropical Cyclones (TC) and enhance physical routines used by NOAA forecast models to predict TC structure and intensity change. Currently, detailed analyses of temperature, moisture, and wind below 500m altitude are extremely limited due to safety concerns and other logistical constraints that make in-situ data collection within the lowest and most dangerous areas of the hurricane prohibitive. Enhanced, reliable, and high-resolution observations are necessary within this important region of the storm. The air-sea boundary is where energy and momentum are exchanged with the sea and where severe winds at landfall can directly affect the lives and property of millions of Americans every year. In order to address this critical data void, this proposal will test and evaluate how using sUAS complement and augment existing data coverage within the boundary layer and potentially lead to improved forecasts of TC intensity through advancements in physical understanding of boundary-layer processes. This enhanced knowledge will be incorporated into physical routines used in NOAA's coupled operational modeling systems and further evaluated using sUAS data. These unique boundary-layer observations will be made available in real-time to improve situational awareness for National Hurricane Center forecasters and emergency managers responsible for making life and death decisions associated with landfalling tropical systems. This project will specifically target Weather Program Office's Research Program Priorities *Obs-2 and Obs-3* to develop and demonstrate innovative observing technologies for advancing observational systems in extreme events, including TCs. In addition, this proposed work is relevant to Program Priorities *Obs-4 and Obs-9*. Previous work by the Principal Investigators using sUAS to sample multiple major hurricanes has advanced the readiness level (RL) of this promising technology to the ~7-8 range. An important end goal of this proposed work is to approach operational transition (at/near RL9).

1. Statement of the problem

Predicting the societal and economic impacts of a tropical cyclone (TC) critically depends upon the successful prediction of both its track and intensity. Over the past several decades, there has been a marked improvement of forecasts related to TC track. A major challenge that remains today is to skillfully forecast changes in TC intensity. Numerical Weather Prediction (NWP) is a key element of TC forecasting, and advances in prediction systems result from advances in the accuracy of the underlying models (Gall et al. 2013; Kaplan et al. 2015; Cangialosi et al. 2020). For instance, recent upgrades of the physics in the operational Hurricane Weather and Research Forecast (HWRF) model based on manned aircraft data have led to substantial improvements in the intensity forecasts (e.g., Zhang et al. 2012, 2015; Tallapragada et al. 2014). Recent advancements in the ability to incorporate observational data from both reconnaissance aircraft and unmanned Global Hawk aircraft into the Hurricane Weather Research and Forecast (HWRF) model through data assimilation have also demonstrated substantial improvements in the simulated TC intensity (Aksoy et al. 2013; Sippel et al. 2014; Tong et al. 2018; Lu and Wang 2020).

Previous numerical studies have shown large sensitivities of simulated TC intensity to boundary layer structure and associated parameterizations and (e.g., Braun and Tao 2000; Nolan et al. 2009; Smith and Thomsen 2010; Kepert 2012; Zhu and Zhu 2014; Bu et al. 2017). Despite these findings, only a limited number of observations are typically available to constrain these sensitivities. As the horizontal grid spacing of the operational TC forecast models approaches 1.5 km, the parameterizations traditionally used in these models may be inappropriate. Since such high-resolution models will ultimately begin to resolve structures at scales close to that of sub-grid turbulence, robust evaluations of TC structure are crucial to assess their realism.

Within the framework of TC intensity change, air-sea interaction processes seemingly are crucial (Emanuel 1986, 1995; Cione et al. 2000, 2013). The planetary boundary layer (PBL) where TCs exchange momentum with the surface and extract and transport heat and moisture from the ocean, has been identified to be of critical importance to TC intensity change (e.g., Smith et al. 2009; Riemer et al. 2010; Montgomery and Smith 2014; Montgomery et al. 2014; Rogers et al. 2016; Zhang et al. 2017). However, routine collection of kinematic and thermodynamic observations in the PBL of a TC remains elusive. Currently, temperature, moisture, and wind observations below 500 m altitude within and surrounding the TC core are limited since the primary source of data at these low altitudes are from GPS dropsonde measurements that provide very limited azimuthal coverage by design. Turbulence observations in the PBL of TCs are even more uncommon than observations of winds (Cione et al. 2015; Cione et al. 2020). The lack of in-situ PBL data is partially responsible for the large uncertainty often found in track and intensity analyses from NWP models (e.g., Landsea and Franklin 2013; Landsea and Cangialosi 2018; Klotz and Nolan 2019).

This project specifically targets Weather Program Office Research Programs' *Observations Priorities Obs-2 and Obs-3* to develop and demonstrate innovative observing technologies for advancing observational systems in extreme events such as TCs, and is also relevant to *Priorities Obs-4, and Obs-9*. The primary objective of this proposal is to evaluate and assess the benefits of using aircraft-deployed low altitude, small unmanned aircraft systems (sUAS) to better predict TC intensity change. This goal can be accomplished through enhanced data coverage within the boundary layer, better evaluation of, and improvement to, the physical routines used within NOAA’s coupled operational modeling systems. The scientific objectives of this project are presented below:

1). Significantly enhance observations within the TC PBL.

2). Derive mean and turbulence structures of the TC PBL at different storm intensities.

3). Identify and quantify model uncertainties as they relate to TC structure.

4). Use enhanced sUAS observations and analyses to improve the physics in NOAA’s coupled TC operational forecast systems.

5). Provide real-time sUAS data to NOAA operational forecast centers.

6). Significantly advance sUAS technology towards operational transition.

2. Project goals, products and collaborations

This proposal will test and evaluate how using sUAS complements and augments existing data coverage within the TC boundary layer. It will potentially lead to improved forecasts of intensity through advancements in physical understanding of boundary-layer processes. This enhanced knowledge will be incorporated into physical routines used in operational models and further evaluated using sUAS data. These unique boundary layer observations will be made available in real-time to improve situational awareness for NOAA operational forecasters and community emergency managers. The data will be provided in near-real time to the National Hurricane Center (NHC), the Environmental Modeling Center (EMC) and the Hurricane Research Division (HRD). Data assimilation development work will be conducted at HRD and EMC as part of a funded project through NOAA’s UxS program, while the model physics evaluation and improvement efforts will be led by PI Zhang under this proposal.

This project builds upon the PI’s previous work on improving the physics packages of operational hurricane forecast models using aircraft observations (Zhang et al. 2015, 2018). The observation-based improvements in model physics have led to significant improvements in hurricane intensity forecasts by HWRF (Tallapragada et al. 2014; Zhang et al. 2018). Similarly, co-PI Cione has led multiple NOAA-funded projects since 2014. Over the past six years, Cione has worked closely with OMAO’s Aircraft Operations Center (AOC) and together, they have successfully conducted nine air-deployed sUAS missions into three Major Hurricanes (Edouard 2014; Maria 2017; and Michael 2018). Using NOAA’s P-3 Hurricane Hunter aircraft as the deployment vehicle, near-surface winds observed during the Maria and Michael missions set sUAS records for low altitude flight and maximum wind speed. More importantly, these unique data were shared with NOAA operational centers (NHC and EMC) in near-real time and were used in public forecast discussions. This recent work has advanced the readiness level (RL) of this promising technology into the 7-8 range. The team will work closely with NHC, EMC, HRD and AOC throughout the project and hopes to transition sUAS research efforts to operations.

3. Outcomes and impacts

A major goal of this project is to provide near real-time sUAS data to NOAA operational centers. It is expected that the timely delivery of these unique observations will improve situational awareness, enhance advanced model diagnostics and ultimately advance our understanding of the processes that control TC intensity change. As the physical representation of routines used within NOAA’s coupled modeling systems progresses, it is expected that future forecasts will improve. The success of this project should also lead to sUAS resource allocation efficiency gains as NOAA looks to enhance the data assimilation capability of the existing TC forecast models (e.g., HWRF) as well as NOAA's Next-Generation Unified Forecast System (UFS).

NOAA's NHC and EMC will be the primary recipients and end-users of the project outcomes that are designed to improve the skill and accuracy of TC forecasts. The PIs will work closely with NOAA forecasters and scientists in order to achieve added value to existing data streams including a dedicated effort to add unique low level, high wind, sUAS observations into NHC's data visualization architecture (i.e., Advanced Weather Interactive Processing System-2, AWIPS2). It is believed that outcomes from this project can be directly transferred to NOAA's operational TC forecast systems, as well as to joint research and operational developments (e.g., Hurricane Analysis and Forecast System, HAFS, efforts). Improving real-time TC situational awareness and operational TC intensity forecasts has the potential to save lives, reduce property damage, and increase the public's awareness and confidence in NOAA's official forecasts and warnings.

4. Methods and activities

4.1 Analysis of existing sUAS data collected in hurricanes

Given the dearth of observations in the TC boundary layer, efforts will concentrate on using aircraft-deployed sUAS to saturate existing low altitude data sparse/void regions. sUAS will also be able to report wind and pressure measurements at very low altitudes (~100-1000m). Possibly more importantly, sUAS will also be able to add critical thermodynamic observations, including atmospheric moisture in the boundary layer within and surrounding the TC inner core. Nine sUAS were successfully deployed between 2014-2018 in three Major Atlantic Hurricanes. The first two missions were flown into Hurricane Edouard (2014), Six flights were conducted in Hurricane Maria (2017) and one mission was in Hurricane Michael (2018). Table 1 provides an overview of these nine unmanned flights.

Table 1. Summary of UAS flights in the 2017–2018 seasons

Flight Number	Date	Type of Mission	Flight duration (minutes)	Maximum wind speed (m s^{-1})
1	16 Sept. 2014	Eyewall	27.0	55.5
2	17 Sept. 2014	Inflow	68.0	27.0
3	22 Sept. 2017	Eyewall	40.9	63.6
4	23 Sept. 2017	Inflow	30.0	38.8
5	23 Sept. 2017	Eyewall	31.6	69.5
6	23 Sept. 2017	Eyewall	32.4	51.9
7	24 Sept. 2017	Eyewall glider	6.1	46.5
8	24 Sept. 2017	Eyewall glider	7.0	47.6
9	10 Oct. 2018	Eyewall	13.5	87.0

Figure 1 shows a summary of altitudes and wind speed measurements, demonstrating that most missions featured low-level flight which is advantageous for measurements of turbulence properties. Altogether, 256.5 minutes of data were collected within the hurricane PBL at altitudes primarily below 1 km. The longest flight lasted 68 minutes. The lowest altitude of controlled flight was 110 m. The strongest sUAS wind speed measured was 87 m s^{-1} at 641 m altitude.

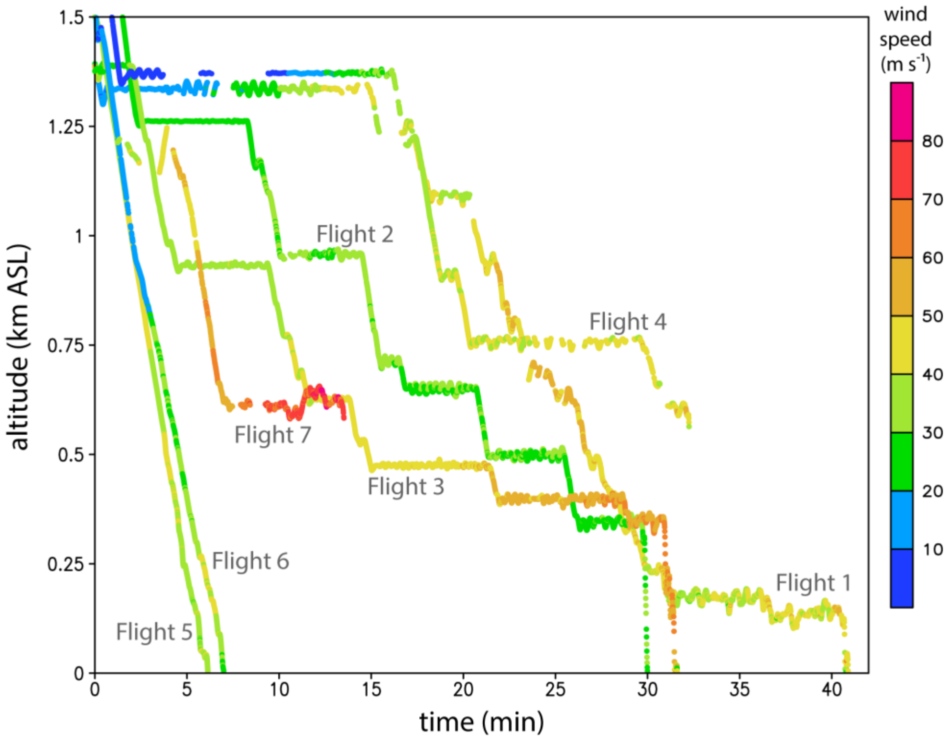

Figure 1. Summary of all wind speed data collected during Coyote flights (colored dots, m s^{-1}) as a function of time and height above sea level (ASL). Flights 1–4 and 7 were typical "stepped descent" flight patterns, while flights 5–6 were "glider" flights.

As previously mentioned, there are a very limited number of studies that have measured turbulent properties of the hurricane boundary layer. Most notable is the Coupled Boundary Layer Air-sea Transfer (CBLAST) experiment (French et al. 2007; Zhang et al. 2008), in which the NOAA P-3 flew at altitudes as low as 70 m and was instrumented with special turbulent gust probes including NOAA's Best Aircraft Turbulence (BAT) probe sampling at 50 Hz and Rosemount gust probe sampling at 40 Hz. However, all of these flights were conducted far from the hurricane center in tropical-storm-force wind speeds (i.e., 10-m wind speed < 33 m s^{-1}). French et al. (2007) described these data and provided values of turbulence momentum flux magnitude, $|\tau| = [<u'w'>^2 + <v'w'>^2]^{\frac{1}{2}}$, where u, v and w are the radial, tangential and vertical velocity, respectively, the brackets indicate an average value of a variable over some time period, and primes indicate perturbations from that average with trend removed. In addition, Zhang et al. (2011) examined data from unusually low-level flights into major Hurricanes Allen (1980) and Hugo (1989) using the NOAA P-3. These flights were as low as 422 m and measured winds in the inner core of these hurricanes at nearly one altitude. However, the maximum flight-level wind speed was as high as 64 m s^{-1} for the flux calculation using the 1 Hz wind velocities.

In this project, we will analyze existing and new sUAS data to compute turbulent fluxes. Our preliminary analysis of existing sUAS data is shown in Fig. 2a which plots the estimates of $|\tau|$ from the sUAS flights as a function of average flight-level wind speed U. It demonstrates that reasonable values are determined when compared with estimates using manned aircraft data from previous studies. The same data normalized by U^2 and plotted as a function of height (Fig. 2b), show similarly encouraging results. Both the P-3 flights and sUAS flights show an overall trend for $|\tau|$ to decrease with height in the hurricane boundary layer. These data will be used to evaluate HWRF forecasts.

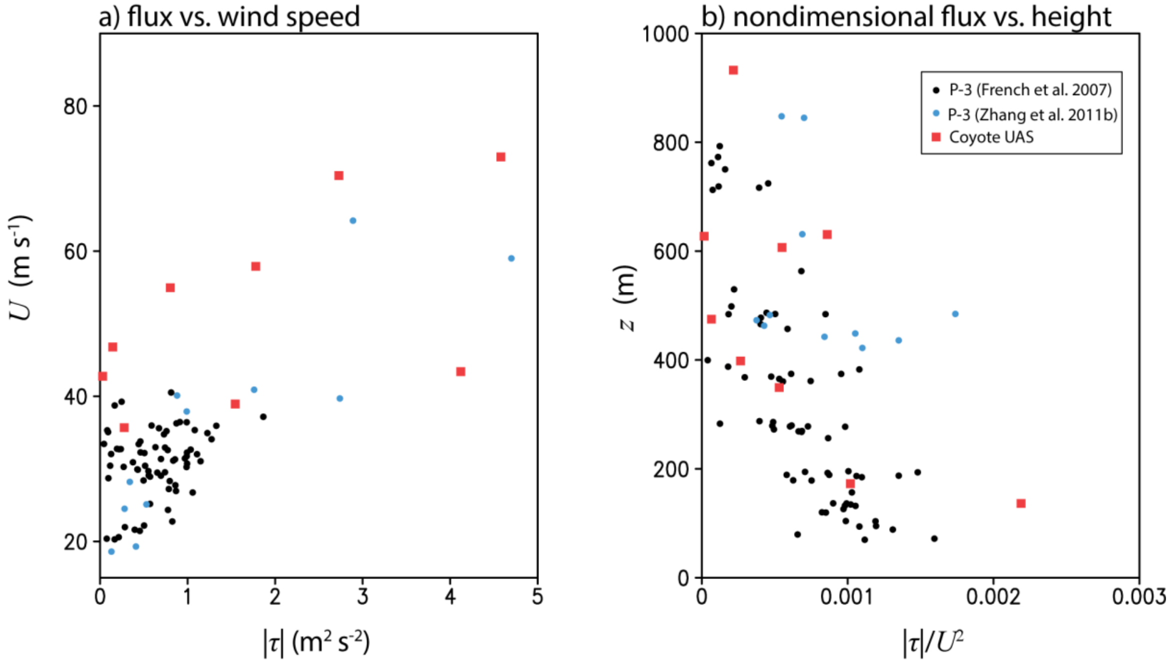

Figure 2. Scatterplots of the magnitude of turbulence momentum flux ($|\tau|$), from UAS flights in 2017–2018 (red) and from NOAA P-3 flights as in French et al. (2007) (black) and Zhang et al. (2011b) (blue). (a) Momentum flux versus mean wind speed (U), showing how the UAS flights operated at higher wind speeds compared to most P-3 flights. (b) Nondimensional momentum flux versus height, highlighting the similarity between the UAS and P-3 measurements.

Our next step is to estimate the vertical eddy diffusivity (K) that relates turbulent fluxes to the vertical gradient of the mean quantities, in the forms of:

$$|\tau| = \rho\ K\ S = \rho\ K\ [(\frac{\partial v_t}{\partial z})^2 + (\frac{\partial v_r}{\partial z})^2]^{\frac{1}{2}}, \qquad (1)$$

where ρ is the air density and S is the strain rate. This K parameterization has been widely used in PBL schemes in atmospheric and ocean models, as well as in theoretical models studying hurricane dynamics. One difficulty for estimating K using the existing sUAS data is that we lack collocated dropsonde data for estimation of the strain rate. This limitation will be remedied in future field work by collecting collocated dropsonde and sUAS observations. In Year 1, we will estimate S using the existing sUAS data during the periods when they were descending before flying at nearly constant altitudes. We will then compute K based on Eq. (1). Other indirect methods (i.e., Hanna and TKE methods) will also be used to estimate K following Zhang et al.

(2011). The estimated *K* using observations will be used to calibrate that used in the HWRF and HAFS PBL schemes.

4.2 Evaluate TC mean structure in HWRF using sUAS observations

HWRF is NOAA's primary operational modeling system for the prediction of tropical cyclones. The sUAS data allow us to better assess the current performance of the operational HWRF model within the low-level atmospheric boundary layer. The goal is to identify any existing model biases in terms of TC structure forecasts. Here, we add available sUAS measurements to existing PBL datasets (e.g., dropsonde) to characterize systematic biases in the HWRF forecasts. sUAS Flight 4 completed a partial orbit of Hurricane Maria's eyewall, providing an opportunity to evaluate thermodynamic conditions in a strong-wind environment and to compare the observations to model-derived fields from the simulated eyewall (Cione et al. 2020). To perform this comparison, retrospective forecasts of Hurricane Maria were made with the 2017 operational HWRF configuration. Eight different model cycles were selected for analysis, with forecast hours that ranged from 0–120 hours. All of the forecasts had a valid time of 1800 UTC on 23 September 2017, approximately one hour prior to the sUAS flight. To avoid penalizing the model for errors in hurricane track and size, both the sUAS observations and the model output were re-gridded by normalizing the radial coordinate by the radius of maximum wind speed (RMW). The sUAS trajectory (in normalized coordinates) was then recreated in the forecasts so that the azimuths and heights sampled in the modeled storm were the same as the ones sampled in the observed storm. As an example, Figure 3 compares the observed versus simulated air and dewpoint temperatures for the analysis cycle and for the 72-hour forecast cycle.

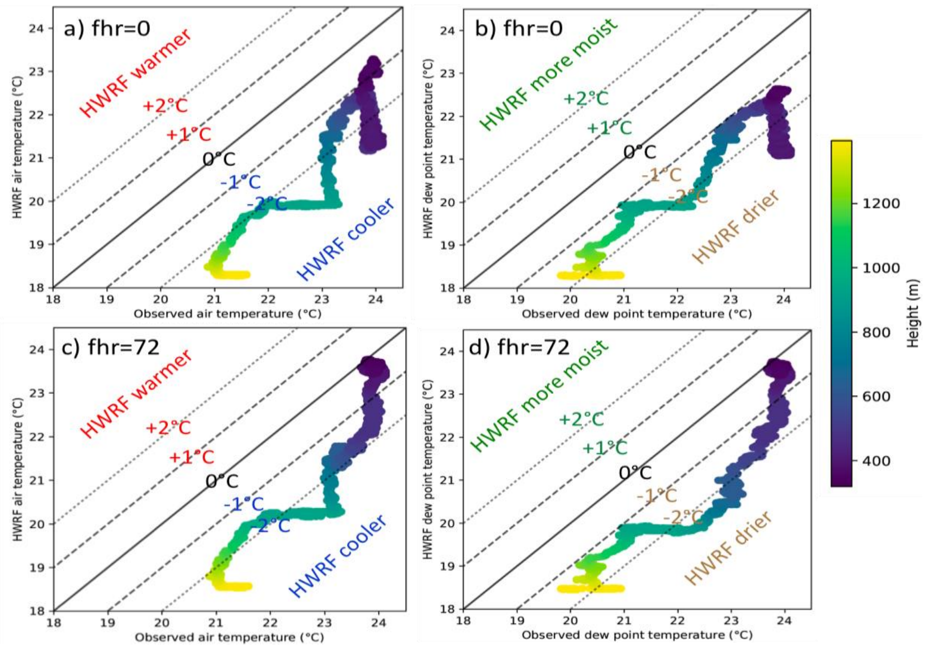

Figure 3. Scatterplots comparing the Coyote observed (x-coordinate) and HWRF-simulated (y-coordinate) air temperature (left column) and dewpoint temperature (right column). Colors indicate the height of the data. The upper panels use the HWRF initialization from the 18 UTC 23 September 2017 model cycle, and the lower panels use the 72-hour forecast from the 18 UTC 20 September 2017 model cycle.

This comparison reveals a strong correlation between the observed and simulated air and dewpoint temperatures (Fig. 3). However, the HWRF conditions are consistently 1–2 °C cooler and drier than the sUAS observations. This discrepancy shows little overall dependence with height in the portion of the boundary layer sampled by the sUAS (300–1400 m altitude). Other forecast cycles exhibited similar behavior (not shown). To determine whether the sUAS observations were in error, temperature and dewpoint profiles from dropsondes deployed from the same flight were also examined and were found to be similar to the sUAS data. Similar model biases have also been identified by comparing idealized HWRF simulations of TCs with the dropsonde composites (Zhang et al. 2020). These model biases may have important implications for the representation of air-sea fluxes, lower boundary layer stability, and the accuracy of hurricane intensity change predictions.

Modeled air-sea structure will also be compared to observations. Utilization of WP-3D aircraft deployed ocean expendables and modified GPS dropsondes with an infrared temperature sensor should enable air-sea thermal contrast comparison between the HWRF forecasts and observations within the storm environment. The inflow angle in HWRF forecasts will also be compared to sUAS and dropsonde data. The inflow angle is a key dynamic parameter that represents the relative strength of the radial wind to the tangential wind (Zhang et al. 2015).

Initial model evaluation studies will focus on Hurricanes Edouard (2014), Maria (2017) and Michael (2018), where available sUAS measurements were collected. We will compare the mean TC structure in HWRF forecasts to observations in order to identify deficiencies in the model. These findings will then be shared with EMC. Further analysis will be conducted as additional sUAS data becomes available during this project period. Findings based on HWRF analyses will be used to guide evaluations of other NWP models such as HAFS.

4.3 Evaluate and improve boundary layer parameterizations in HWRF using sUAS observations

In recent versions of the operational HWRF model, the non-local PBL schemes (i.e., Global Forecast System scheme and hybrid Eddy Diffusivity and Mass Flux scheme) were used to parameterize the flux transport and subsequent vertical mixing in the atmosphere above the surface layer (Hong and Pan 1996; Gopalakrishnan et al. 2013; Wang et al. 2018; Zhang et al. 2015, 2020). In the PBL scheme, the vertical eddy diffusivity for momentum flux is formulated as:

$$K = k\,(u^*/\Phi_{\mathrm{m}})\,Z\,\alpha\,(1 - Z/h)^{2}, \qquad (2)$$

where k is the Von Kármán constant (k =0.4), u^* is the surface frictional velocity scale, Φ_{m} is the stability function evaluated at the top of the surface layer, Z is the height above the surface, and h is the PBL height. In neutral condition, $\Phi_{\mathrm{m}} = 1$. Here, parameter α is used to tune K. α was set to 1 in pre-2012 version HWRF models and α was a function of wind speed and height in the 2016-2020 versions of HWRF (Wang et al. 2018; Zhang et al. 2020). The PBL height (h) is determined using the critical Richardson number (Ri_{bcr}) as:

$$h = Ri_{bcr}\,\frac{\theta_{vs}(U_H - U_s)^2}{g(\theta_{vH} - \theta_{vs})}, \qquad (3)$$

where Θ_v is virtual potential temperature, U is the wind speed, and subscripts s and H represent the surface and PBL top, respectively.

The goal of this activity is to assess the current performance of the operational HWRF model in terms of turbulence structure. Modeled turbulent fluxes and turbulent kinetic energy (TKE) will be compared to sUAS observations. Note that other types of PBL schemes such as the TKE-type scheme can also be evaluated and improved using the sUAS data. For evaluating the boundary-layer height parameterization, we will use two methods. The first method will use Eq. (3) as a baseline to formulate the PBL height and then determine the correct critical Richardson number that matches observations. The second method will use direct fluxes obtained by sUASs to determine the top of the PBL and use this estimate to evaluate the modeled PBL height. New parameterization of vertical eddy diffusivity will also be developed using the sUAS data and will be implemented in the PBL scheme in HWRF, in order to reduce the biases in the mean structure identified in Section 4.2. The findings and improvements in the HWRF PBL physics can be transitioned to other operational forecast models such HAFS.

4.4 Conduct field experiment to collect targeted observations using sUAS for operational use

Besides the data analysis and model evaluation noted in sections 4.1-4.3, we also propose to conduct field experiments to collect new data in the PBL of TCs. Like other experiments utilizing NOAA's WP-3D aircraft, the sUAS missions will be conducted using procedures as described in the Hurricane Research Division's annual Hurricane Field Program. Several flight "modules" for the sUAS have already been developed. The two primary modules that will be explored are "eyewall" and the "inflow" modules. In the eyewall module, the UAS is launched in a hurricane's eye and is then directed towards the eyewall for an eventual circumnavigation, ideally at the RMW. The primary goal of the eyewall module is to more accurately measure the radial extent of the maximum winds azimuthally and vertically. The inflow module involves launching sUAS well outside of the storm's core and flying radially inward eventually reaching the hurricane eyewall where it can fly a pattern similar to that of the eyewall module. The primary purpose of the inflow module is to measure turbulence fluxes in the hurricane boundary layer and to determine mean properties of the TC boundary layer. Dropsondes will be released by the WP-3D aircraft in order to collect measurements that are co-located with the sUAS.

The three sUAS platforms targeted to collect these new observations include Area-I's Altius 600, Black Swift Technologies' S0 and Barron Associates Wingsonde (Fig 4). All three platforms are currently under contract with NOAA for testing, with in-storm flight operations expected in 2021 (Altius 600). The three platforms range in size from ~2.5lbs (S0), 8.8lbs (Wingsonde) and 25 lbs (Altius 600). Flight duration is expected to be between 1.5h and 5h depending on the particular platform, environmental conditions and flight profile employed. All three sUAS platforms will be required to sample and record conditions of extreme turbulence within the hurricane PBL at ranges up to 150nmi from the deployment aircraft (NOAA's WP-3D). Each of these observing platforms offer significant upgrades over previous TC PBL-sampling sUAS as well as baseline GPS dropsonde technology that, to date, has been the primary 'instantaneous' observing system used to measure winds and thermodynamic conditions within the hurricane boundary layer. These efforts will have the added advantage of leveraging NOAA's existing manned reconnaissance resources at AOC and HRD. While the initial RL for these platforms will likely range between 5-8 in early 2022, each are expected to be at/near RL 9 by the end of this two year project, thanks in part to ongoing research and development as well as a wealth of experience gained from previous, successfully completed WP-3D/sUAS TC deployments.

Figure 4. Images of three new sUAS platforms NOAA plans to fly into the high wind turbulent environments of hurricanes beginning in 2020. Blackswift's S0 is shown in (A), Barron's Wingsonde in (B) and Area-I's Altius 600 is depicted in (C).

The concept of operation (CONOP) to be used for all proposed sUAS missions using NOAA's WP-3D manned aircraft (i.e. Area-I Altius 600 in 2021; Black Swift S0, Barron Wingsonde in 2022) has already proven to be operationally viable. Furthermore, the lessons learned from previous Coyote sUAS missions conducted over the past six years will be applied to all new activities and deployments proposed under this effort. Specific flight patterns will be similar to sUAS missions previously conducted as part of NOAA HRD's annual Hurricane Field Program under the Small Unmanned Aircraft Vehicle Experiment (SUAVE, Cione et al. 2020). Storm missions planned under this proposal in 2022 would be conducted during the active portions of the hurricane season (August through October) in the tropical waters of the Atlantic, East Pacific, Gulf of Mexico and Carribean Sea. As previously noted, sUAS data collected under this project will be provided to NHC, EMC and HRD for real-time situational awareness, intensity and storm-surge forecast utilization, and data assimilation interests.

5. Timeline and deliverables

The PIs will carry the overall responsibility for supervision, conduct and dissemination of the results of this project. Dr. Cione will be responsible for the coordination of sUAS deployment. Dr. Zhang and the team will be responsible for data analysis and model diagnostics.

Procurements will be made building on experience and existing NOAA contracts with Area-I, Black Swift and Barron as well as contacting personnel within NOAA Acquisition and Grants Office (AGO) and NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML). Airspace and other clearances related to flight operations should not be a limiting factor given previous successful sUAS/WP-3D operations coupled with the ability to fly Beyond Line of Sight (BLOS) using contingencies under "due regard".

Below are the proposed timeline and deliverables for this project:

- Coordinate with our contractors, Black Swift Technologies (BST), Barron Associates (BA), and Area-I on sUAS related tasks and services to be completed under this project: 31 Aug 2021
- Post-process and analyze sUAS and P3 data collected in 2014-2018 seasons: 1 July - 31 Dec 2021
- Project quarterly progress report/briefing: 30 Sept 2021
- Complete sensor calibration and integration for both BST's and BA's sUAS: 1 Dec 2021
- Project quarterly progress report/briefing: 31 Dec 2021
- Conduct a Clear Air Test (CAT) using BST's S0 sUAS: 31 Jan 2022
- Conduct a CAT using BA's Wingsonde sUAS: 28 Feb 2022
- Analyze existing sUAS and P3 data to derive the mean boundary layer structure: 28 Feb 2022
- *Provide quality controlled existing sUAS data to EMC and HRD for DA purposes*: 31 Jan 2022
- Project quarterly progress report/briefing: 31 Mar 2022
- Analyze existing sUAS data to derive turbulence parameters: 30 Apr 2022
- Peer-review publication submitted for review: 31 May 2022
- Conduct CAT using Area-I's Altius 600 with BST's multi-hole turbulence probe (MHTP): 30 May 2022
- *Delivery of 8 field-ready, BST S0, and BA Wingsonde sUAS*: 1 July 2022
- *Delivery of four integrated MHTPs with laser or radar altimeters on the Altius 600*: 1 July 2022
- Project quarterly progress report/briefing: 1 July 2022
- Finalize Experimental Hurricane Field Plan Layouts for all sUAS platforms: 31 July 2022
- Conduct up to 3 multi-day hurricane field deployments using sUAS: 1 Aug - 30 Nov 2022
- *Provide real-time (2022) sUAS data to NHC and EMC operational centers*: 1 Aug - 30 Nov 2022
- Project quarterly progress report/briefing: 30 Sept 2022
- Acquire and post-process operational HWRF forecasts: 30 Nov 2022
- Compare recently collected sUAS data with existing other types of data for QC purposes: 31 Dec 2022
- Project quarterly progress report/briefing: 31 Dec 2022
- Post-analysis of 2022 sUAS data collected: 31 Jan 2023
- *Provide quality controlled sUAS data to EMC and HRD for DA purposes*: 31 Jan 2023
- *Synthesize all sUAS and manned aircraft data for validation of HWRF forecasts*: 31 Jan 2023

- Model output vs. all sUAS data comparisons for the mean boundary layer structure: 28 Feb 2023
- Model output vs. all sUAS data comparisons of the turbulence structure: 31 March 2023
- Project quarterly progress report/briefing: 31 Mar 2023
- Model output vs. all data comparisons of multi-scale hurricane structures: 31 April 2023
- *Improve model physics based on observations targeting the model deficiencies*: 30 June 2023
- Peer-review publication submitted for review: 30 June 2023
- Submit end-of-project technical report & operational transition assessment review: 31 July 2023

Based on previous DoD operations, and NASA definitions provided here: https://www.nasa.gov/sites/default/files/trl.png, we believe that the Altius 600 as of November 2020 is at RL 7 and at the completion of this project will be at/near RL 9. While the SBIR Phase II S0 and Wingsonde projects have both been designed from scratch to meet prescribed NOAA tropical cyclone requirements, the testing that will have already transpired prior to the requested Year 1 funding should have both platforms in the RL 6/7 range and potentially at/near RL9 at the completion of this 2 year project. As noted in the "in-kind" portion of the project budget for Dr. Cione, the intention would be to use existing AOML/HRD Flight hours (up to 75h) to execute these experiments over a two-year period. The breakdown would be three (3) clear air tests (~5h in duration each) for each sUAS platform in year 1 (15h total). One of the CATs would be conducted to validate the multi-hole probe to be integrated onto Altius 600 sUAS platforms. In year 2, six (6) in-storm missions (8-10h each) would be conducted (2 missions per sUAS platform).

6. Additional information

6. 1 NOAA collaborators and/or resources

The proposed project is built upon the data analysis and methods that the PIs are familiar with, leveraging on the tools and knowledge obtained from previous NOAA projects that they gained. Working closely with NHC, EMC, HRD and AOC colleagues in the past, the PIs have advantages of assessing aircraft data and operational model (e.g., HWRF) forecasts. During this project, the PIs will continue their collaborations with NOAA operational centers. Support letters from Dr. Brain Zachry from NHC, Dr. Avichal Mehra from EMC and Commander Christian Sloan from AOC are enclosed in the Appendix and point to the widespread internal support this work has within NOAA operations. It should also be noted that our proposal meshes well with a submission from Dr. Dongxiao Zhang from NOAA Pacific Marine Environmental Laboratory (PMEL) that will be focusing on using unmanned ocean assets in hurricane environments to sample the atmospheric surface layer (below 10 m altitude) and upper ocean structure, as our project will be focusing on observations above the surface layer. If both efforts are funded, our plan would be to logistically coordinate our sUAS operations with their in-field efforts using Saildrone and Ocean Glider platforms in 2022. In addition, objectives from this proposal are synergistic to a project that was funded by NOAA's UxS program and led by Dr. Sippel at AOML. Dr. Sippel's project will focus on the impacts of existing (and new) sUAS observations on TC operational forecasts using HWRF in collaboration with EMC. We will also collaborate with Drs. Frank Marks and Joshua Wadler from AOML/HRD, and Dr. Ronald Dobosy formerly retired from NOAA/ARL/Atmospheric Turbulence and Diffusion Division on analyses of the sUAS data.

6.2 High-performance computing request

The PIs have access to the NOAA's Jet supercomputer with no additional cost, which ensures adequate computing resources for running TC forecast experiments. In addition, the PI has full access to the University of Miami's PC-cluster computer systems. These resources will help meet the computational needs for this proposed project.

7. Outreach and Education

The project team plans to share project progress and results with the general public and scientific community through HRD's website and blogs. The results from this project will also be presented at international and domestic conferences and workshops. Observational and modeling results will be shared with university students during classwork and lab sessions. PI Zhang will give lectures as part of the Tropical Meteorology course at the University of Miami and share the field work and modeling results of this project with the students. The PIs will also share the project results with K-12 educators. This project will also provide internship opportunities for undergraduate students and additional possibilities for graduate work. Undergraduate and graduate students will also have opportunities to participate in the field work.

8. Diversity and inclusion

The PI is of minority descent and the collaborators in the project also have diverse educational and work experience backgrounds. Our team includes scientists from academia and the federal workforce. We also will be working closely with multiple private sector engineers and technicians from Georgia, Virginia and Colorado. Our PI, Co-PI and collaborators are at various stages in their career ranging from post-doctoral associate to senior scientists. It is also our expectation that NOAA will host a summer student to work on data collected from this project (at no additional cost). This opportunity will allow us to help foster the next generation of NOAA scientists. The full Diversity and Inclusion statement of the University Miami is available under: https://www.hr.miami.edu/working-at-the-u/diversity-and-inclusion/index.html and https://diversity.rsmas.miami.edu/. The diversity and inclusion statement from the University of Miami is also attached to this proposal.

9. Data management plan

The data collected in the field and generated by the models in this project will be archived separately. The field data will be archived by NOAA HRD with no cost as part of the Annual Hurricane Field Program. The sUAS data will be stored in ASCII format (binary format if necessary) and will be made publicly available. The modeling data will be stored in NetCDF format. The model outputs related to physics development will be stored in the data archiving system of the University of Miami and will be made publicly available. Operational HWRF products for real-time and retrospective TC forecasts are publicly available at NOAA/EMC. Once the data has been analyzed for publication, operational HWRF data obtained from NOAA collaborators will also be archived, although these would not be made publicly. Interested users can request to access the HWRF data through NOAA and the PIs will provide contact information of the NOAA collaborators.

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Curriculum vitae

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Education:	2007	*Ph.D.*, Applied Marine Physics, *Univ. of Miami*, Miami, FL
	2005	*M.S.*, Applied Marine Physics, *Univ. of Miami*, Miami, FL
	2000	*B.S.*, Naval Architecture, *Dalian Univ. of Technology*, China

Experience:

- 2017-present Scientist, University of Miami, Miami, FL
- 2012-2017 Associate Scientist, University of Miami, Miami, FL
- 2010-2012: Assistant Scientist, University of Miami, Miami, FL
- 2008-2010: National Research Council Postdoctoral Res. Assoc., Hurricane Research Division, Miami, FL

Awards and Professional Services:

Banner I. Miler Award (2020)
Associate Editor, *Frontiers of Earth Science, 2019-present*
Editor in Chief, *Dynamics of Atmospheres and Oceans*, 2018-present
Member, Editorial Board, *Forecasting*, 2018-present
Aviation Laureate Award for Unmanned Aircraft Hurricane Observations (2018)
NOAA AOML Award for Doppler Wind Lidar Operations (2016)
NASA Hurricane and Severe Storm Sentinel Group Achievement Award for HS3 (2015)
University of Miami CIMAS Gold Medal equivalent to NOAA Gold Medal (2015)
NOAA AOML Outstanding Research Paper Award (2011)

Relevant Publications:

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VITAE: Project co-Principal Investigator

Dr. Joseph J. Cione – NOAA/AOML/Hurricane Research Division (1997-)

Education: Ph.D., 1996, North Carolina State University, Meteorology

Leadership: NOAA Senior Scientist and Project Manager for small UAS Research and Operations in Tropical Cyclones
USWRP Deputy Director (1995-1996)
Coordinated USWRP initiatives with federal agencies and academia
NOAA/NASA UAS Field Program Director & Lead PI (2004-2008)
Hurricane Forecast Improvement Project (HFIP) Oceanic and Atmospheric Operational Model Physics Evaluation Lead (2012-)
NOAA Executive Leadership Program Graduate
John A. Knauss National Sea Grant Fellow
2010 National Oceanic and Atmospheric Administration Bronze Medal
2015 US Department of Commerce Silver Medal

Selected Relevant Experience:

Two areas of expertise include analysis of atmospheric and oceanic boundary layer thermodynamic processes in hurricanes and extratropical winter storms. Throughout his career, Cione has explored difficult to observe regions and demonstrated an ability to incorporate promising research results into improved forecast operations. In late 2005 and again in November 2007, Cione led a NOAA/NASA team that successfully utilized unmanned aircraft systems (UAS) to fly into the core of two tropical systems. The 2005 mission (Tropical Storm Ophelia) was the first-ever UAS flight into a tropical cyclone while the 2007 flight (Hurricane Noel) established records for duration (17.5h) and minimum altitude (82m). Both flights collected critical near-surface wind measurements that were reported to NOAA's NHC in real time, enabling the observations to be used in subsequent public forecasts and warnings. Using NOAA's manned P-3 aircraft, two Coyote UAS, each measuring 13 pounds and 5 feet across were successfully air-deployed into the atmospheric boundary layer of Major Hurricane Edouard in 2014. Follow-on P-3/Coyote sUAS hurricane missions were also successfully conducted in Major Hurricanes Maria in 2017 and Michael in 2018.

Selected Relevant Publications and Presentations:

Cione, J.J., G. Bryan, R. Dobosy, J. A. Zhang, G. de Boer, A.Aksoy, J. Wadler, E.Kalina, B. Dahl, K. Ryan, J. Neuhaus, E. Dumas, F. Marks, A. Farber, T. Hock and X. Chen 2020: Eye of the Storm: Observing Hurricanes with a Small Unmanned Aircraft System. *Bull. Amer. Meteor. Soc.* *https://doi.org/10.1175/BAMS-D-19-0169.1*

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Cione, J.J. 2015: The relative roles of the ocean and atmosphere as revealed by buoy

air-sea observations in hurricanes. *Mon. Wea. Rev.* doi: 10.1175/MWR-D-13-00380.1

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