Coyote UAS observations in Hurricane Maria (2017) and a brief look at what's next on NOAA's sUAS horizon

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NOAA Acknowledgments: Office of Oceanic and Atmospheric Research
Office of Marine and Aviation Operations
Aircraft Operations Center

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ISARRA 2018
Boulder, Colorado

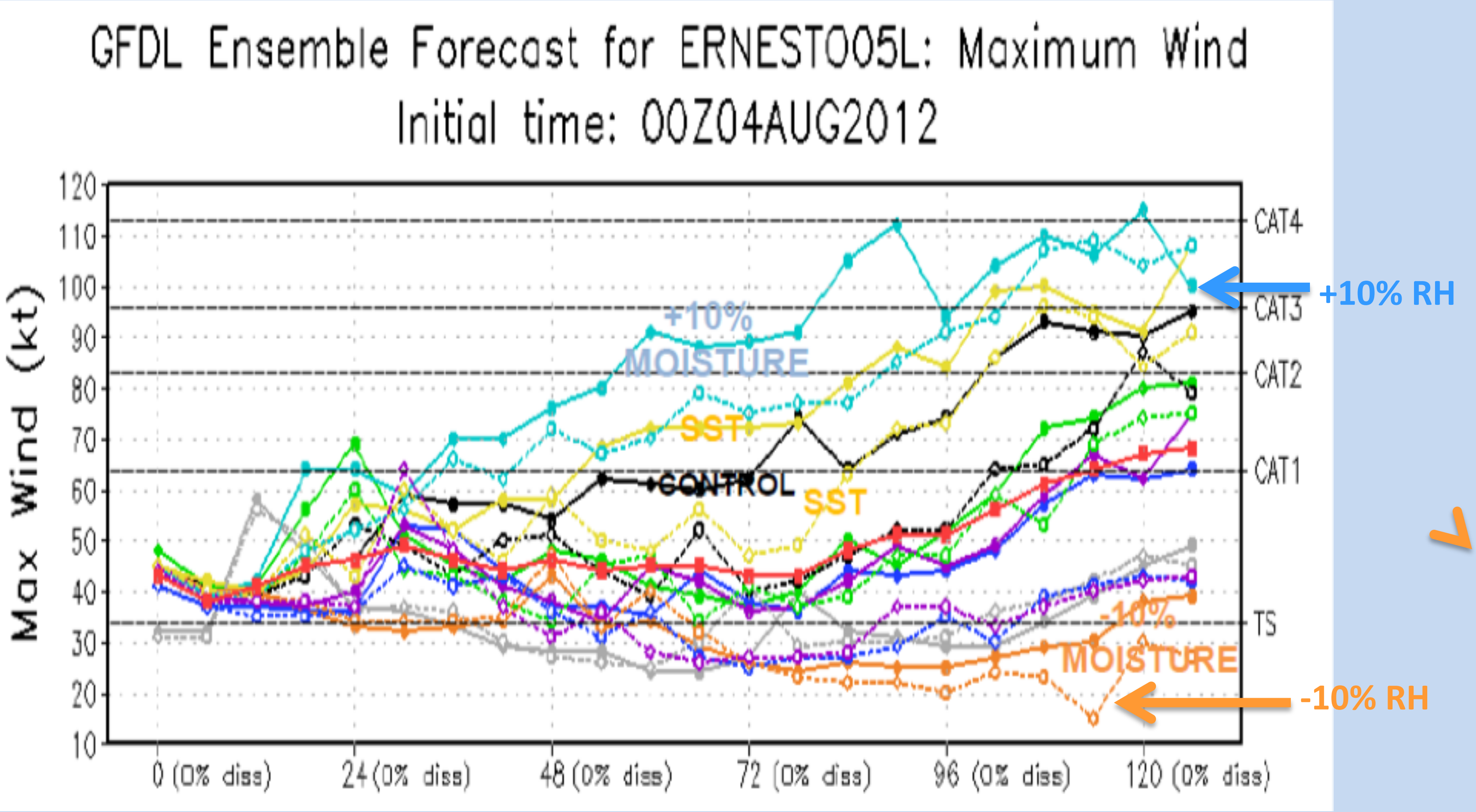
Observational Team Objective:

Leverage key attributes of NOAA's existing Hurricane Hunter P-3 aircraft to develop emerging unmanned technologies designed to enhanced data coverage of the critically important, yet sparsely-sampled tropical cyclone boundary layer environment.

End goal:

Through enhanced observation, improve basic understanding, operational situational awareness and ultimately, hurricane intensity forecast performance.

Model Extreme Sensitivity to Small Differences in boundary layer moisture as it relates to forecasts for hurricane intensity…



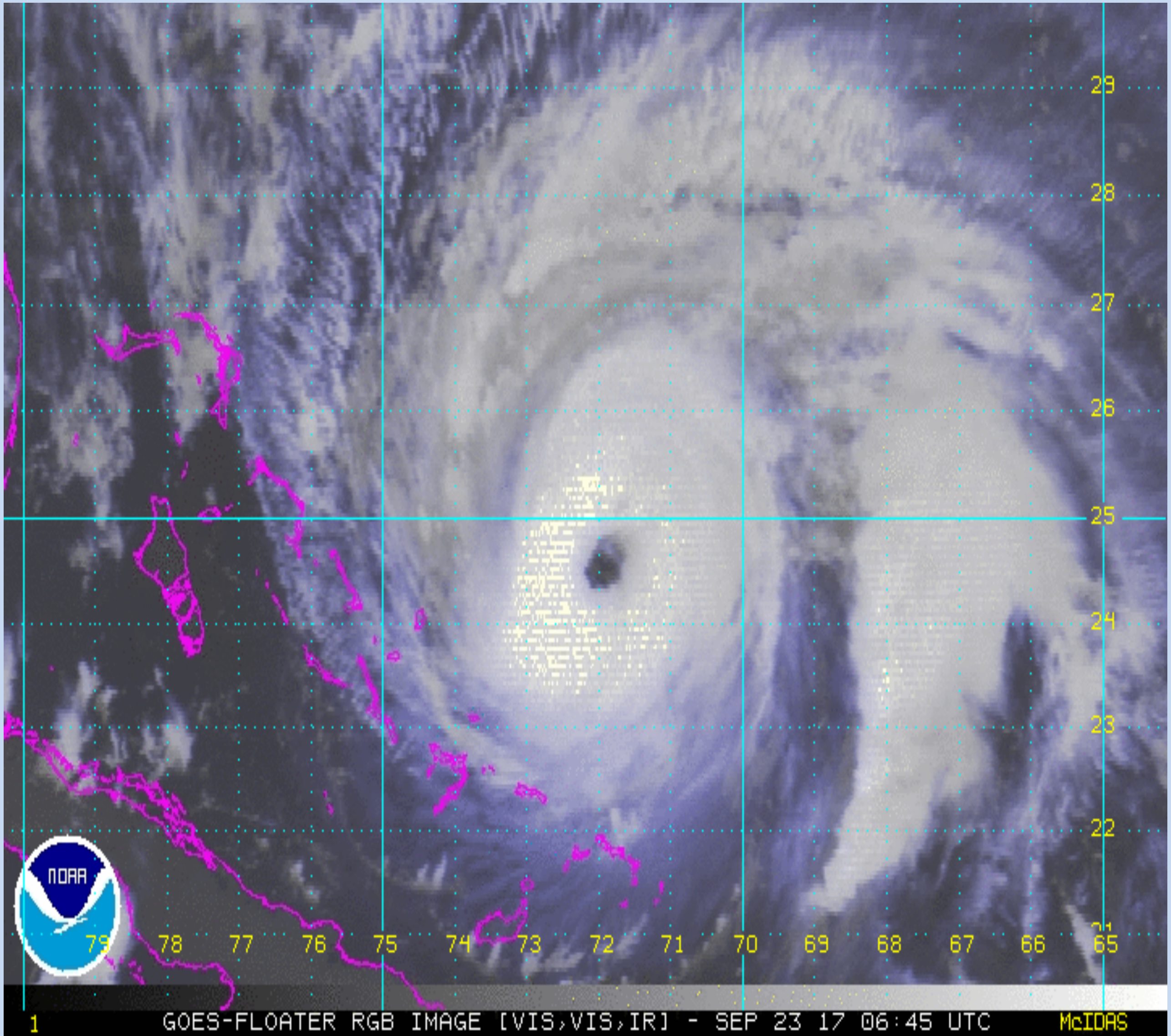
Coyote UAS – Deployment Sequences

Coyote UAV – Deployment Sequences

Hurricane Maria

22-24 Sep 2017

Approx. Category 3: Min pressure ≈950 mb; Max 10-m wind speed ≈100 kt



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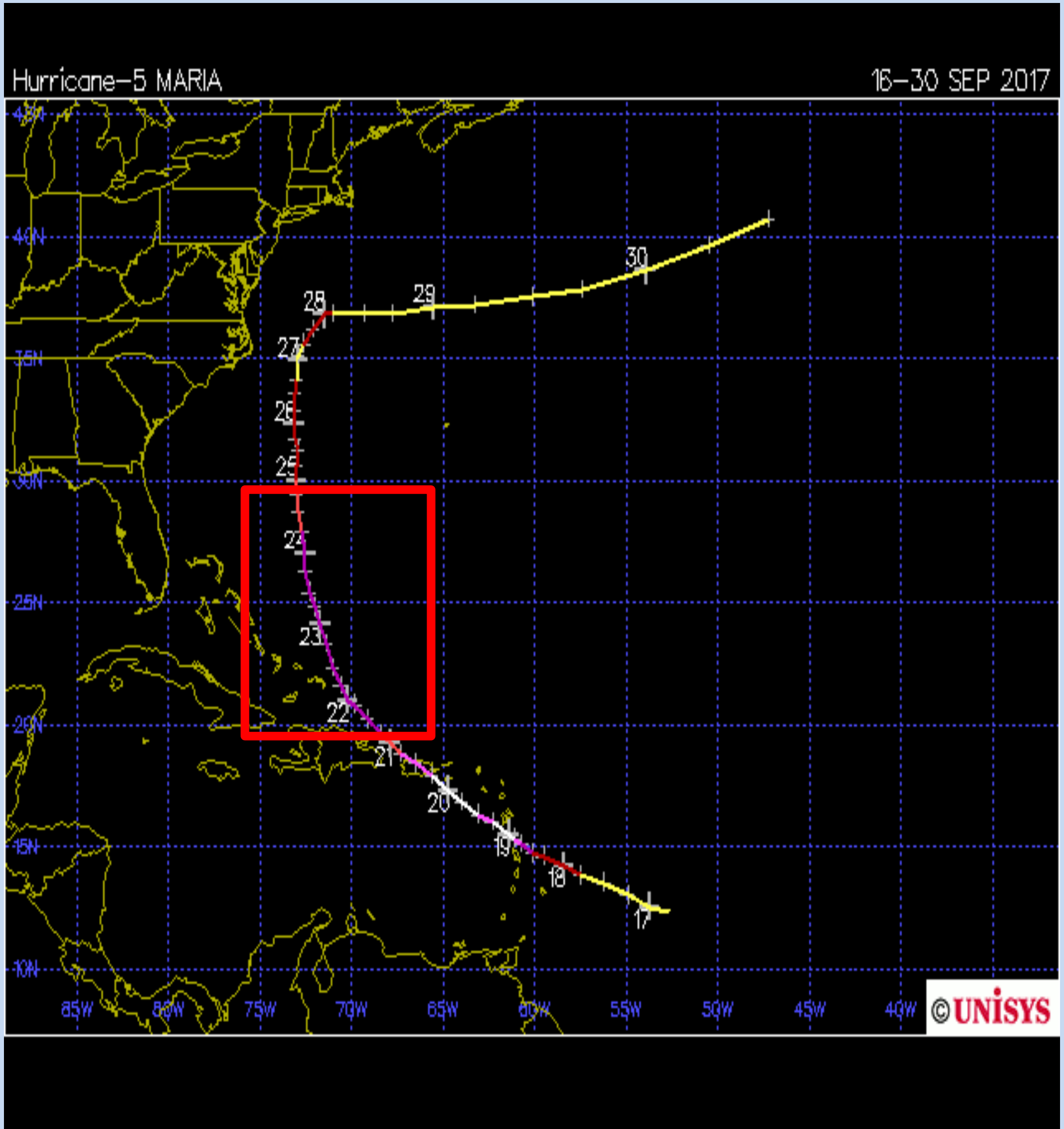
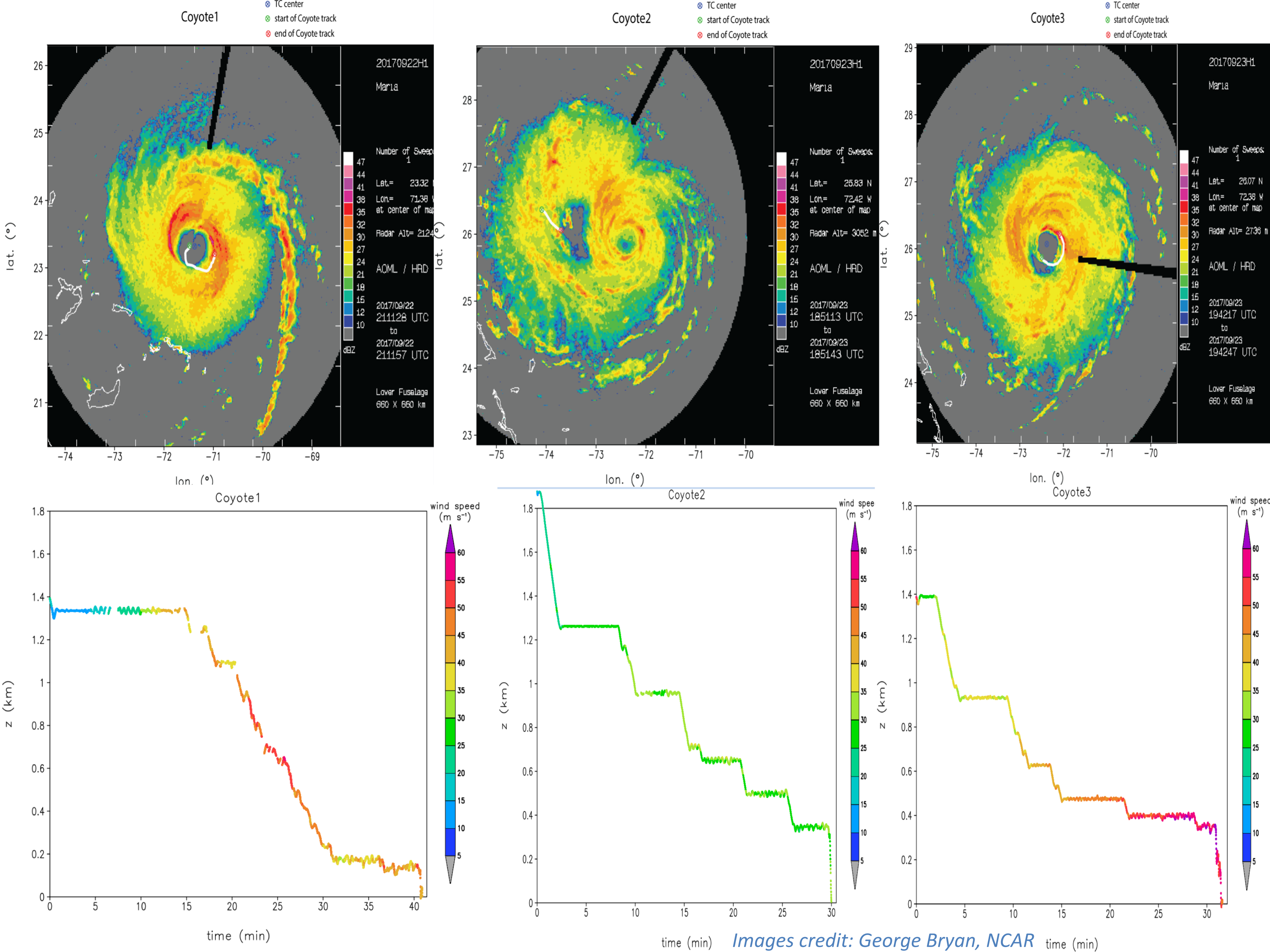
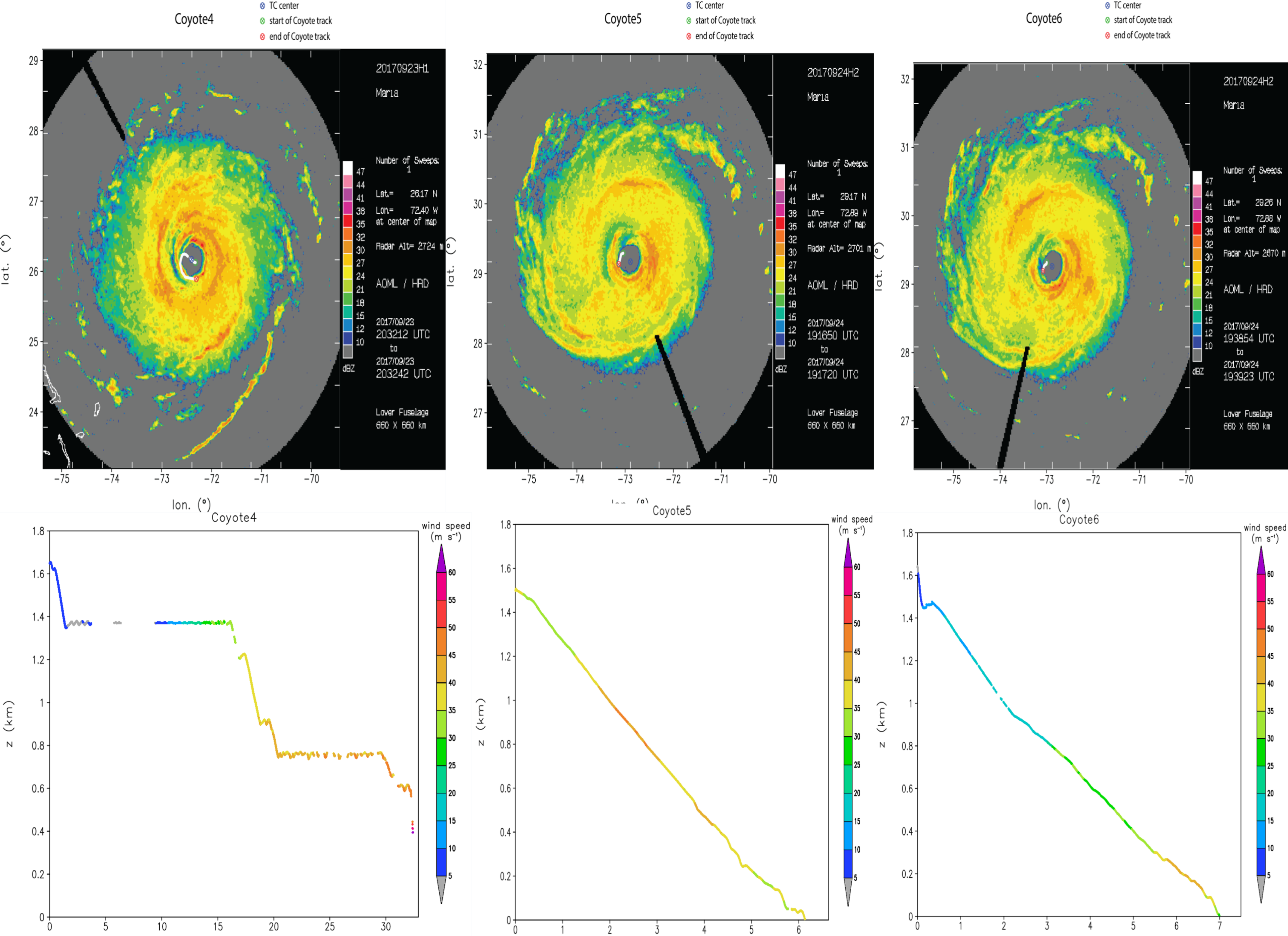




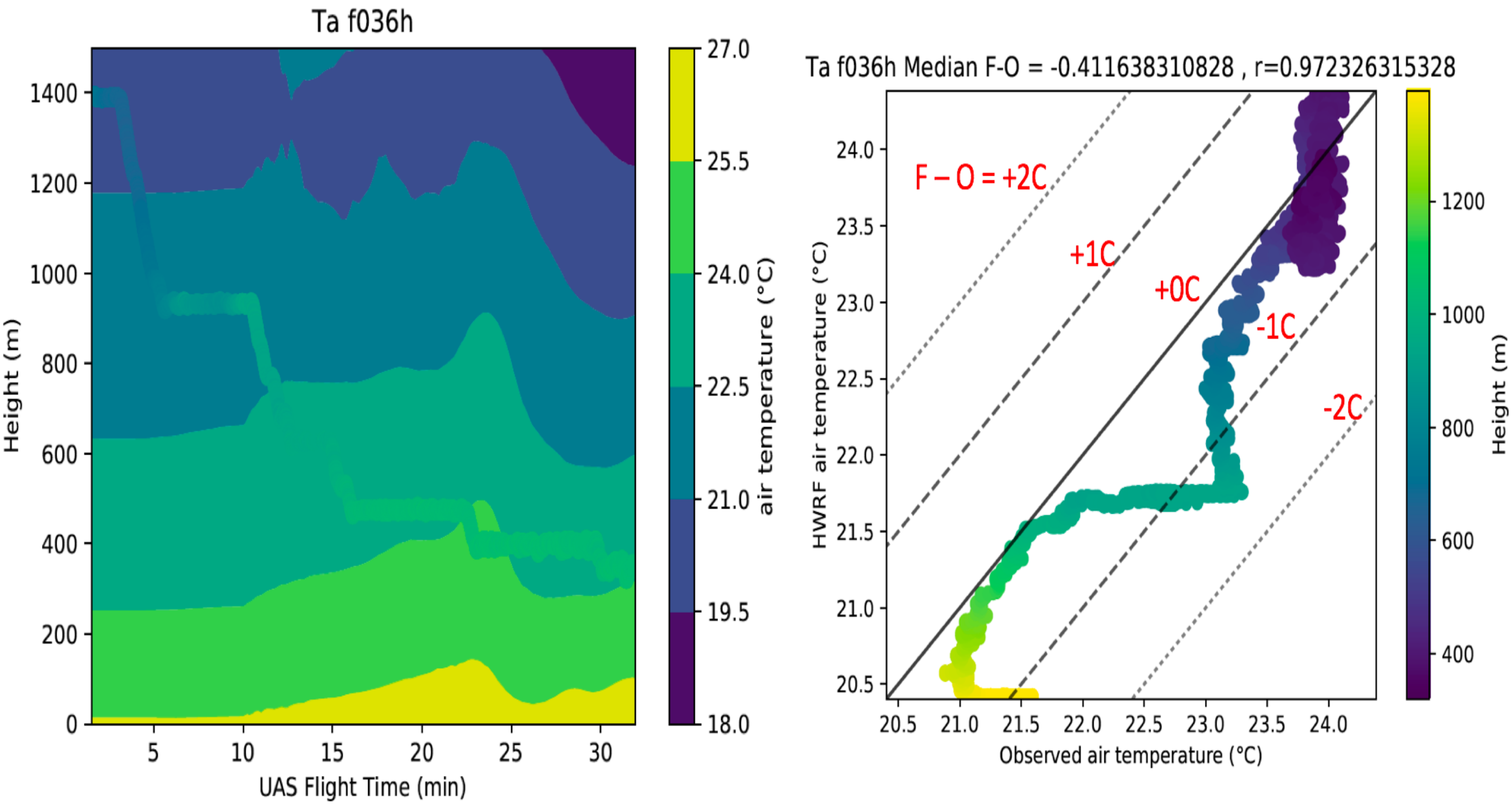
Images credit: George Bryan, NCAR



Images credit: George Bryan, NCAR

Operational Numerical Model Evaluation- Foci 1:

Evaluation of Physical Parameterization Boundary Layer Schemes in NWP Models (HWRF)



Sep 23, 36-h forecast: Model BL generally cooler than Coyote data

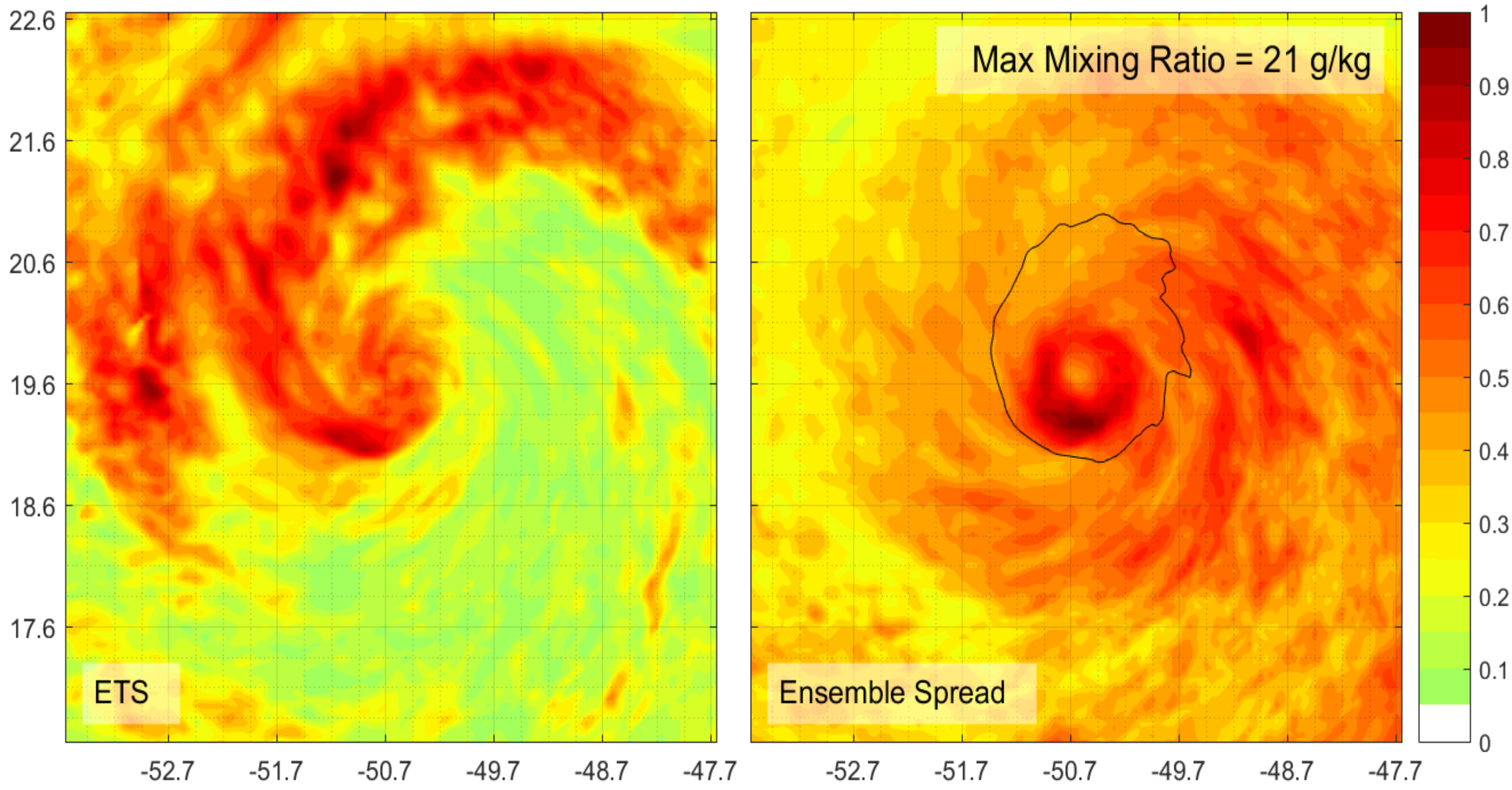
Image credit: Evan Kalina, NOAA/DTC/CIRES

Data Impact Studies (OSE/OSSE/Optimal Sampling Strategies) - Foci 2:

Optimizing Boundary Layer UAS sampling strategies
(e.g. Atmospheric Moisture)

100m

Image credit: Rani Wiggins, NOAA/AOML/HRD (NRC)

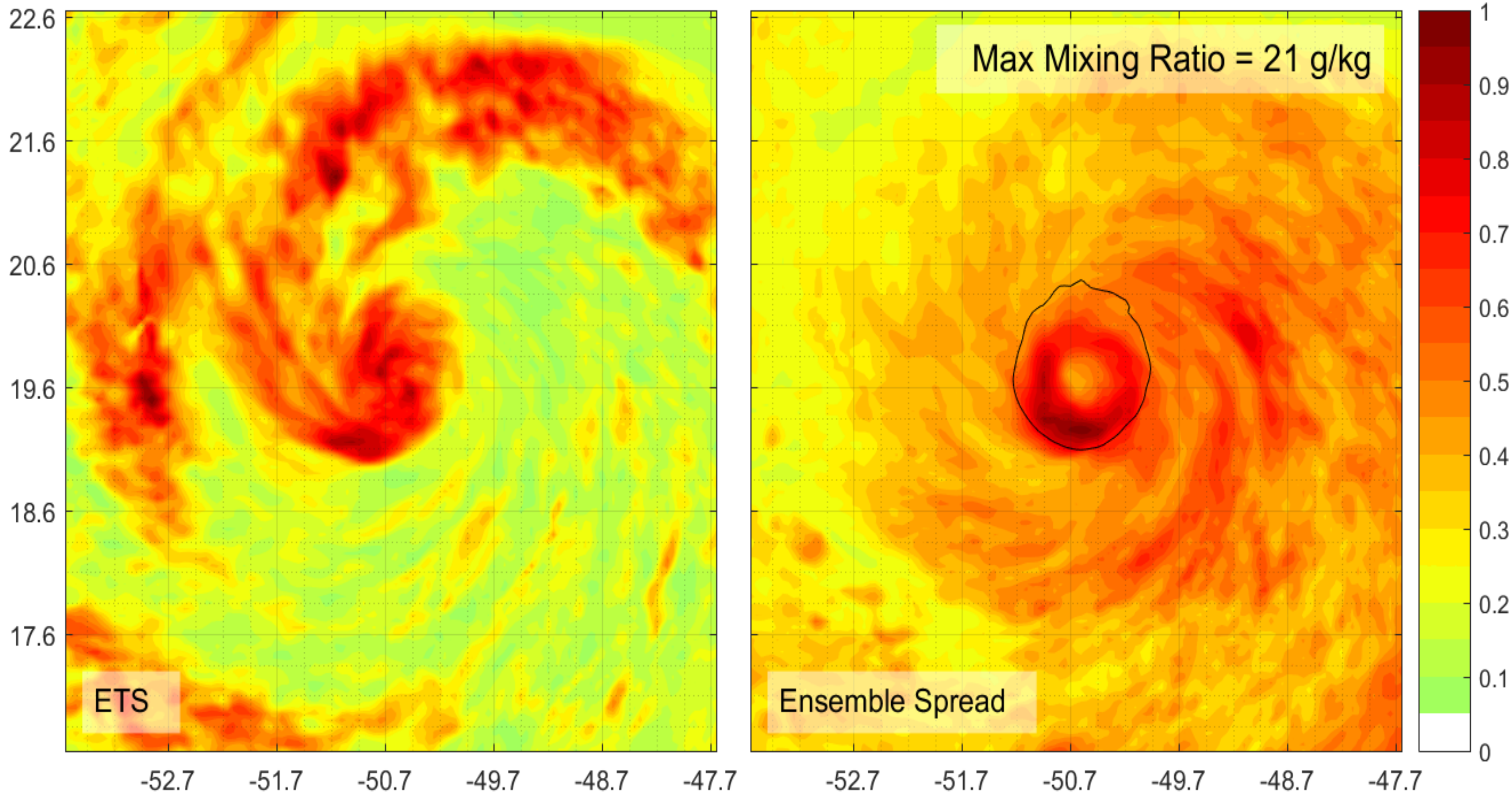


Data Impact Studies (OSE/OSSE/Optimal Sampling Strategies) - Foci 2:

Optimizing Boundary Layer UAS sampling strategies (e.g. Atmospheric Moisture)

300m

Image credit: Rani Wiggins, NOAA/AOML/HRD (NRC)

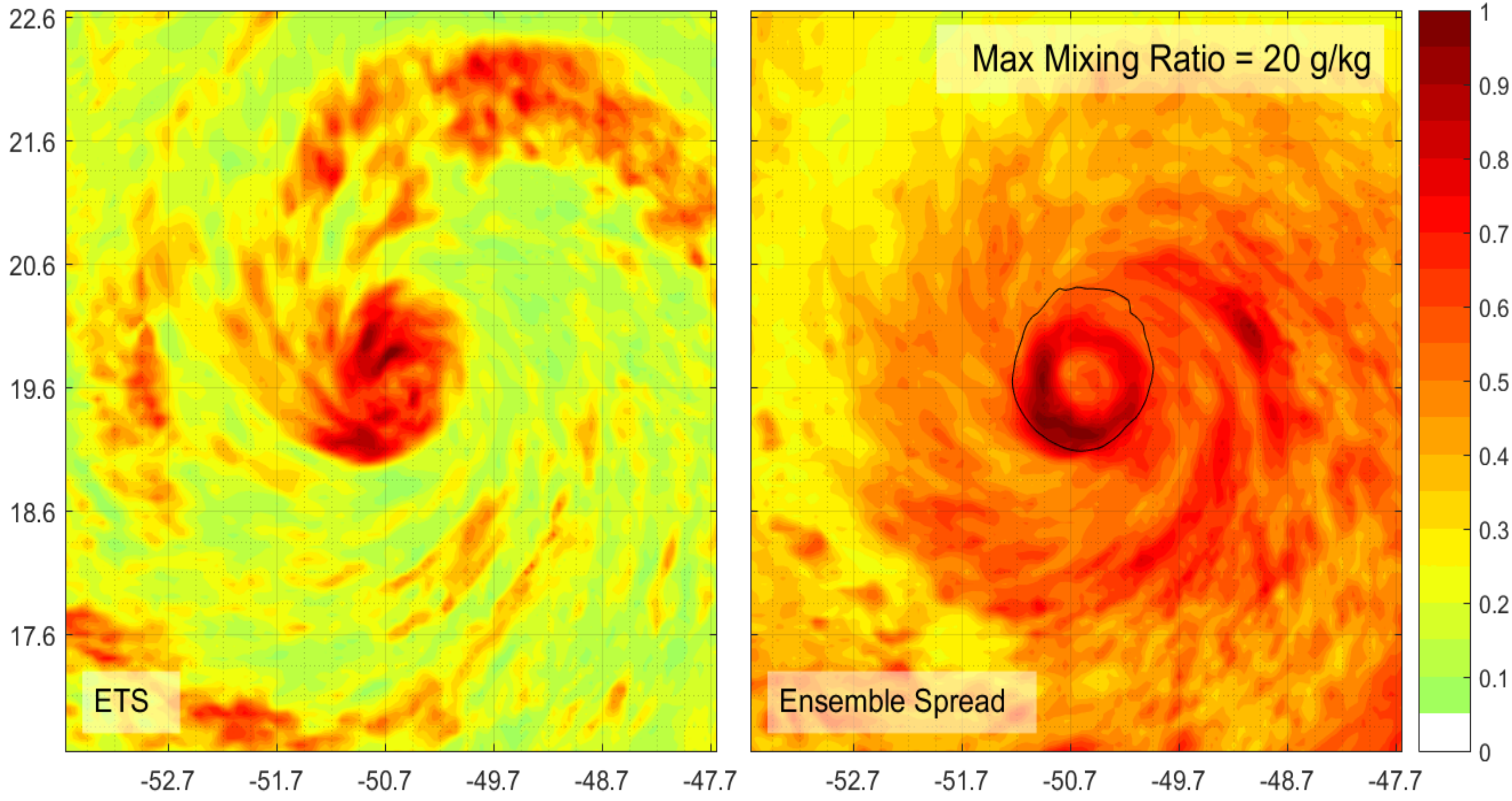


Data Impact Studies (OSE/OSSE/Optimal Sampling Strategies) - Foci 2:

Optimizing Boundary Layer UAS sampling strategies (e.g. Atmospheric Moisture)

500m

Image credit: Rani Wiggins, NOAA/AOML/HRD (NRC)

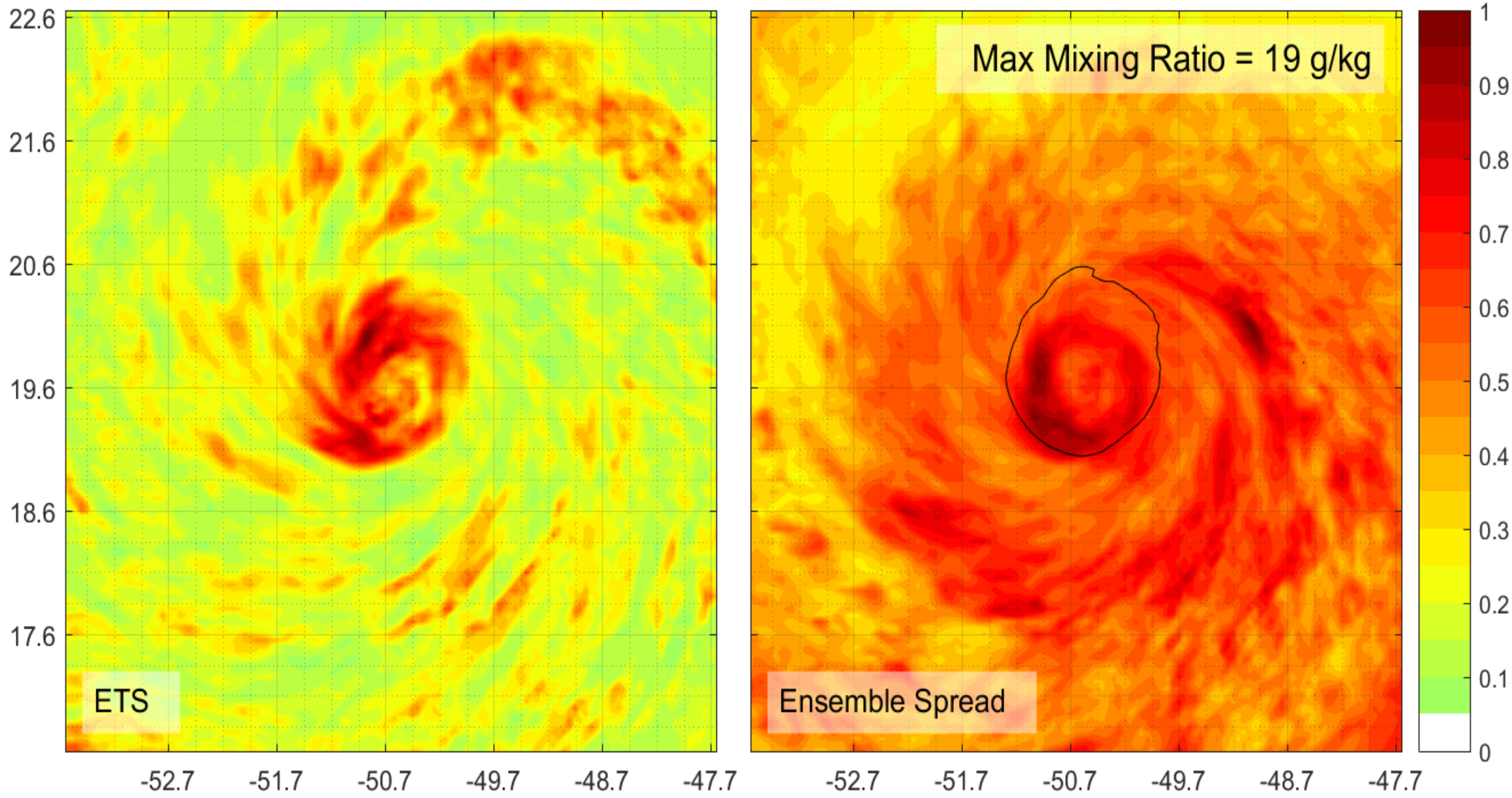


Data Impact Studies (OSE/OSSE/Optimal Sampling Strategies) - Foci 2:

Optimizing Boundary Layer UAS sampling strategies (e.g. Atmospheric Moisture)

700m

Image credit: Rani Wiggins, NOAA/AOML/HRD (NRC)

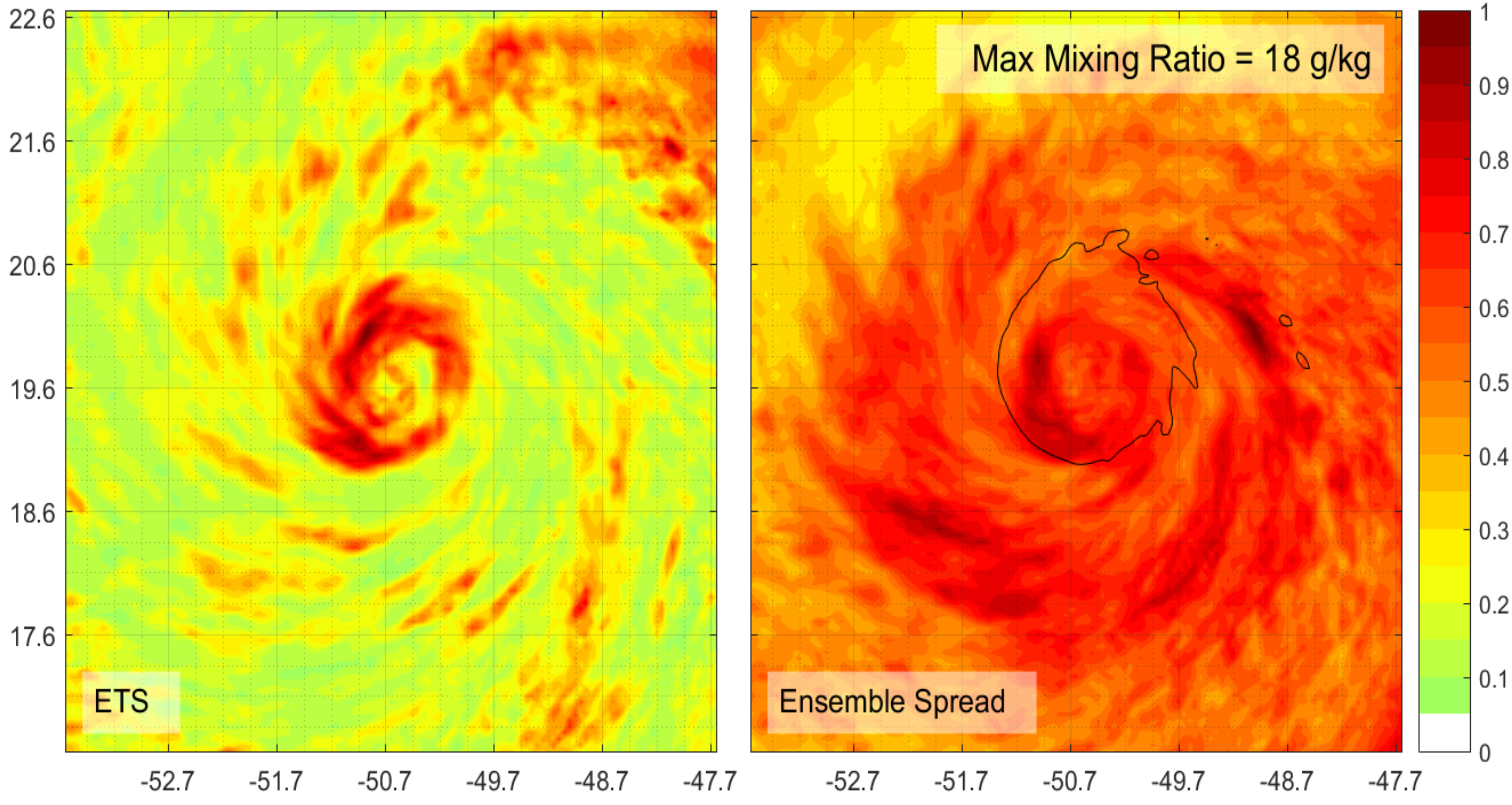


Data Impact Studies (OSE/OSSE/Optimal Sampling Strategies) - Foci 2:

Optimizing Boundary Layer UAS sampling strategies (e.g. Atmospheric Moisture)

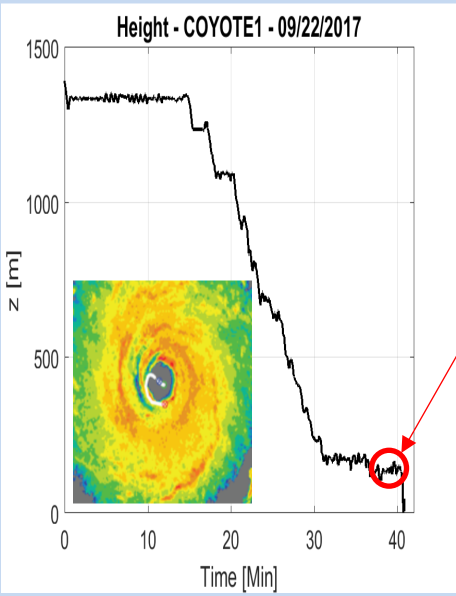
900m

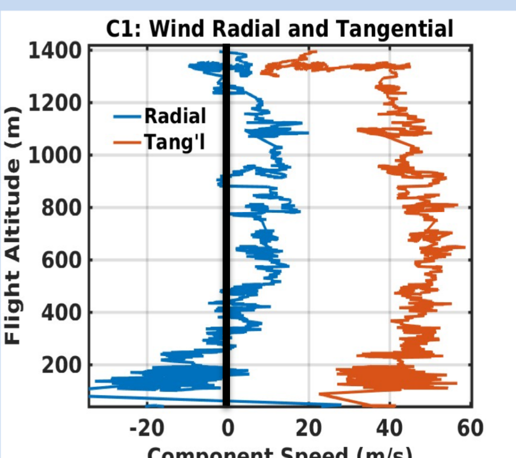
Image credit: Rani Wiggins, NOAA/AOML/HRD (NRC)

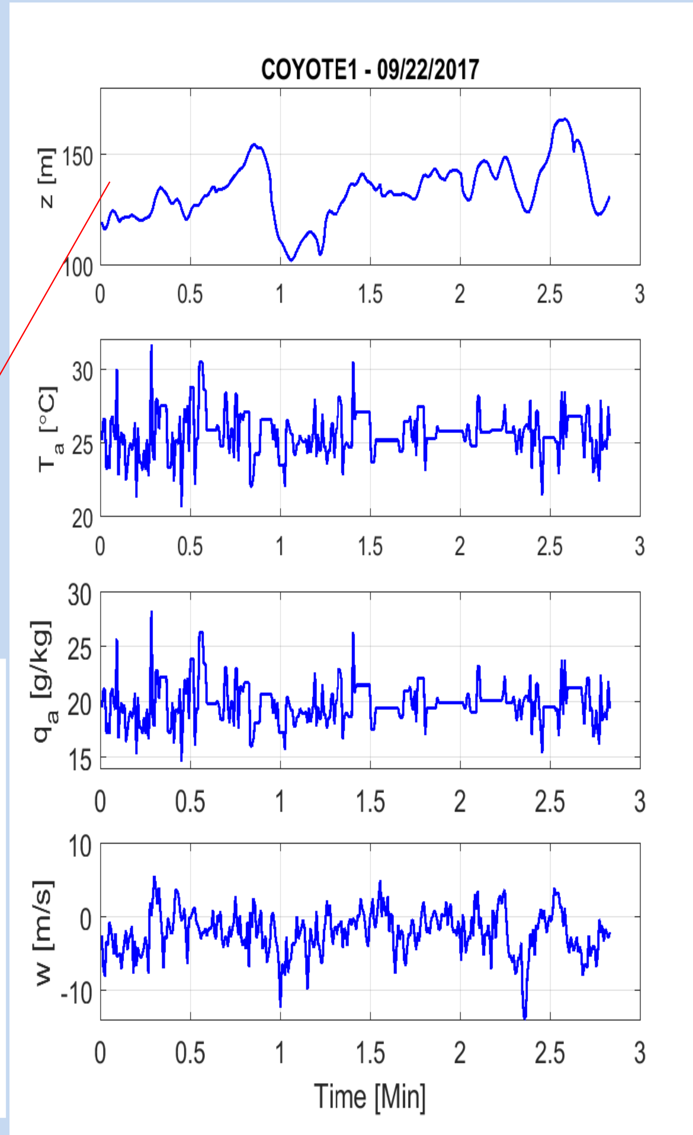


Turbulent Processes - Foci 3:

First-ever Direct Measurements of Enthalpy Flux in the Surface Layer of a Hurricane Eyewall (Major Hurricane Maria; September 22, 2017; Coyote Flight #1)







Eddy-correlation method:

$H = \rho\ Cp \langle w'T_a' \rangle = 228.0\ Wm^{-2}$

$E = \rho\ Lv \langle w'q_a' \rangle = 855.6\ Wm^{-2}$

Bulk method:

$H = \rho\ C_H\ Cp\ U_{10}\ (SST - T_a) = 168.1\ Wm^{-2}$

$E = \rho\ C_E\ Lv\ U_{10}\ (q_0 - q_a) = 744.0\ Wm^{-2}$

H – sensible heat flux
E – latent heat flux
$C_H = C_E = 0.0012$ (J. Zhang et al. 2008)

*Note1: Latent and sensible heat heat flux values derived from using Coyote eddy correlation methodology yields values of **0.0016 for C_H** (+33%) and **0.0015 for C_E** (+25%)*

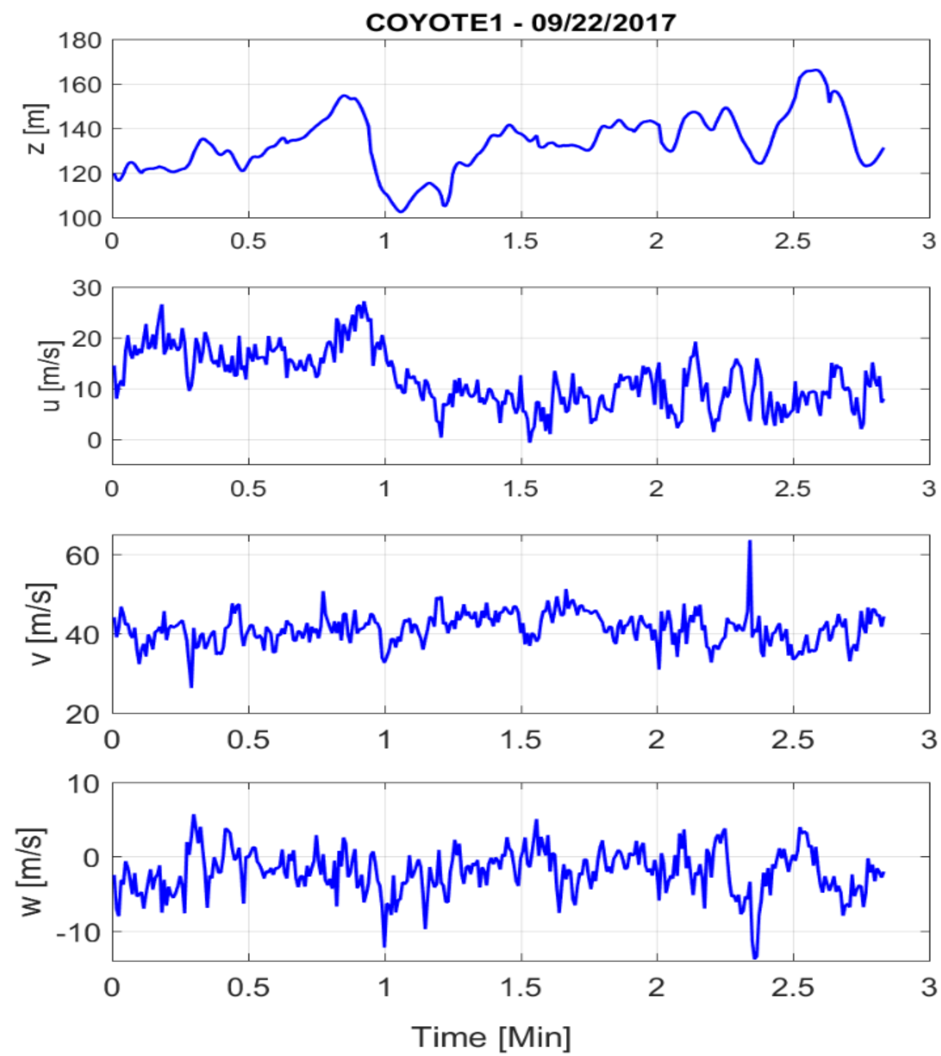
***HWRF avg. H and E:** 140.8; 625.9 (Wm^{-2})*

*$Note_2$:**Using C_H=0.0016;C_E=0.0015** (vs 0.0013) E_{Hwrf} and H_{Hwrf} become: **722.2; 173.3 (Wm^{-2})***

Images: Dobosy (NOAA/ARL/ATDD); Zhang (NOAA/AOML/HRD)

Turbulent Processes - Foci 3:

First-ever Direct Measurements of Momentum Flux (Reynolds Stress τ_R) in the Surface Layer of a Hurricane Eyewall (Major Hurricane Maria; Coyote Flight #1)



Eddy-correlation method:

$\tau_R = \rho\ (<u'w'>^2 + <v'w'>^2)^{1/2} = 3.29\ Nm^{-2}$

Note$_1$ Using Coyote measured Reynolds Stress and 10-m wind speed yields $C_d = 0.0016$, which is close to values from previous observations (e.g., Black et al. 2007; Powell et al. 2003; Bell et al. 2012).

Bulk method:

$\tau_R = \rho\ C_d\ U^2_{10} = 4.99\ Nm^{-2}$

Here, $C_d = 0.0022$ (Donelan et al. 2004) for $U_{10} > 33\ ms^{-1}$

Note$_2$ Using Coyote derived C_d of 0.0016 (in lieu of C_d= 0.0022 used by Donelan et al.) yields:

$\tau_R = \rho\ C_d\ U^2_{10} = 3.63\ Nm^{-2}$

Which is very close to the direct, eddy-correlation value for Reynolds stress calculated above.

***HWRF avg. Momentum Flux:* 4.69 Nm^{-2}**

Note$_3$: HWRF C_d varies between… 0.0022 (@40ms-1) and 0.0016 (@50ms-1)

Image credit: Zhang (NOAA/AOML/HRD)

Summary

- Why Coyote UAS data collected in Hurricane Maria are special…
  - 1st Successful 3 day deployment of a small UAS into a Major Hurricane (repeatability)
  - Highest UAS-measured wind speed in a tropical cyclone (64 m/s at 340 m)
  - Lowest controlled UAS flight in a hurricane eyewall (100-140 m) or by ANY aircraft for that matter!
  - Record UAS endurance within a hurricane eyewall environment (42 minutes)
  - High-frequency continuous wind measurements collected at very low altitudes (up to 10 Hz)
  - Preliminary analyses depict high quality data, enabling unprecedented study of physical processes in extreme high wind environments (e.g. direct turbulent fluxes in eyewall surface layer, eddy dissipation)
  - Preliminary direct flux measurements from Coyote UAS observations in Maria may suggest that momentum, heat and moisture flux transfer coefficient (C_d, C_h and C_e) "assumptions" may be somewhat overestimated (momentum?) and underestimated (enthalpy?) at windspeeds over $40 ms^{-1}$ More cases needed !
  - UAS data transmitted in real time to NHC each day (as noted in NHC discussions on 9/22 and 9/23)

These highly unique data have the potential to significantly enhance physical understanding of a rarely observed region of the storm, improve operational situational awareness and provide valuable insights for (coupled) model evaluation and improvement…

Whats next for NOAA as it relates to sUAS and Tropical Cyclones?

- **Future Plans, Opportunities and Research Transition to Operations:**
  - **Where we are right now…2018**
    - After flying 6 UAS in Hurricane Maria, the NOAA Coyote research and operation team has 1 UAS remaining. Given this reality, coupled with the desire to upgraded to the "Block III" Coyote platform (3h duration; 6 lb payload capacity) and move to the more reliable Vaisala RD41 payload, the decision was to stand down for 2018 operations and gear up for 2019. Several tasks are ongoing including final testing by Raytheon for the new Block III variant, as well as transitional testing of the Vaisala payload.
  - **Plans for 2019….**
    - Acquisition of 6 Block III Coyote UAS, new RD41 Vaisala payloads is planned for Q1/2019 assuming of Hurricane Supplemental resources and support from NOAA's UAS Program Office become available.
    - Funds permitting, efforts will also be made to incorporate a Laser Altimeter (height assignment improvement) and IR sensor (SST) as part of the new payload suite.
    - Clear air testing of the full equipped new Block III long endurance Coyote UAS could begin as soon as spring/early summer of 2019.
    - If all goes as planned, follow-on in-storm Coyote UAS missions using the six (6) 3h UAS missions would follow during the 2019 Hurricane Season.
  - **Longer term (R20) plans for Coyote 2019 ->**
    - To fully reach TRL9 "operational status" the Coyote UAS must continue to enhance its payload. Assuming funding is in place, the Coyote team will internally (NOAA) and externally (Private Sector, University and other Agencies) look to design, test and fully integrate a low cost, expendable, 3D winds-capable turbulence probe starting in 2019. With sufficient funding, it is envisioned that this system could be ready to fly in a storm environment by late 2020.
    - Another "must have" to attain full operational viability is full autonomy. This would include transitioning to the AVAPS data system used by NOAA and out global partners who currently deploy GPS dropsondes. Since AVAPS is a 1-way communication system, the sUAS will also need to incorporate an on board Artificial Intelligence (AI) capability. This work is currently unfunded but could begin as early as 2020 and conceivably could be ready for flight in a storm environment by the 2022 Hurricane Season.
  - **Other exciting small UAS possible future NOAA options NOT named Coyote are also on the horizon!**
    - TWO new SBIR projects that NOAA will be overseeing will be using a similar air-deployed "Concept of Operations" but will employ different techniques and technologies. A major focus of these efforts will be to take the (ongoing) lessons learned from the multi-year Coyote UAS project and apply them in such a way that NOAA will retain similar or improved sampling capabilities but do so at significantly reduced cost and with simplified operational complexity.
    - Both of these companies will begin work on their SBIR Phase I projects ($120K each) later this summer.
    - Phase II follow-on efforts ($400K), assuming additional investment from NOAA is warranted, would begin in '19 and continue for 2yrs.

Coyote Telemetry Video in Hurricane Maria