Atmosphere-Wave-Ocean Coupling in Extreme Conditions and High-Impact Weather Prediction

Shuyi S. Chen
Brandon Kerns, Dalton Sasaki, Alton Daley, Ben Barr

Department of Atmospheric Sciences
University of Washington

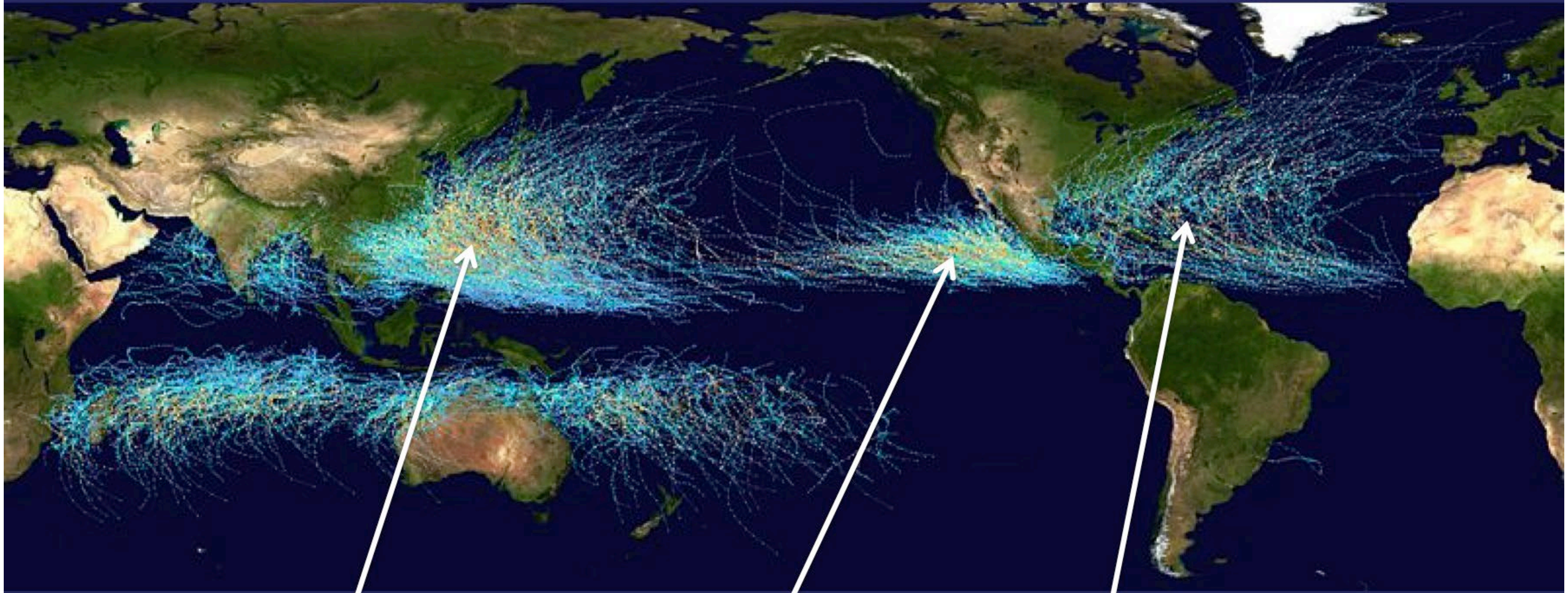



Contributions from M. Curcic, C. Fairall, E. D'Asaro, & many others

Outline of the talk:

1. Progress - field campaigns and coupled model development
   - Unified Wave Interface – Coupled Model (UWIN-CM)
   - Observations and UWIN-CM simulations/predictions of tropical cyclones
2. Impacts of seastate-dependent sea spray heat fluxes on landfalling hurricanes
3. Effects of surface waves on storm surge
4. Challenges, gaps, and ways forward

Tropical Cyclone Field Experiments



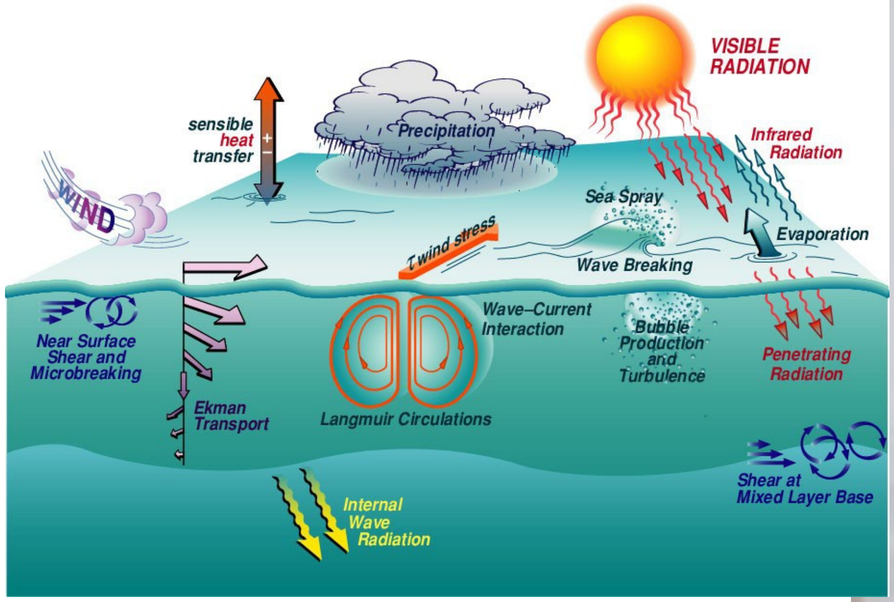
2010: ITOP/TCS10
2008: TCS08/DOTSTAR
1990: TCM90

2005: TCSP
1991: TEXMEX

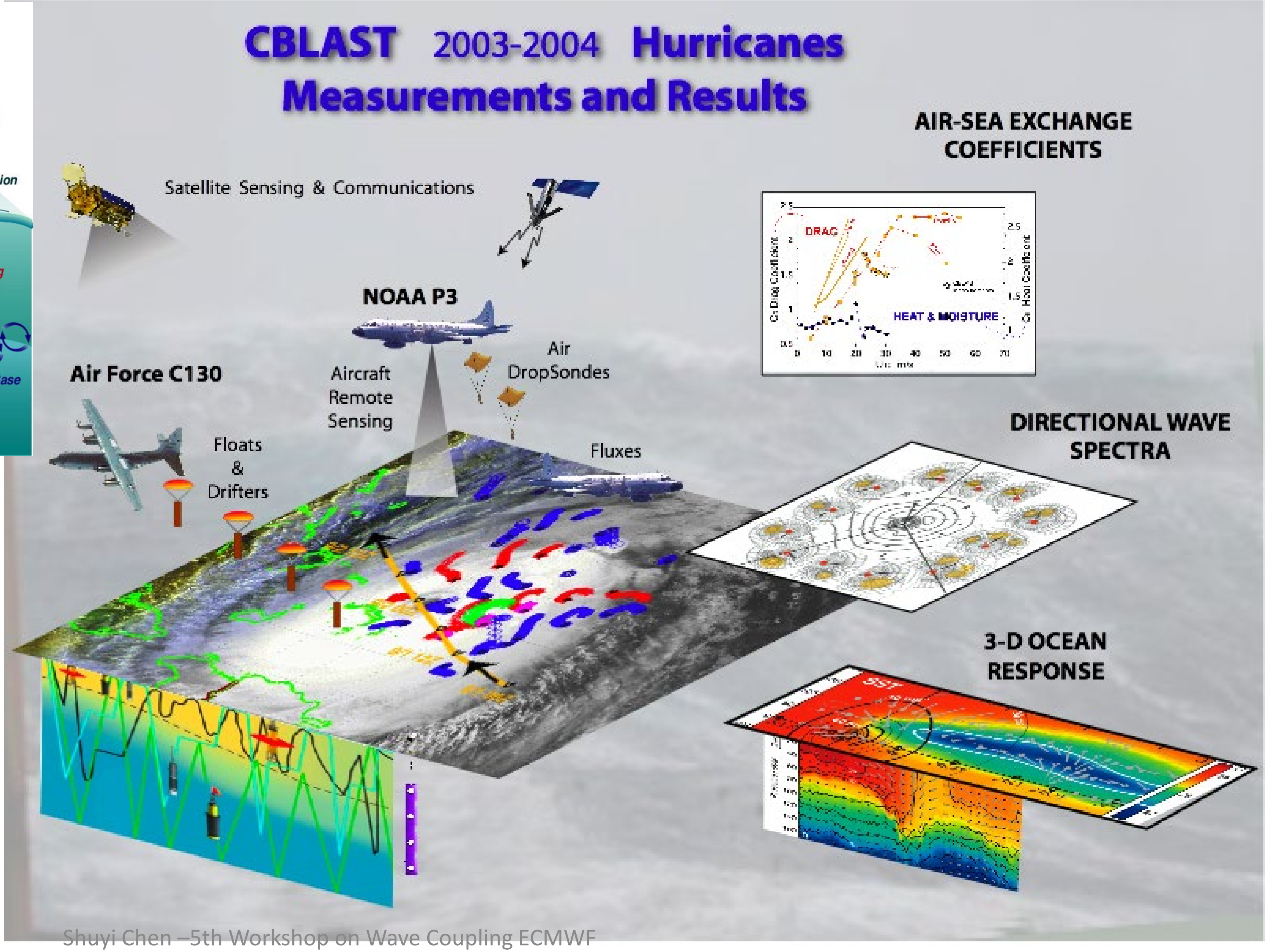
2010: PREDICT/GRIP/IFEX
2005: RAINEX
2003-04: CBLAST
2001 & 1998: CAMEX
1961-71: STORMFURY
1959: NHRP

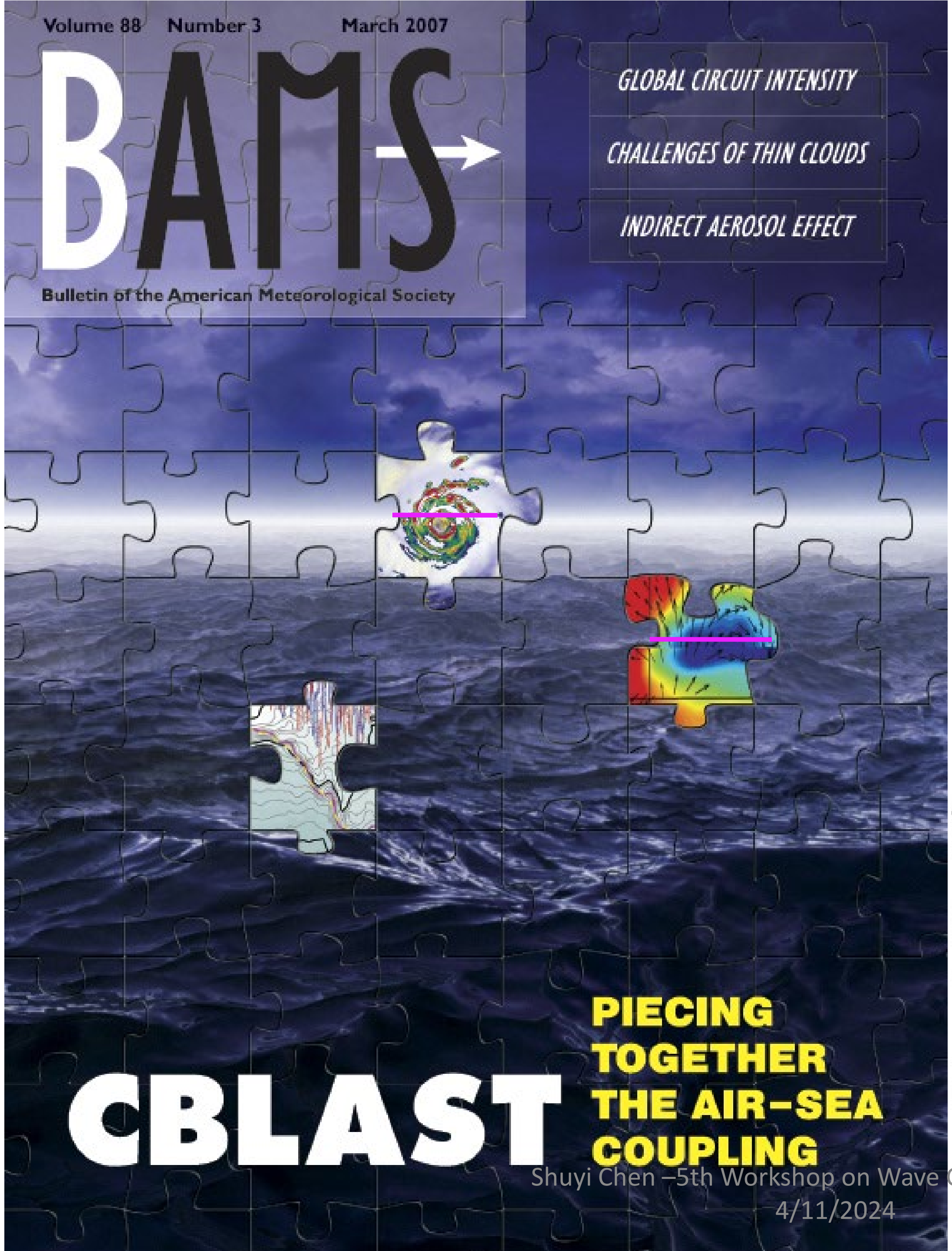
2012-16: CARTHE
2021-22: Saildrones

How surface waves affect air-sea fluxes in TCs?



Coupled Boundary Layers Air-Sea Transfer (CBLAST)



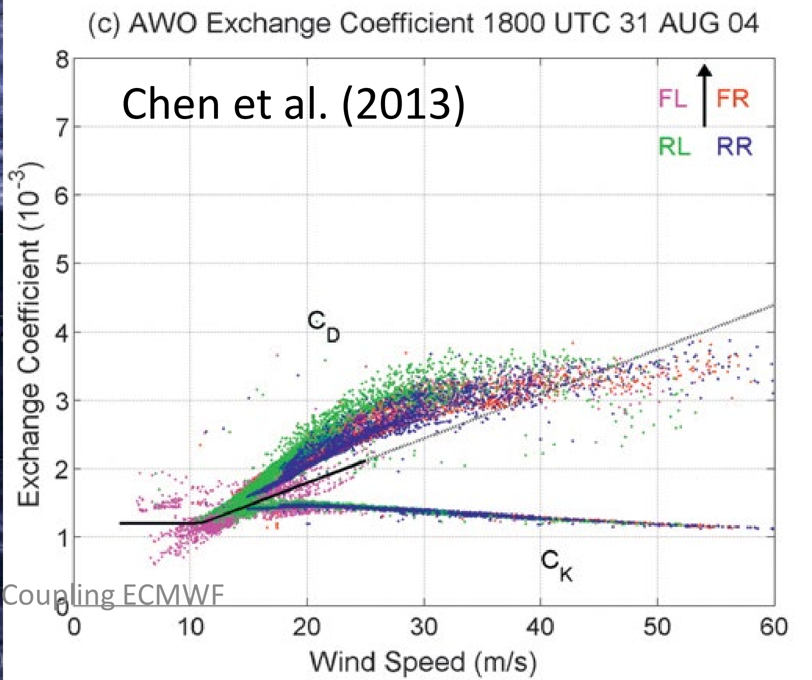


BAMS issue on CBLAST:

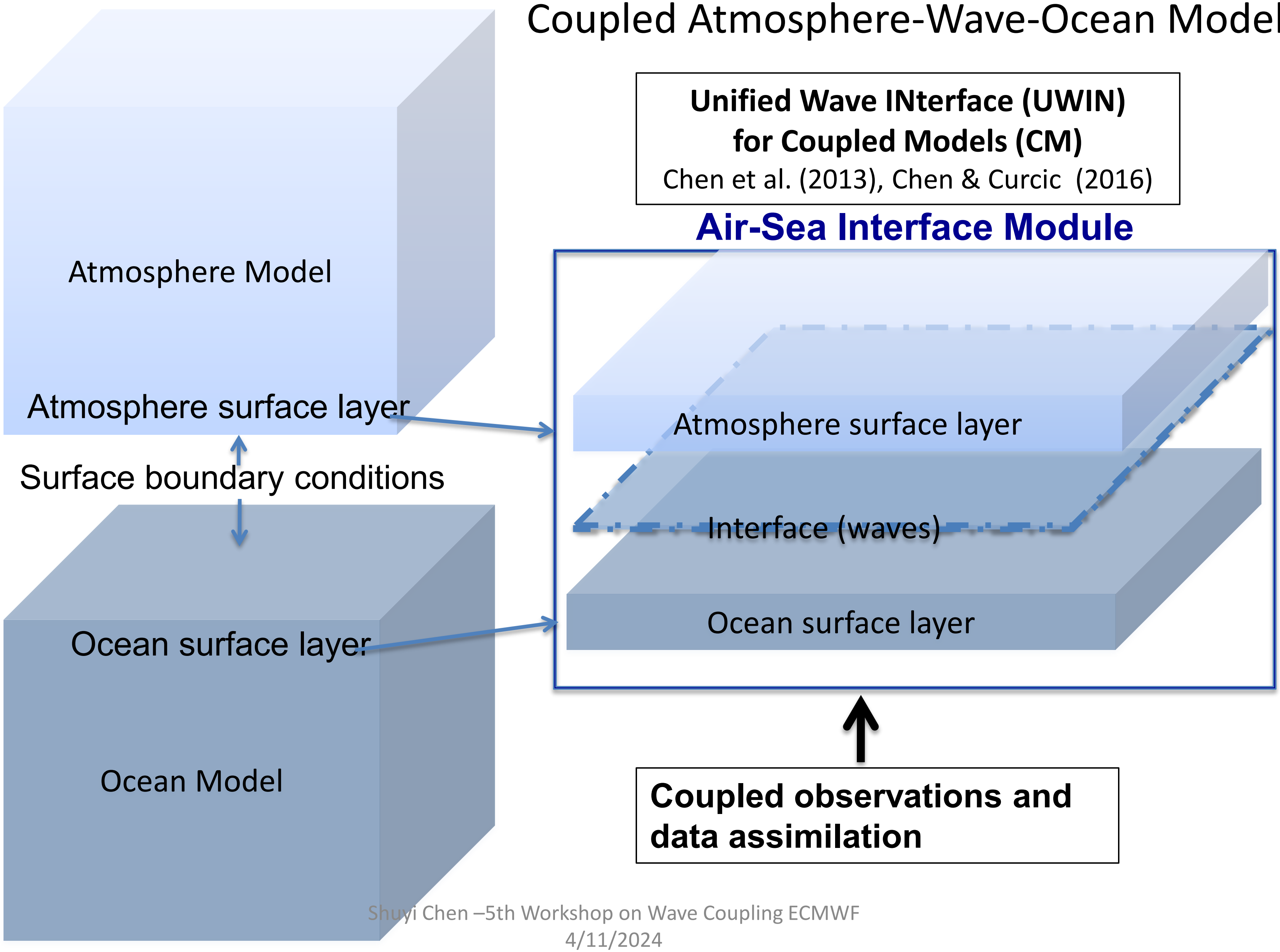
Black et al. 2007**:** Air-Sea Exchange in Hurricanes: Synthesis of Observations from the Coupled Boundary Layer Air-Sea Transfer Experiment, *BAMS*, 357-374.

Chen et al. 2007**:** The CBLAST-Hurricane Program and the next-generation fully coupled atmosphere-wave-ocean models for hurricane research and prediction. *BAMS, 311-317*.

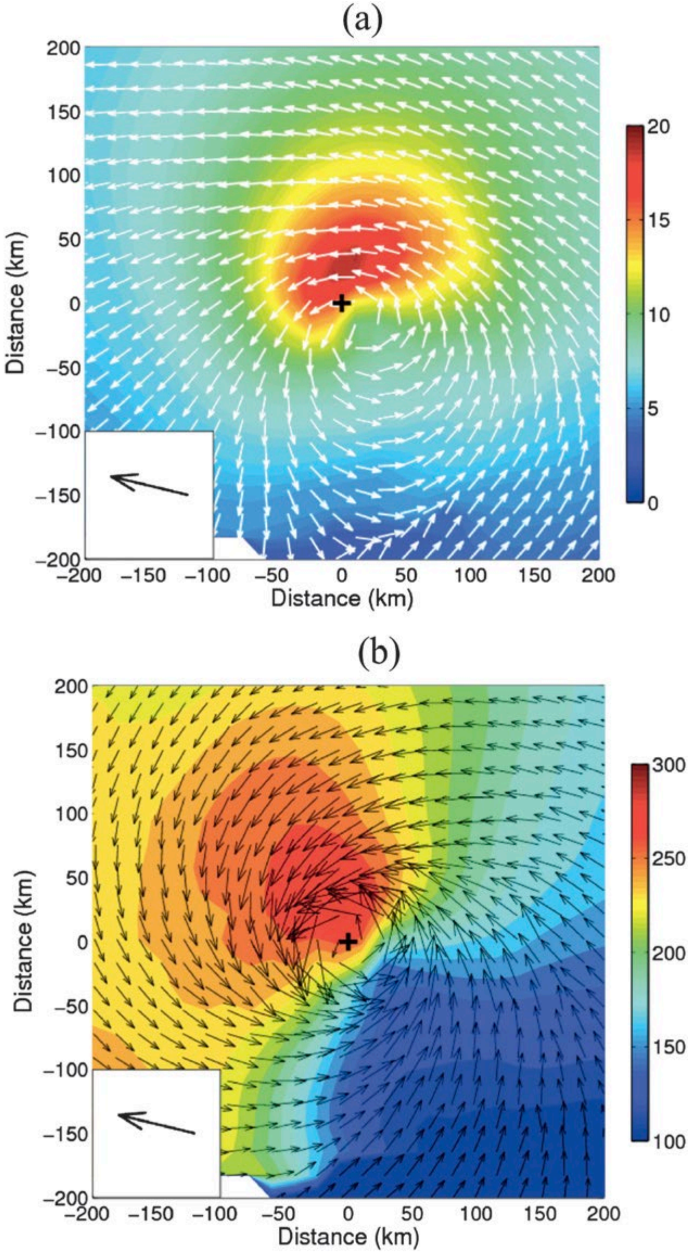
Edson et al. 2007**:** The Coupled Boundary Layers and Air-Sea Transfer Experiment in Low Winds (CBLAST-LOW).



Coupled Atmosphere-Wave-Ocean Modeling



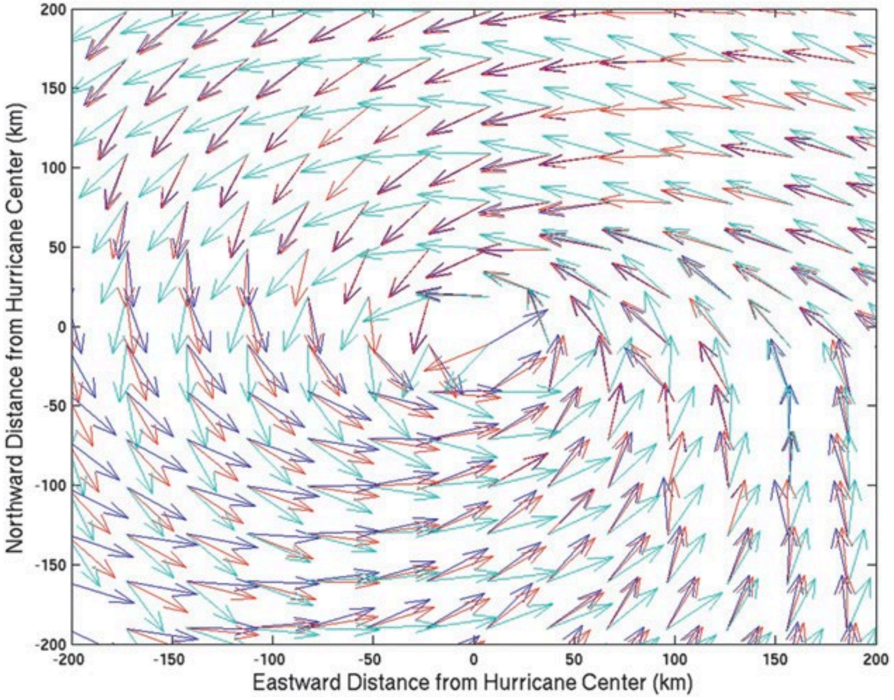
Chen et al. (2013) – Directional wave stress coupling

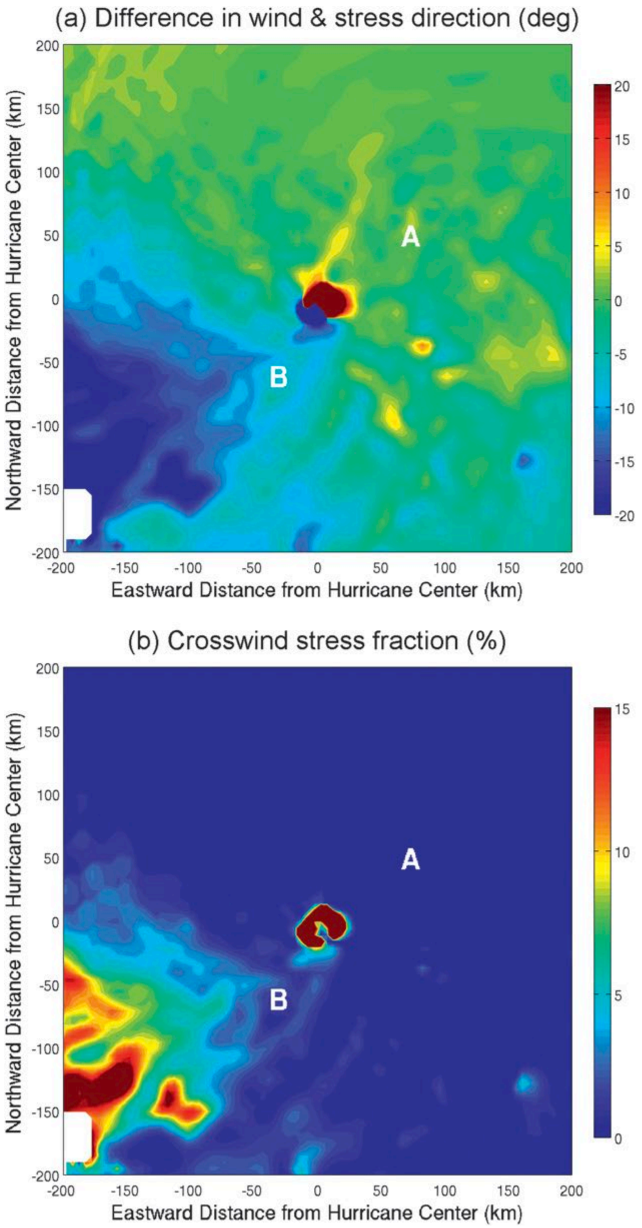


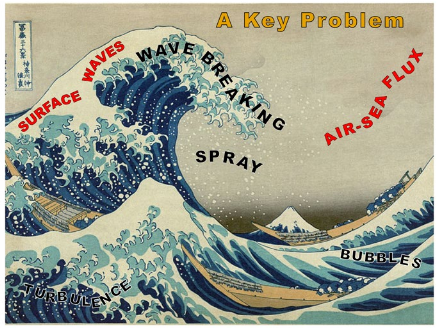
$$\tau_x = \tau_{wx} + \tau_{sx}$$
$$\tau_y = \tau_{wy} + \tau_{sy}$$

$$\tau_{wx} = g\rho_w \int_0^{\infty} \int_{-\pi}^{\pi} \frac{\gamma}{\omega} F(k,\theta) k_x k dk d\theta$$

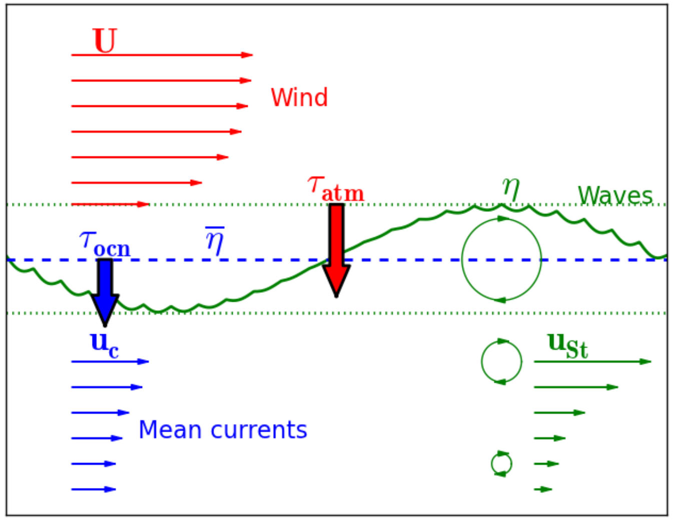
$$\tau_{wy} = g\rho_w \int_0^{\infty} \int_{-\pi}^{\pi} \frac{\gamma}{\omega} F(k,\theta) k_y k dk d\theta$$







- Air-Sea Momentum Exchange through Surface Waves
- $\tau_{atm} > \tau_{ocn}$, when wave growth is greater than dissipation



Unified Wave INterface (UWIN) for Coupled Models (CM)

Chen and Curcic (2016), Curcic et al. (2016)

Atmosphere Momentum:

$$\frac{d(\rho \boldsymbol{u})}{dt} = -2\Omega \times \rho \boldsymbol{u} - \nabla p + \frac{\partial \boldsymbol{\tau}}{\partial z} + \boldsymbol{\Phi}$$

Wind stress from wave growth

Wave energy balance:

$$\frac{\partial E}{\partial t} + \frac{\partial \left(\boldsymbol{c_g} + \boldsymbol{u_E}\right)E}{\partial \boldsymbol{x}} + \frac{\partial \dot{k}E}{\partial k} + \frac{\partial \dot{\theta}E}{\partial \theta} = S_{in} + S_{ds} + S_{nl}$$

Ocean stress from wave dissipation

Stokes Drift

$$\boldsymbol{u_{St}} = \int_{-\pi}^{\pi}\int_{0}^{\infty} \omega k^2 \frac{\cosh[2k(z+d)]}{\sinh^2(kd)} F d\boldsymbol{k} d\theta$$

Ocean Momentum:

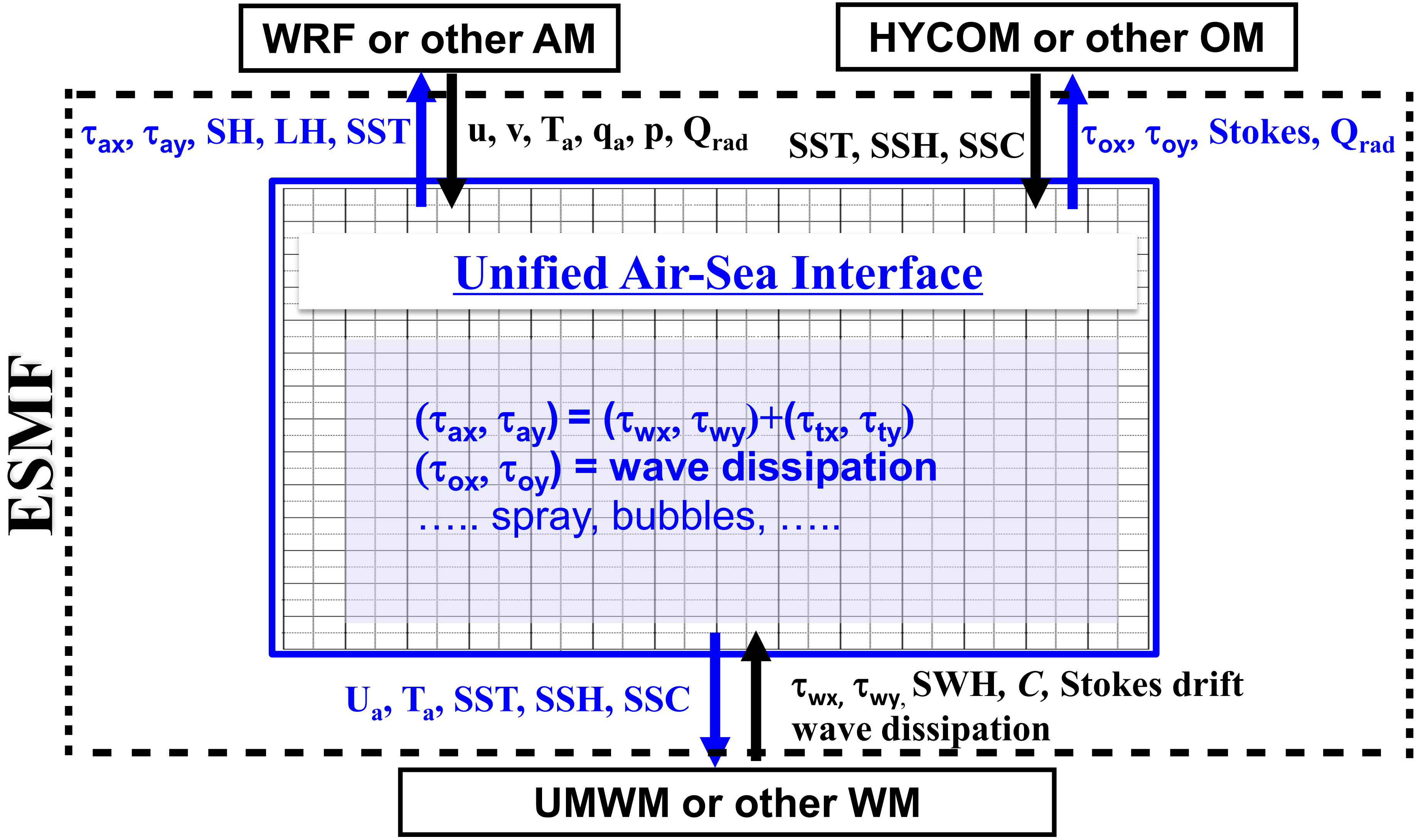
$$\frac{d(\rho \boldsymbol{u_E})}{dt} = -2\Omega \times \rho(\boldsymbol{u_E} + \boldsymbol{u_{St}}) + \rho \boldsymbol{u_{St}} \times \zeta - \nabla p + \frac{\partial \boldsymbol{\tau}}{\partial z} + \boldsymbol{\Phi}$$

Scalar tracer transport:

$$\frac{\partial C}{\partial t} = -(\boldsymbol{u_E} + \boldsymbol{u_{St}}) \cdot \nabla C$$

$\boldsymbol{u_L}$ - Total Lagrangian velocity

Unified Wave INterface – Coupled Model (UWIN-CM) (Chen et al. 2013, 2023)



University of Miami Wave Model (UMWM, Donelan et al. 2012)

Unified Wave INterface-Coupled Model (UWIN-CM) (Chen et al. 2013, Chen & Curcic 2016)

- Weather Research and Forecasting (WRF):

  12/4/1.3 km horizontal resolution with storm following nests, 45 vertical levels (phys: YSU, Donelan+Garrat sfc., WSM5)

  Initial and boundary conditions from NCEP GFS/FNL

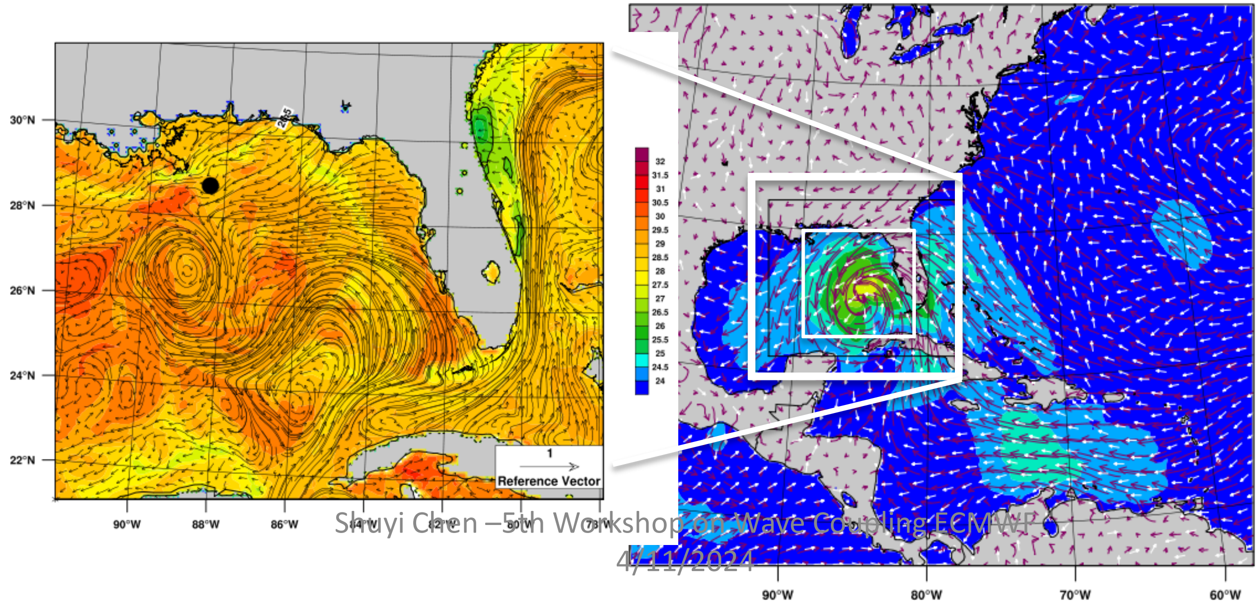
- University of Miami Wave Model (UMWM):

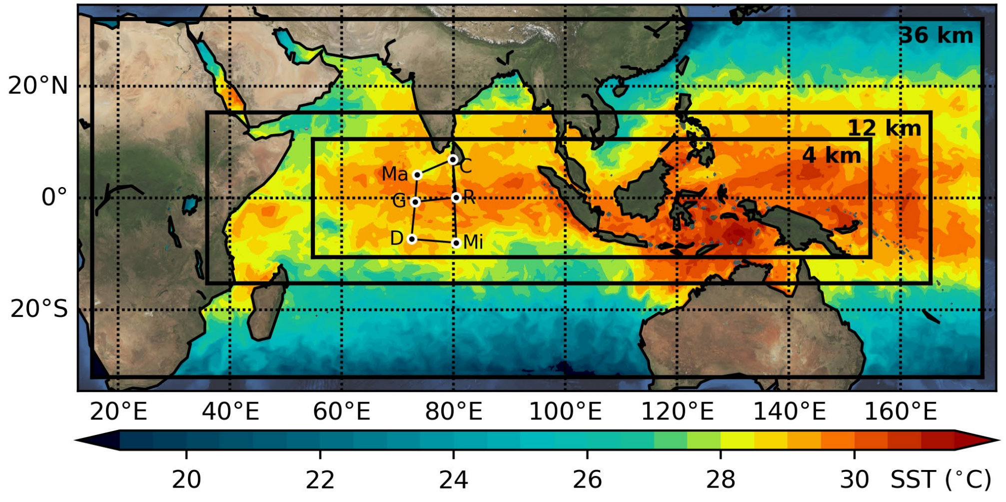
  4 km horizontal resolution, 36 directional bins and 37 frequency bins from 0.0313 - 2 Hz

- HYbrid Coordinate Ocean Model (HYCOM):

  1/25 degree (~4 km) horizontal resolution, 41 vertical levels;

  Initial and boundary conditions from global 1/12 deg. HYCOM





Savarin and Chen (2022a, 2022b)

Evaluating Wind and MSS: CYGNSS, NDBC buoys, and UWIN-CM

Wave spectrum:

$$F(f) = \int F(f,\theta)d\theta$$

Mean Square Slope (MSS):

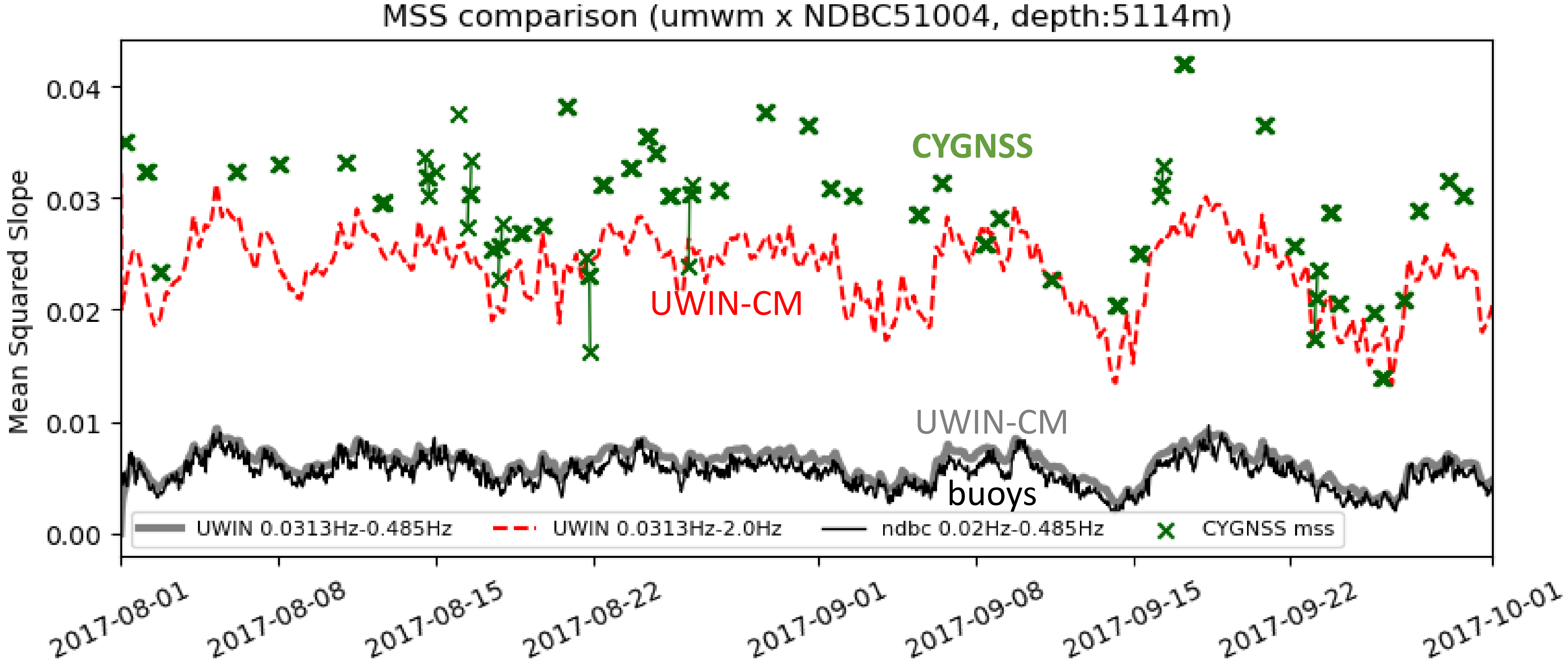
$$mss = \int_{f_0}^{f_1} \frac{(2\pi f)^4 F(f)}{g^2} df$$

Frequency range:

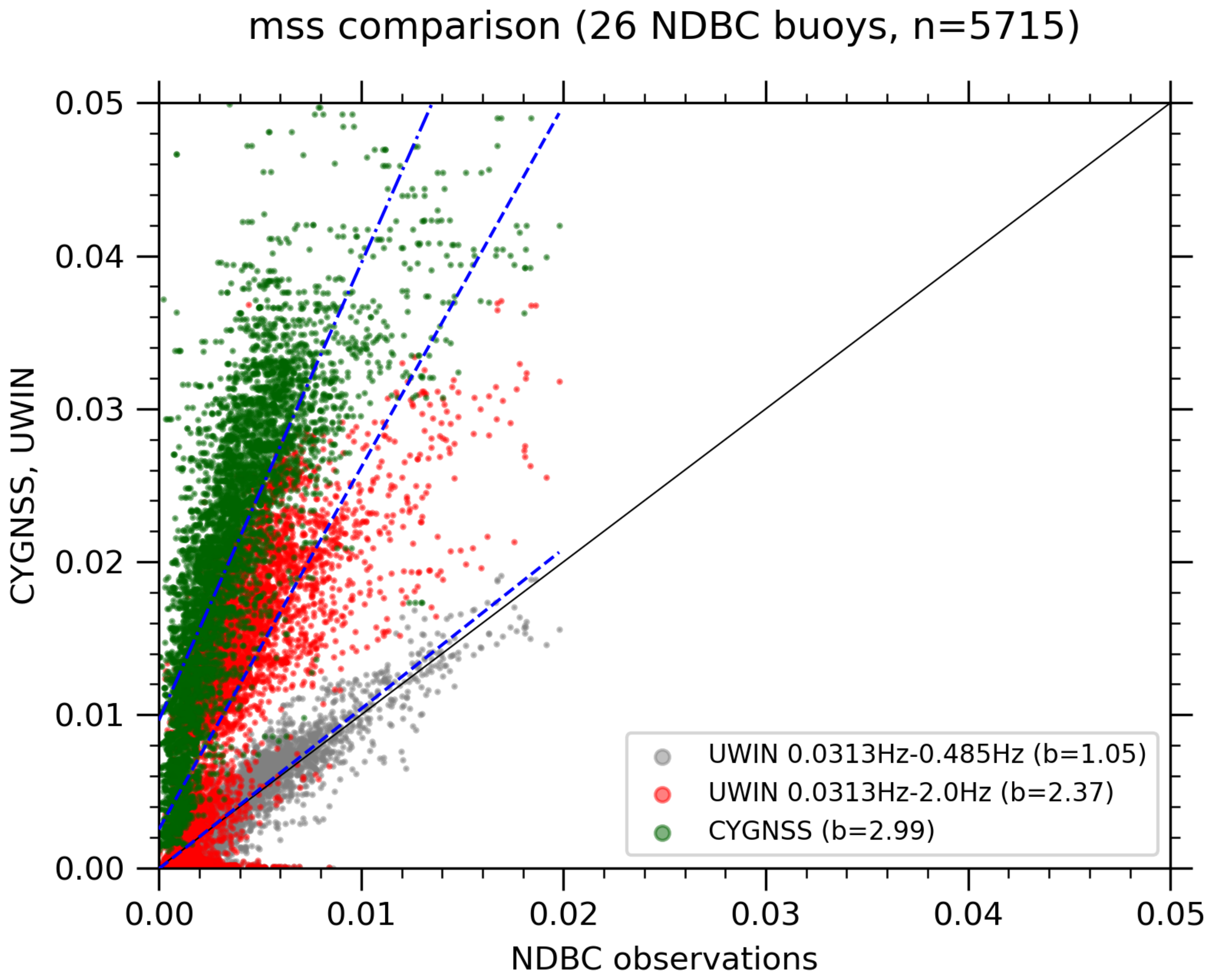
UWIN-CM: f_o=0.03, f_1=2.0 Hz (wind-sea waves)

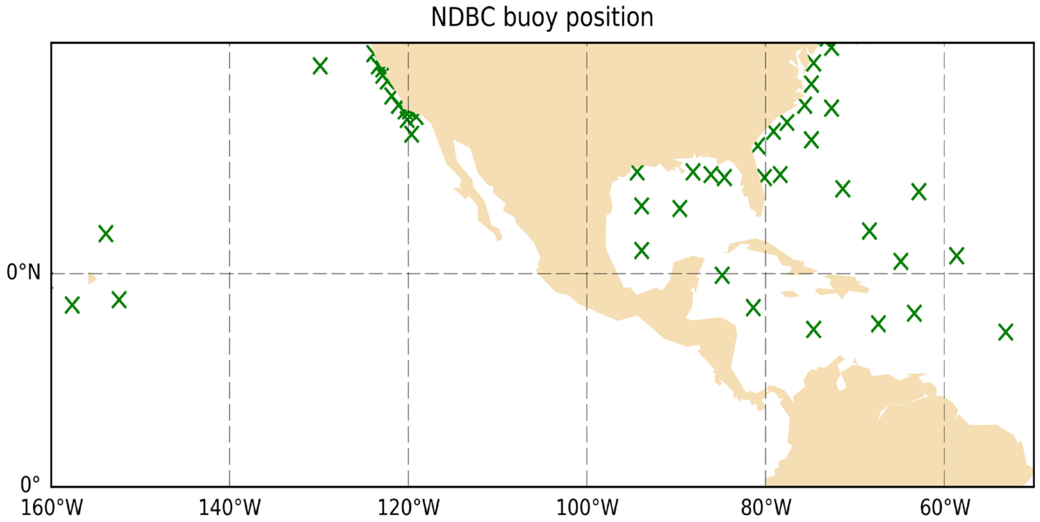
UWIN-CM: f_o=0.03, f_1=0.485 Hz (long waves)

NDBC buoys: f_o=0.02, f_1=0.485 Hz



MSS increases with frequency range





Does CYGNSS MSS represents higher frequency waves beyond 2.0 Hz?

Air-Sea Interaction in Hurricanes – A Multiscale Problem

4. Storm (Resolved):
- Storm-scale vertical (~15 km) and horizontal (~500 km to ~1000 km) extent
- Changes to surface layer, feedback from BL, and coupling of storm-scale dynamics and thermodynamics

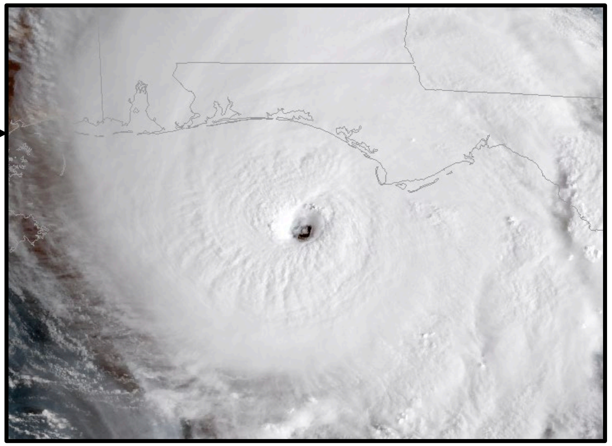


Photo: NOAA

3. Atmospheric Boundary Layer (ABL) and Ocean Mixed Layer (OML) (Resolved):
- ABL (~1 km) and OML (~100 m) mediate heat and moisture transfer between the ocean and atmosphere.
- Spray HFs modify ABL, creating feedbacks on HFs.

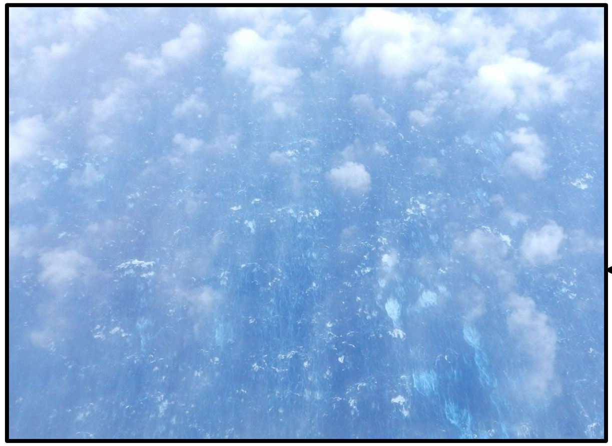


Photo: NOAA

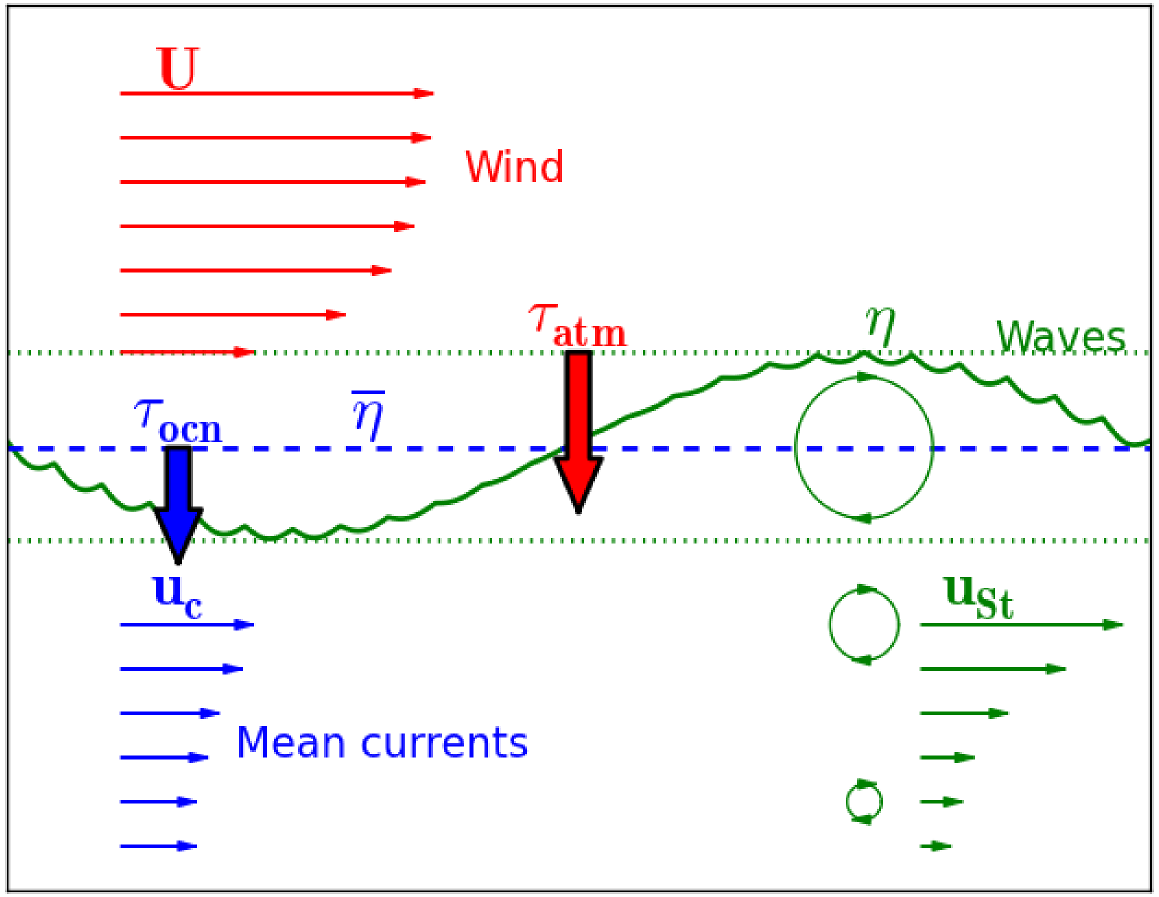
2. Air-Sea Interface (Subgrid):
- Spray heats/cools and moistens air (lowest ~1-10 m), creating feedbacks on spray and interfacial HFs.


Photo: Ray Collins

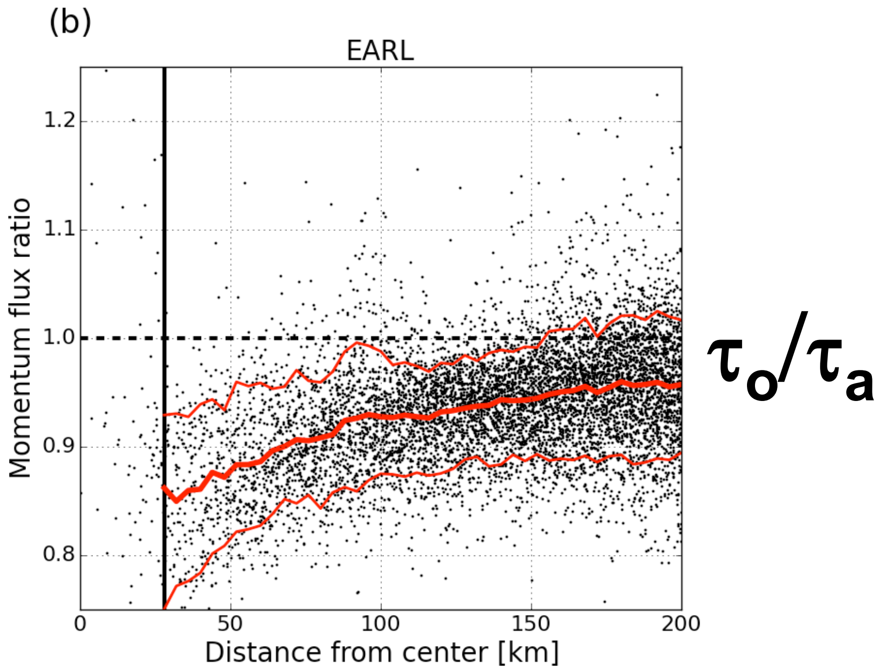
1. Breaking Waves and Spray Droplets (Subgrid):
- Droplets (r ~10 μm to ~1 mm)ejected from breaking waves exchange sensible and latent heat fluxes (HFs).

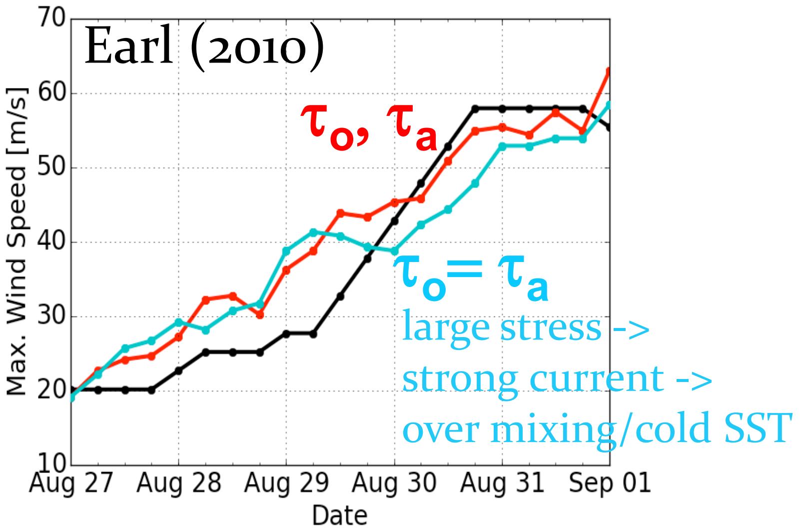

Photo: Ray Collins

Air-Sea Momentum Exchange through Surface Waves

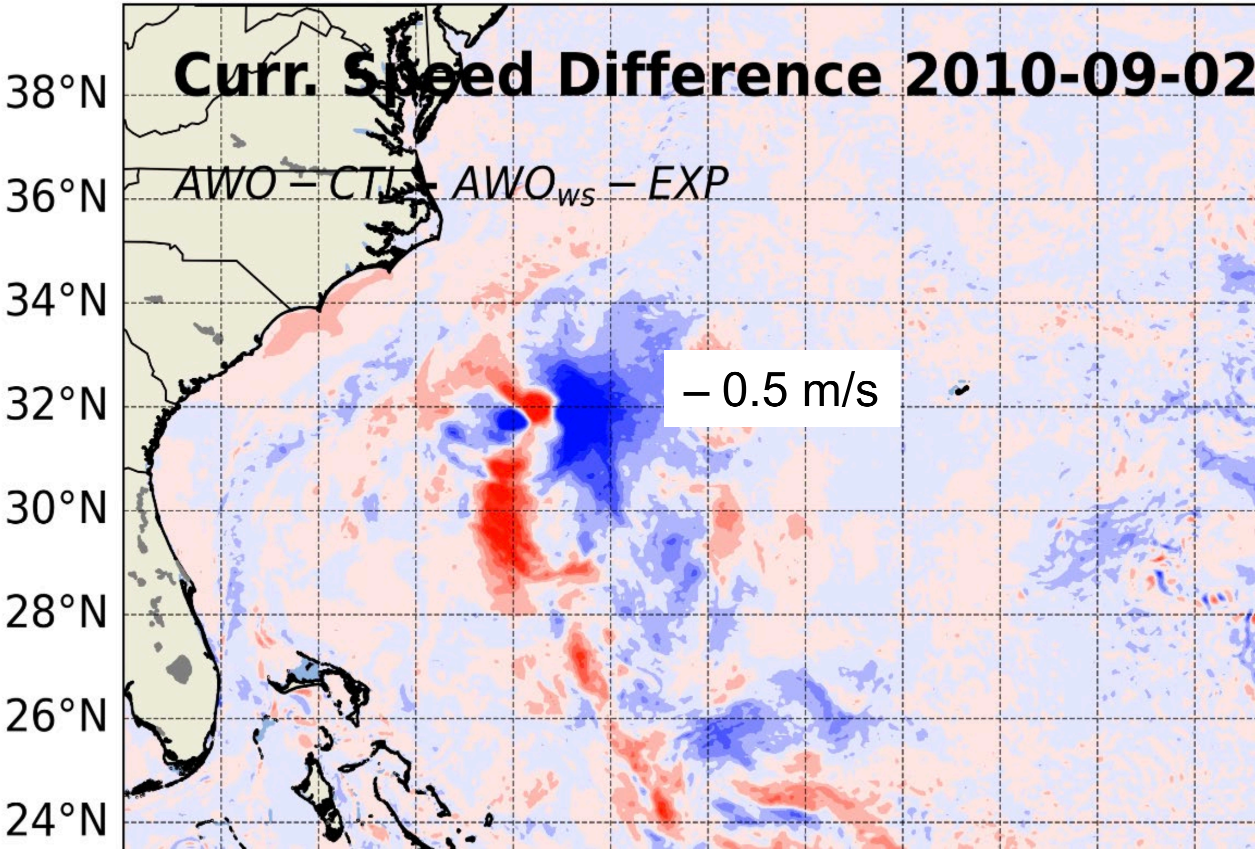


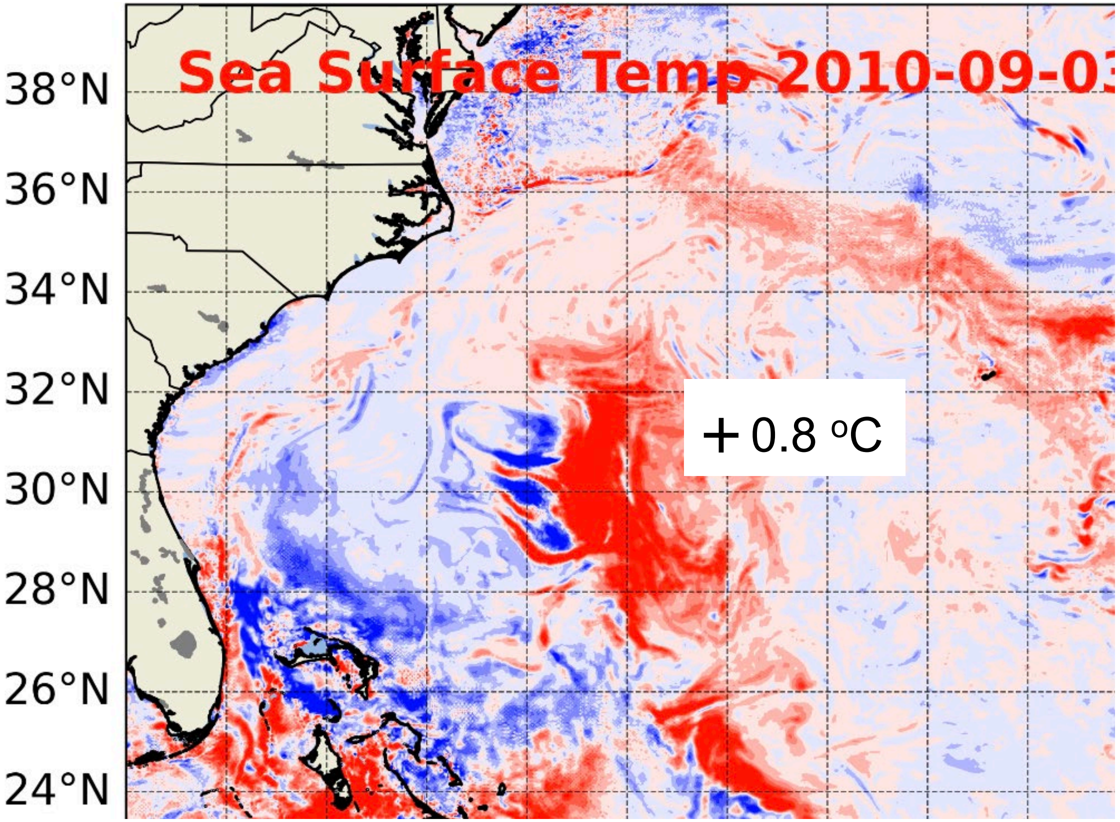
$\tau_{atm} > \tau_{ocn}$, when wave growth is greater than dissipation





Effects of Separating Wave-induced Wind and Current Stress





AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL067619

Hurricane-induced ocean waves and stokes drift and their impacts on surface transport and dispersion in the Gulf of Mexico

Milan Curcic[1], Shuyi S. Chen[1], and Tamay M. Özgökmen[1]

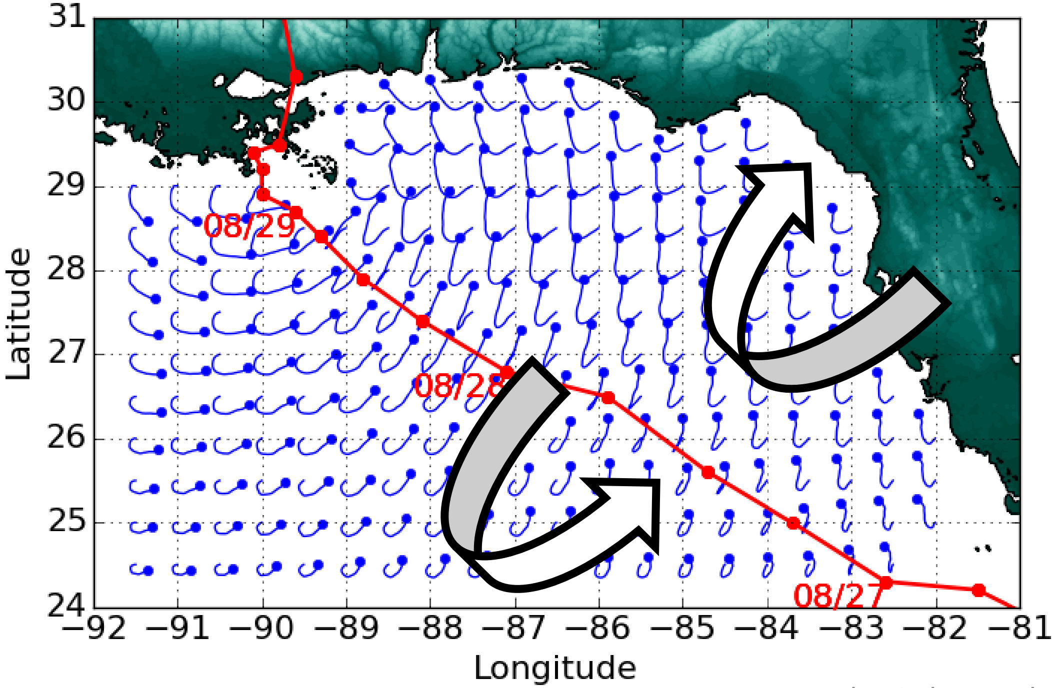
[1]Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Coral Gables, Florida, USA

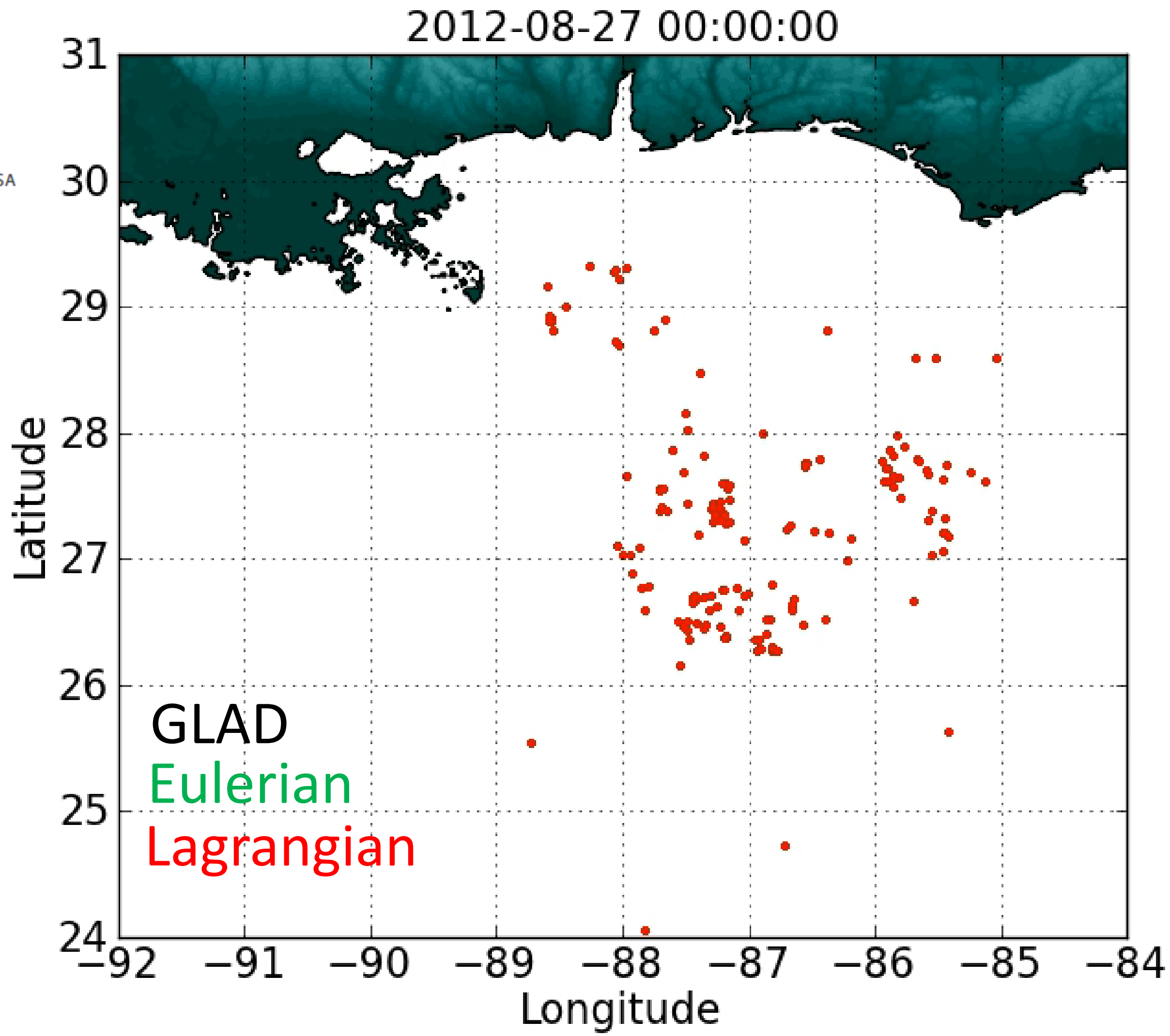
Key Points:
- Drifter observations and coupled model quantify hurricane impact on surface transport
- Hurricane-induced Stokes drift contributes up to 20% surface

Curcic et al. (2016, GRL): Transports in Hurricanes

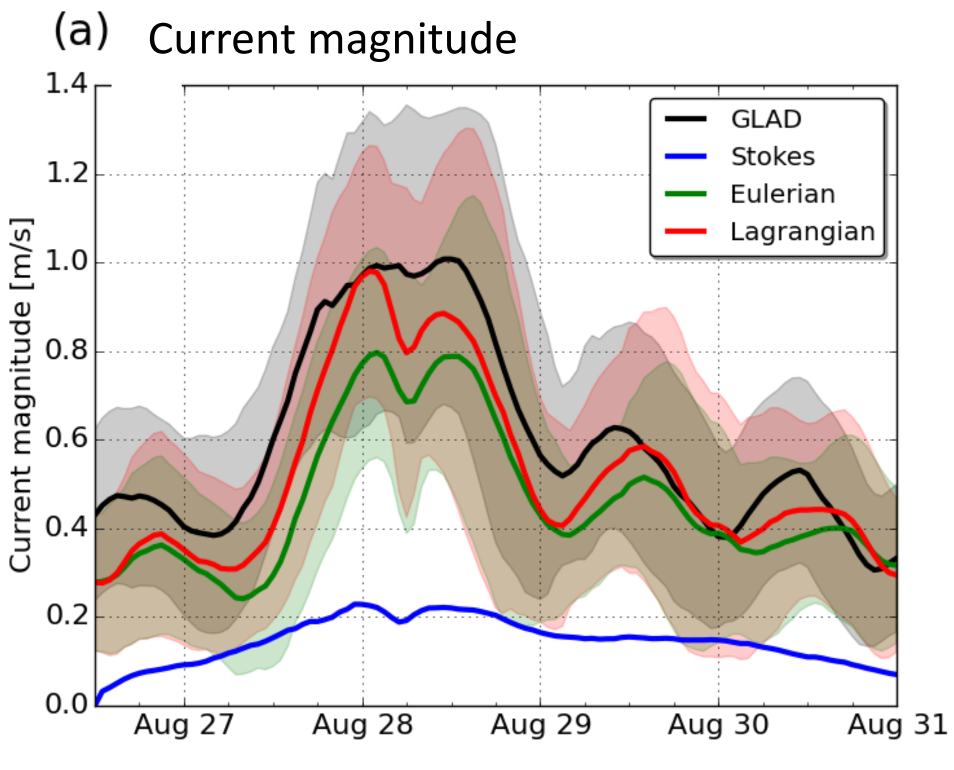
Ocean surface transport in Hurricane Isaac (2012): GLAD surface drifter data and UWIN-CM forecast

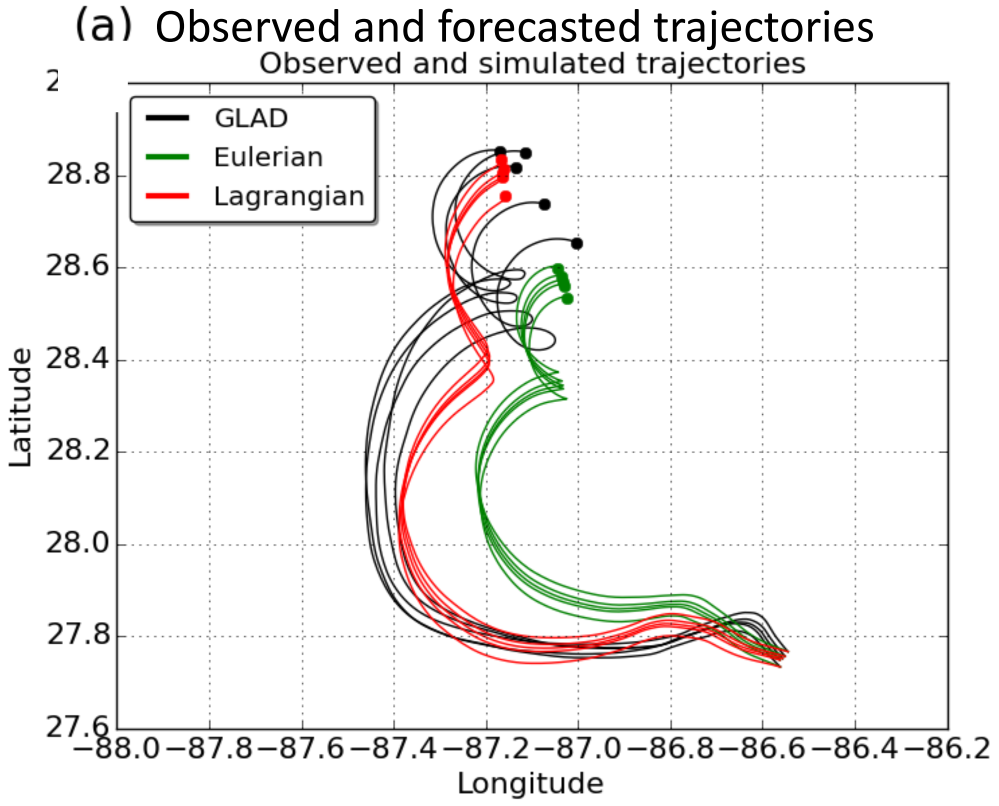
Stokes drift trajectories





Stokes drift contribution to GLAD-averaged drifter velocity magnitude and trajectories

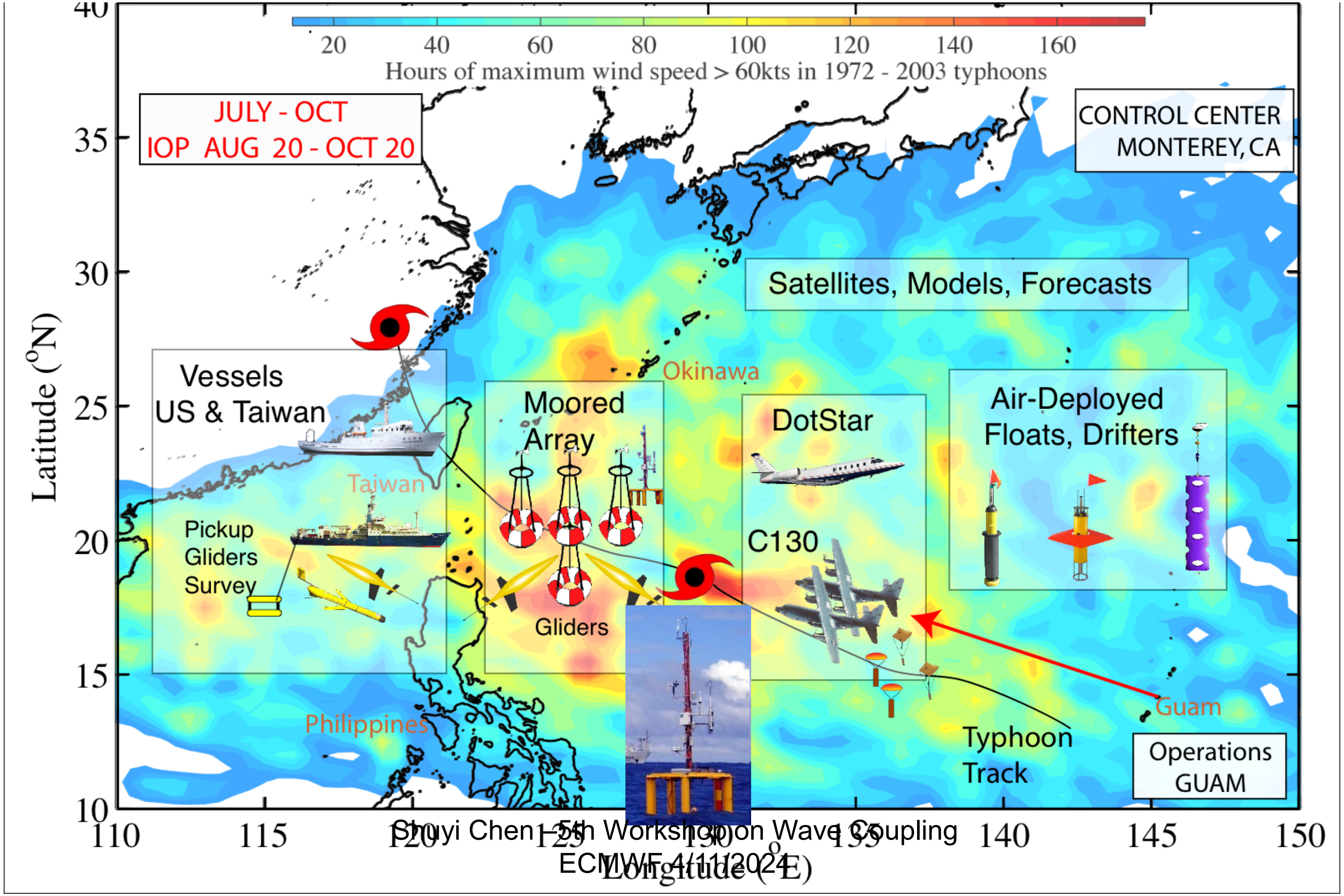




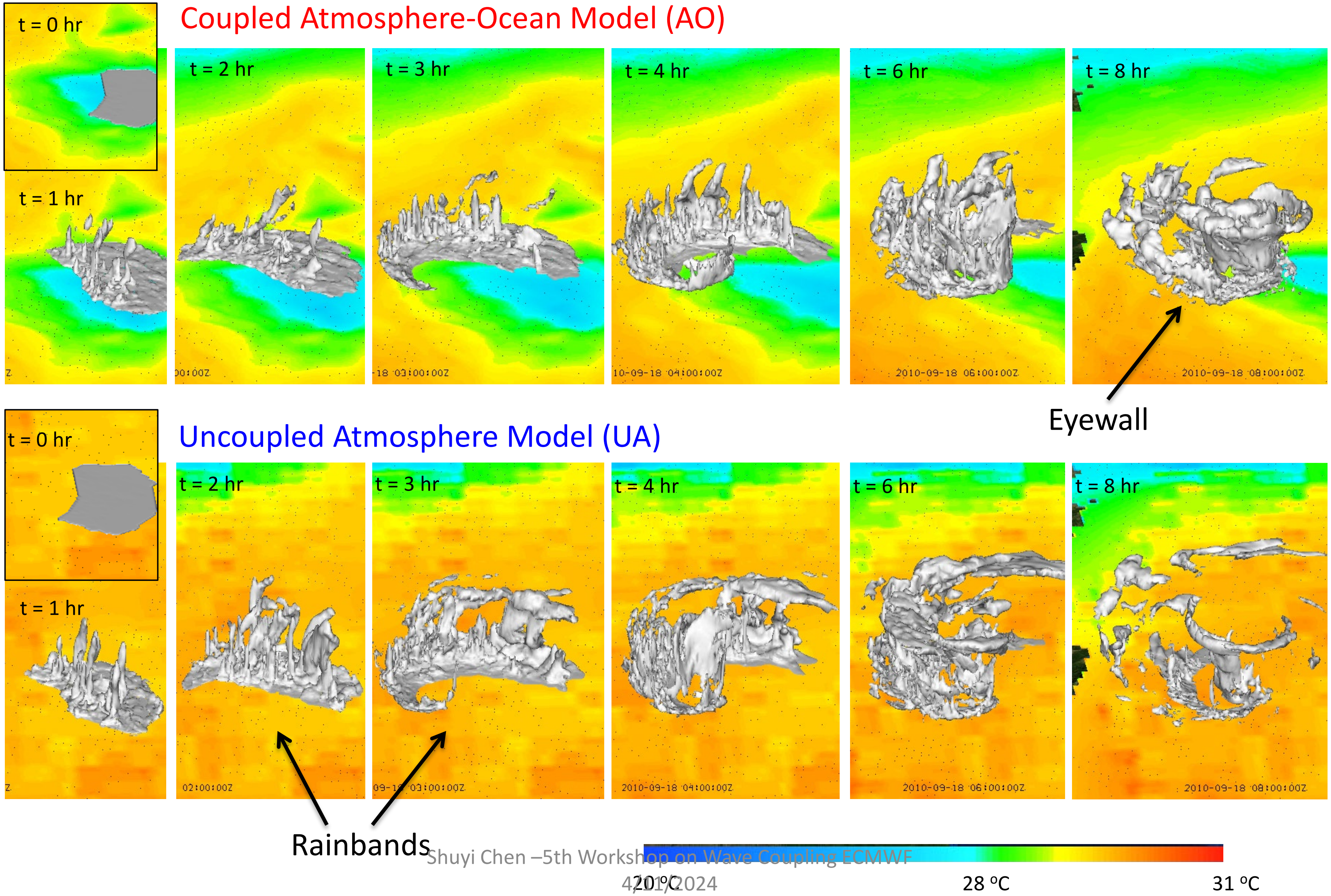
Curcic et al. (2016, GRL)

ITOP 2010 (Impact of Typhoons on the Ocean in Pacific) - D'Asaro et al. (2014)

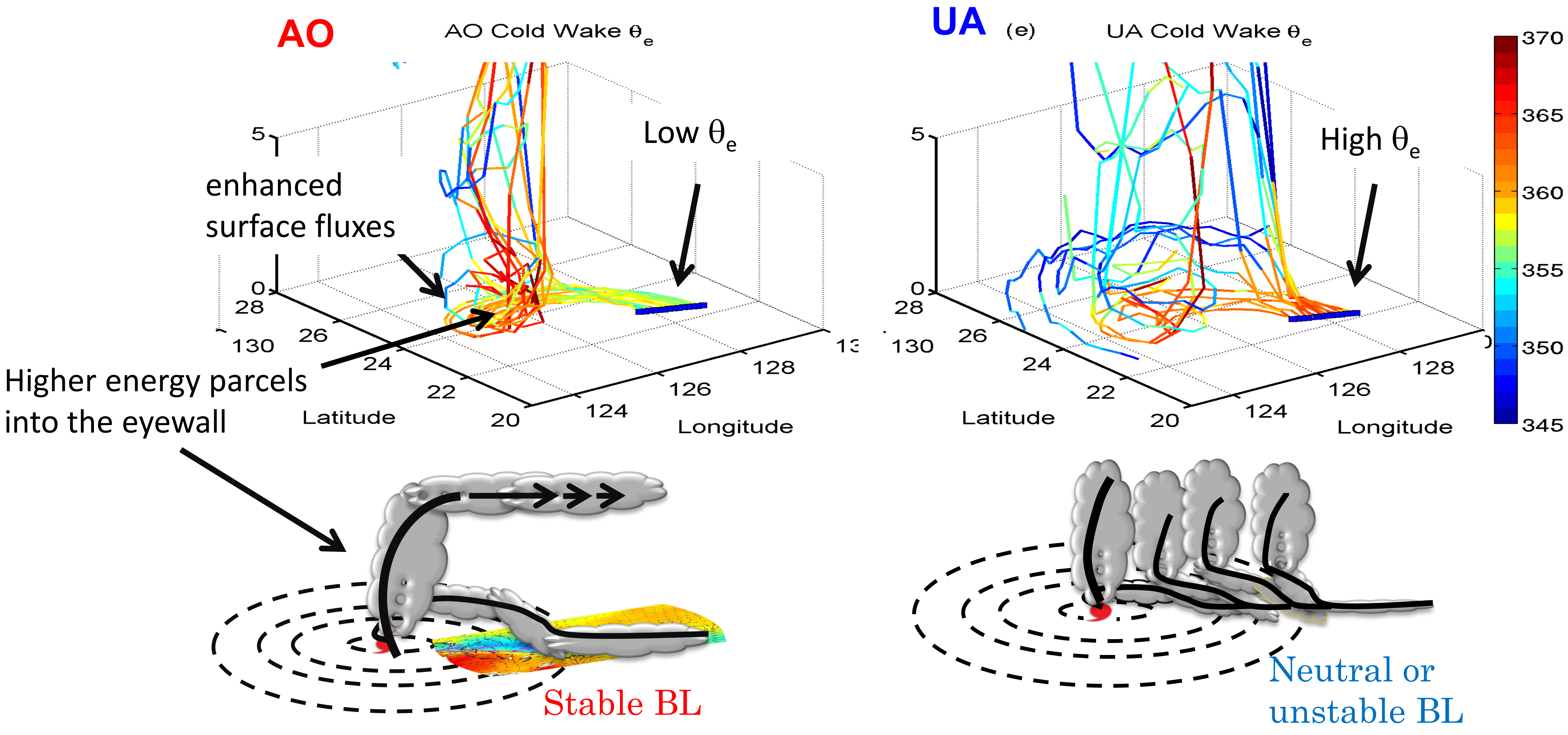
How TC-induced cold wake affect TC structure and intensity?



Typhoon Fanapi (2010): Enhanced Inflow from “in situ” Cold Wake to Eyewall



Lee and Chen (2014): Effects of Stable Boundary Layer over Cold Wake on TC Energetics and Structure

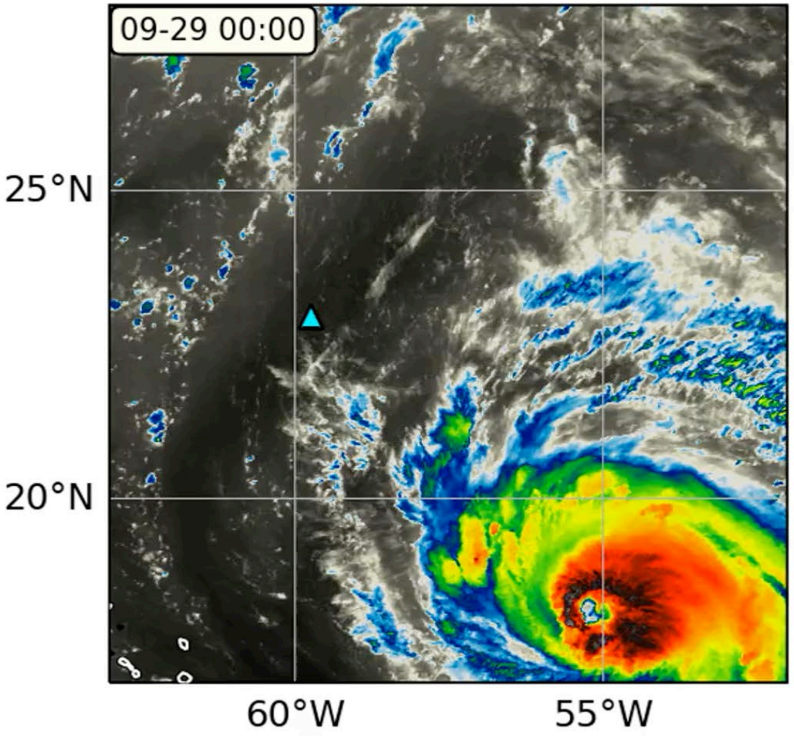


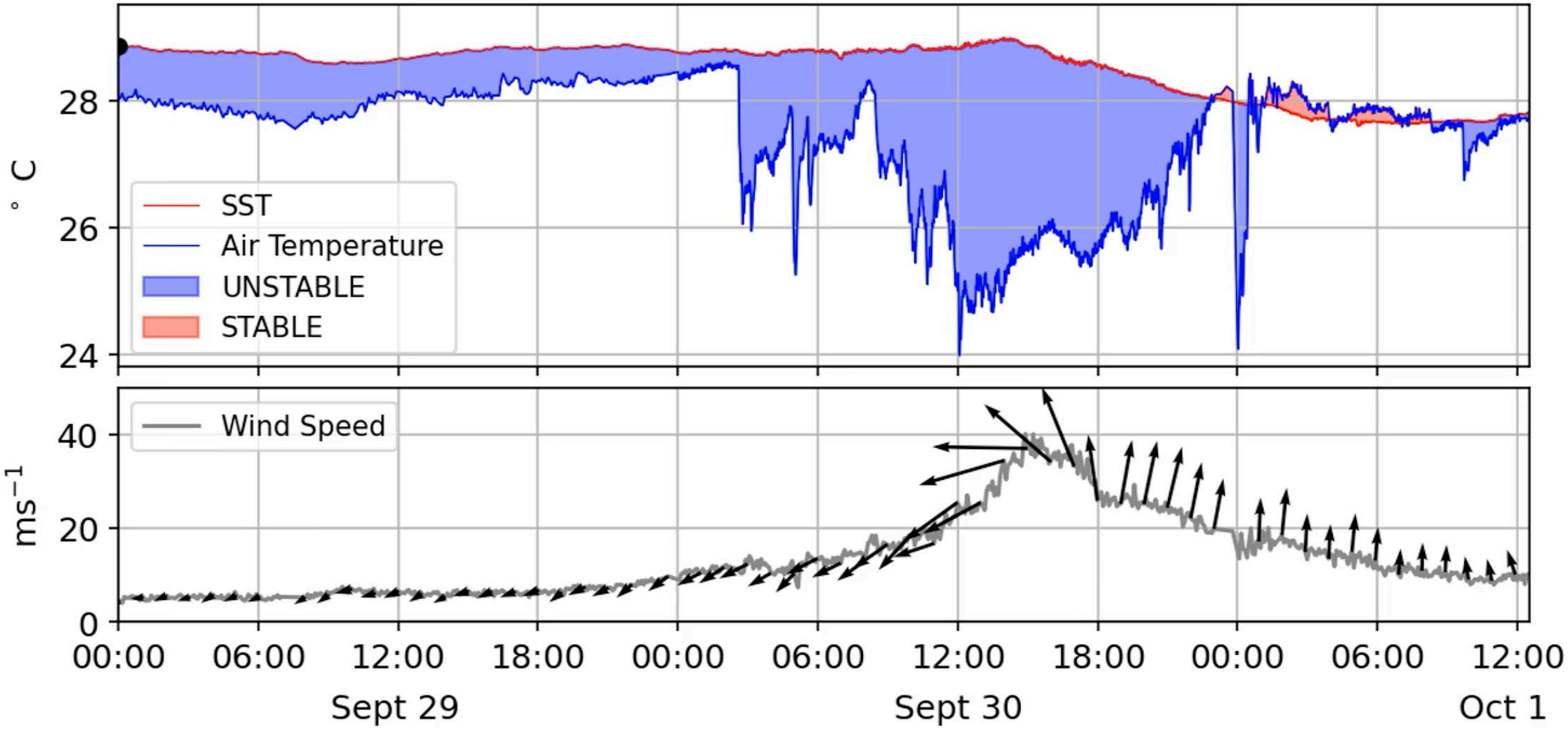
- **SBL leads to less rainband convection, increased inflow angle, enhanced heat fluxes downstream of the cold weak**
- **Although TC-induced ocean cooling reduce TC intensity, SBL over the cold wake can mitigate the negative oceanic feedback and increase the storm efficiency**

Saildrone in Hurricane Sam (2021)

Captured by SD 1045's onboard camera during
Category 4 Hurricane Sam, Sept. 30 2021

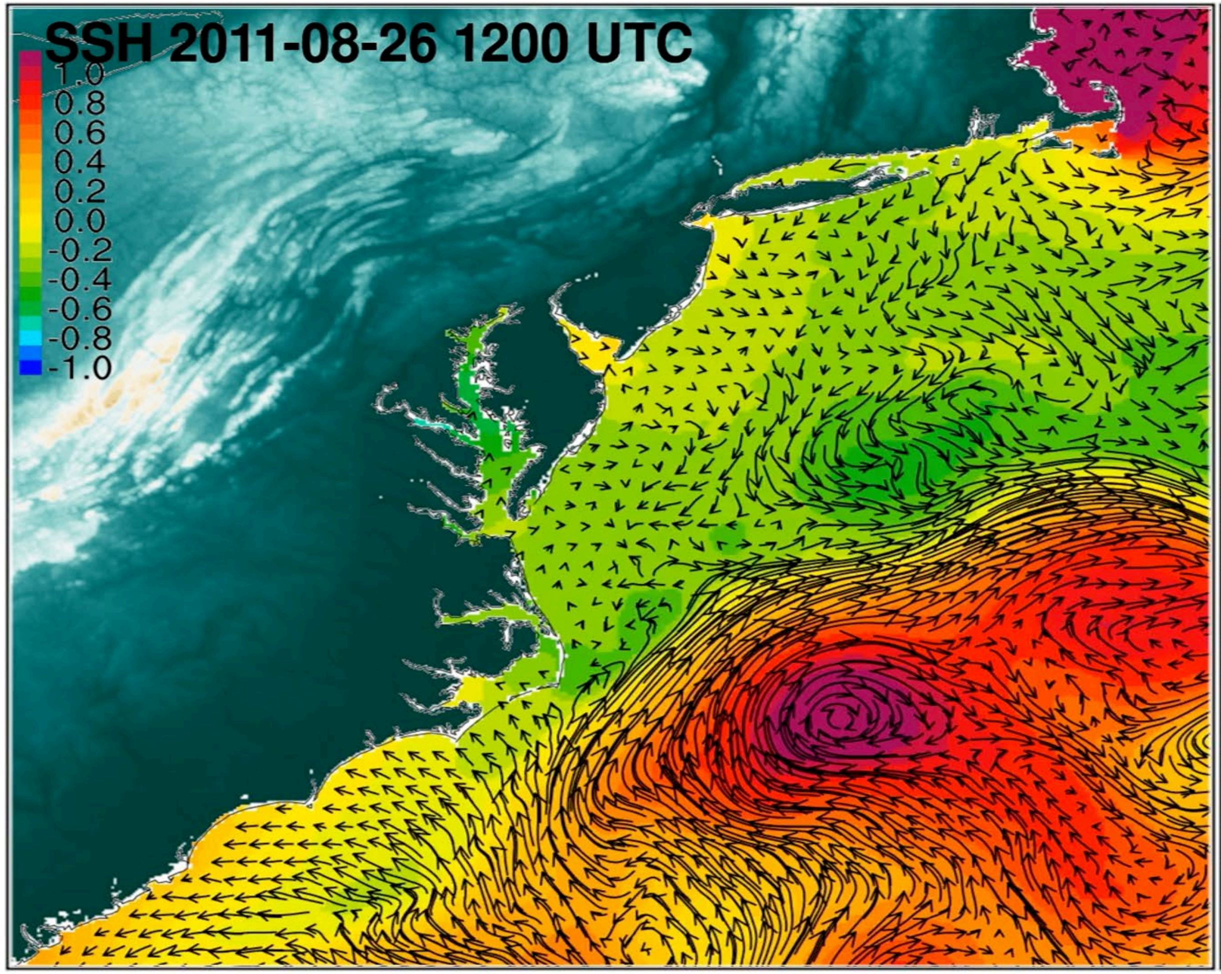
Saildrone Observations in Hurricane Sam (2021) - Zhang et al. (2023, BAMS)



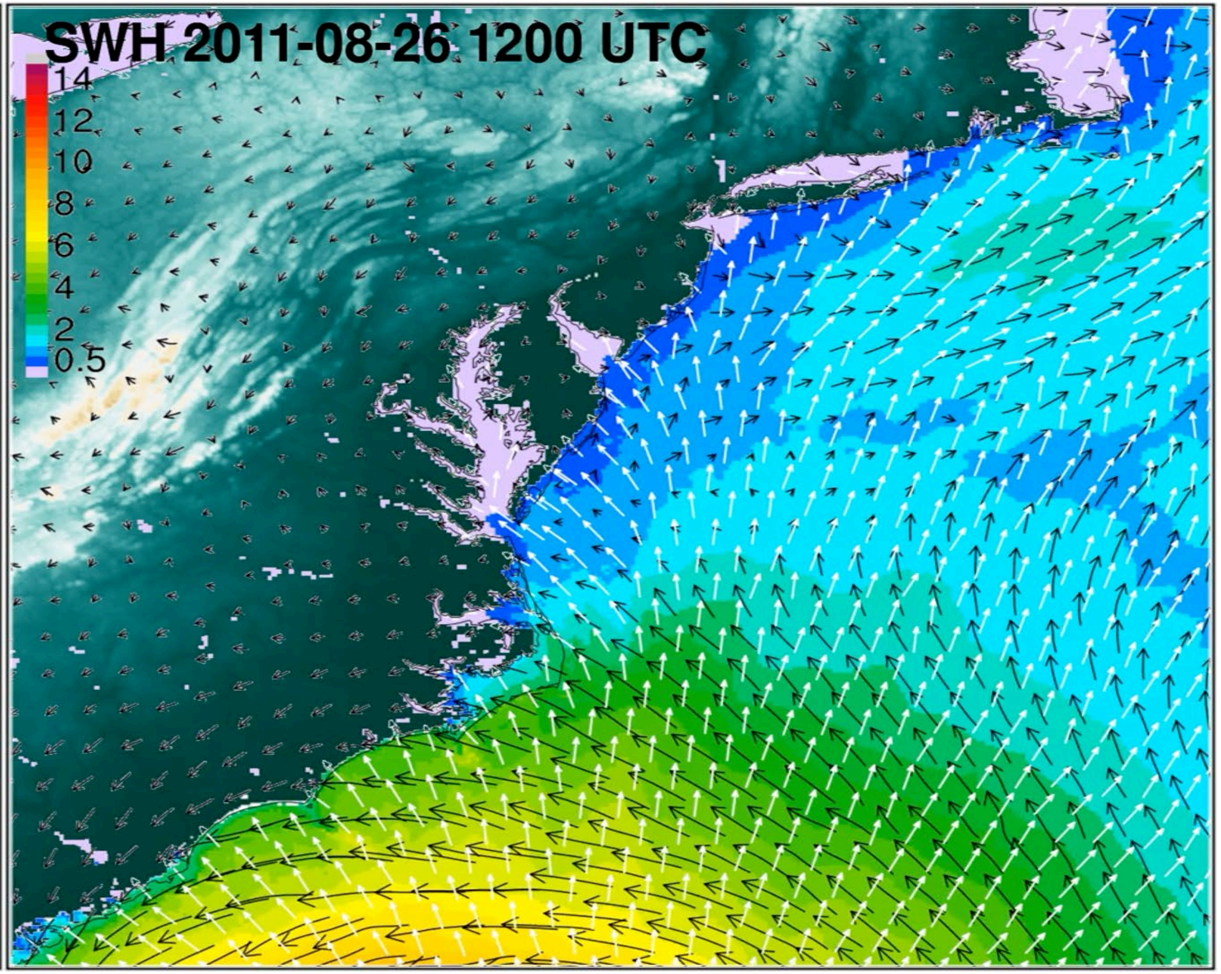


Hurricane Irene (2011)

Sea Surface Height Anomaly

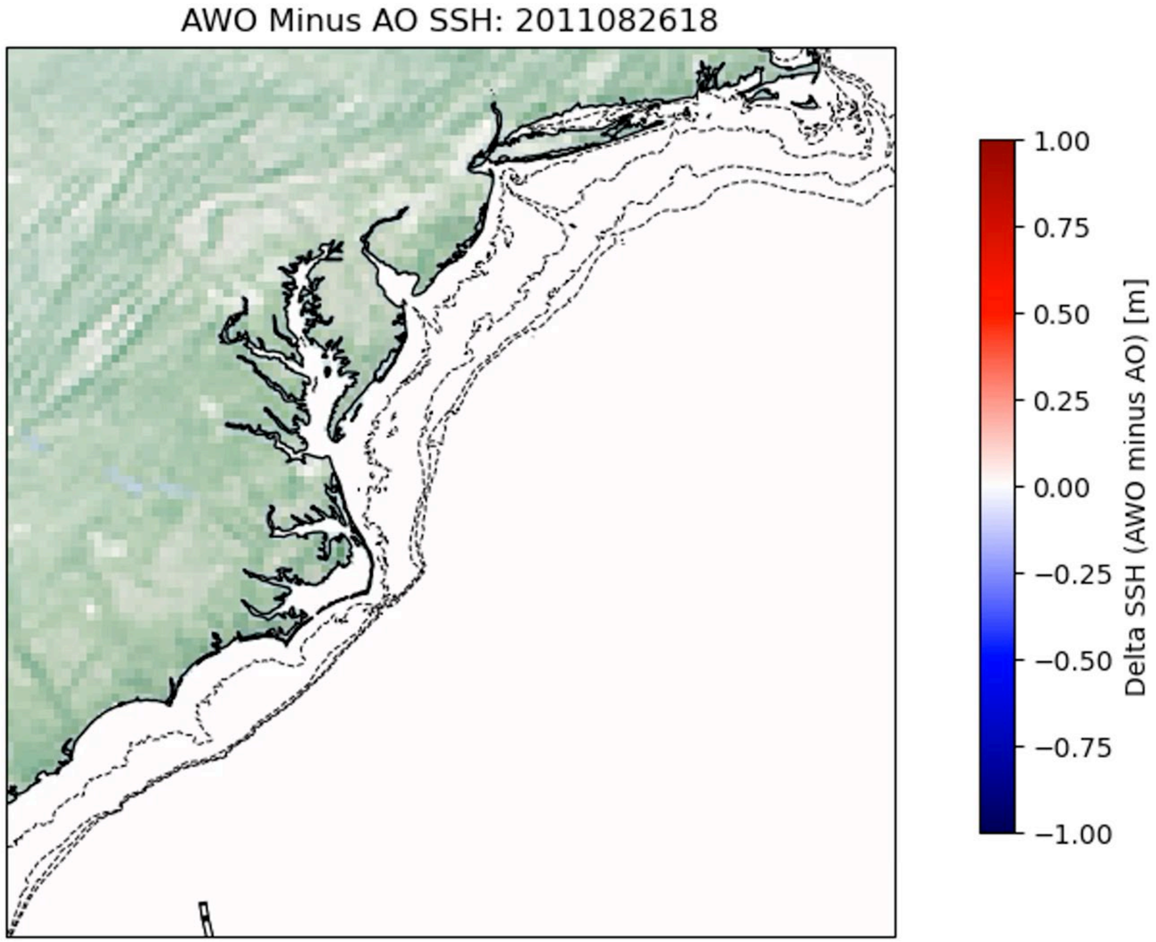


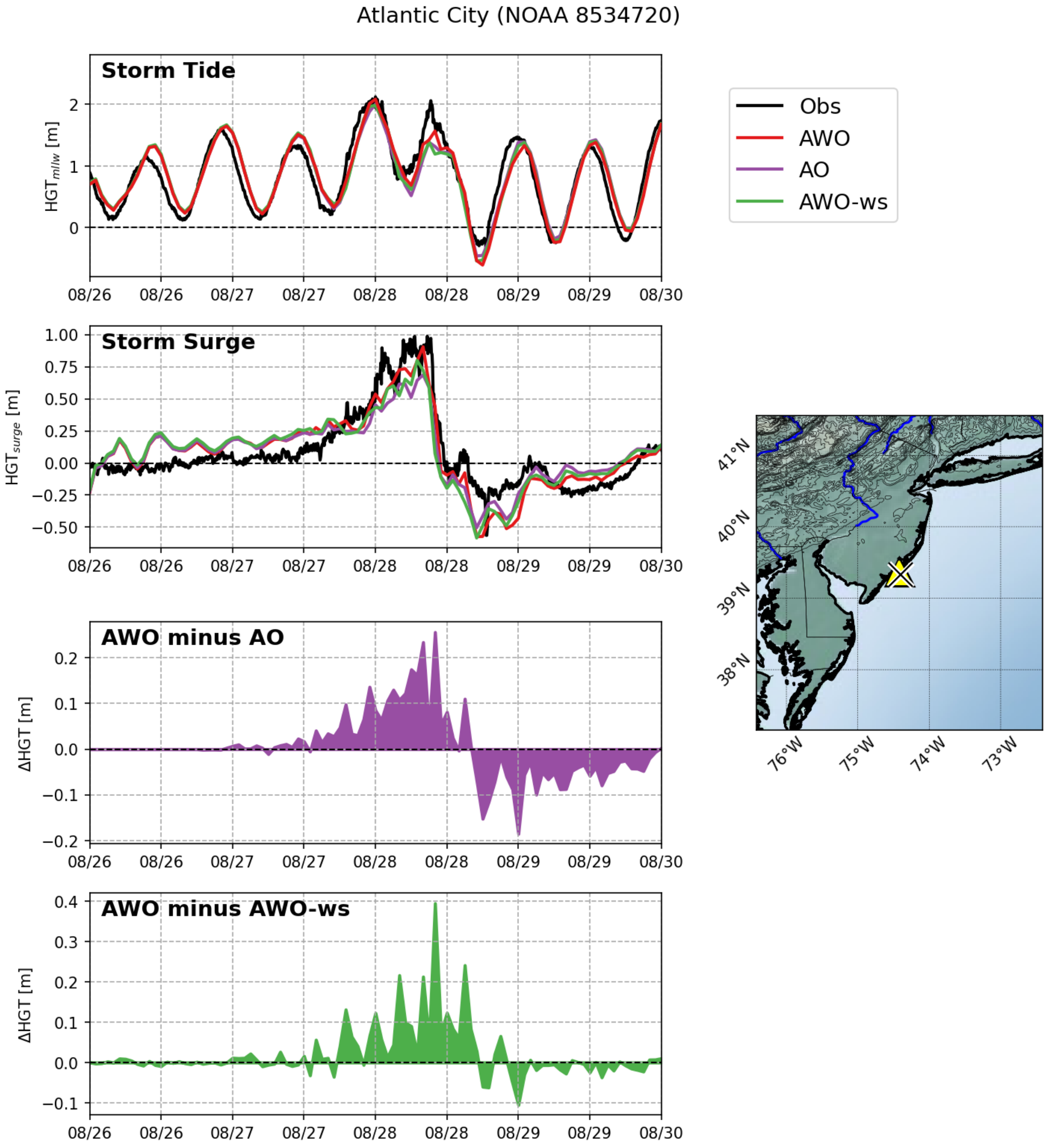
Significant Wave Height and Wind



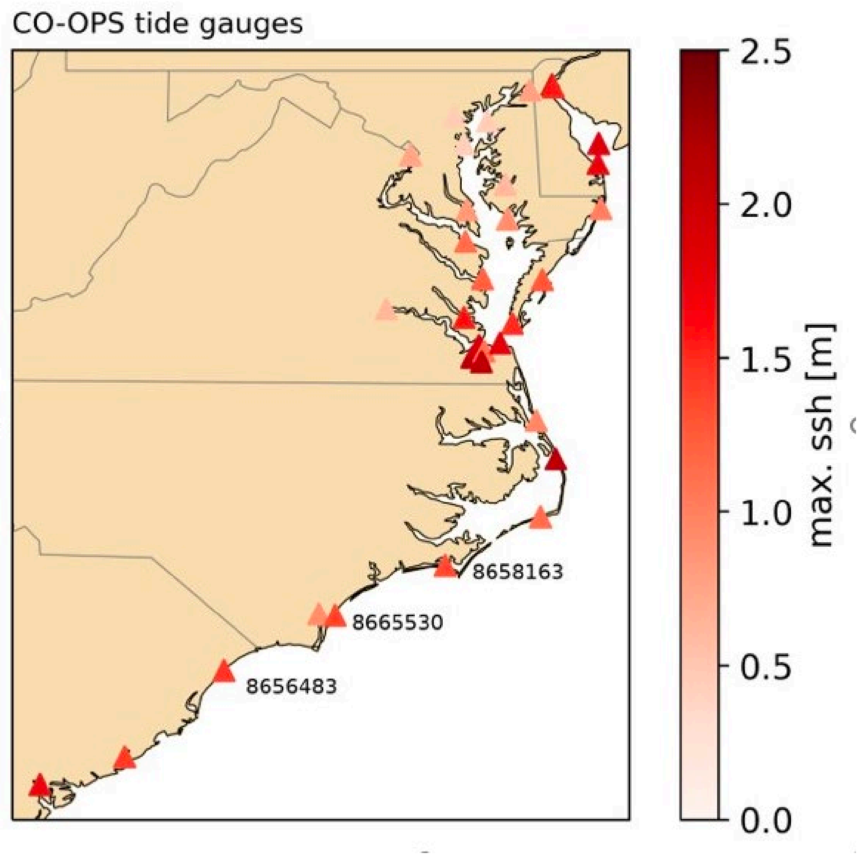
Kerns and Chen (2022, 2023)

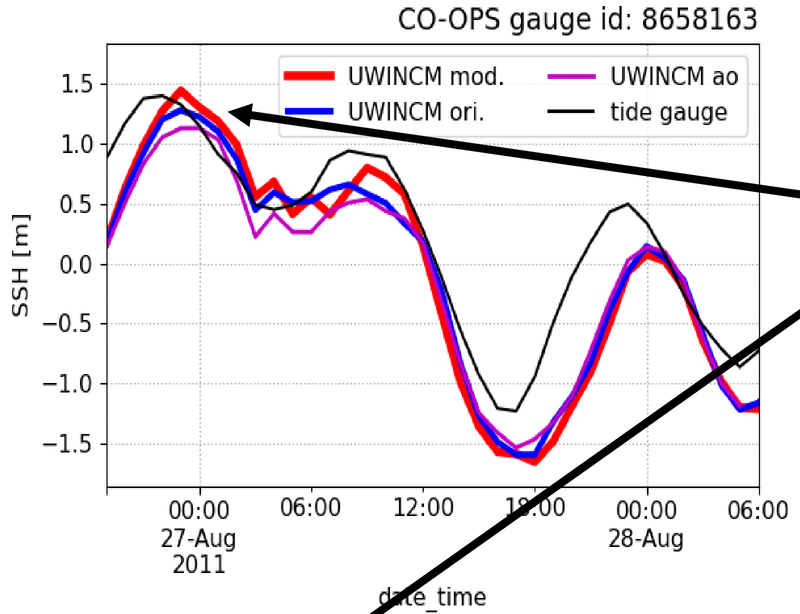
Effects of Surface Waves



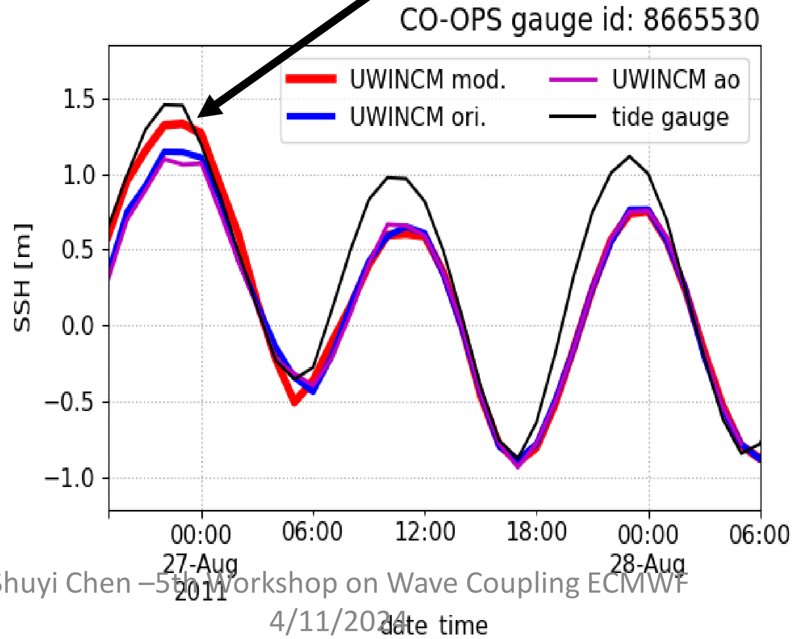


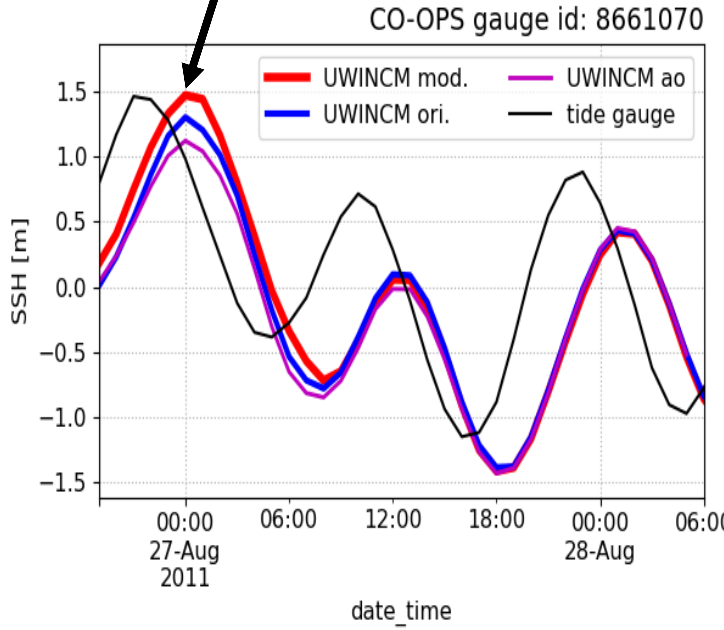
Effects of Surface Waves on Storm Surge – Hurricane Irene (2011)





Wind-wave-current coupling improves SSH (storm surge) by 30-50%.

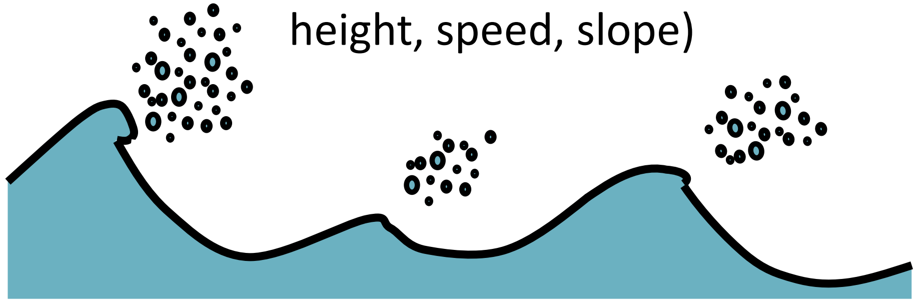


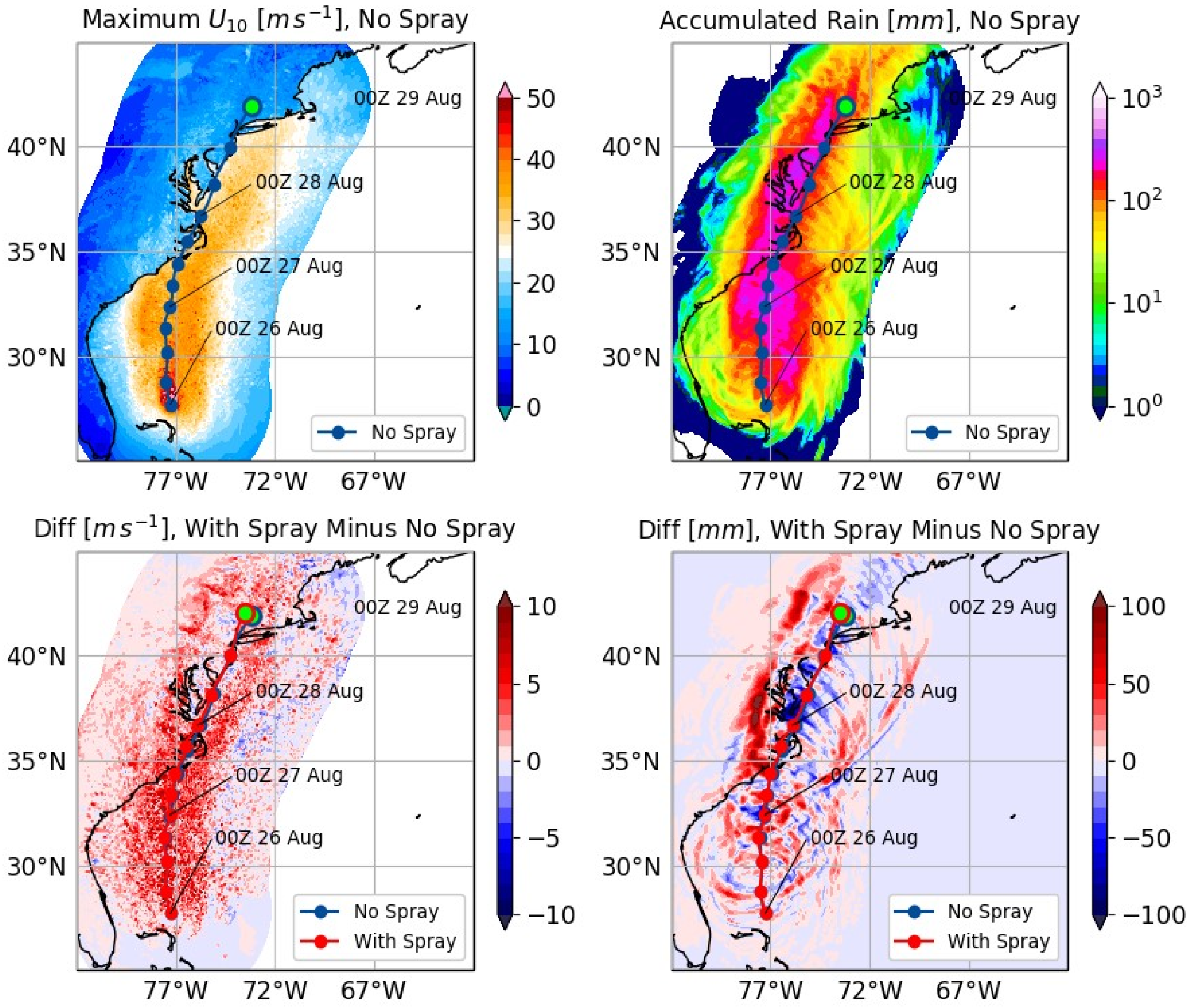


Effects of Sea Spray

(UWIN-CM simulations with/without spray)

Takeaway:
1. **Enhanced wave dissipation increases spray production.**
2. **Spray increases winds and rainfall at landfall and over land.**

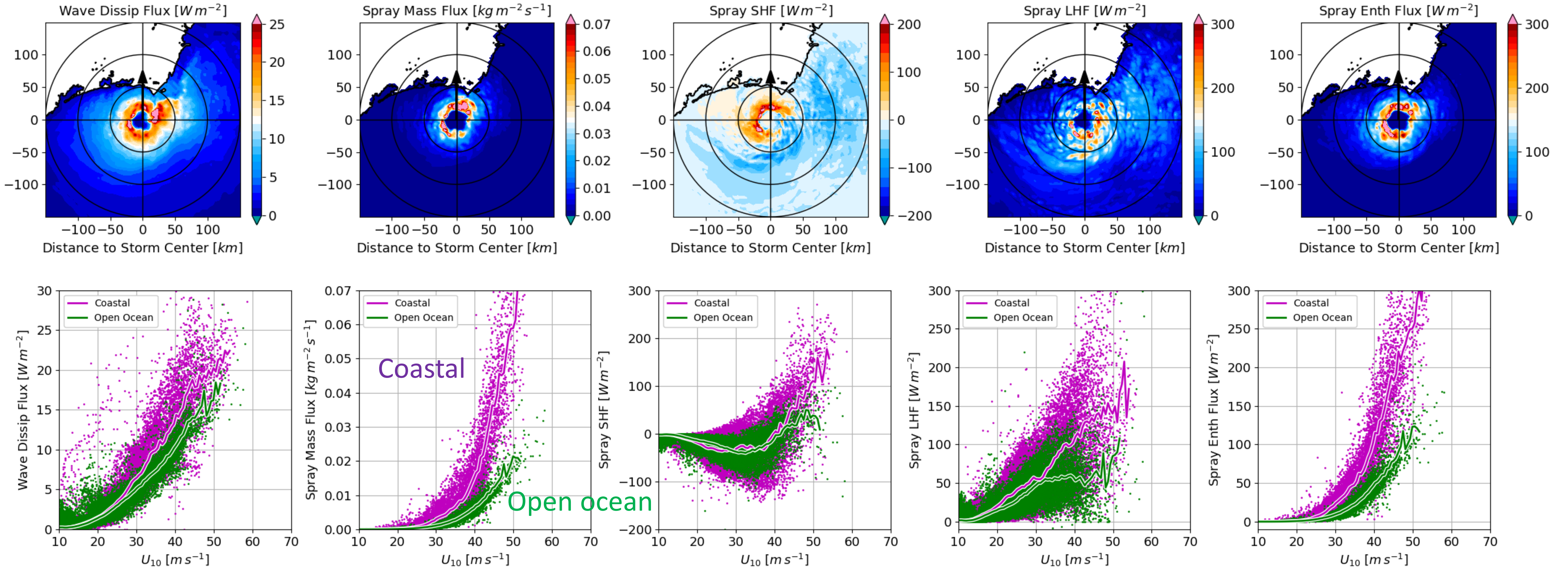




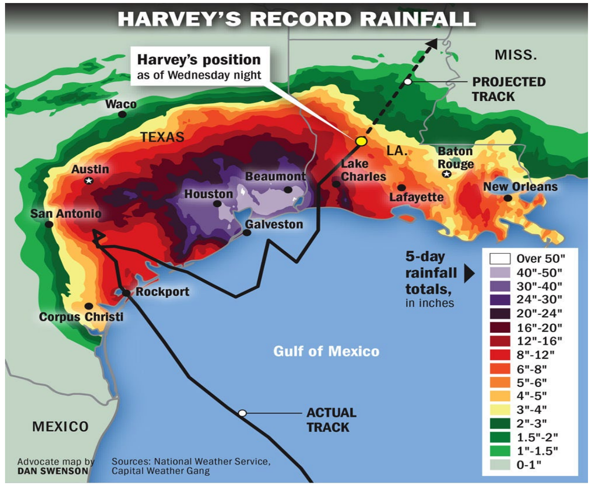
Barr-Chen-Fairall (2023)

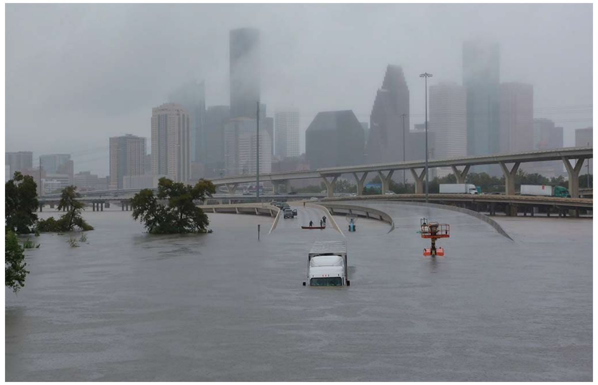
Hurricane Michael (2018)

18:00:00 UTC 10 Oct 2018



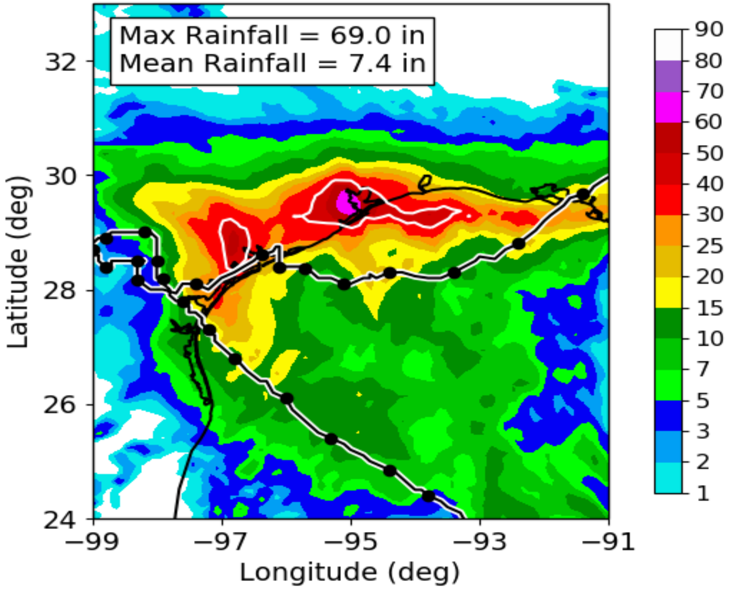
Hurricane Harvey (2017) – **Flooding**: Rain, Surge, Built Environment

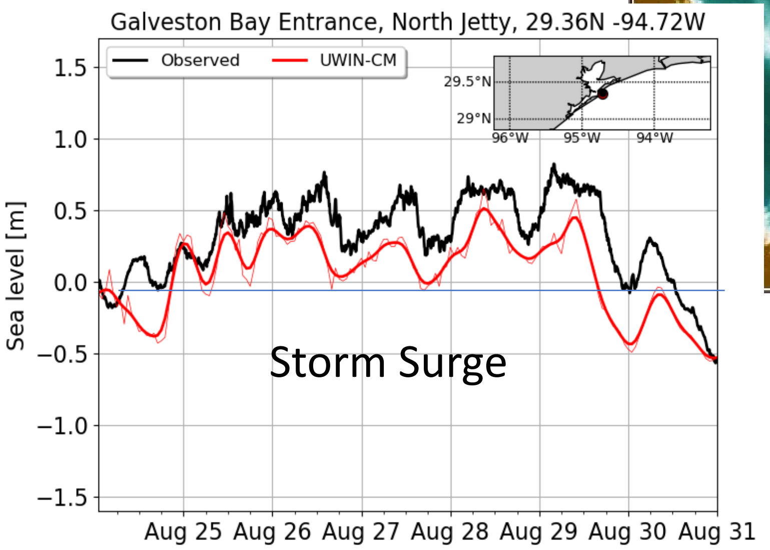


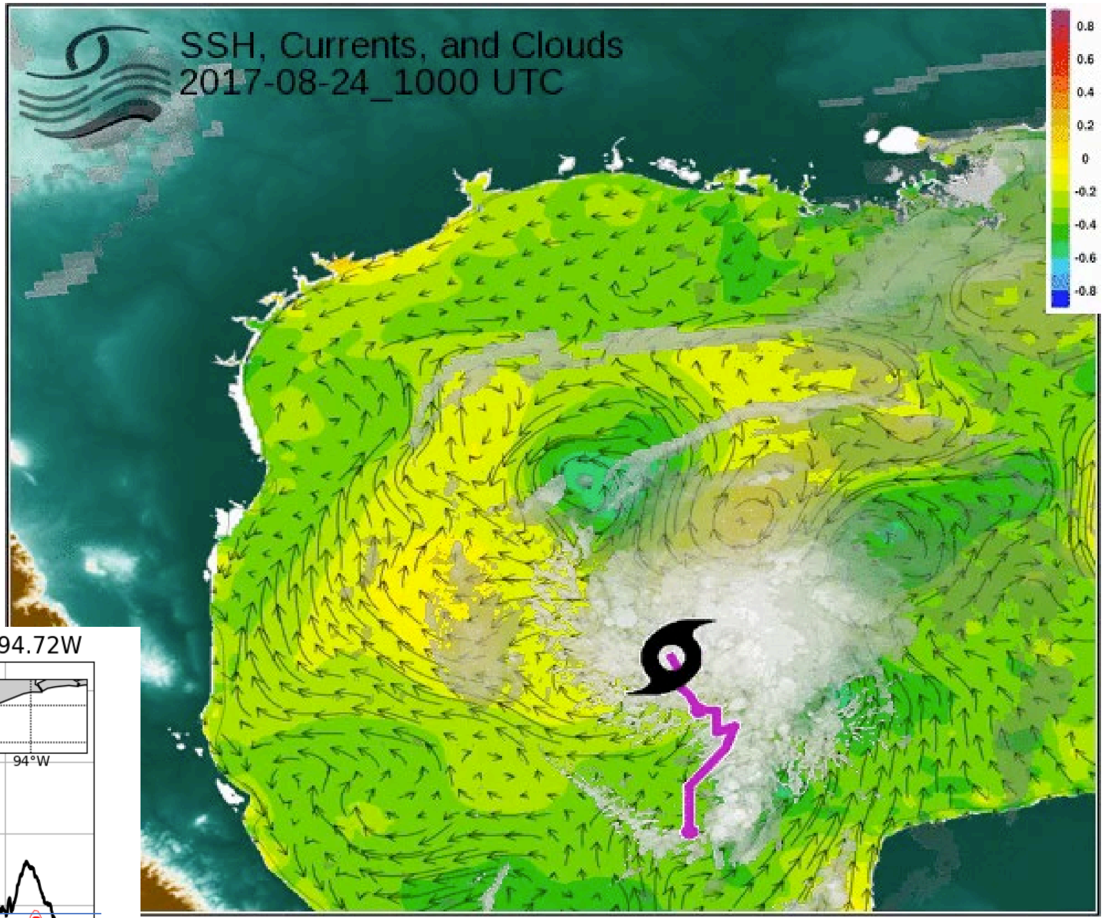


Built environment without good natural drainage

UWIN-CM Simulation





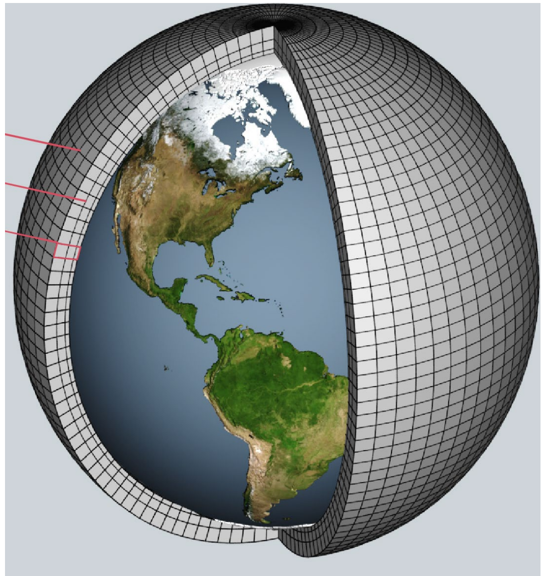


UWIN-CM Simulation of Rain and Storm Surge

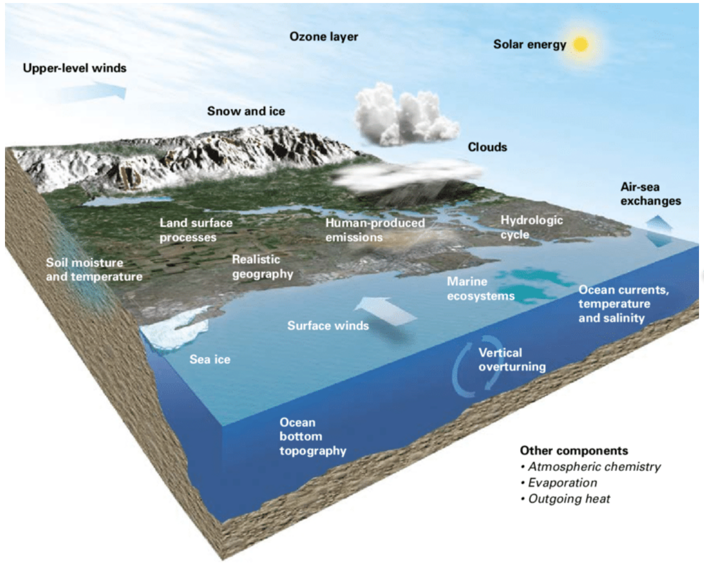
<u>Challenges</u>: High-resolution full physics models are computational expensive, data volume, etc.

<u>Ways forward</u>: New ways of downscaling: Global Earth system models -->AI/ML --> Regional coupled atmosphere-wave-ocean-land models --> AI/ML --> Flooding

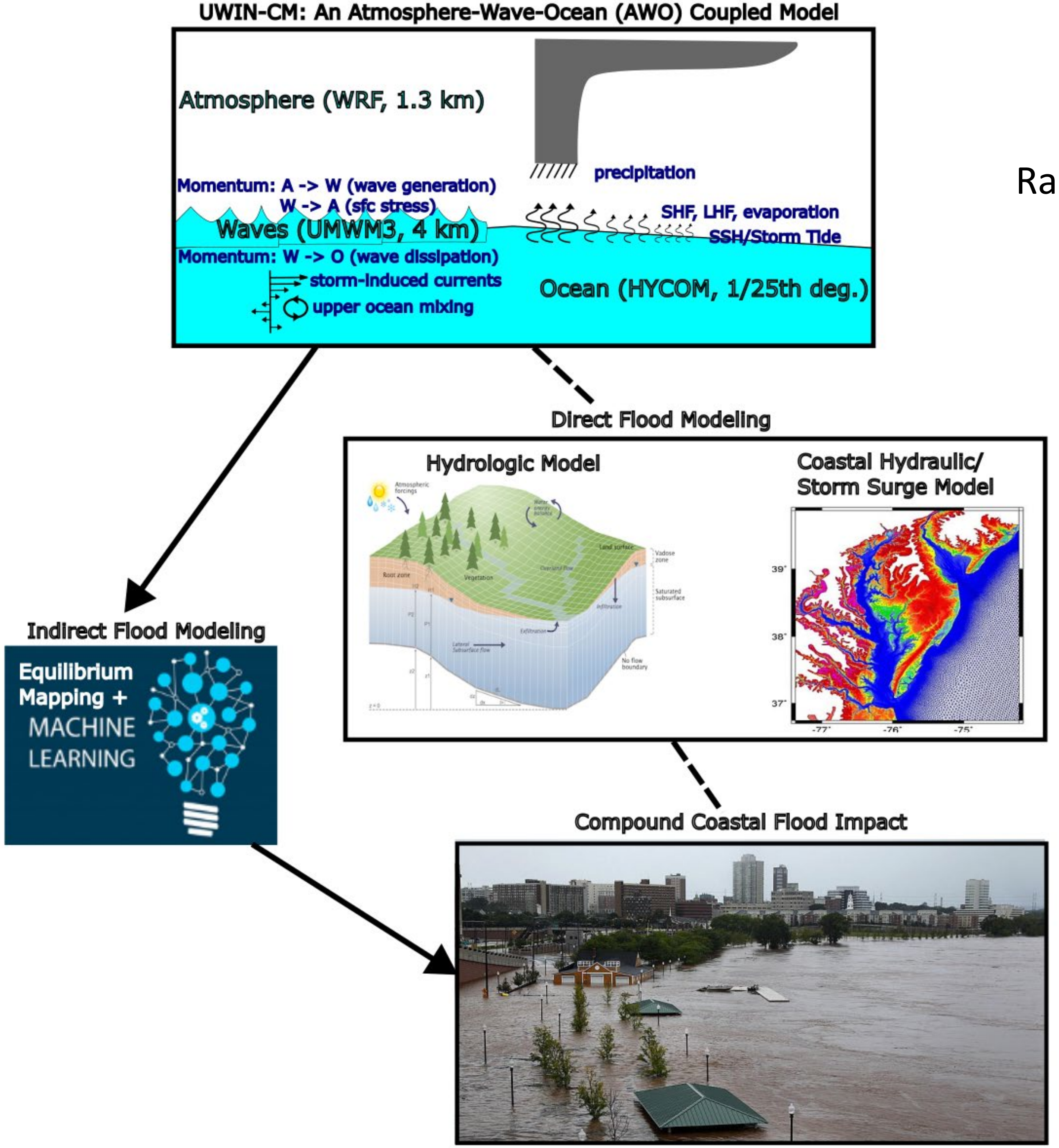
<u>Must haves</u>: Earth system models Atmosphere-Wave-Ocean-Land-Ice



AI/ML

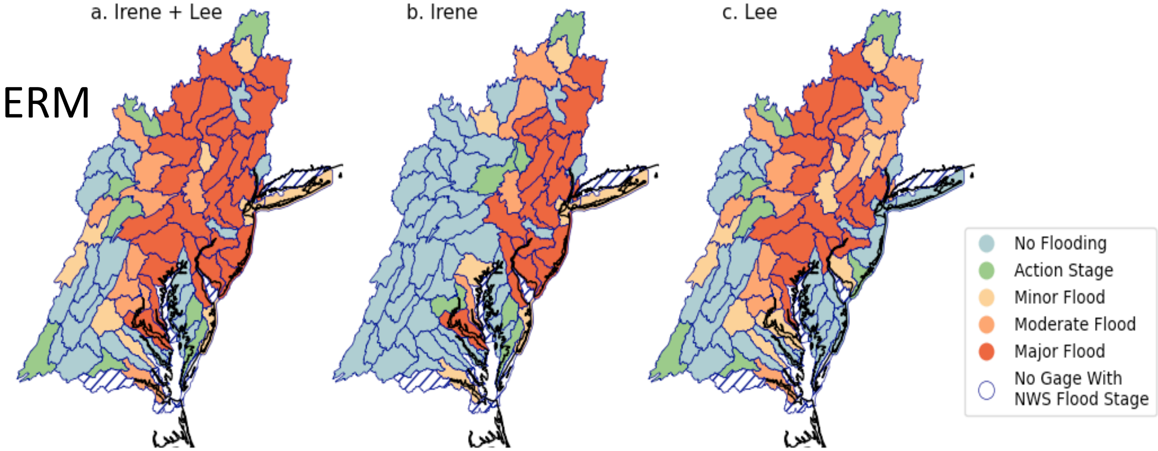


AI/ML

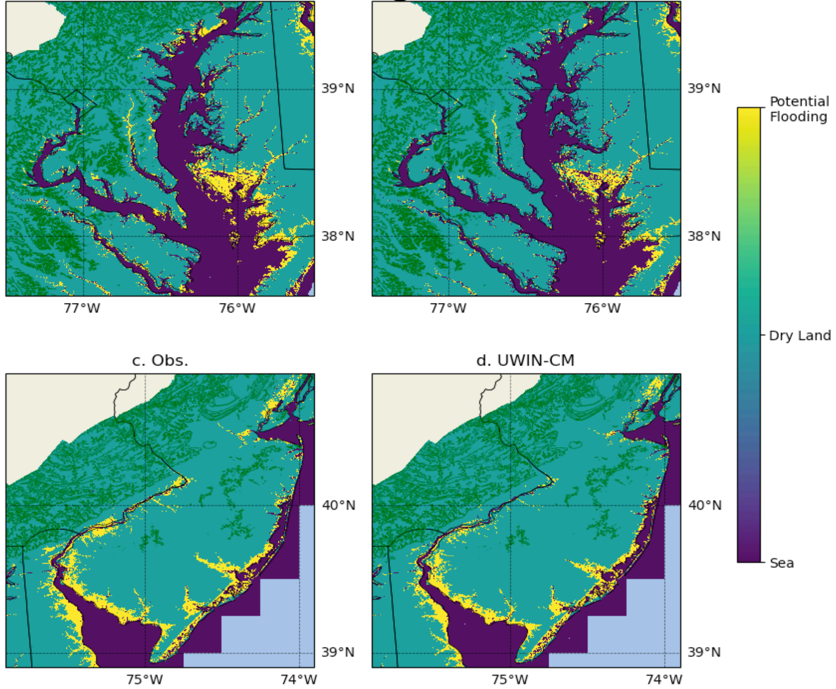


Kerns and Chen (2022a, Natural Hazards)

Rain->ERM

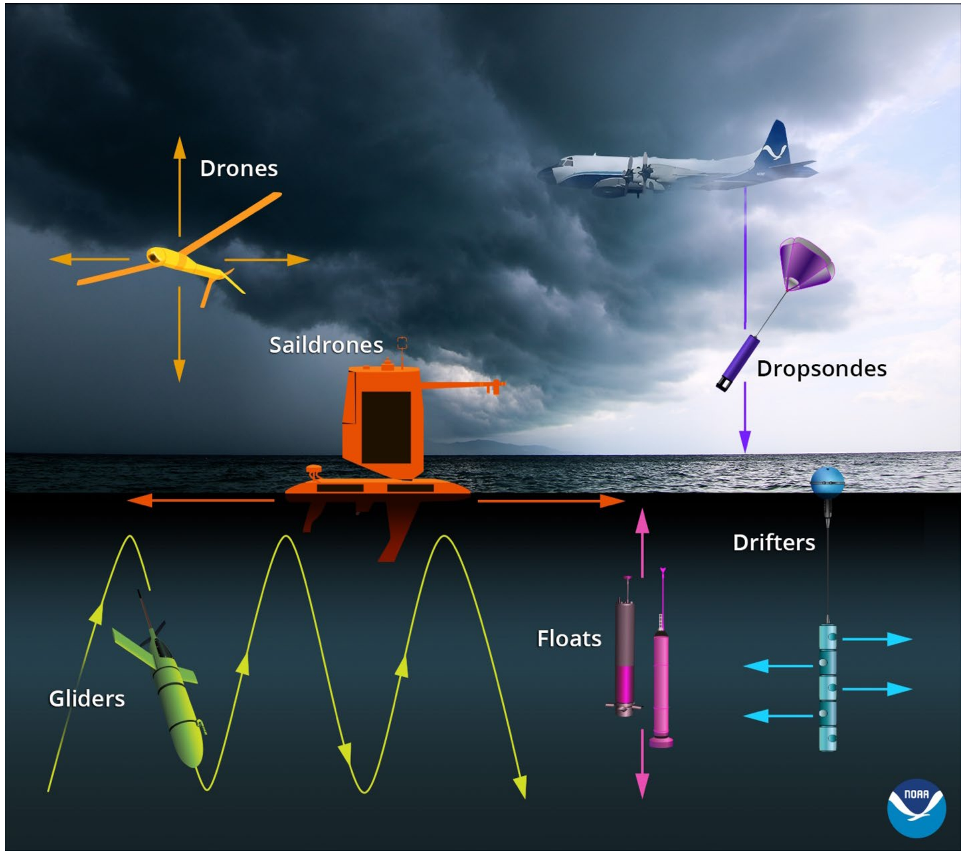


Rain+SSH -> local flooding



Observation Requirements to Meet Challenges and Fill Gaps

- Sea spray (mean concentration obs, in situ size spectrometers, size distribution, characteristic height, whitecap, stress)
- Air-sea fluxes above the spray layer
- Accurate measurements of wind, humidity, waves, current, and temperature (across air-sea transition zone)



PROGRESS, CHALLENGES, AND WAY FORWARD

- Field campaigns and coupled atmosphere-wave-ocean-land model development
- Better understanding of the physical processes in air-sea interaction
- Regional Earth system modeling and forecasting capabilities
- Multiscale, multidisciplinary processes affecting flooding and other hazards
- Coupled atmosphere-ocean-land observations
- Earth system modeling with AI/ML, ensemble prediction, coupled air-sea-land-ice observations and data assimilation
- Integrated forecasting, communication, and decision-making system