Coupled Atmosphere-Wave-Ocean Modeling and Observations: Ocean Transport, Atmospheric Convective Processes, and MJO

Milan Curcic and Shuyi S. Chen

Dept. of Atmospheric Sciences

University of Washington

CARTHE CONSORTIUM for ADVANCED RESEARCH on TRANSPORT of HYDROCARBON in the ENVIRONMENT

W UNIVERSITY of WASHINGTON

Science Visitor and Colloquium Program

July 19, 2017

Jet Propulsion Laboratory

Outline

- Introduction
  - Motivation
  - Scientific objectives
- The coupled modeling system
  - Conceptual model of air-sea momentum exchange
  - Governing equations
  - Unified Wave INterface – Coupled Model (UWIN-CM)
- Stokes drift impacts on transport in Hurricane Isaac (2012)
- Real-time forecasting and verifications in support of field campaigns:
  - GLAD (July-August 2012)
  - LASER (January-March 2016)
  - CPEX (May-June 2017)
- Coupled atmosphere-ocean modeling of MJO propagation
- Summary and Conclusions

Motivation for Wind-Wave-Current Coupling

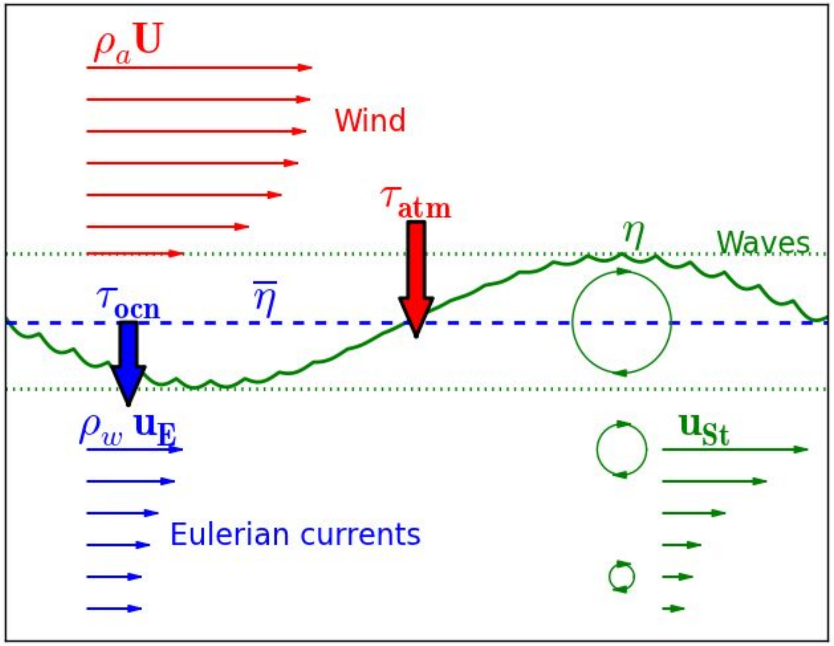
- Surface waves mediate the momentum exchange between atmosphere and ocean
- Explicit representation of surface waves in coupled atmosphere-ocean models is essential for accurate prediction of weather and climate
- Waves induce mass transport in the direction of their propagation (Stokes drift) and force the ocean with wave-dissipative surface stress
- Need for better prediction of extreme weather events and mitigating impacts of environmental hazards such as oil spills

Scientific Objectives

- Better understand the physical processes of wind-wave-current interaction and their impacts on the coupled atmosphere-ocean system:
    - Atmospheric stress, determined by wind-wave-current interactions
    - Oceanic stress, determined by wave energy dissipation
    - Conservative stress treatment
    - Wave-induced Stokes drift
- Explicit air-sea momentum exchange in the Unified Wave INterface (UWIN), and a fully coupled atmosphere-wave-ocean model, UWIN-CM
- Real-time coupled atmosphere-wave-ocean prediction in support of several field campaigns: <u>GLAD (2012)</u>, SCOPE (2013), <u>LASER (2016)</u>, SPLASH (2017), <u>CPEX (2017)</u>

- Applications:
    - Impact of wave-induced Stokes drift on near-surface ocean transport during Hurricane Isaac (2012)
    - Convective Processes in CPEX (2017)
    - Eastward propagation of MJO during DYNAMO (2011)

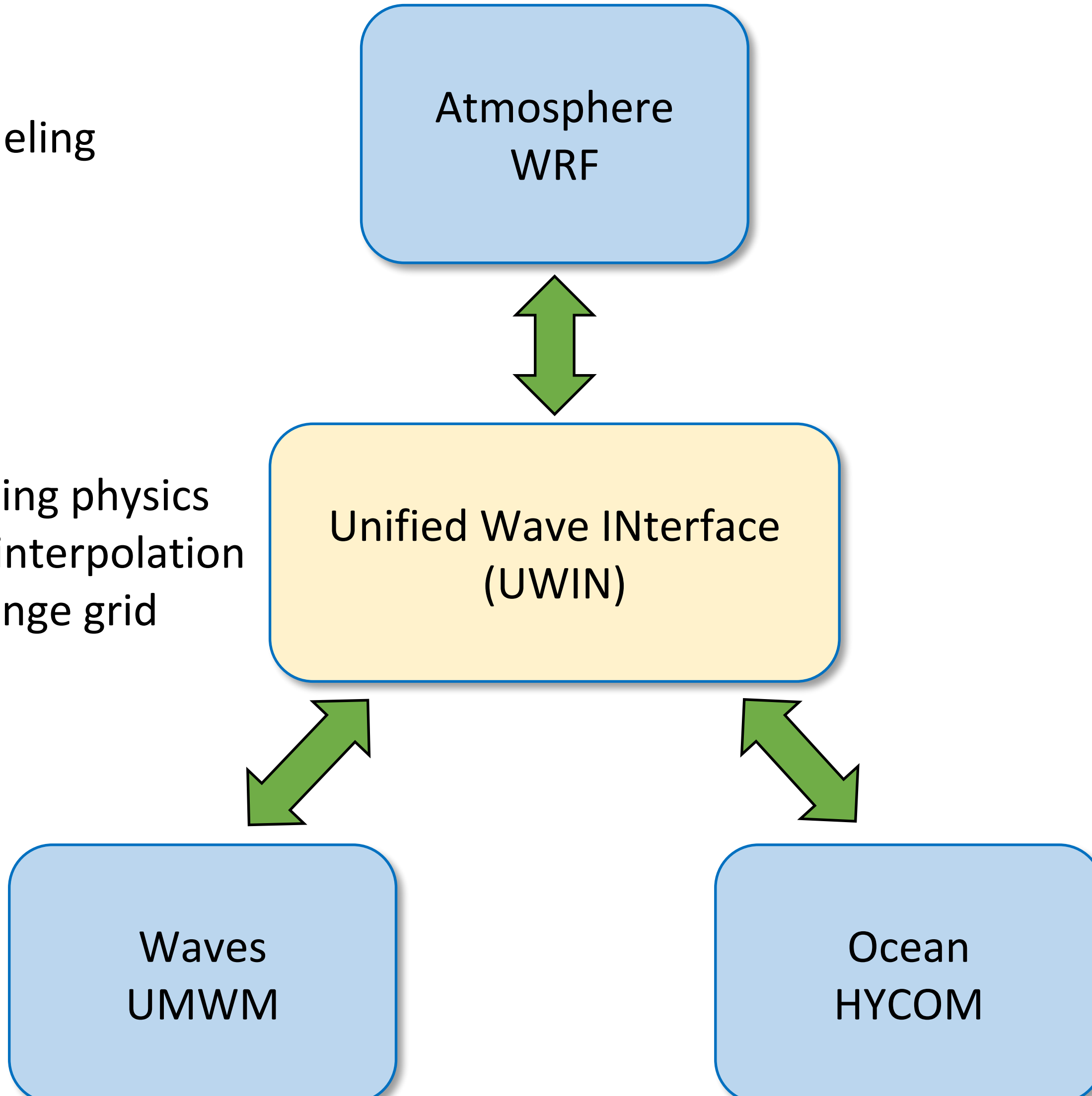
Principal Processes of Air-Sea Momentum Exchange



Unified Wave INterface – Coupled Model UWIN-CM

Based on the Earth System Modeling Framework (ESMF)

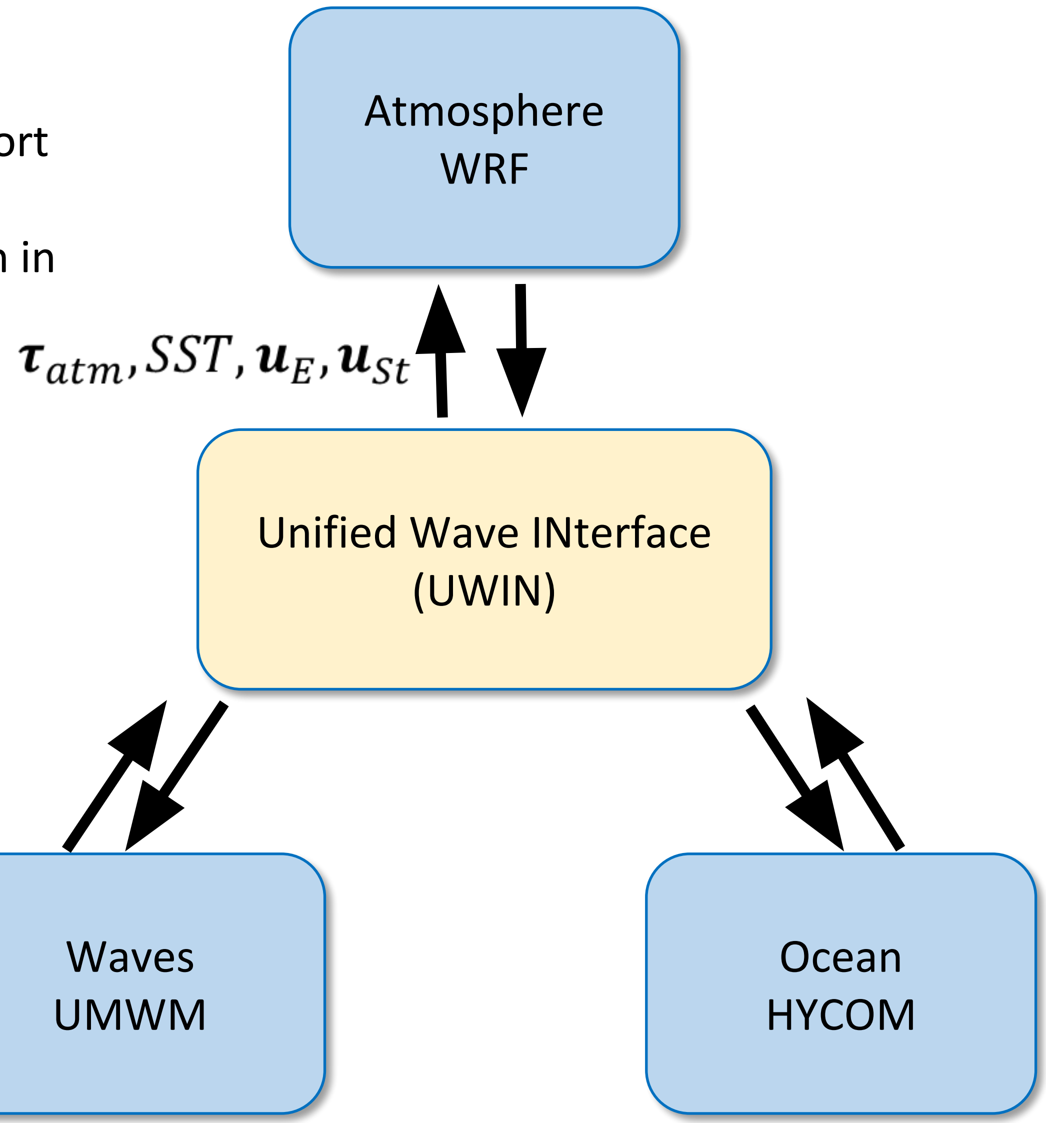
- Coupling physics
- Field interpolation
- Exchange grid



Chen et al. (2013), JAS
Chen and Curcic (2016), OM
Curcic et al. (2016), GRL
Judt et al. (2016), JGR

UWIN-CM Exchange Fields

- Each model component has import and export fields
- Unified physics and interpolation in the coupling interface - UWIN



UWIN-CM - Momentum coupling equations

Atmosphere Momentum:

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

Wave energy balance:

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

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

Ocean Momentum:

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

Stokes-Coriolis Stokes-Vortex Force

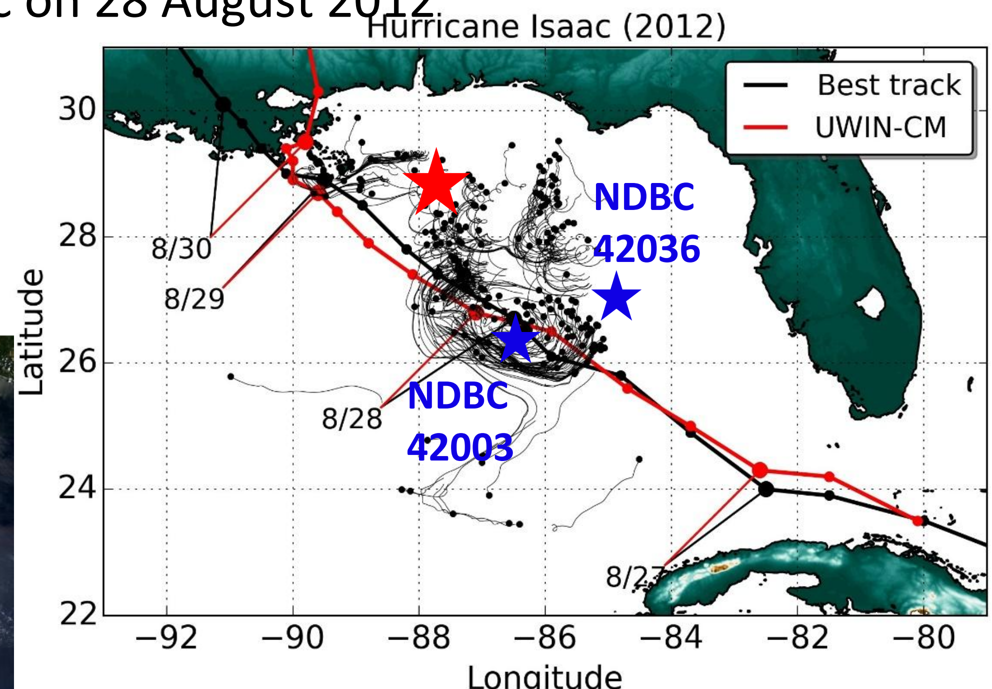
Scalar tracer transport:

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

$\boldsymbol{u_L}$ - Total Lagrangian velocity

Grand LAgrangian Deployment (GLAD)

- Field campaign in northeast Gulf of Mexico from July-August 2012 to quantify submesoscale and mesoscale surface transport – where does the oil go?
- 300+ CODE-style Lagrangian surface drifters (GPS positions)
- 7 meteorological drifters (MiniMet) - WSPD, SLP, SST
- 3 ADOS drifters – WSPD, sub-surface temperature (0-150 m)
- Direct impact by Hurricane Isaac on 28 August 2012



Wind and wave verification against NDBC buoys

Along track

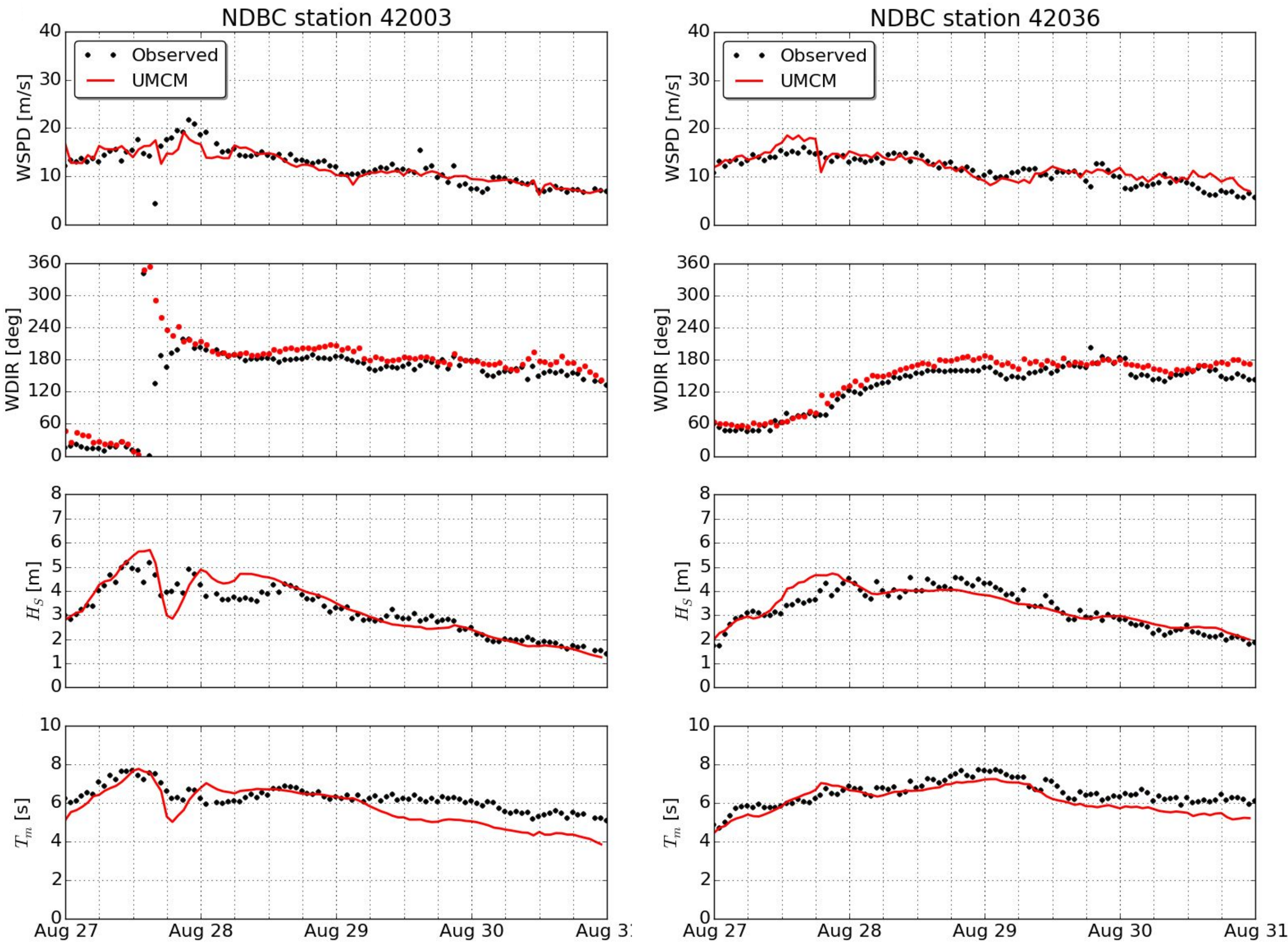
Right of track

Wind speed

Wind direction

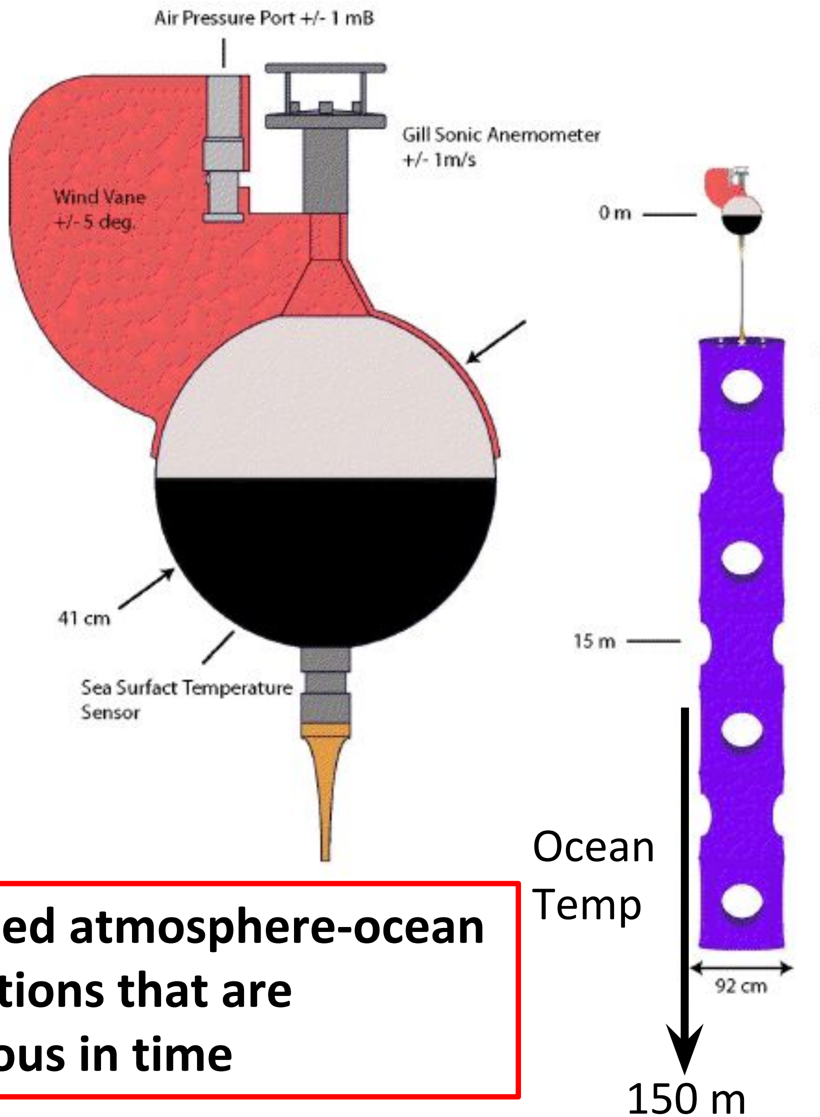
Significant wave height

Mean wave period



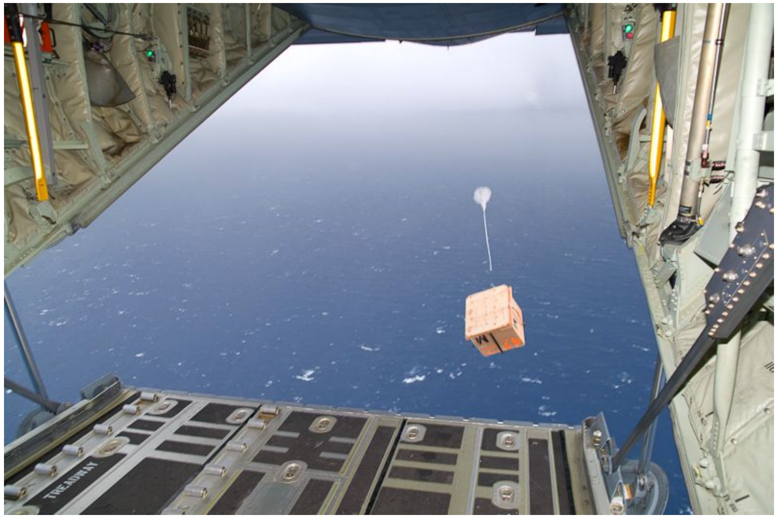
Observations: Sonic miniMet and ADOS drifters (17)

(Wind, SLP, SST) (Wind, SLP, SST, T-profile 150m)

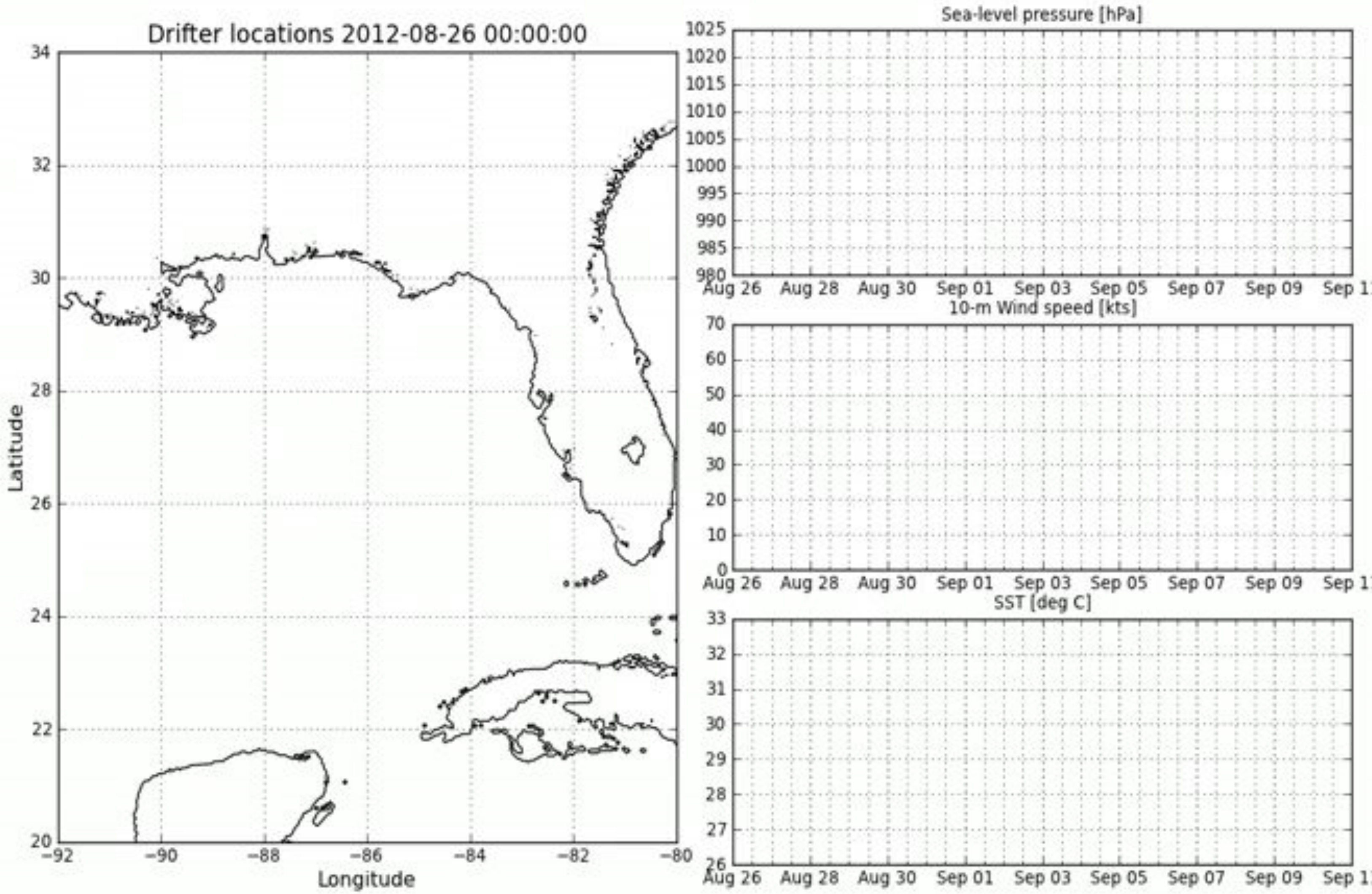


Co-located atmosphere-ocean observations that are continuous in time

Ship & Air Deployment



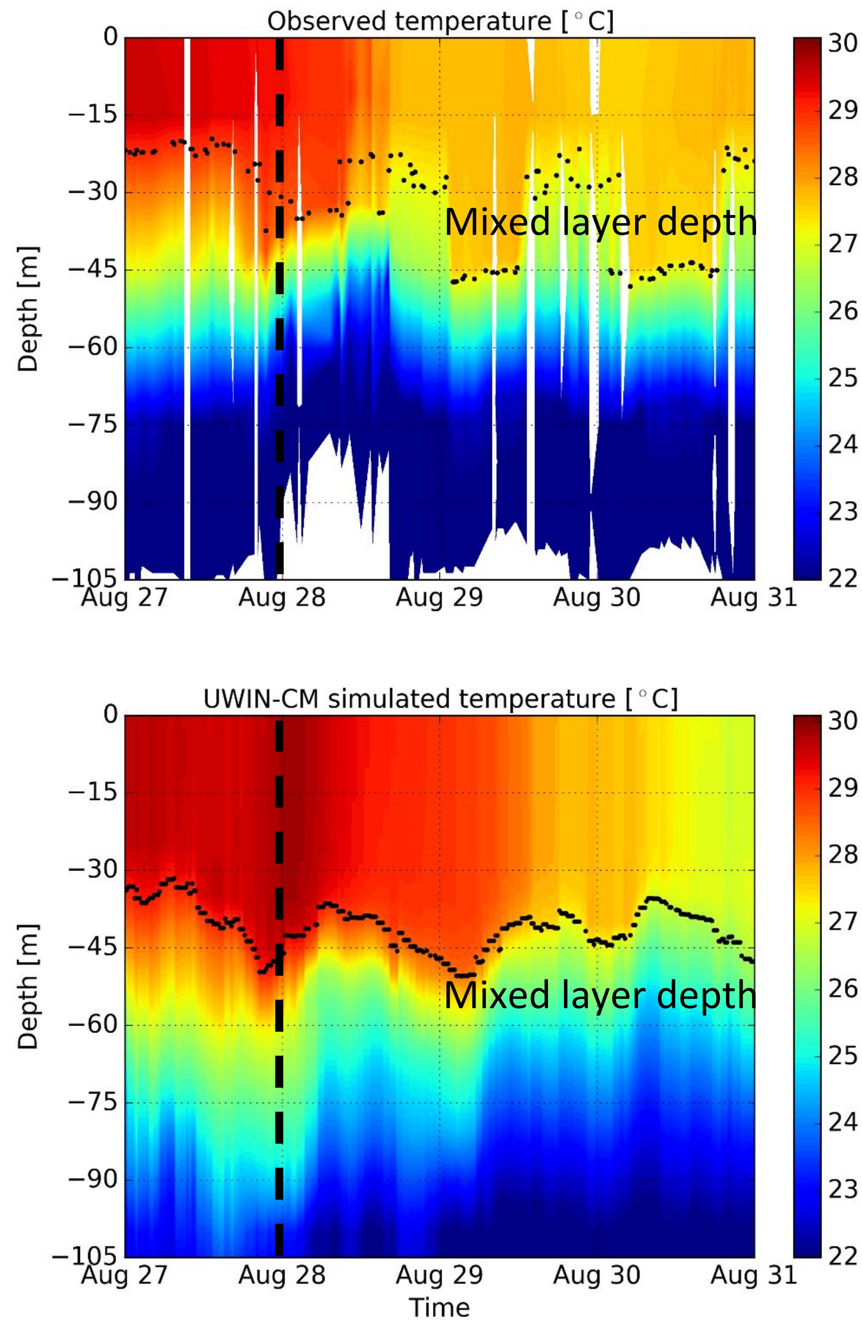
In situ observed ocean cooling and SST recovery during and after Hurricane Isaac (2012)



Judt, Chen and Curcic (2016), JGR

ADOS observations: Mixing, upwelling, and inertial oscillations during passage of Hurricane Isaac (2012)

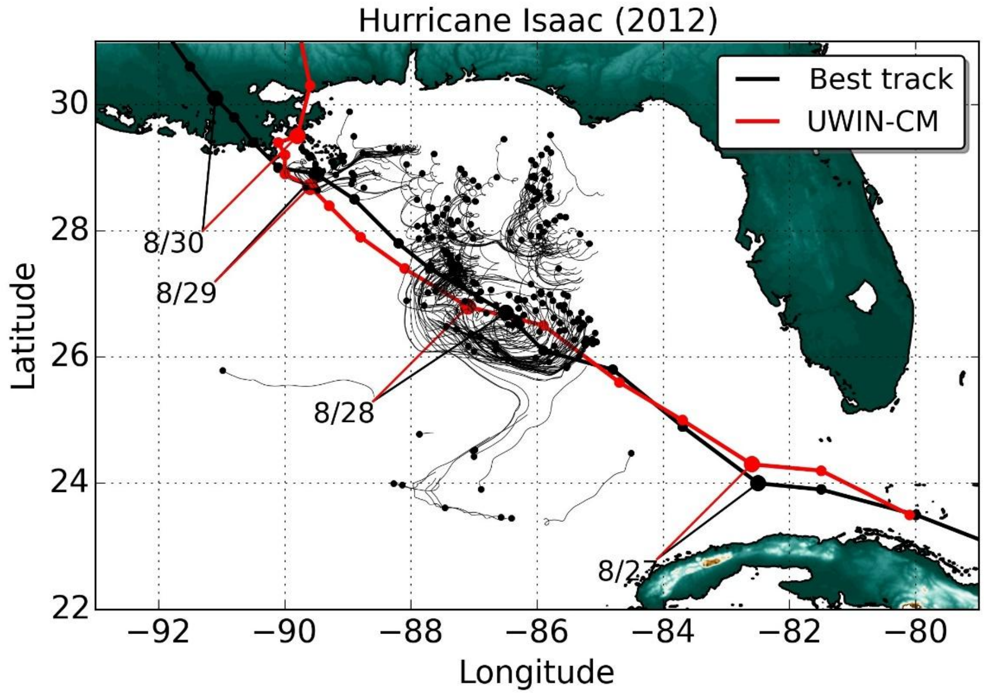
- Cold water upwelling immediately following the passage of the storm
- Strong inertial oscillations in the wake of the storm
- Initial mixed layer in the model deeper and warmer than observed



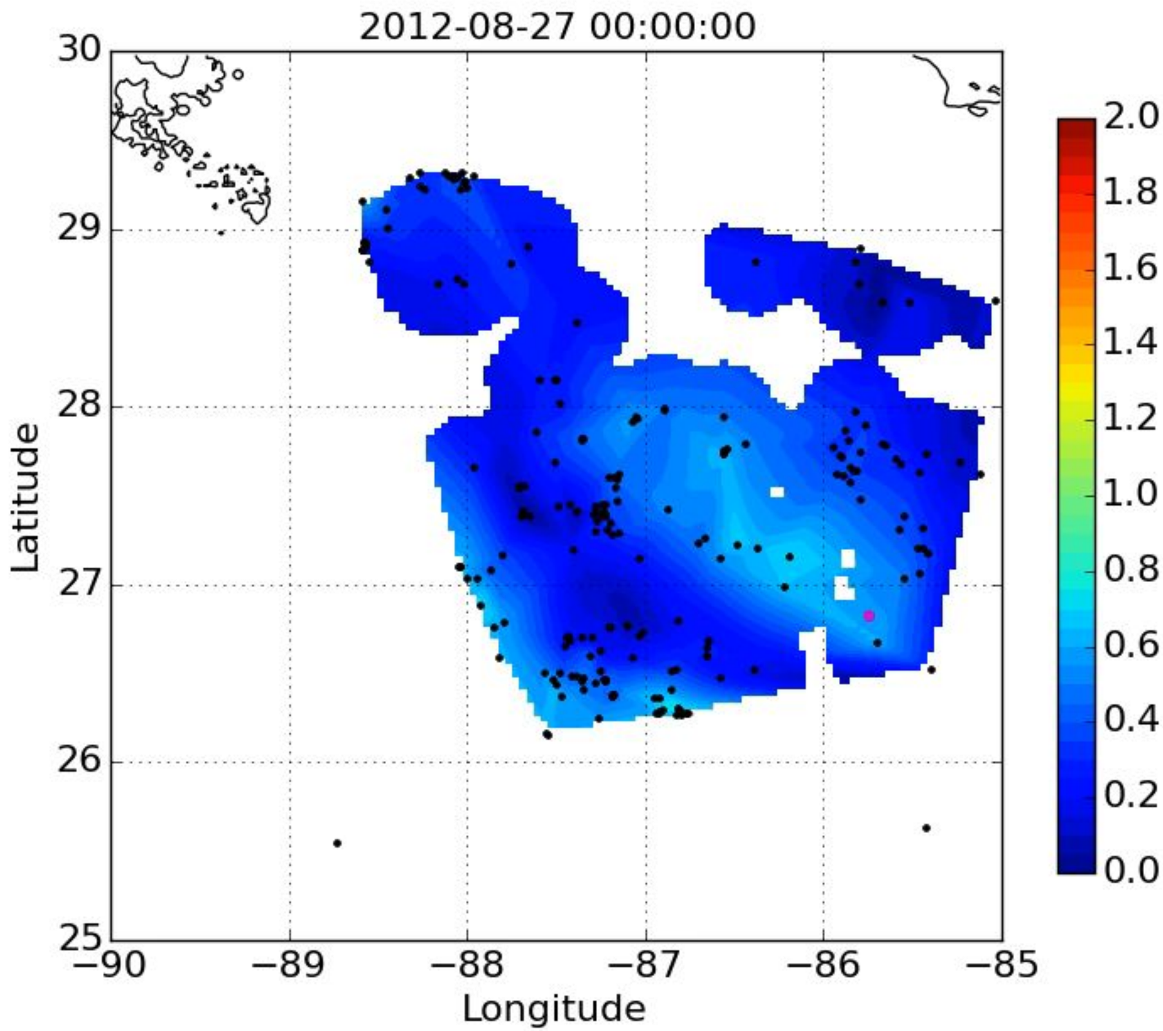
Judt, Chen and Curcic (2016), JGR

Quantifying wave impacts on ocean surface transport using Lagrangian surface drifters from GLAD

- >**300** CODE-style drifters deployed near Deepwater Horizon Oil Spill Site in July 2012
- CODE drifters sample upper 1-m Lagrangian current, including wave-induced Stokes drift
- ~200 drifters in direct impact by Hurricane Isaac on 28 August 2012



Mapping the surface ocean velocity based on GLAD Drifters



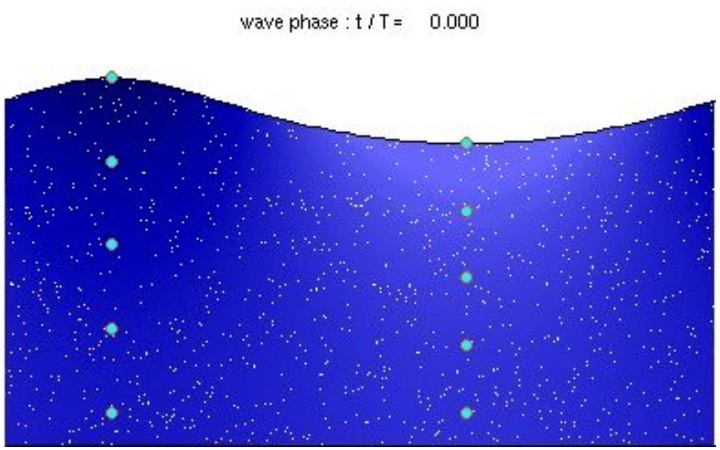
Upper 1-m current [m/s]

Wave-induced Stokes drift

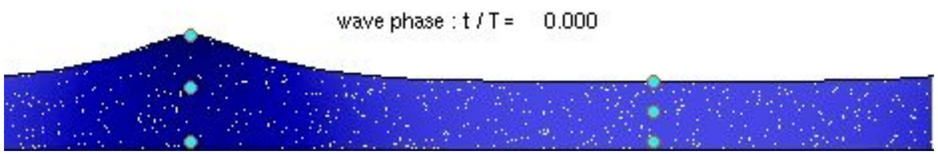
$$\boldsymbol{u_{St}} = \int_{-\pi}^{\pi}\int_{0}^{\infty} \omega k^2 \frac{\cosh[2k(z+d)]}{\sinh^2(kd)} F d\boldsymbol{k} d\theta$$

- Water particle orbits not closed under wavy surface
- Residual drift with exponential decay with depth

Deep water



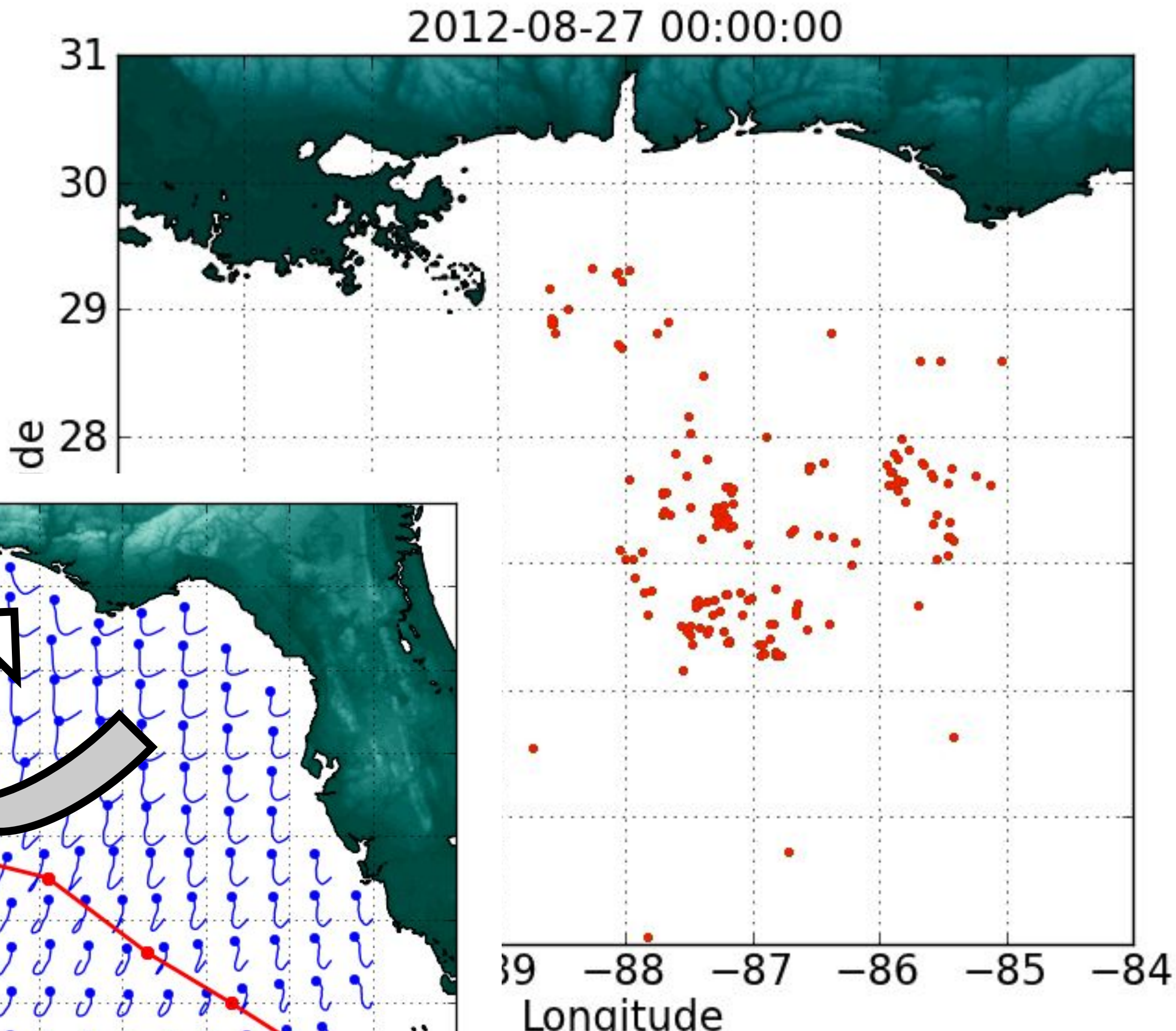
Shallow water

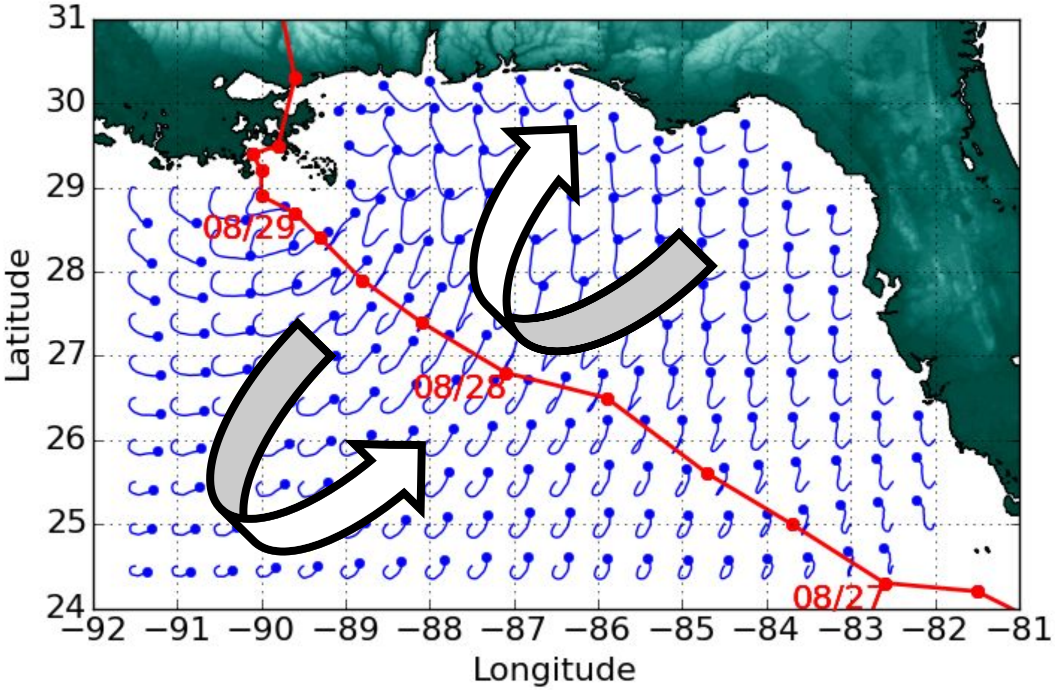


What was the impact of Stokes drift on ocean transport during the passage of Hurricane Isaac?

$$\boldsymbol{u_L} = \boldsymbol{u_E} + \boldsymbol{u_{St}}$$

Stokes drift trajectories

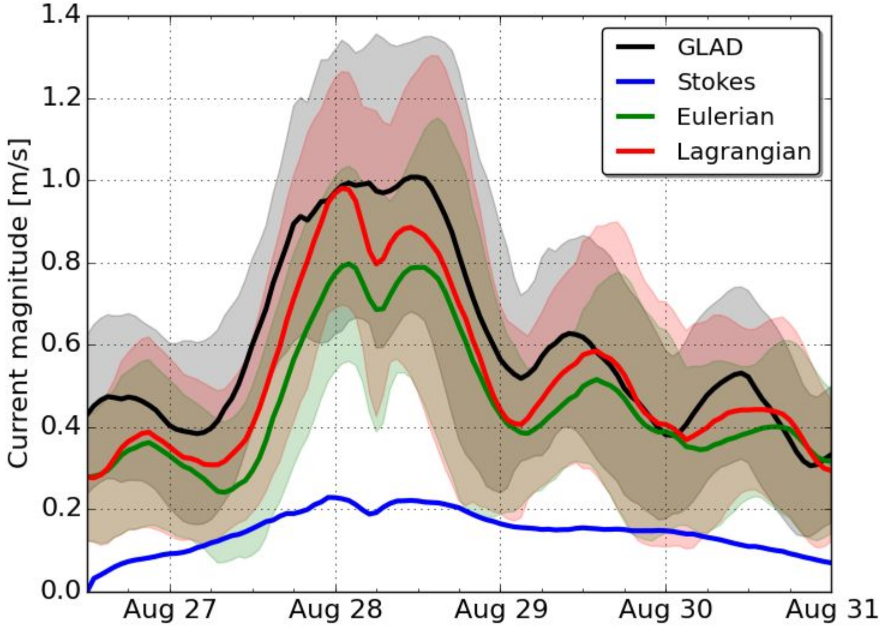




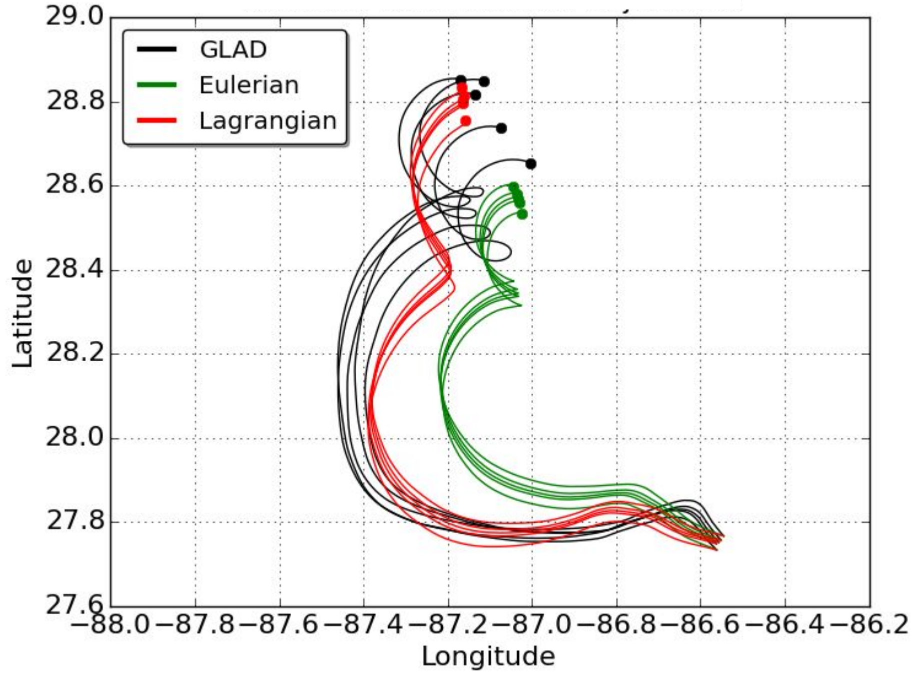
Curcic, Chen and Özgökmen (2016), GRL

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

Current magnitude

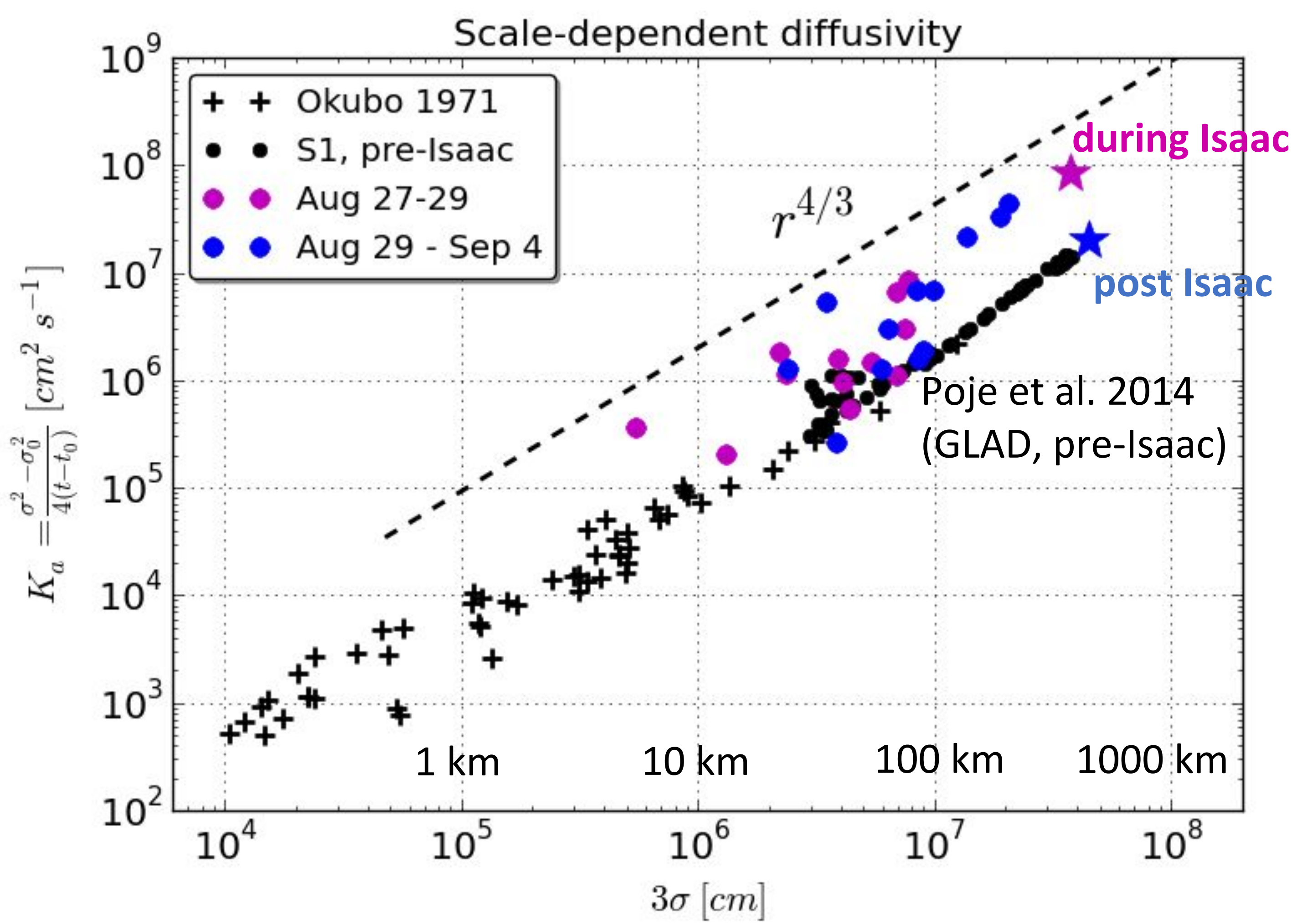


Observed and simulated trajectories



Curcic, Chen and Özgökmen (2016), GRL

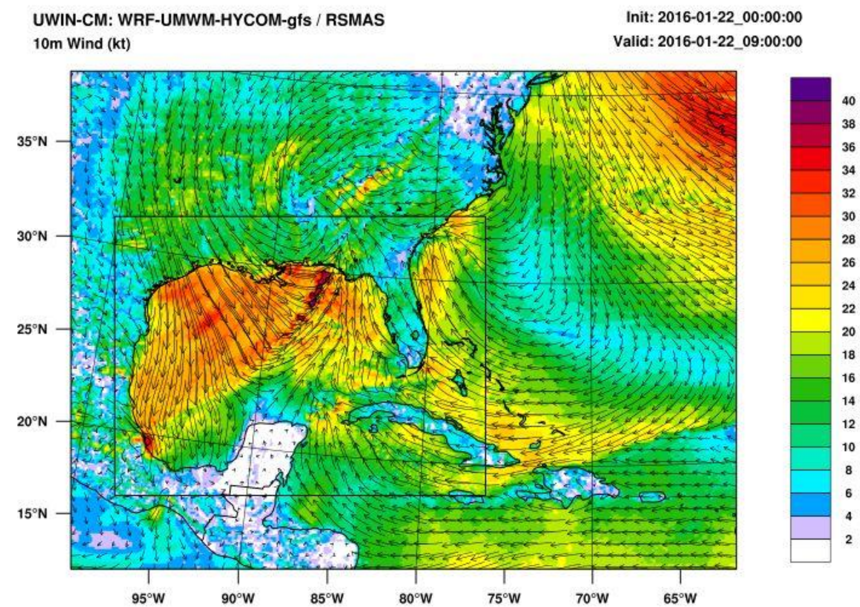
Large-scale diffusivity peaks during Hurricane Isaac



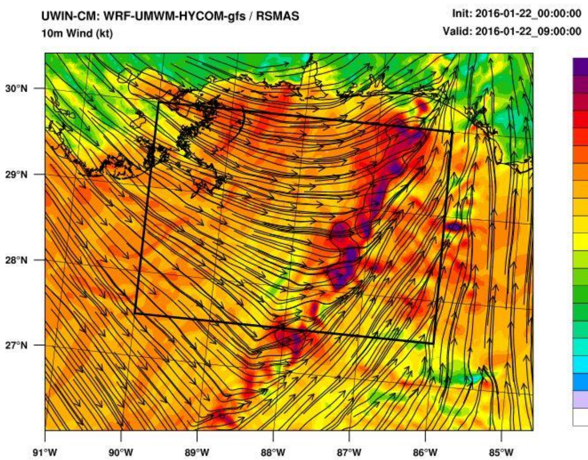
Curcic, Chen and Özgökmen (2016), GRL

Real-time UWIN-CM forecasts in support of the Lagrangian Submesoscale ExpeRiment (LASER): January-March 2016

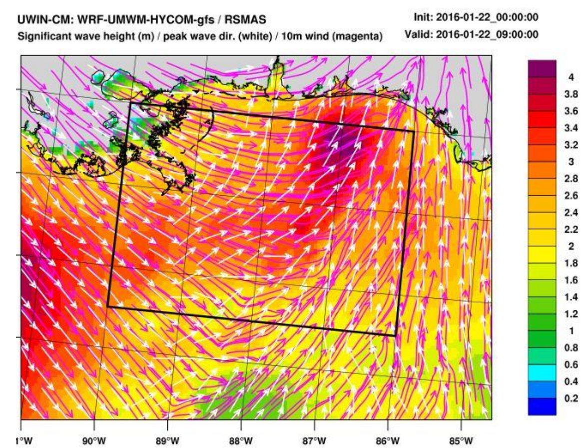
- Fully coupled atmosphere-wave-ocean forecasts from January 1, 2015 – April 1, 2016
- Real-time 72-hour forecasts of atmosphere, waves and currents during LASER
- All components at 4 km resolution in the Gulf of Mexico



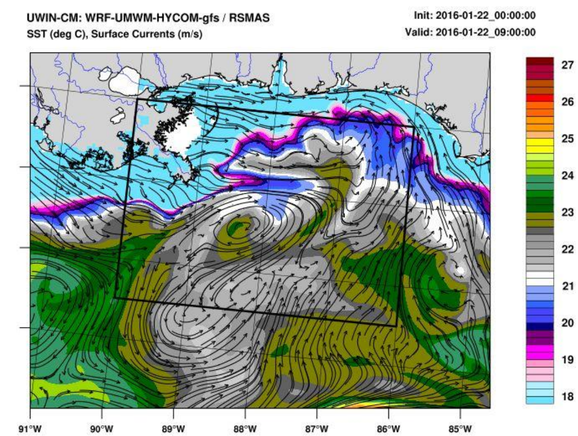
Wind



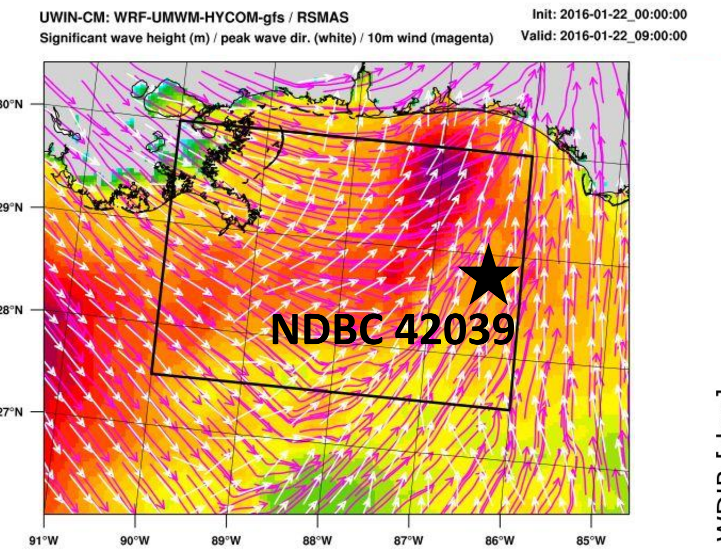
Waves

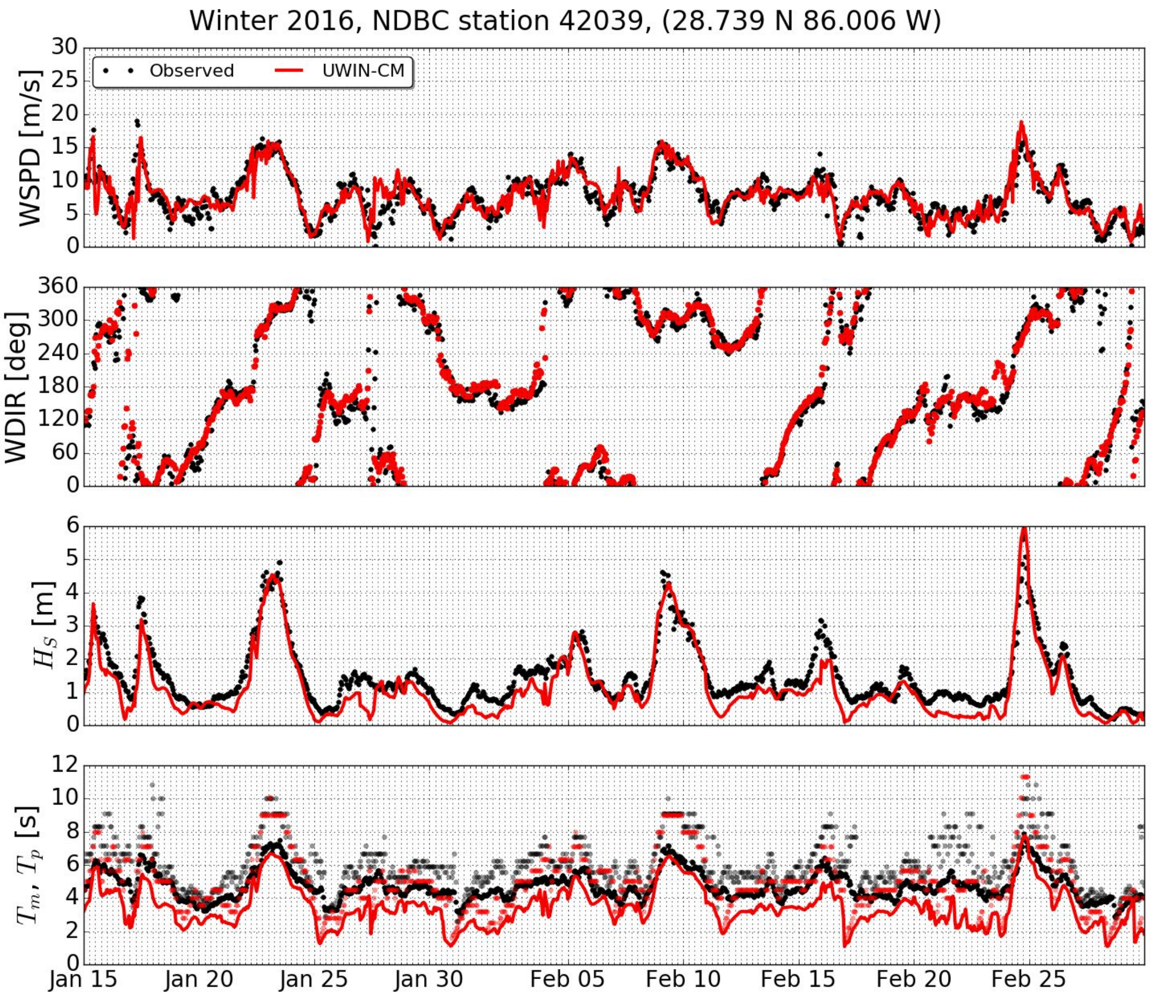


Currents and SST



UWIN-CM wind and wave verification with NDBC buoy observations





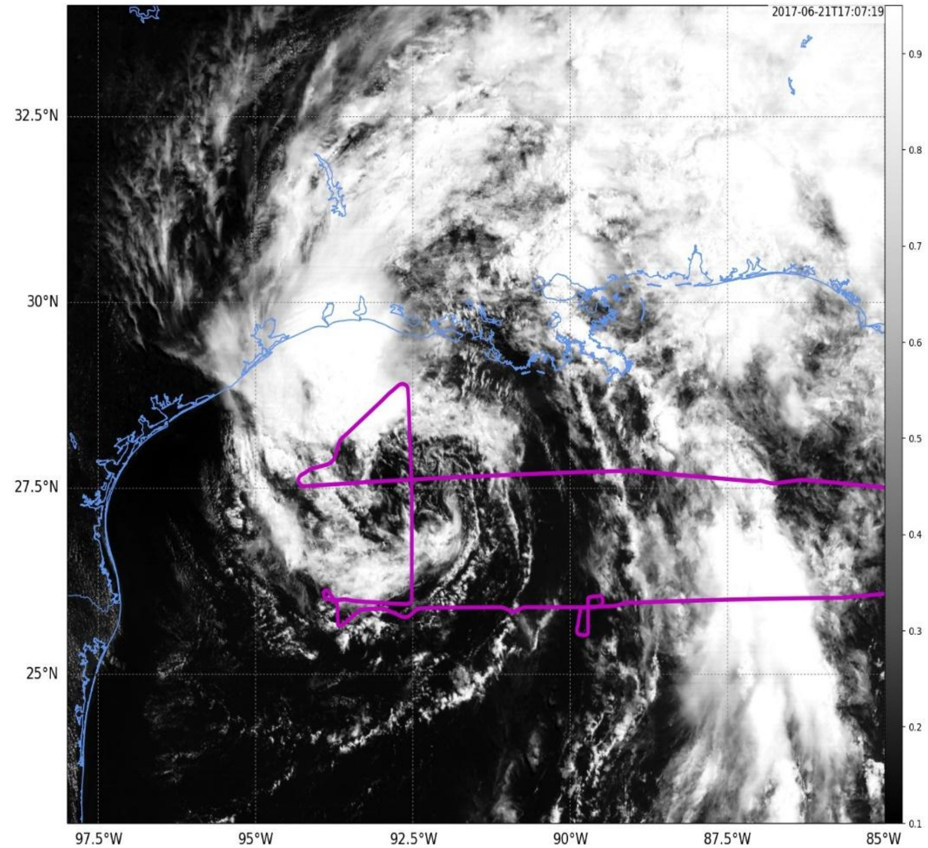
Real-time 72-hour forecasts of atmosphere, waves and currents during LASER in support of field campaign

24-48 hr forecast period ->

NASA Convective Process Experiment (CPEX) 2017

Science objectives:
- Improve understanding of tropical convective processes.
- Obtain wind, temperature, and moisture profiles in vicinity of deep convection in all phases of convective life cycle.
- Improve model representation of convective and boundary layer processes.

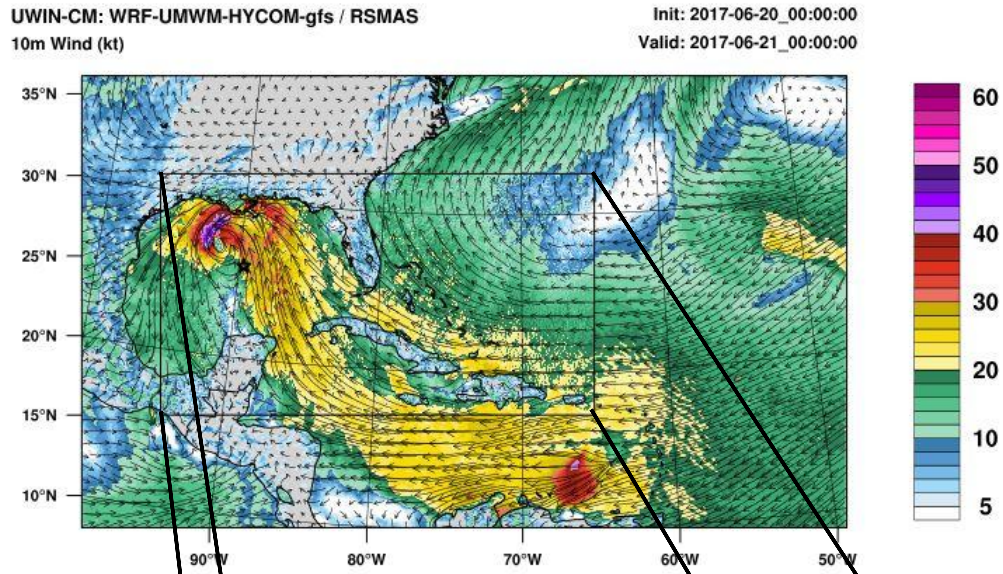
Highlights:
- ➢ 16 DC-8 missions from 27 May-24 June.
- ➢ Covered a wide range of weather conditions.
- ➢ Collected observations from pre-tropical disturbance in the Caribbean Sea, to tropical depression, and formation of Tropical Storm Cindy in the Gulf of Mexico prior to landfall in Louisiana on 22 June.



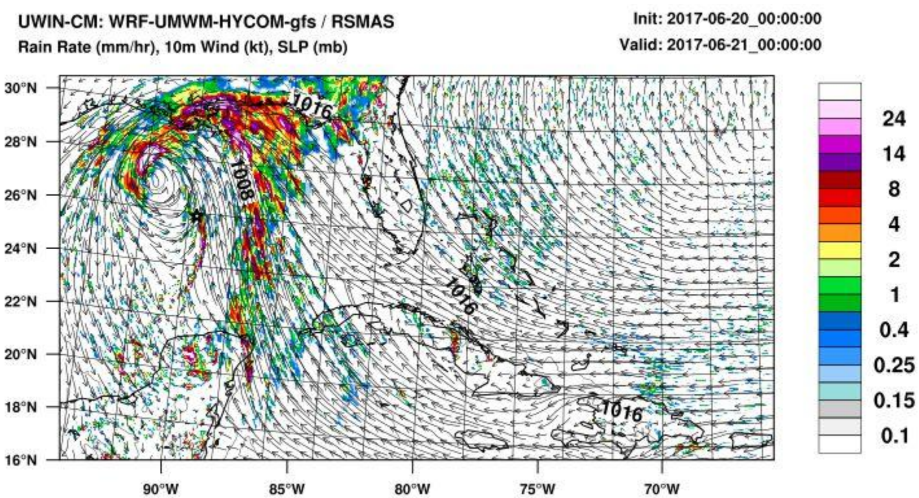
CPEX mission on June 21, 2017

UWIN-CM real-time coupled prediction during CPEX

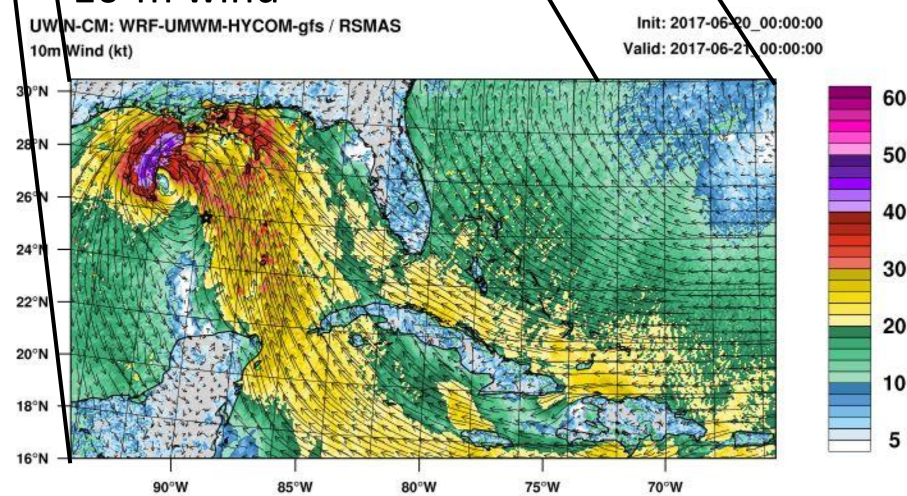
- Fully coupled atmosphere-wave-ocean forecasts from May 25 – June 25
- Real-time 72-hour forecasts of atmosphere, waves, and currents
- Same configuration as for LASER



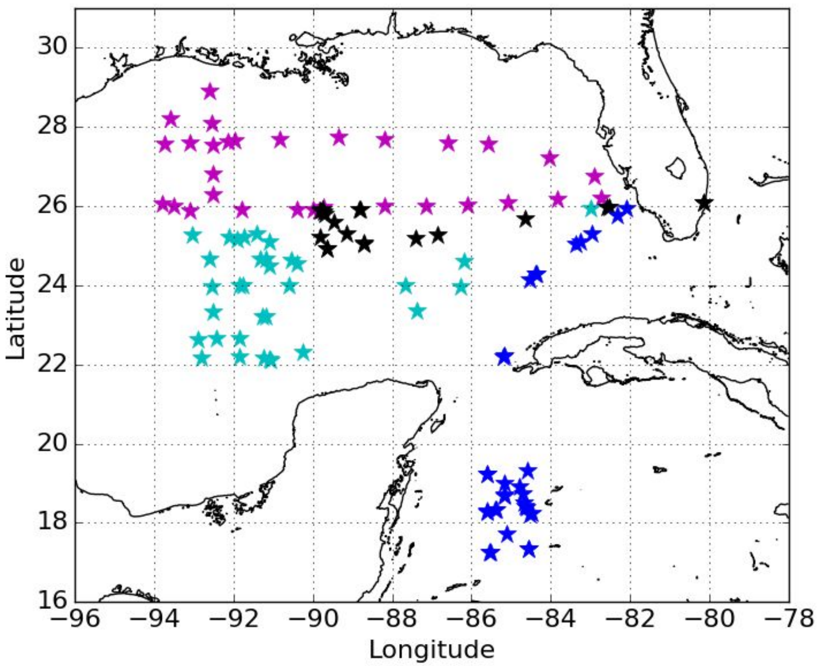
Rain rate

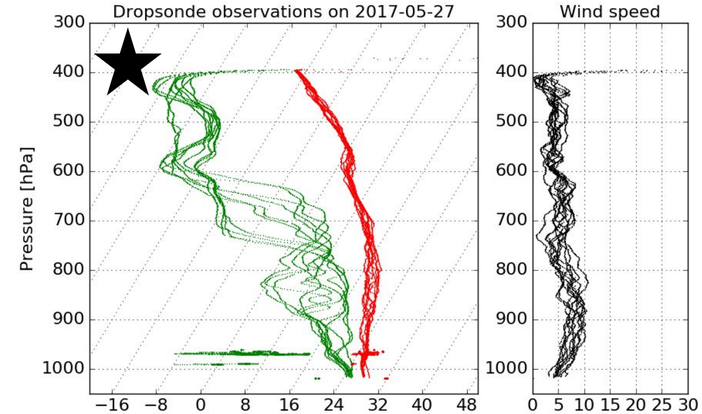


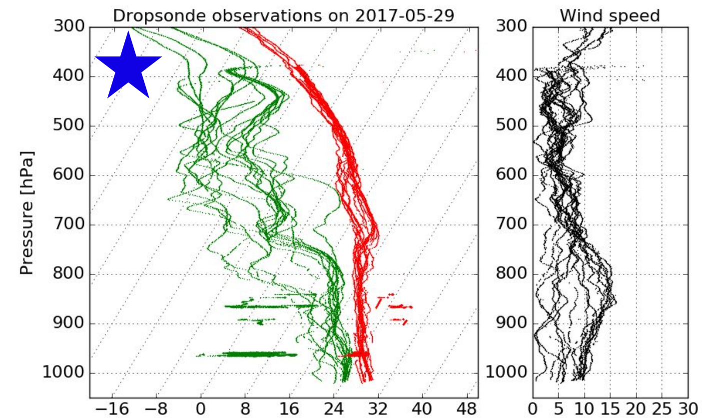
10-m wind



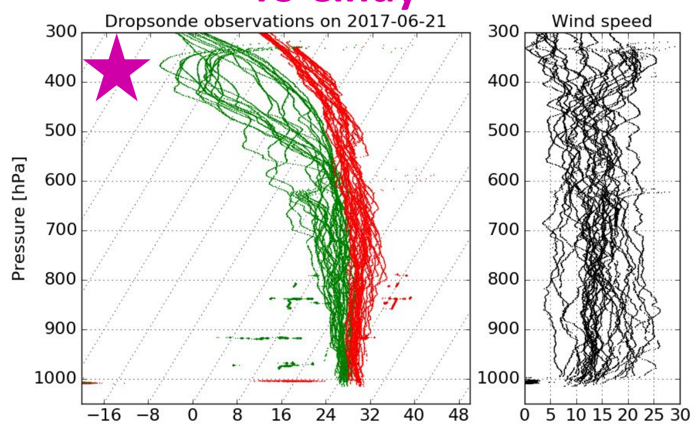
Dropsonde observations from 4 flights

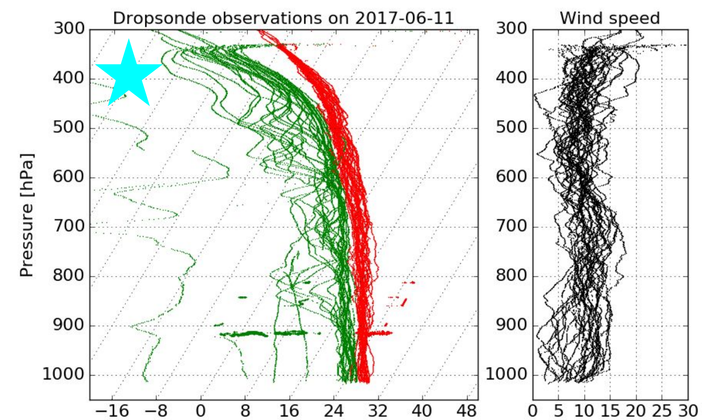






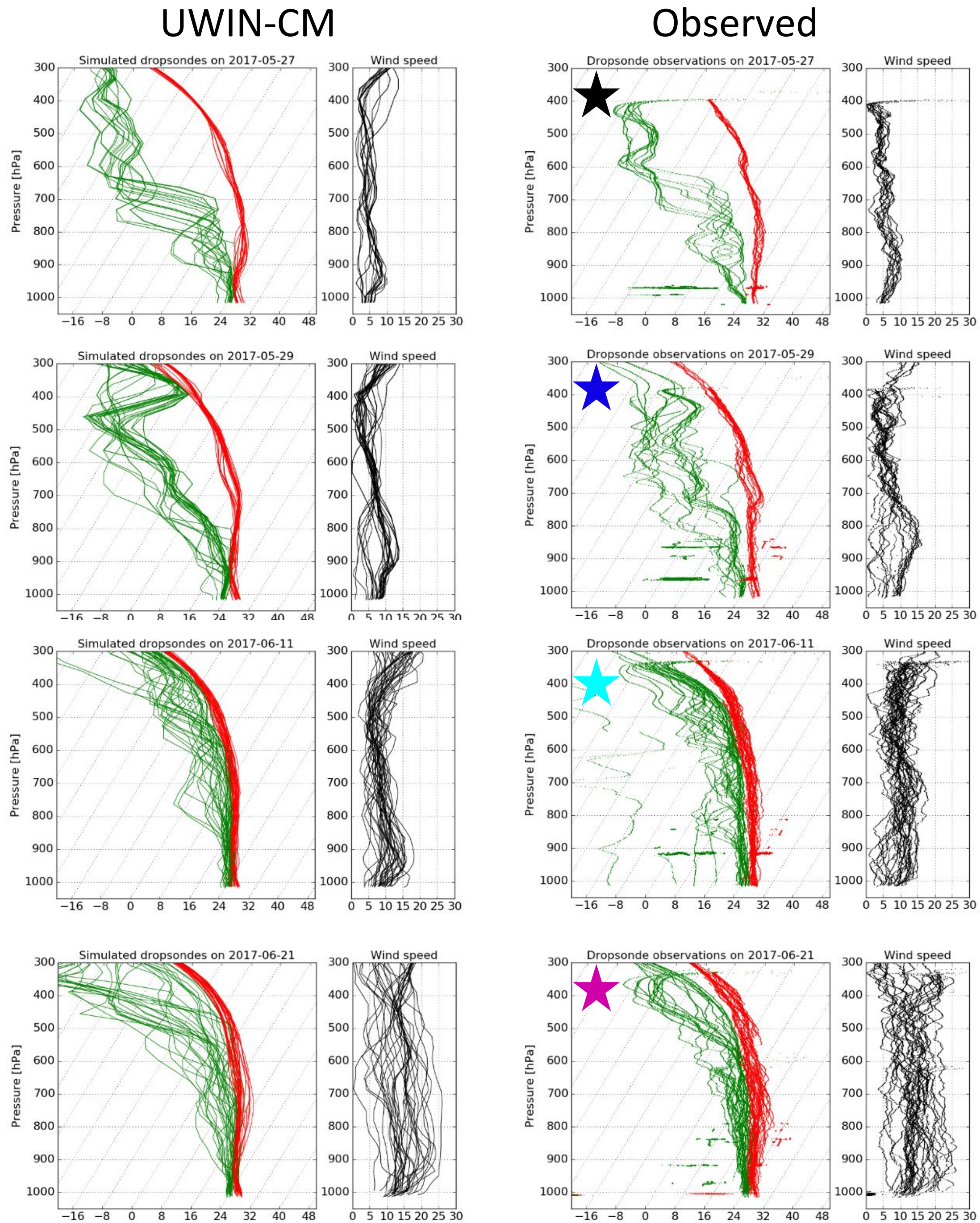
TS Cindy



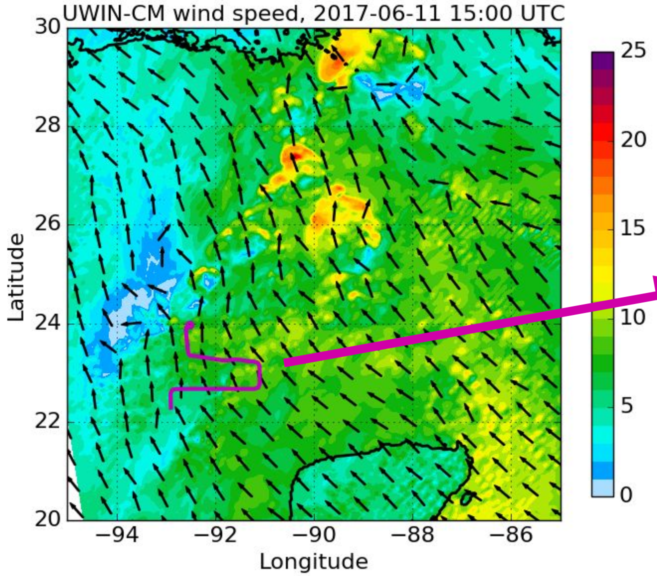


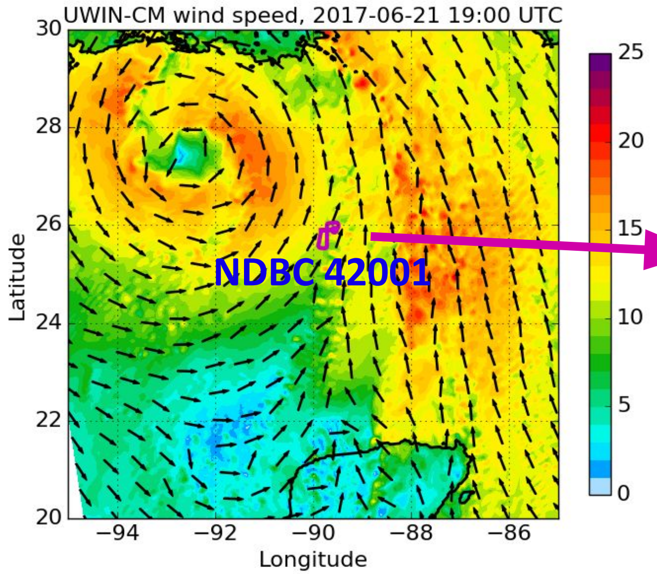
Preliminary dropsonde comparison with UWIN-CM prediction

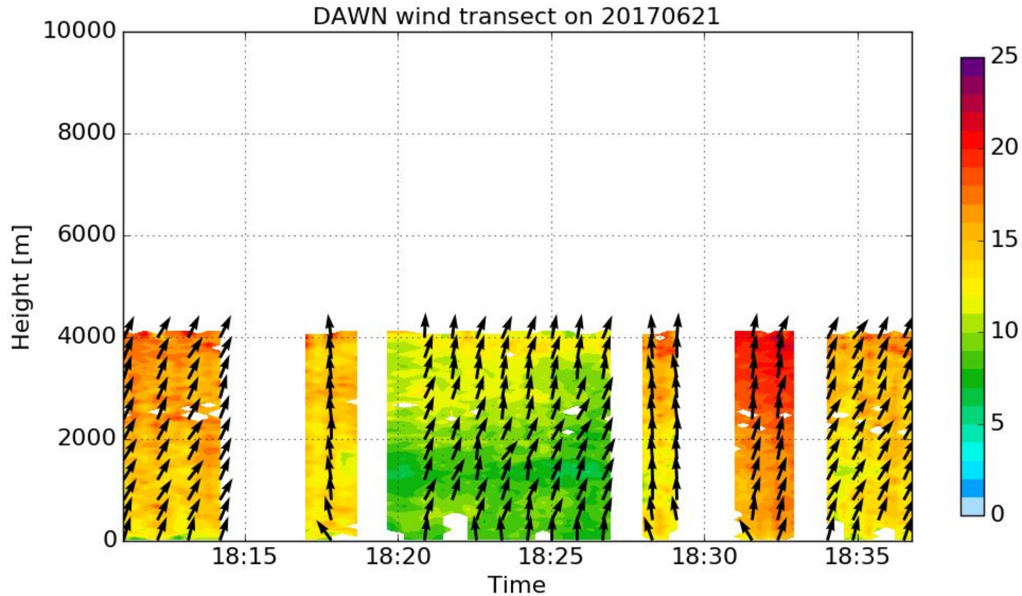
- Overall good vertical structure of the troposphere in the coupled model
- Dropsonde data still L1 (quick look) – next step is to quantify model biases after data QC
- Data capture both TS Cindy and its environment



Doppler Wind Lidar (DAWN) observations



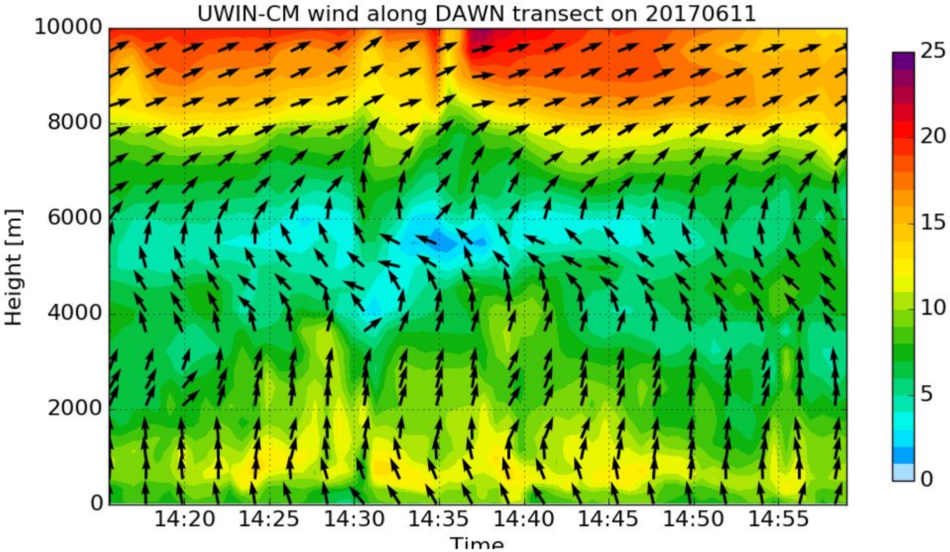


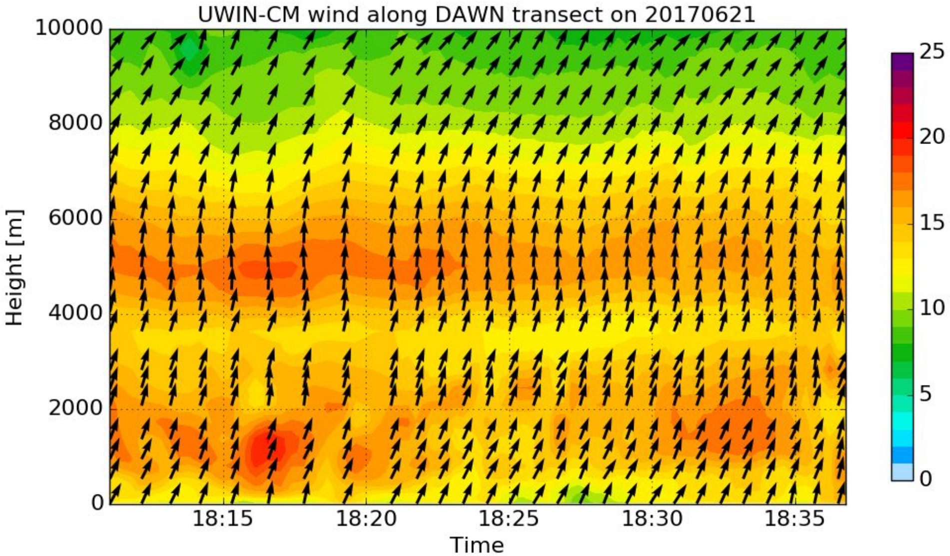


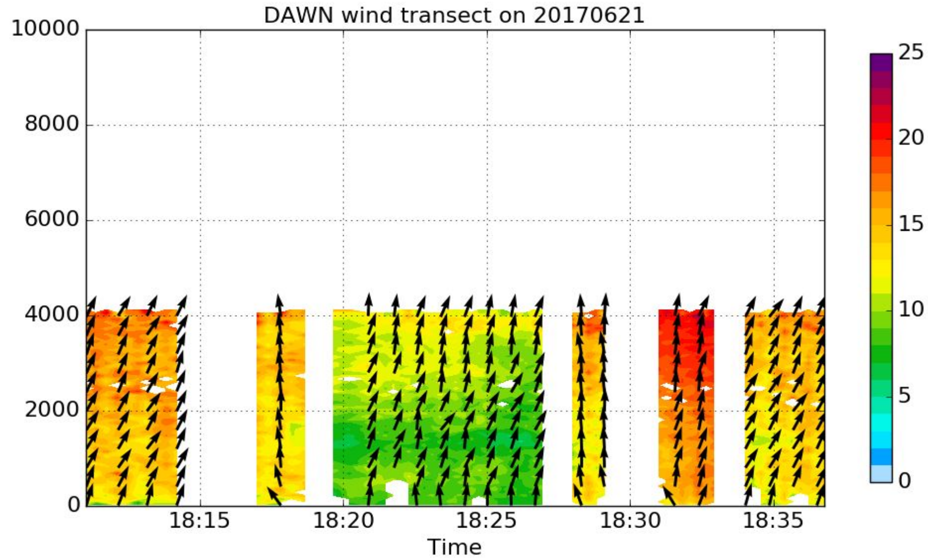
Coupled model comparison with DAWN observations

UWIN-CM

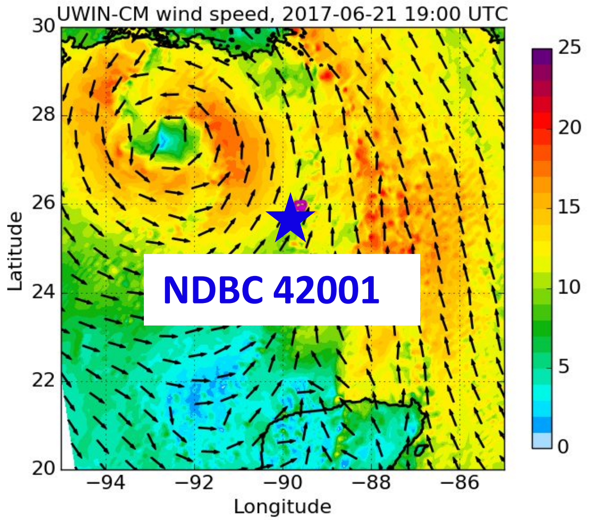
Observations

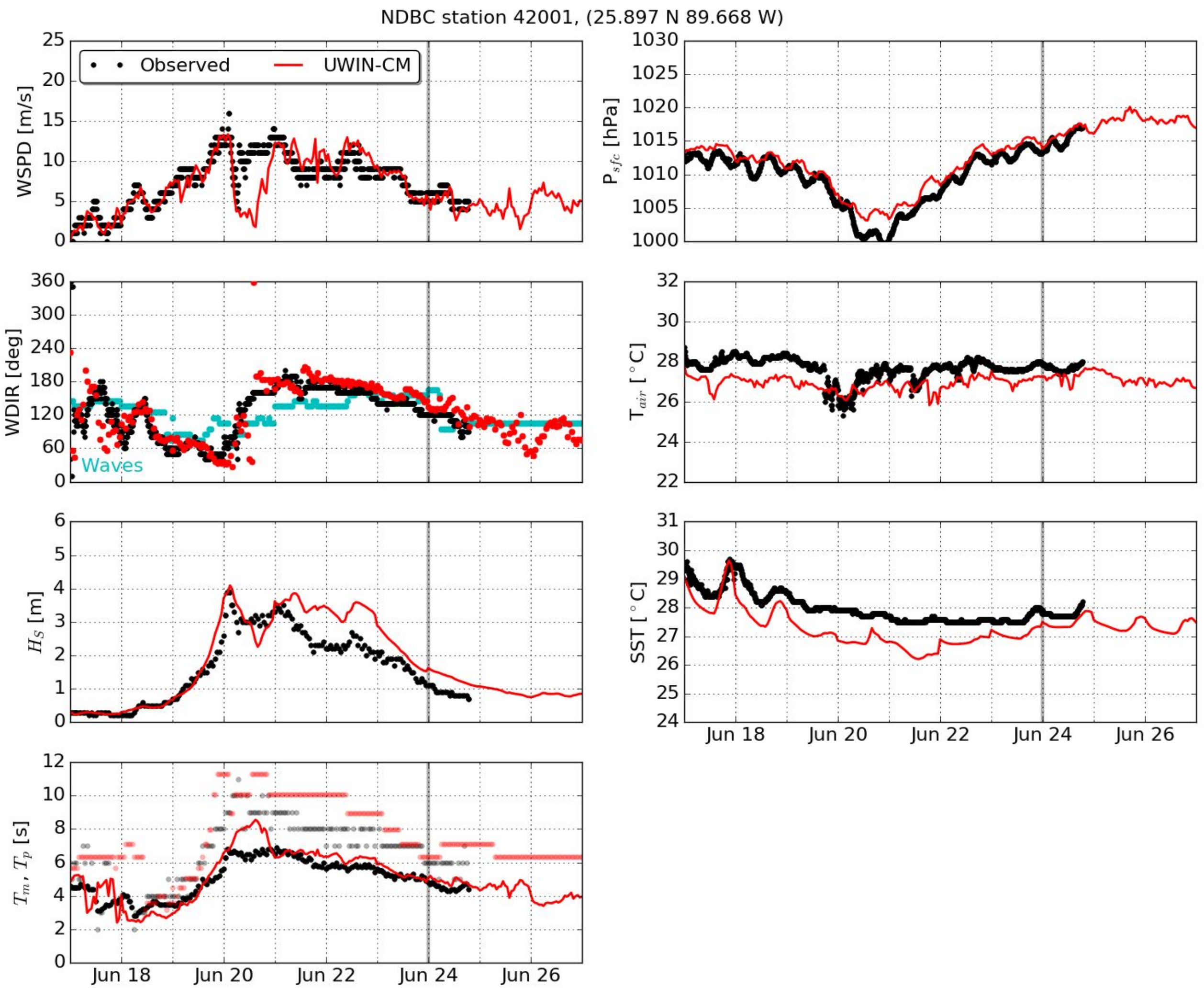






Coupled model comparison with NDBC 42001





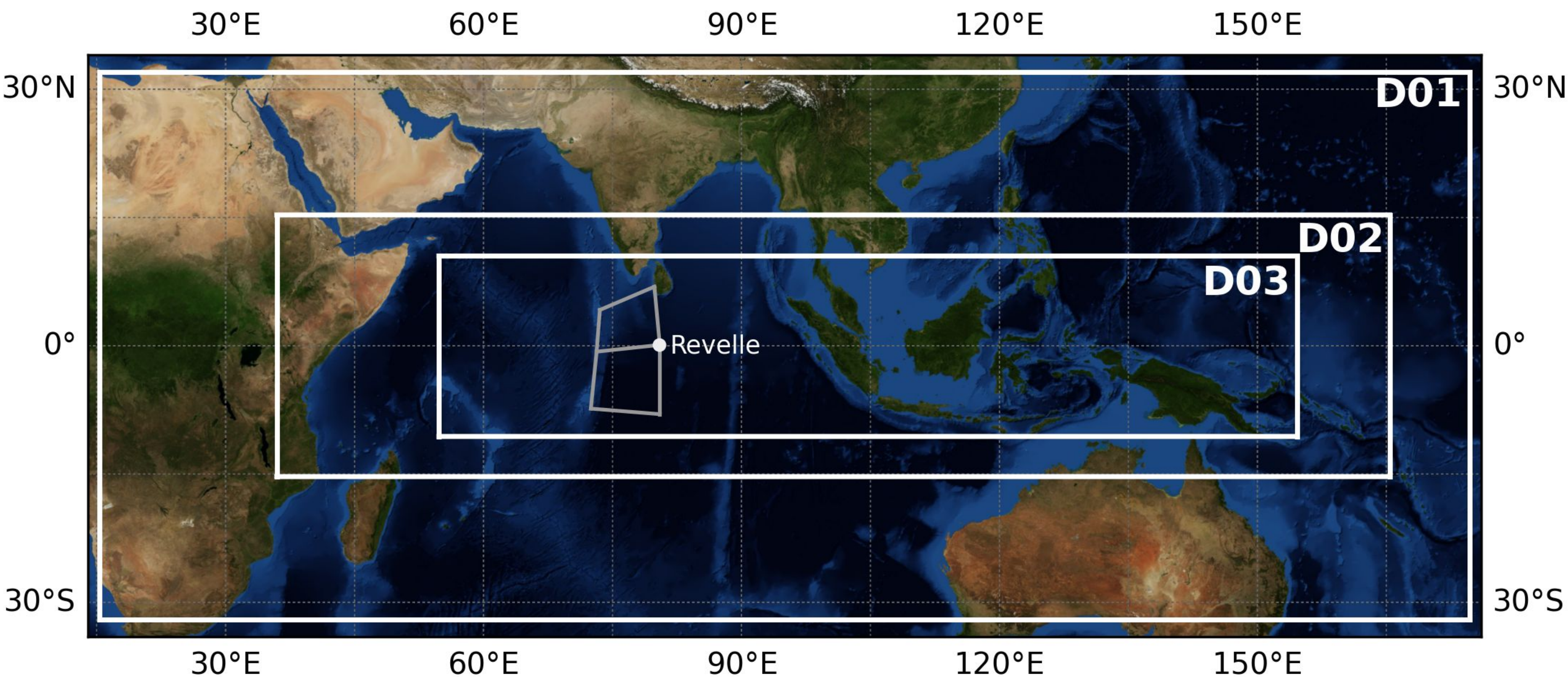
Coupled modeling application to MJO propagation

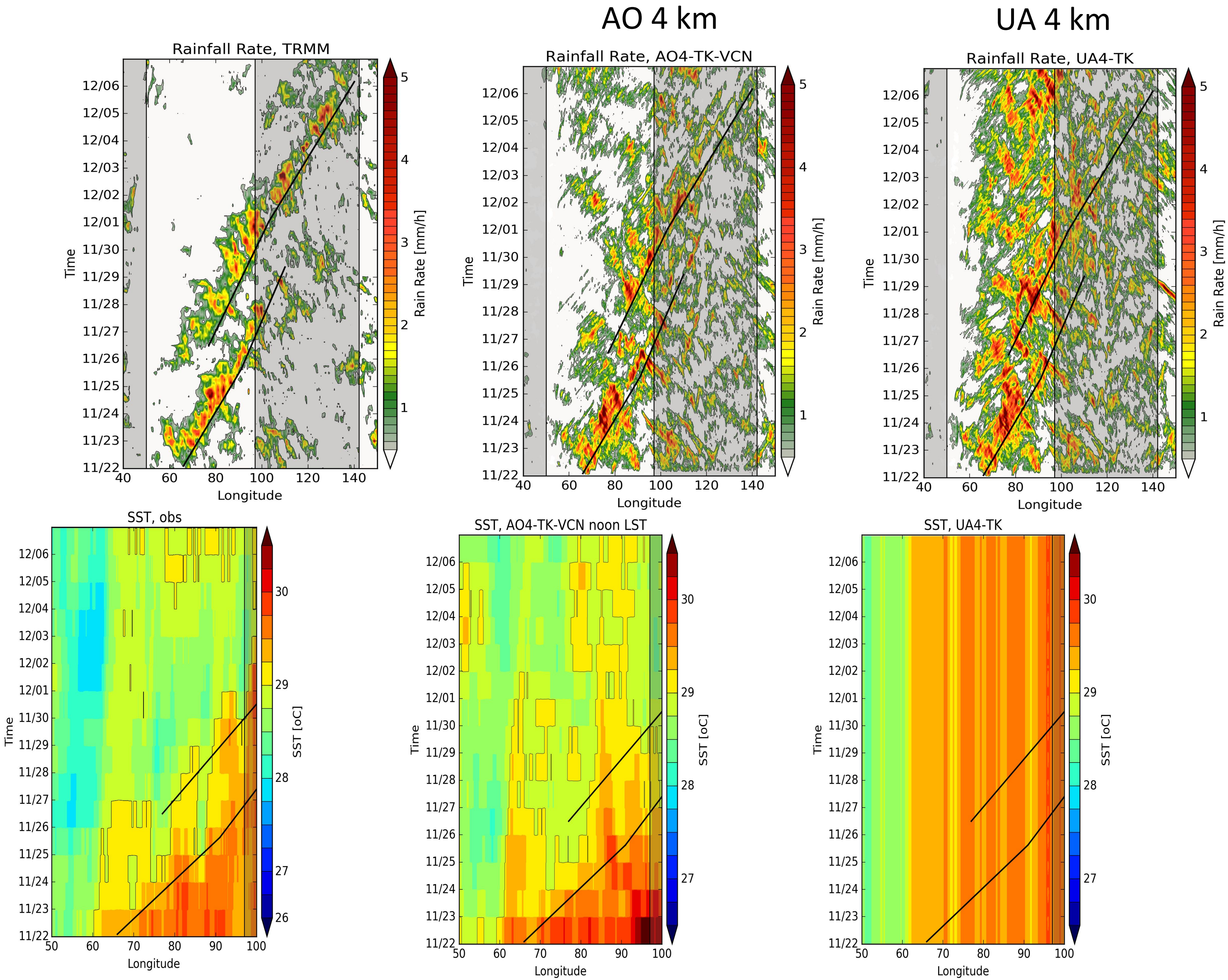
Ajda Savarin & Shuyi Chen

UWIN-CM Experiments:

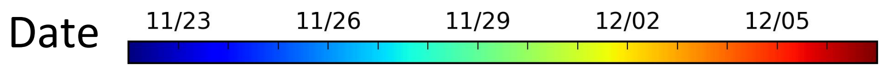
- WRF: 36/12/4/1.3 km nests, HYCOM: 1/12 degree
- UA: Uncoupled Atmosphere (WRF)
- AO: Coupled Atmosphere-Ocean (WRF-HYCOM)

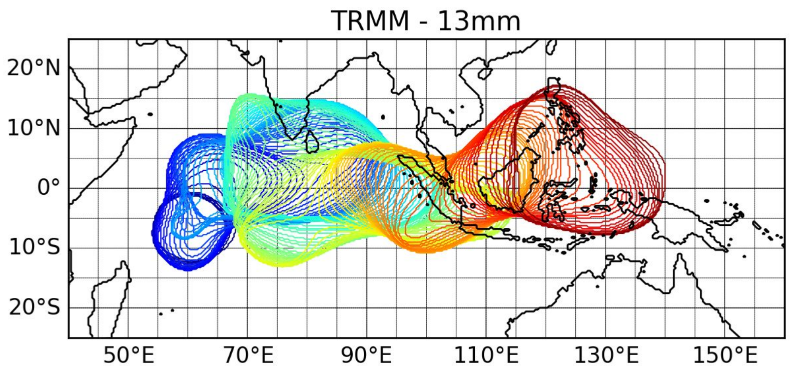
DYNAMO, 2011




AO 4 km
UA 4 km
Rainfall Rate, TRMM
Rainfall Rate, AO4-TK-VCN
Rainfall Rate, UA4-TK
Rain Rate [mm/h]
Time
Longitude
SST, obs
SST, AO4-TK-VCN noon LST
SST, UA4-TK
SST [oC]

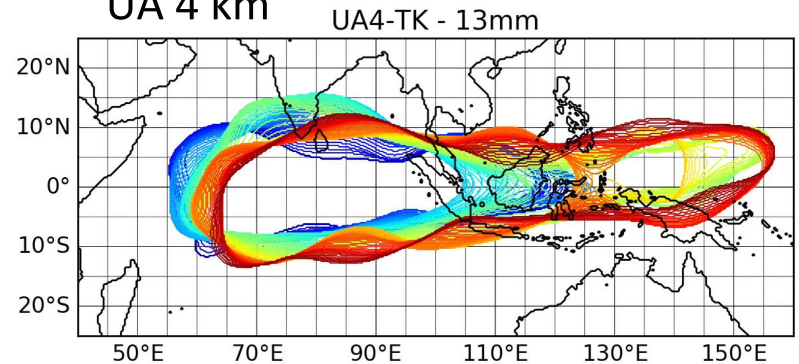
Large-scale Precipitation Tracking (LPT) of MJO Convection
Kerns and Chen (2016, JGR)





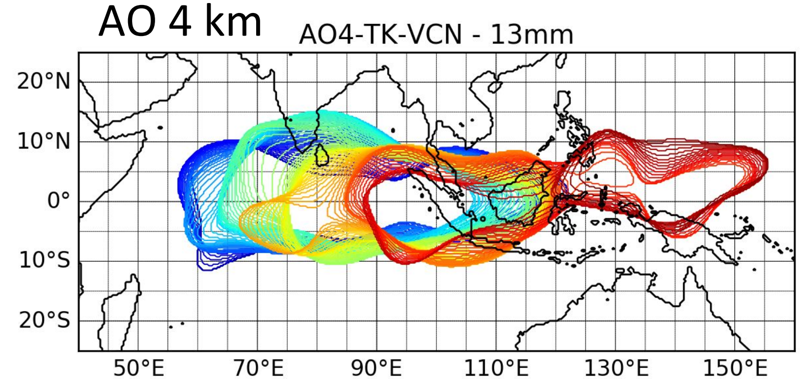
DYNAMO MJO-2

UA 4 km



Unrealistically warm ocean produces stationary MJO

AO 4 km



Ocean cooling helps eastward propagating MJO

Summary & Conclusions

- Fully-coupled atmosphere-wave-ocean model has been validated in several field campaigns
- Wave impacts on ocean surface transport in Hurricane Isaac:
  - Stokes drift had significant impact (> 20%) on surface transport during Hurricane Isaac as found from GLAD observations
  - Large-scale diffusivity based on GLAD during Isaac an order of magnitude larger than canonical Okubo (1971) observations and pre-storm GLAD observations
- Preliminary model-observation comparison from CPEX shows promising results on convective processes
- Upper ocean cooling played an important role in eastward propagation of MJO convection during DYNAMO