UNIVERSITY OF MIAMI
ROSENSTIEL SCHOOL of MARINE, ATMOSPHERIC & EARTH SCIENCE

Air-Sea Interaction in Rapidly Intensifying Tropical Cyclones over Mesoscale Ocean Features

Benjamin Jaimes de la Cruz and Lynn K. Shay

University of Miami, Rosenstiel School, Department of Ocean Sciences, Upper Ocean Dynamics Laboratory, Miami, FL

INTRODUCTION

Rapid intensification (RI) of a tropical cyclone (TC) often occurs over anticyclonic mesoscale ocean features—and rapid weakening over cyclonic features. Operational TC forecast numerical models fail to correctly simulate rapid intensity change events. Herein, this limitation is addressed with state-of-the-art measurement techniques in combination with non-linear upwelling theory and novel perspectives of air-sea heat fluxes. This approach includes adaptive 3-D measurements of temperature, salinity and current from autonomous floats and airborne expendable ocean profilers, as well as measurements of atmospheric properties. As part of NOAA Intensity Forecasting Experiments, airborne expendable bathythermographs (AXBT), Conductivity-Temperature-Depth (AXCTD), Current Profilers (AXCP) probes, APEX-EM floats, and atmospheric GPS dropsondes have been deployed in several major hurricanes from the NOAA research aircraft and USAF reconnaissance aircraft over the mesoscale eddy field in the Gulf of Mexico and Western Caribbean Sea.

KEY RESULTS

The presence of mesoscale ocean features impacts TC intensity change by:

① Accelerating TC-driven upwelling/downwelling responses;

② Driving downwelling and thermocline warming underneath the inner-core region of TCs;

③ Sustaining the TC energy source for longer time over warm mesoscale oceanic features;

④ Enhancing SST gradients that impact the stability of the TC atmospheric boundary layer;

⑤ Amplifying air-sea moisture disequilibrium over warm anticyclonic features, which facilitates TC atmospheric boundary layer recovery and RI;

⑥ Reducing moisture disequilibrium over cyclonic features that contribute to rapid TC weakening.

These results underscore the gaps in our understanding of TC intensity change over mesoscale oceanic eddy features that require high-resolution collocated 3-D measurements of current, temperature and salinity in assessing parameterizations in coupled models for the TC intensity forecast.

EXPERIMENTAL APPROACH

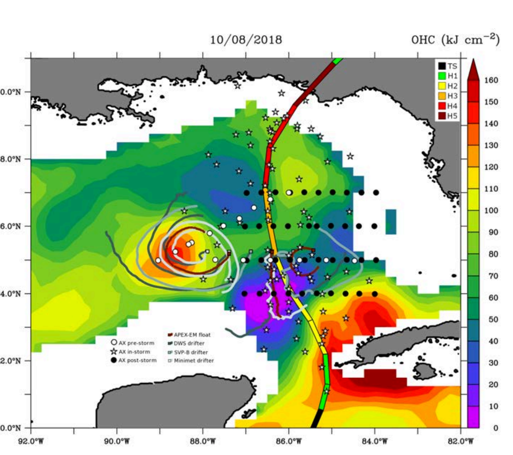

Fig. 1. Air-sea interaction experiment in Hurricane Michael (2018) over the Gulf of Mexico mesoscale eddy field.

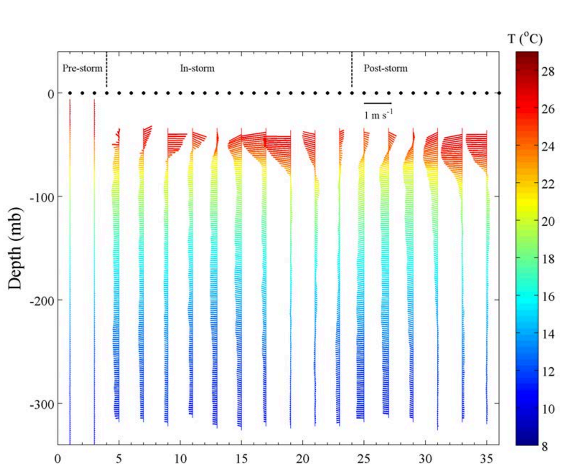

Fig. 2. Time series of velocity vectors (colored by water temperature) from APEX-EM float measurements during the rapid intensification of Hurricane Michael (2018) over the Loop Current mesoscale eddy field.

Observational Platforms

- NOAA's WP-3D research aircraft
- USAF C-130 reconnaissance aircraft
- Altimeter based daily products (includes Sentinel-6)
- APEX-EM floats: P, V, T, and S
- Airborne expendable current profilers (AXCP): P, V, T
- Airborne expendable CTD (AXCTD): P, T, S
- Airborne expendable bathytermographer (AXBT): P, T
- Atmospheric GPS dropsonde: P_a, V_a, T_a, RH

WIND-DRIVEN, INNER-CORE UPPER OCEAN WARMING

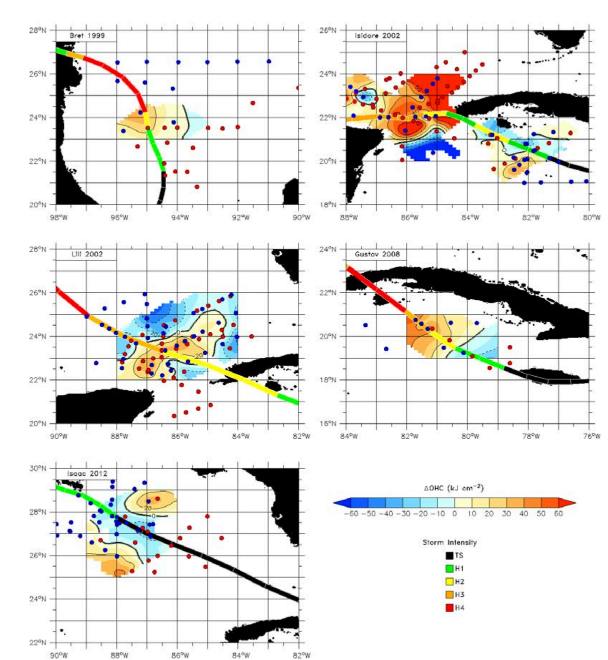

Fig. 4. Wind-driven upper ocean warming in intensifying hurricanes, from airborne ocean profilers (dots) deployed from consecutive NOAA's WP-3D research aircraft flights.

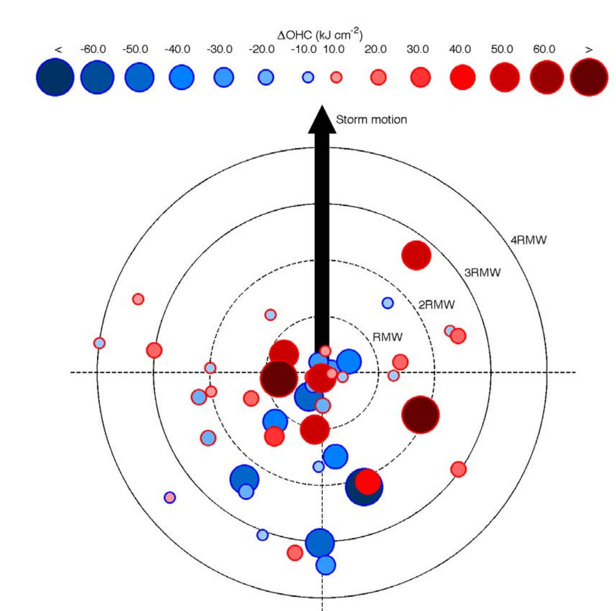

Fig. 5. Distribution of upwelling and downwelling regimes in relation to the hurricane quadrants (circles signify radial distance normalized by the radius of maximum winds in the corresponding storm).

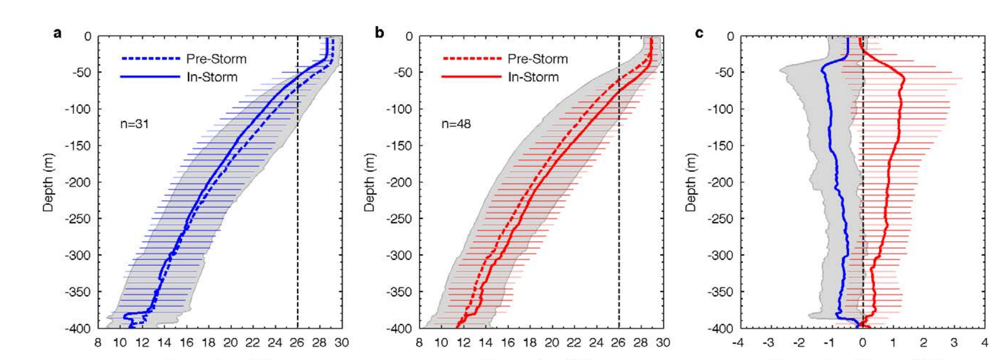

Fig. 6. Vertical structure of upwelling and downwelling regimes.

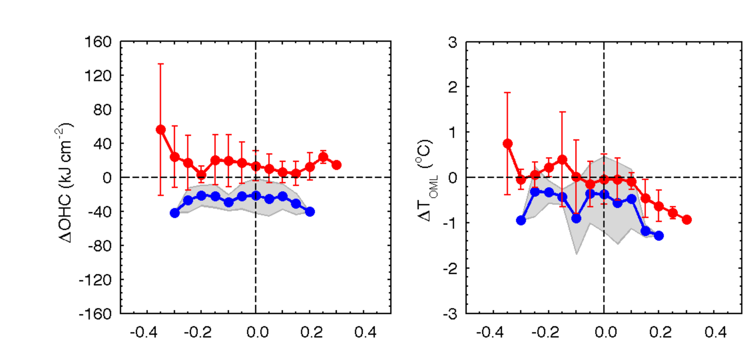

Fig. 7. Upper ocean temperature response as a function of strength in the mesoscale eddy fields ($Ro=\zeta_g/f$).

The upwelling response is a function of the curl of wind-intensified geostrophic currents, rather than just a function of the curl of the wind stress.:

$$W_s = \mathbf{k}\cdot\frac{\nabla\times\boldsymbol{\tau}}{\rho_0 f} - \frac{h}{f}\left(\frac{\partial\zeta_g}{\partial t} + \frac{\boldsymbol{\tau}\times\mathbf{k}}{\rho_0 f h}\cdot\nabla\zeta_g\right)$$

Downwelling responses often lead to upper-ocean warming over the inner-core region in intensifying hurricanes.

Parametric form:

$$W_s = \frac{\tau_{max}}{\rho_0 U_h} - \frac{\zeta_g}{f}\frac{h}{R_{max}}\left(U_h + \frac{\tau_{max}R_{max}}{\rho_0 h U_h}\right)$$

$$W_s = W_E - Ro_g\delta(U_h + U_{OML})$$

W_E Ekman pumping

$Ro_g = \zeta_g/f$ eddy Rossby number

$\delta = h/R_{max}$ aspect ratio

U_h storm's translation speed

U_{OML} Ekman drift velocity

τ_{max} maximum wind stress

R_{max} radius of maximum winds

COUPLED RESPONSE

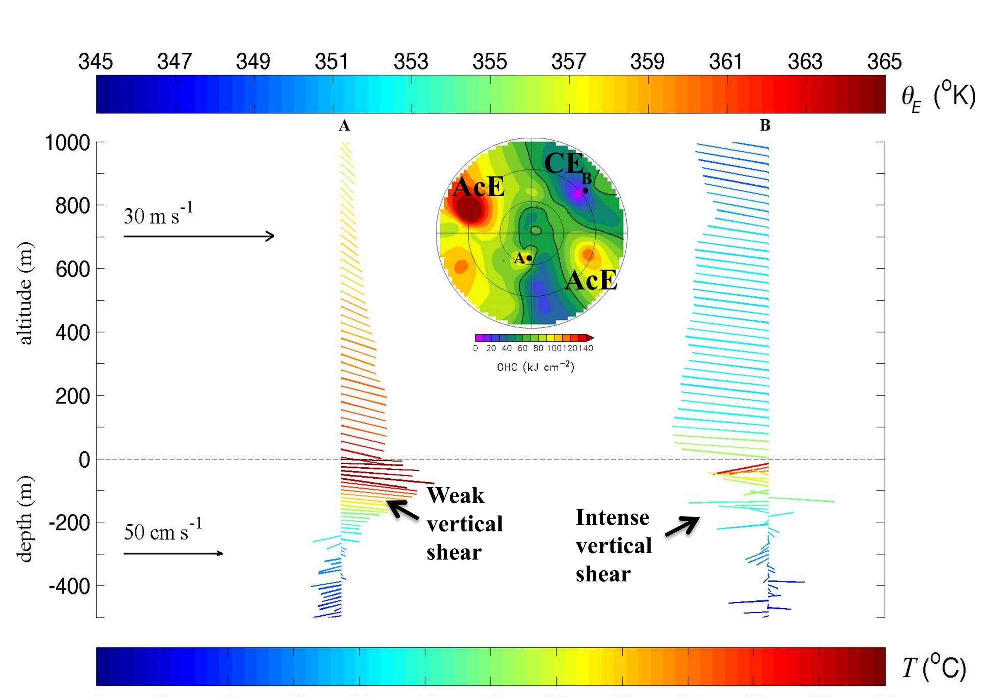

Fig. 3. Air-sea coupled response in Hurricane Isaac (2012). Wind vectors are from atmospheric GPS dropsondes. Ocean currents are from AXCPs. OHC: Ocean Heat Content; CE: Cyclonic Eddy; AcE: Anticyclonic Eddy.

Anticyclonic eddies	Cyclonic eddies
• Weaker vertical shear of horizontal currents;	• Stronger vertical shear of horizontal currents;
• Smaller sea surface cooling;	• Larger sea surface cooling;
• Warmer and more humid air parcels aloft.	• Cooler and drier air parcels aloft.

ENHANCED AND PERENNIAL BUOYANCY FORCING

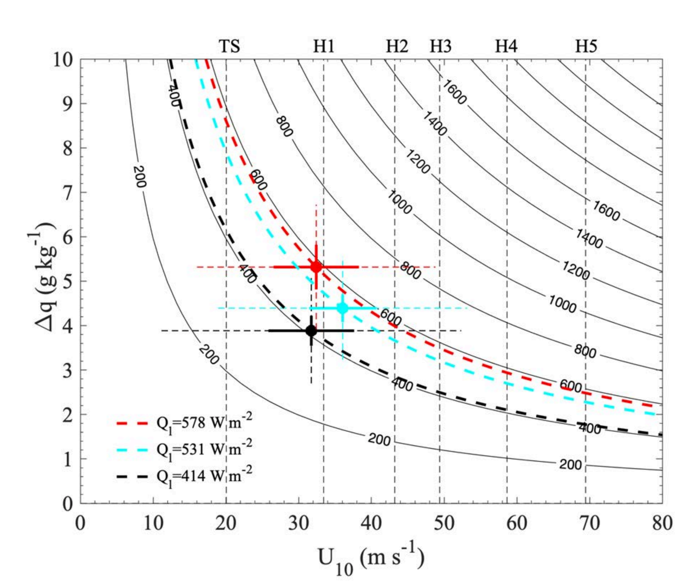

Fig. 8. Average bulk air-sea moisture flux, in the U_{10}-Δq space, during phases of steady state (black), slow intensification (cyan), and rapid intensification (red) in six hurricanes. Contours are for isoflux lines (Q_l = constant).

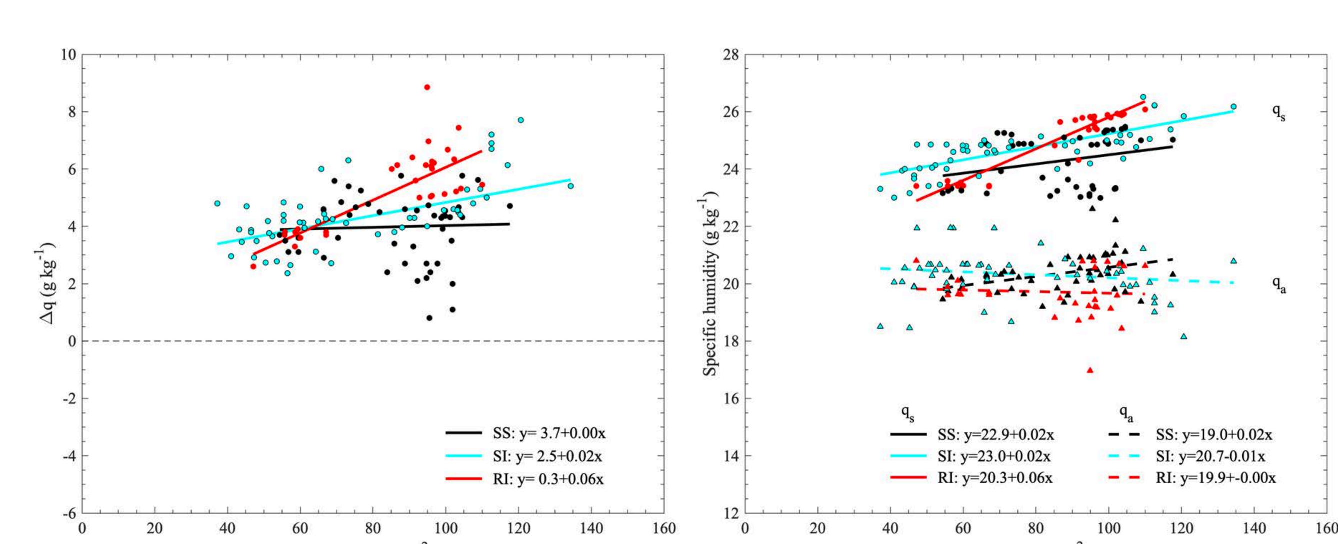

Fig. 9. Bulk air-sea moisture flux—from data in Fig. 8—as a function of upper ocean heat content (OHC) relative to the 26 °C isotherm depth, from in-storm *in situ* data, during phases of steady state (black), slow intensification (cyan), and rapid intensification (red) in six hurricanes.

$$Q_l = \rho_a L_v C_q U_{10}\underbrace{(q_s - q_a)}_{\Delta q}$$

$$OHC = \rho_0 c_p\int_{z=h_{26}}^{z=\eta}[T(z) - 26^{o}C]\,dz$$

Peak values in Δq preferentially occurred over oceanic regimes with higher SST and OHC. Thus, increasing SST and Δq is a very effective way to increase surface heat fluxes—this can easily be achieved as a hurricane moves over deeper warm mesoscale oceanic regimes.

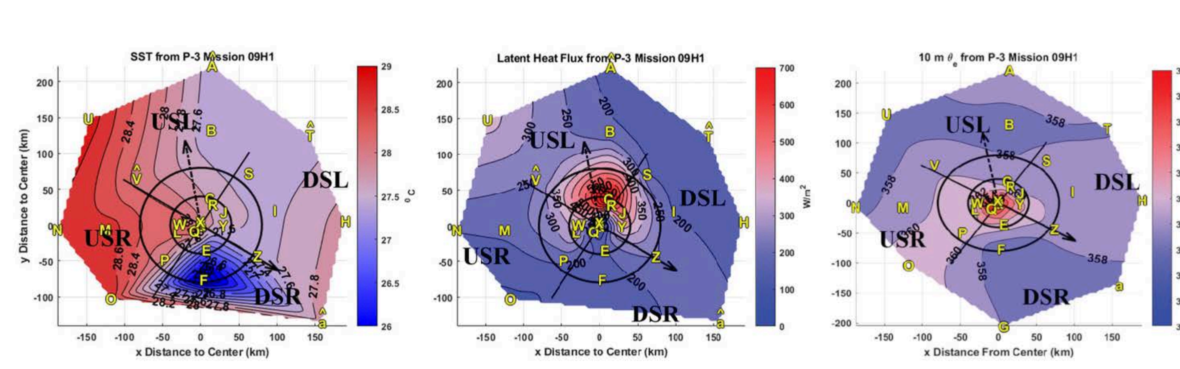

Fig. 10. Intensification of bulk air-sea moisture fluxes, and ensuing increase in equivalent potential temperature (θ_e), across SST gradients during the rapid intensification of Hurricane Michael (2018) over the Gulf of Mexico mesoscale eddy field.

ACKNOWLEDGEMENTS

We gratefully acknowledge NFS (Award FAIN 1941498) and the National Academy of Science, Engineering, and Medicine—Gulf Research Program—Understanding Gulf Ocean Systems (Award Number M2202111 to the GulfCORES research consortium) for supporting this research. The project continues to be grateful to the NOAA Aircraft Operation Center who make it possible to acquire high quality data during hurricanes through the Hurricane Forecast Improvement Project (HFIP) and the collaborative ties with NOAA's Hurricane Research Division directed by Dr. Frank Marks at AOML.

Contact: bjaimes@miami.edu

REFERENCES

Jaimes de la Cruz, B., L. K. Shay, J. B. Wadler, and J. E. Rudzin, 2021: On the hyperbolicity of the bulk air-sea heat flux functions: insights into the efficiency of air-sea moisture disequilibrium for tropical cyclone intensification. *Mon. Wea. Rev.* **149**, 1517–1534.

Jaimes, B., L. K. Shay, and J. K. Brewster, 2016: Observed air-sea interactions in tropical cyclone Isaac over Loop Current mesoscale eddy features. *Dyn. Atmos. Oceans.*, **76**, 306–324.

Jaimes, B., and L. K. Shay, 2015: Enhanced wind-driven downwelling flow in warm oceanic eddy features during the intensification of tropical cyclone Isaac (2012): Observations and theory. *J. Phys. Oceanogr.*, **45**,1667-1689.

Shay, L. K., J. K. Brewster, B. Jaimes, C. Gordon, K. Fennel, P. Furze, H. Fargher, and R. He: 2019: Physical and Biochemical Structure Measured by APEX-EM Floats, IEEE/OES. *Twelfth Current, Waves and Turbulence Measurement (CWTM)*, San Diego, CA, USA, 2019, pp. 1-6.

Wadler, J. B., J. A. Zhang, R. F. Rogers, B. Jaimes, and L. K. Shay, 2021: The rapid intensification of Hurricane Michael (2018): storm structure and the relationship to environmental and air-sea interactions. *Mon. Wea. Rev.*, **149**, 245–267.