Wind-Wave Interaction Under Hurricane Conditions:

A Decade of Progress

Outline

- Introduction
- Waves Beneath Hurricanes
- Wind-Wave Interaction
- New Boundary Layer Observations
- New Parameterizations and Models
- TC Intensity Sensitivity to Fluxes
- Summary

James Doyle[1], Peter Black[2], Clark Amerault[1], Sue Chen[1], Shouping Wang[1]

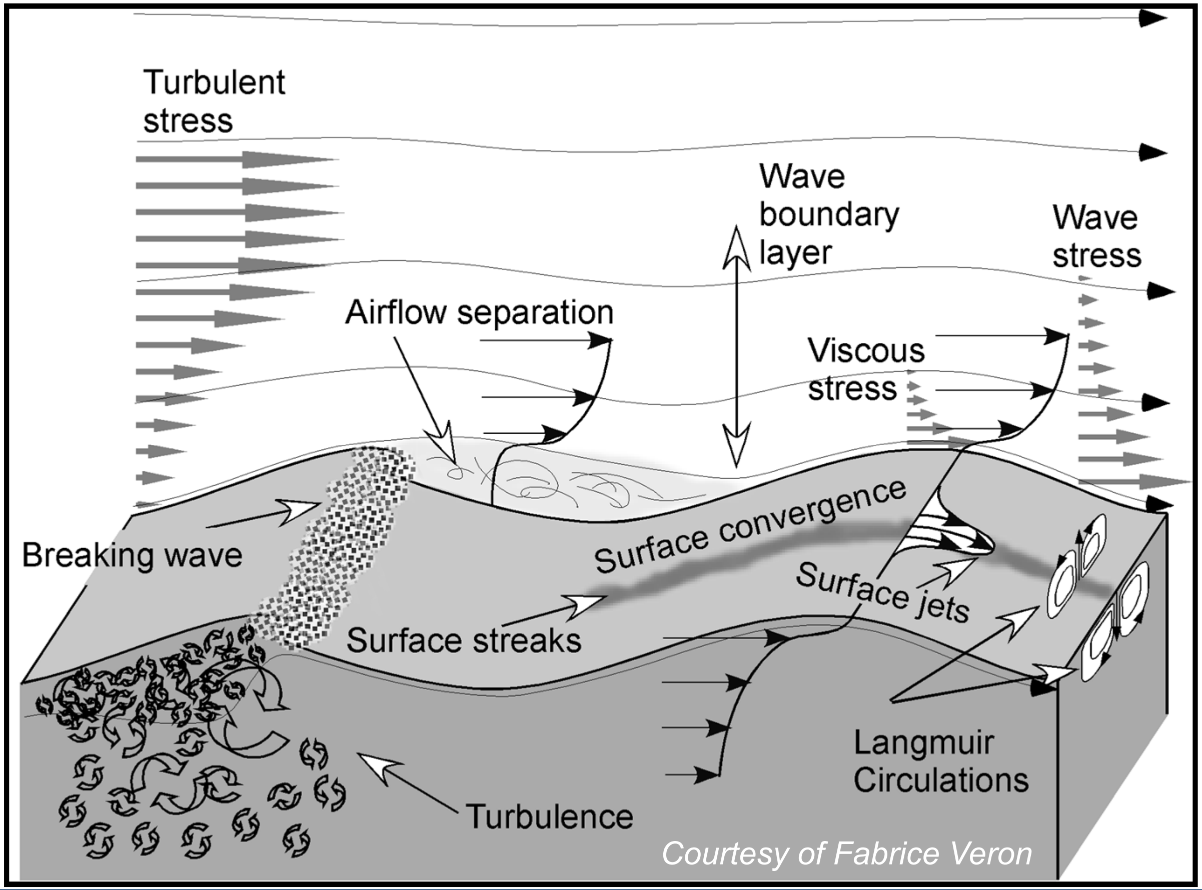
[1]Naval Research Laboratory, Monterey, CA
[2]SAIC, Monterey, CA

Acknowledgements: Shuyi Chen (U. Miami), Mark Donelan (U. Miami), Isaac Ginnis (U. Rhode Island), Qingfang Jiang (NRL)

Hurricane Isabel, 14 Sep 2003 (Courtesy of Peter Black)

Introduction

Air-Sea Interaction Processes

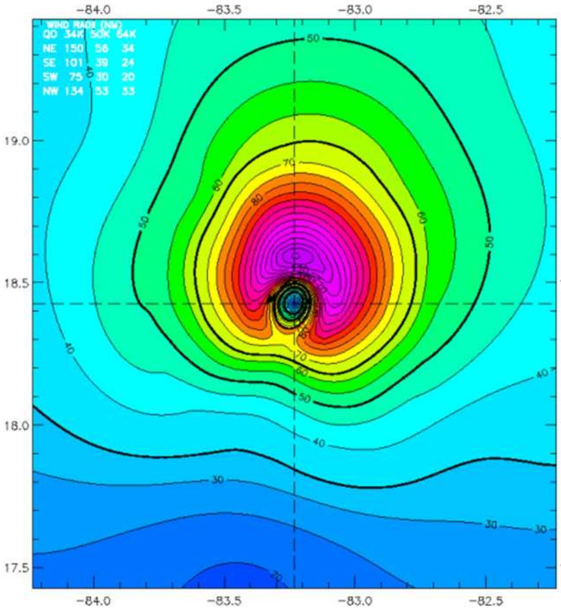


- **Air-sea (momentum, heat, moisture) fluxes and turbulent mixing above/below the air-sea interface in tropical cyclones are greatly modified by surface waves.**
- **New observations, theories, and models over the past decade have provided new insight into key air-sea interaction processes.**

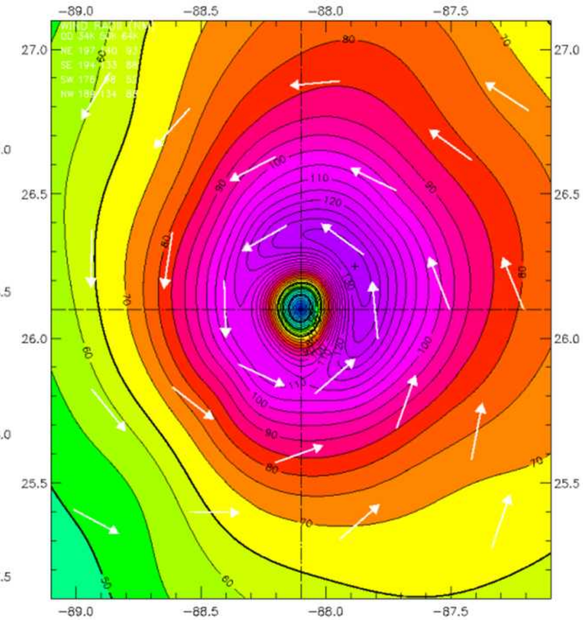
Introduction

Hurricane Size and Structure

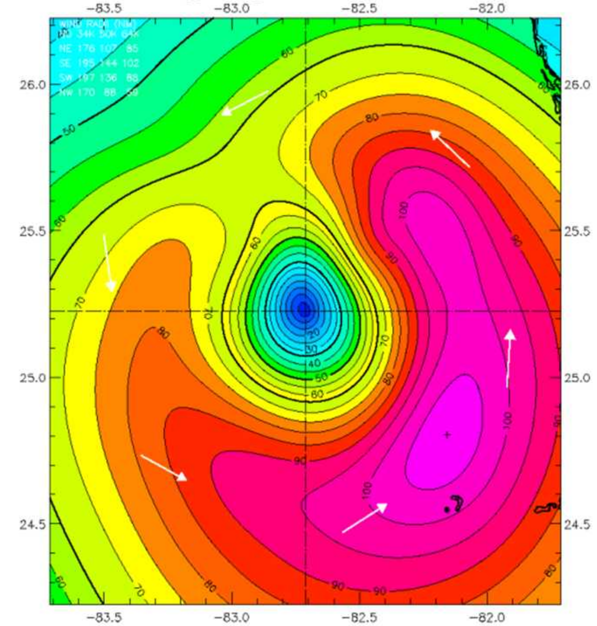
Hurricane Emily
1330 UTC 17 July 2005



Hurricane Katrina
1500 UTC 28 Aug 2005



Hurricane Wilma
0730 UTC 24 Oct 2005



Courtesy of NOAA/AOML Hurricane Research Division

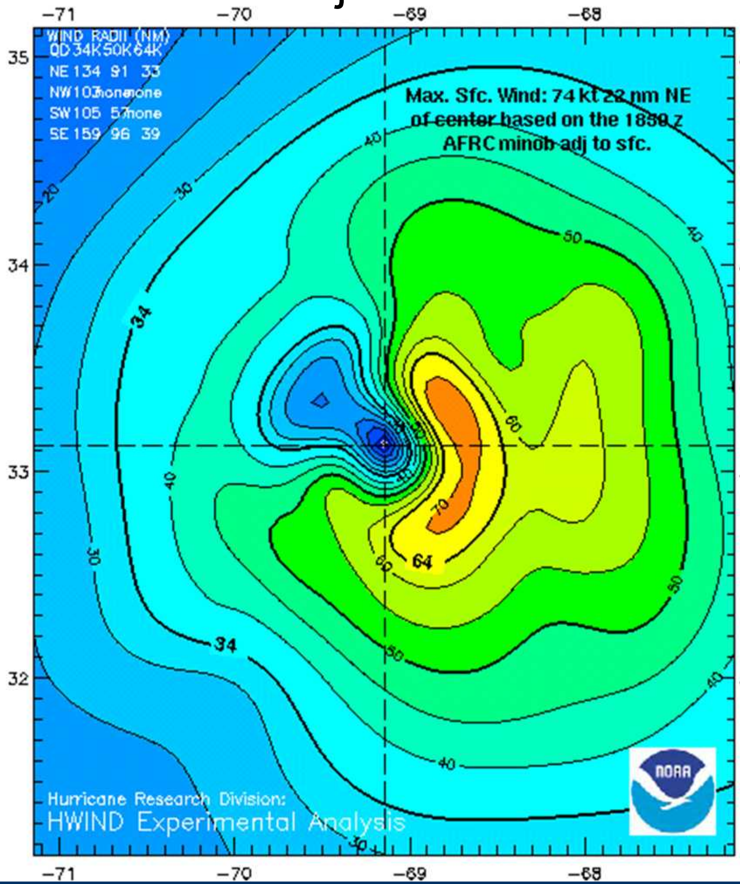
- **Tropical cyclone (TC) structure (e.g., distribution of winds) can vary substantially; small to large, symmetric to asymmetric.**
- **Structure has a fundamental impact on wave generation.**
- **Atmospheric models are very poor in predicting TC structure and intensity, particularly during intensification and structural changes.**

Introduction

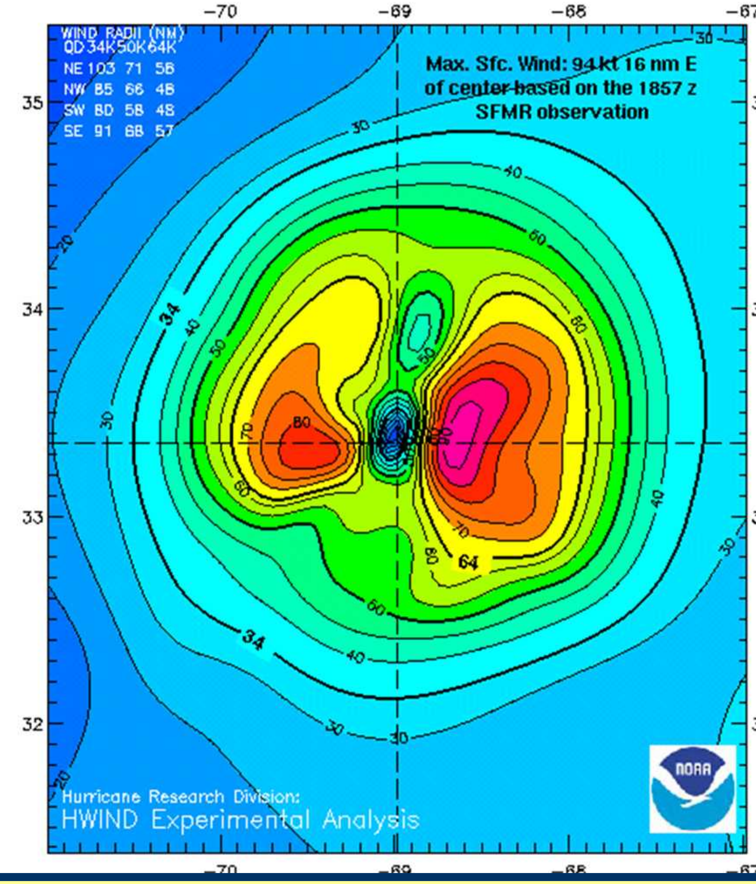
Hurricane Size and Structure

Hurricane Michael 1857 UTC 18 October 2000

700-mb Adjustment to Sfc



SFMR Observations



- **Stepped-frequency microwave radiometer (SFMR) has been a breakthrough to allow more accurate TC surface wind observations.**
- **SFMR observations now routinely document TC structure.**

Courtesy of NOAA/AOML Hurricane Research Division

Surface Waves Beneath TCs

Scanning Radar Altimeter in Ivan

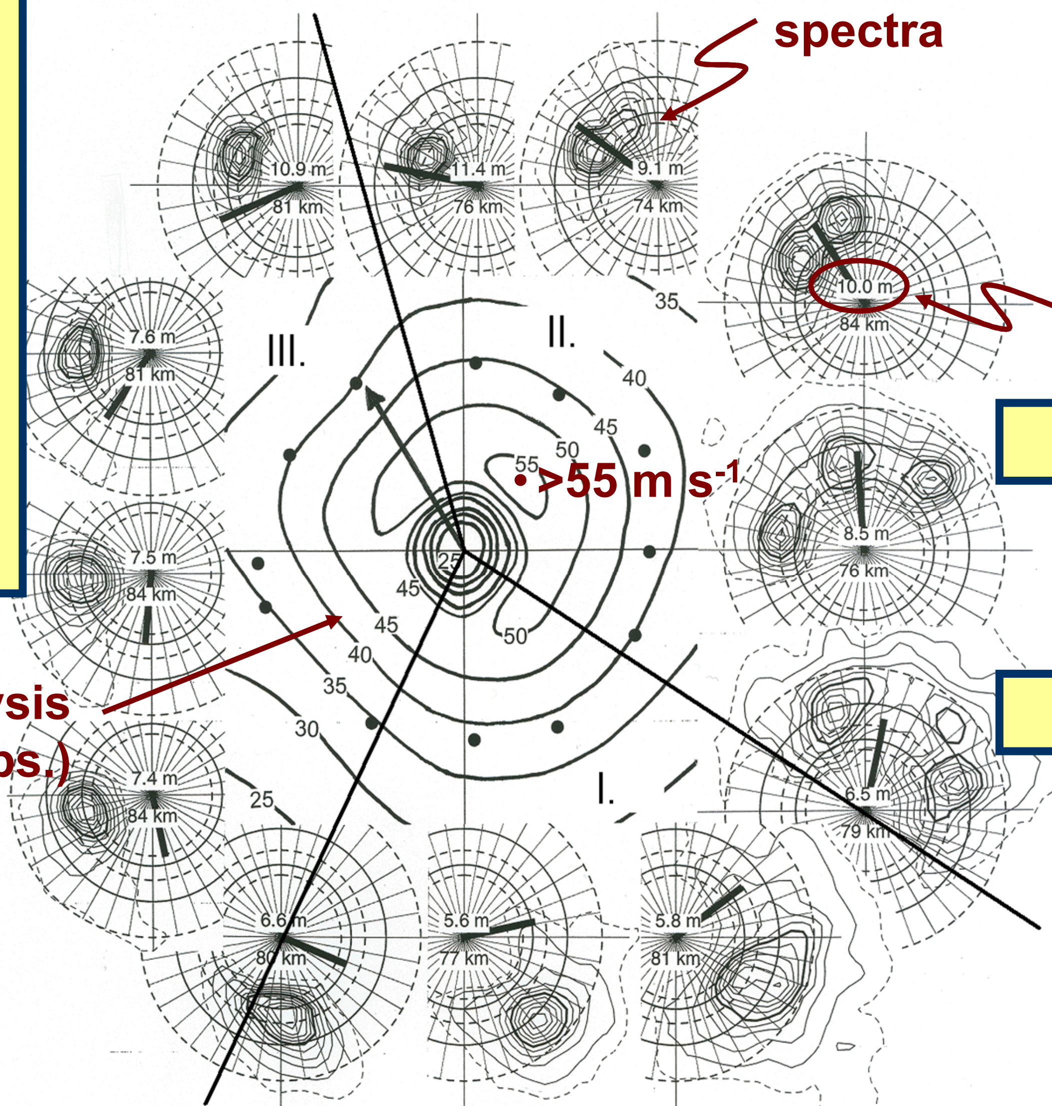
- Young, steep, and short waves in the right-rear quadrant
- Older, flatter, and longer waves in the right-front and left-front quadrants.
- To the left rear and left front of the eye, the wind and waves are at right angles to each other.

Directional wave spectra

Hs

Tri-modal

Bi-modal



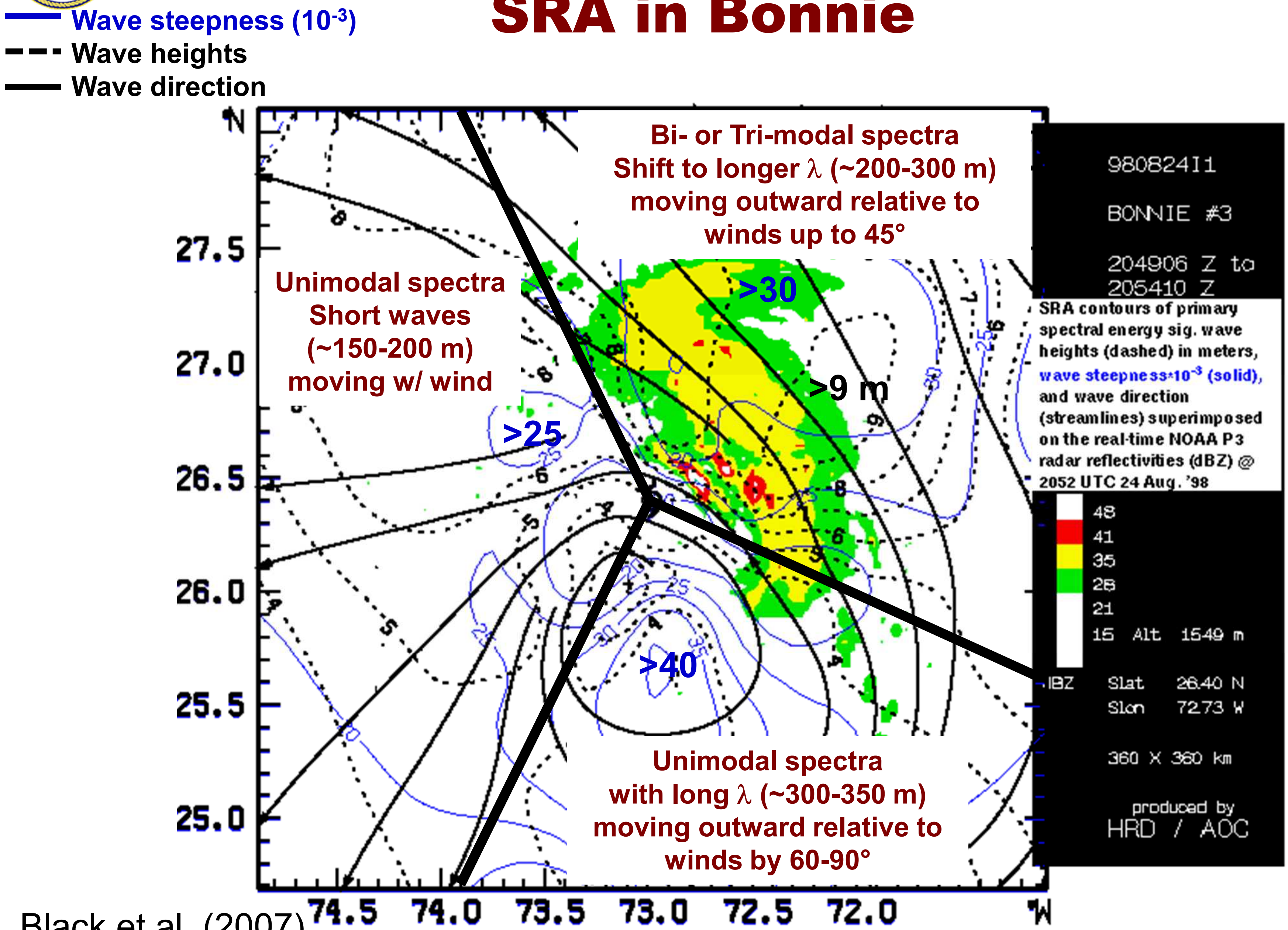
HWIND wind analysis (includes SFMR obs.)

Black et al. (2007)

Courtesy: Ed Walsh

Surface Waves Beneath TCs

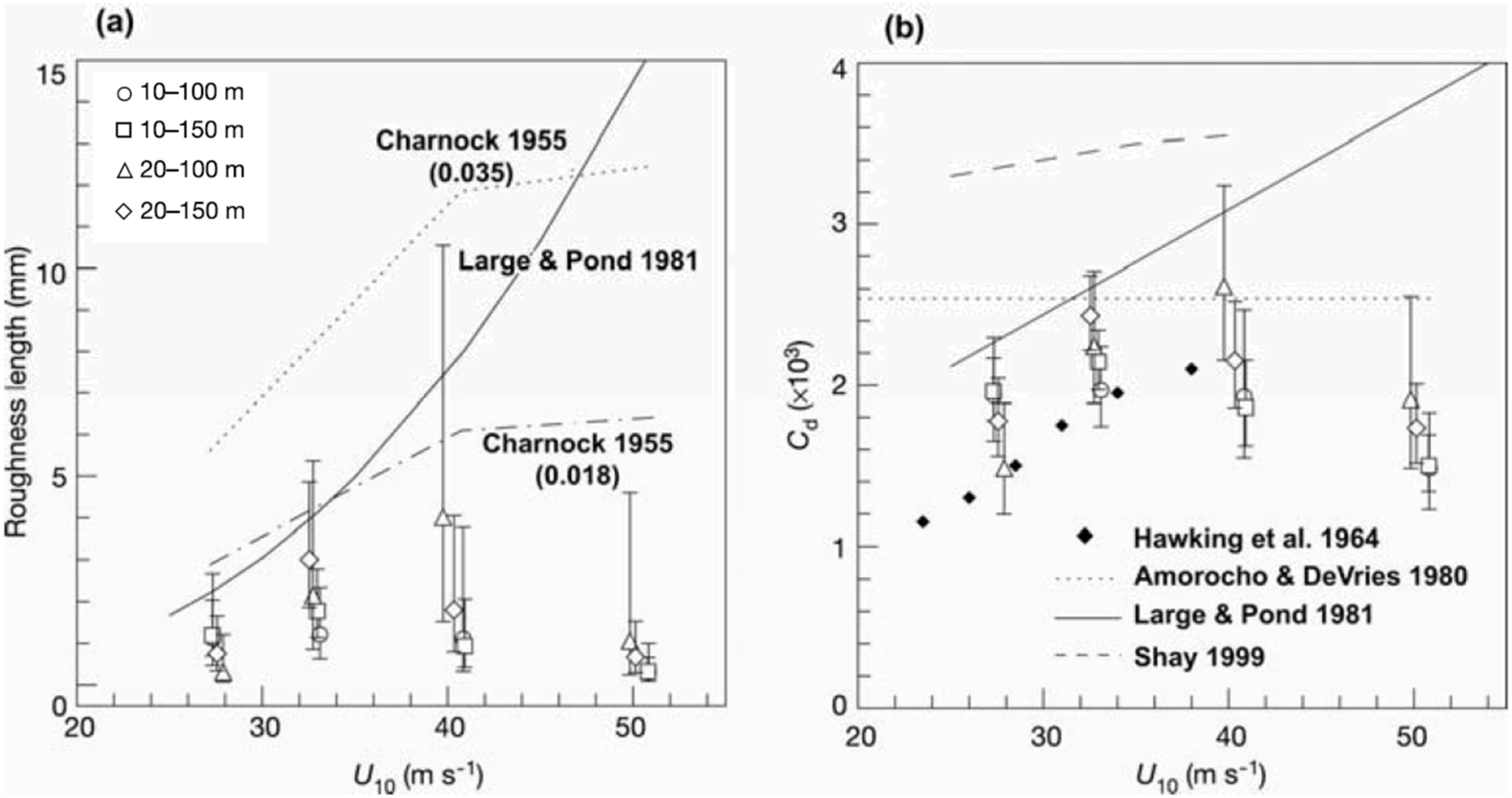
SRA in Bonnie



Black et al. (2007)

Wind-Wave Interaction

Momentum Flux and Drag



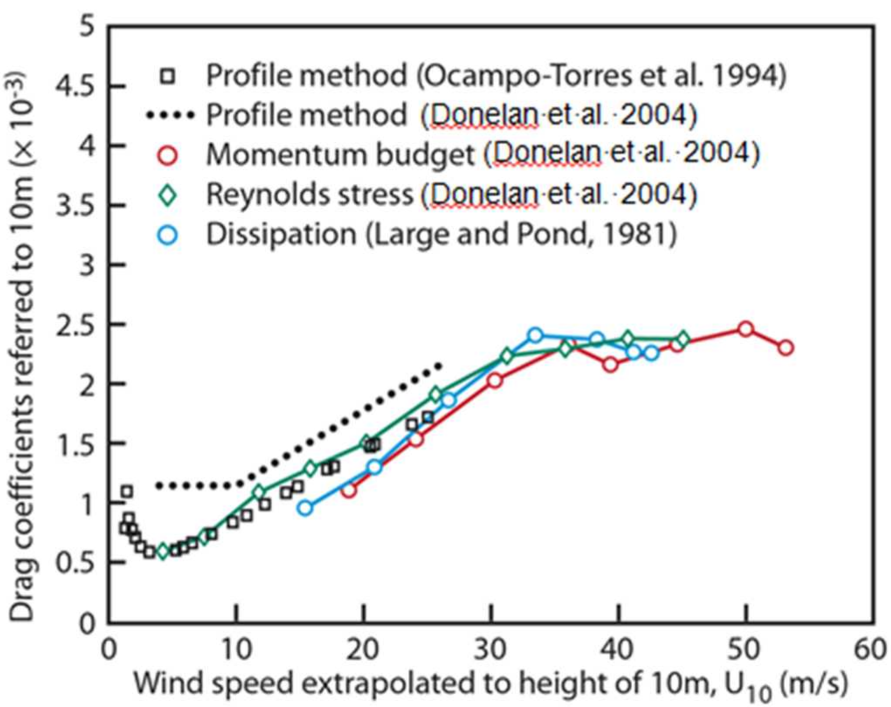
Adapted from Powell et al. (2003)
Modified from Letchford and Zachry (2009)

Powell et al. (2003) breakthrough study on the reduced drag coefficient for high winds in tropical cyclones based on an analysis of over 300 GPS dropsondes in 15 storms (of various intensities).

Wind-Wave Interaction

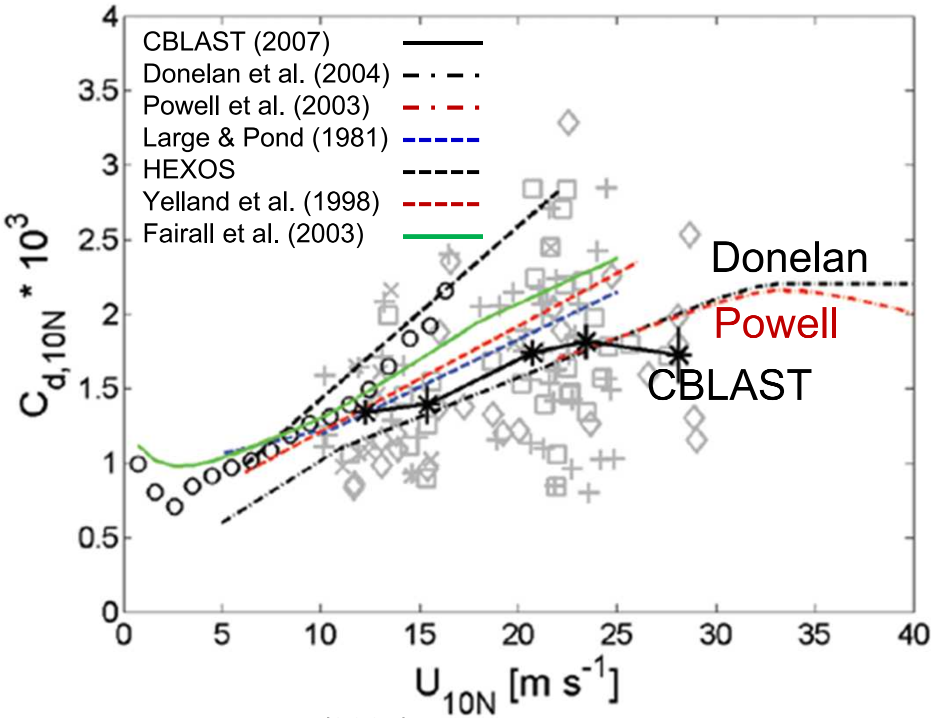
Momentum Flux and Drag

Laboratory Measurements



Donelan et al. (2004)

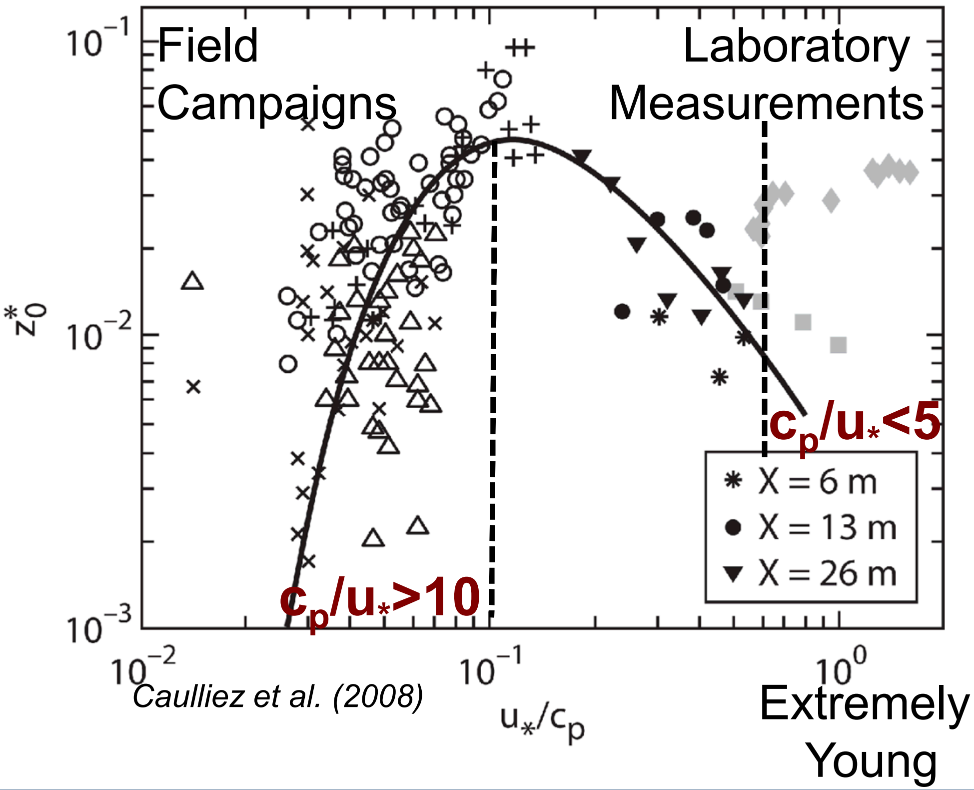
CBLAST Observations



Black et al. (2007)

Follow-on studies using laboratory measurements (Donelan et al. 2004) and CBLAST observations (7 TCs) (Black et al. 2007) extend the Powell et al. C_D estimates and provide further observational evidence of reduced C_D at high wind speeds.

Wind-Wave Interaction
Momentum Flux and Drag

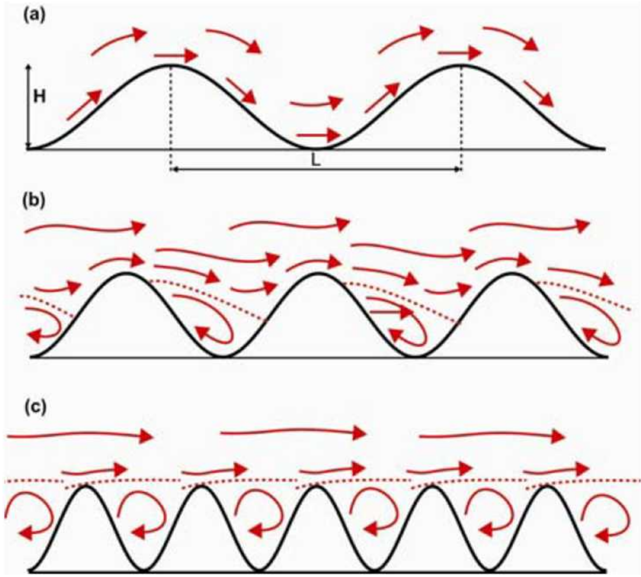


- Hurricanes are characterized by an extremely young wind sea ($c_p/u_* < 5$)
- Steep waves are generated, roughness increases; wave breaking and nonlinear interactions occur that limit the roughness (Janssen 2009).
- Measurements and analysis by Caulliez et al. (2008) confirm this.

Wind-Wave Interaction

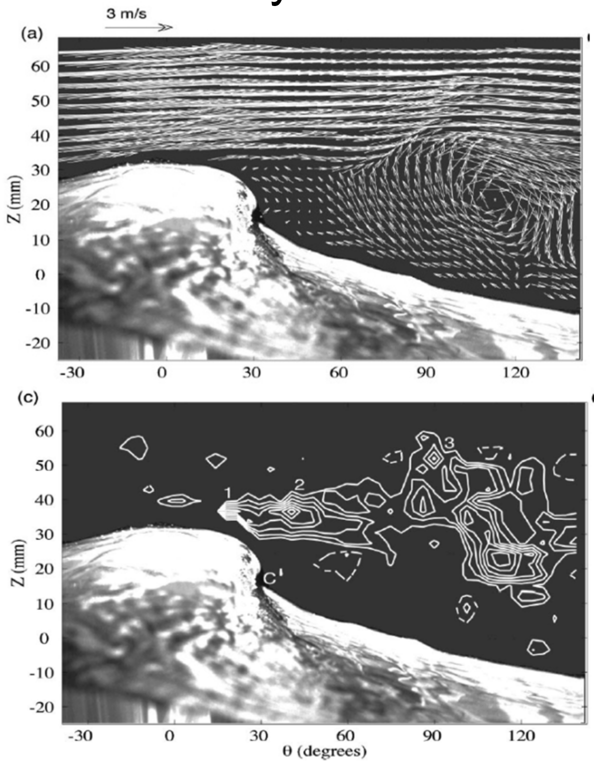
Momentum Flux and Drag

Flow Over Hills Schematic



Letchford and Zachry (2009)

Laboratory Measurements



N. Reul, H. Branger, and J.-P. Giovanangeli (1999)

Spray Effects on Drag

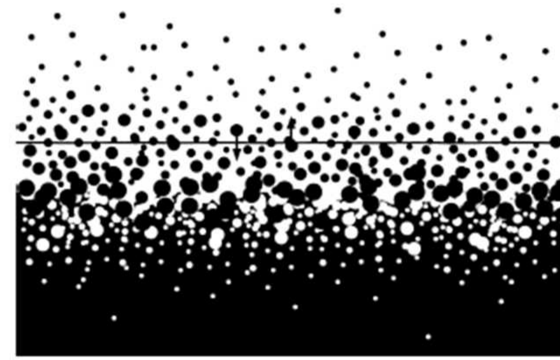


FIG. 2. Momentum and enthalpy transfer through an emulsion. Spray droplets are ejected upward and accelerate toward the free stream velocity, absorbing momentum from the atmosphere.

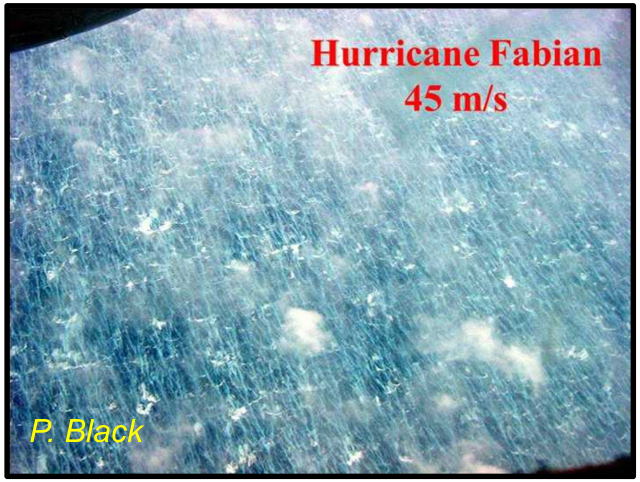
Emanuel (2003)

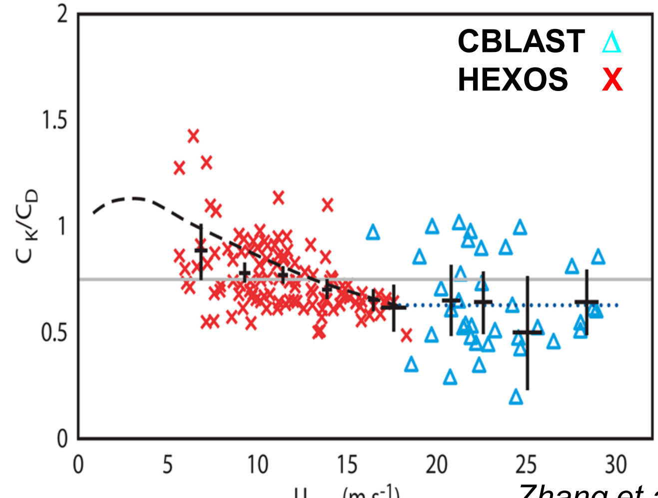
Possible theories for reduction in C_D at high wind speeds include:

- **Separated and nonseparated sheltering** (Powell; Black;Savelyev et al. 2010)
- **Extremely young waves ($c_p/u_* < 5$)** (Caulliez et al. 2008; Janssen 2009)
- **Spray lubricating effect** (Emanuel 2003; Rastigejev & Lin 2010)

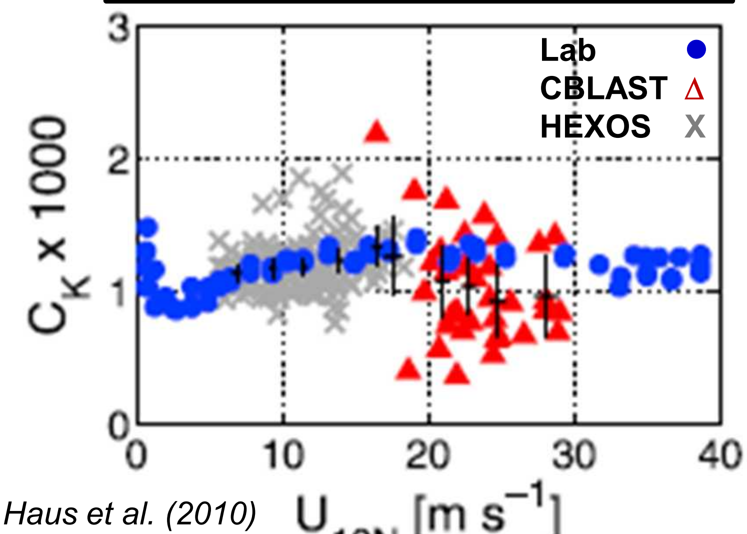
Wind-Wave Interaction

Enthalpy Flux

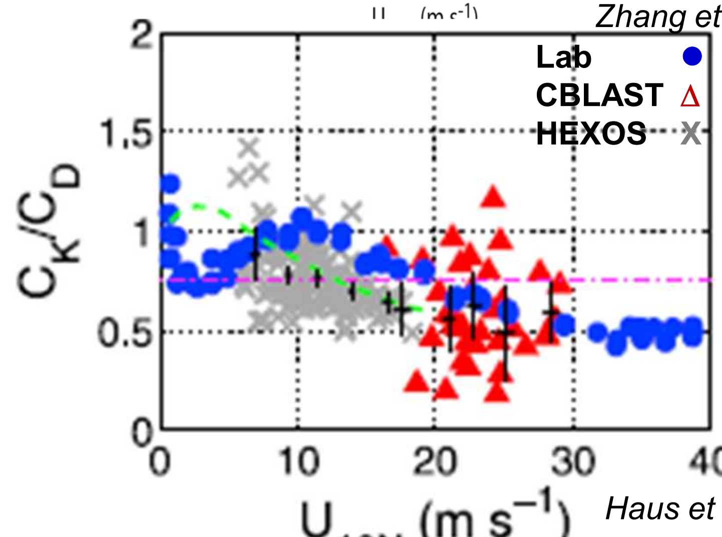




Zhang et al. (2008)



Haus et al. (2010)

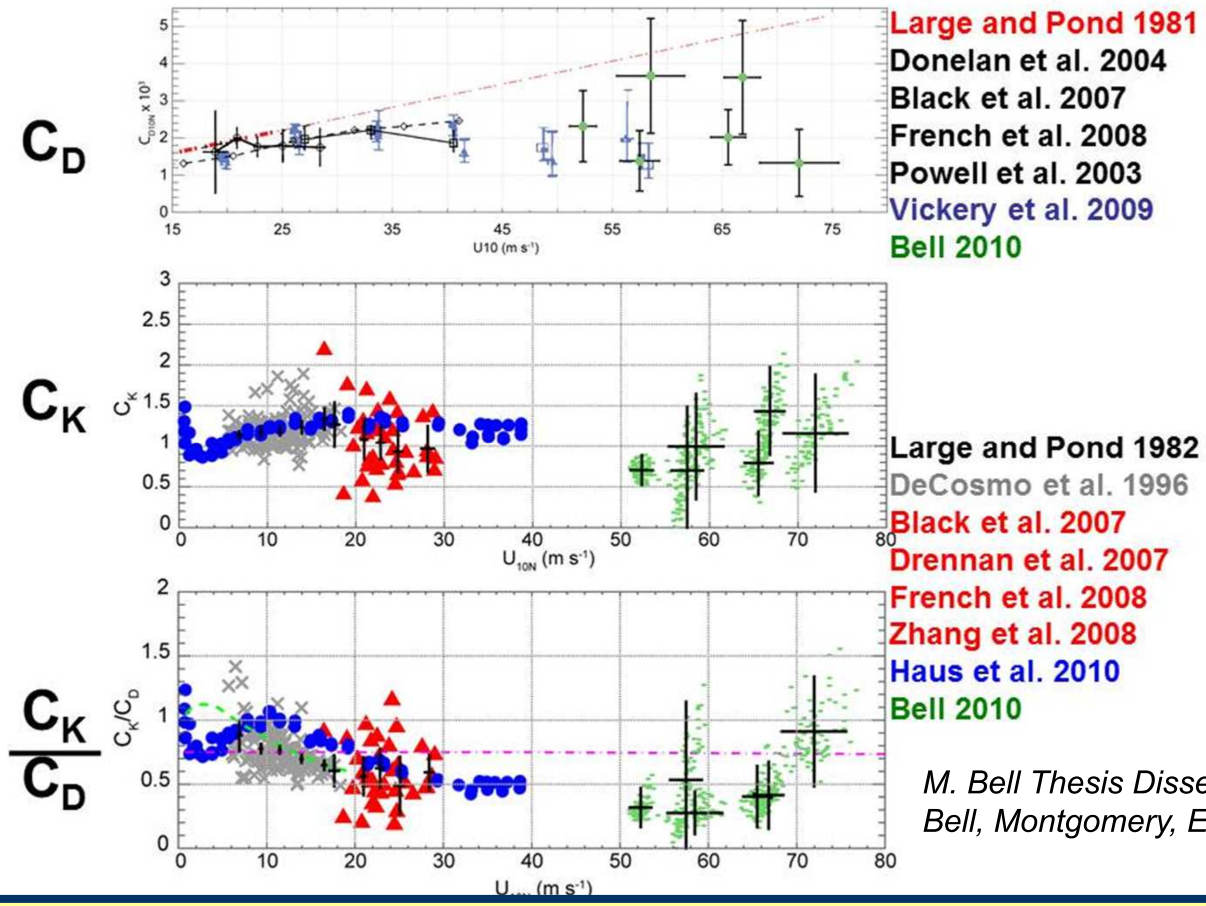


Haus et al. (2010)

- **Breaking and spray is commonly observed in winds > ~30 m s^{-1}**
- **No evidence of an increase of C_K with wind speed.**
- **C_K/C_d average is 0.63, below 0.75 threshold for TCs (Emanuel 1995).**

Wind-Wave Interaction

Momentum and Enthalpy at High Wind

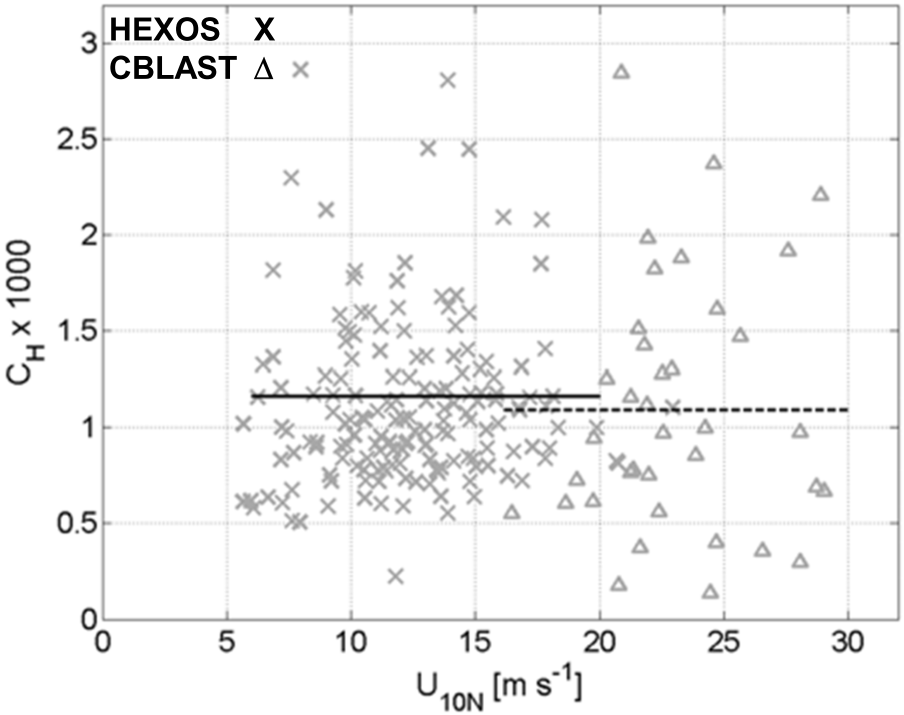


M. Bell Thesis Dissertation (2010)
Bell, Montgomery, Emanuel (2012)

Bell et al. (2012) deduced momentum and enthalpy fluxes from absolute angular momentum and total energy budgets for Fabian and Isabel (U>50 m s^{-1}) during CBLAST. Ratio C_K/C_D *does not* significantly increase for U>50 m s^{-1}.

Wind-Wave Interaction

Sensible Heat Flux



Zhang et al. (2008)

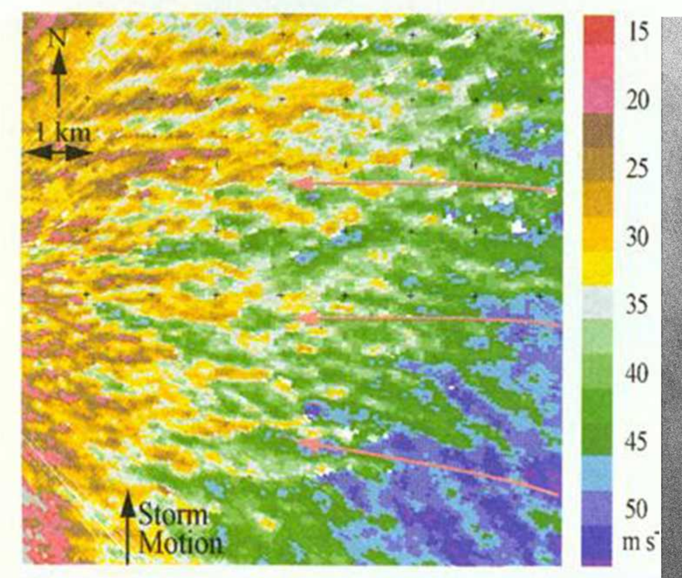
- **Mean value of the Stanton number (1.09 ± 0.11) agrees w/ HEXOS**
- **No dependence of the Stanton number on the surface wind speed.**

New Boundary Layer Observations

Hurricane Boundary Layer Rolls

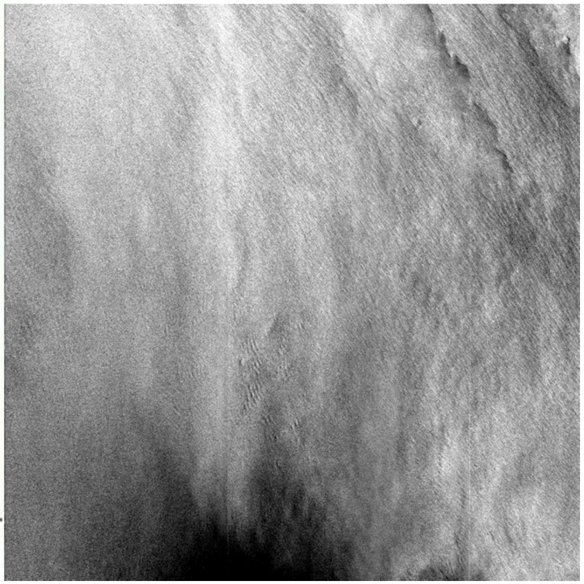
Doppler On Wheels (DOW) | RADARSAT-1 Synthetic Aperture Radar imagery

Hurricane Fran

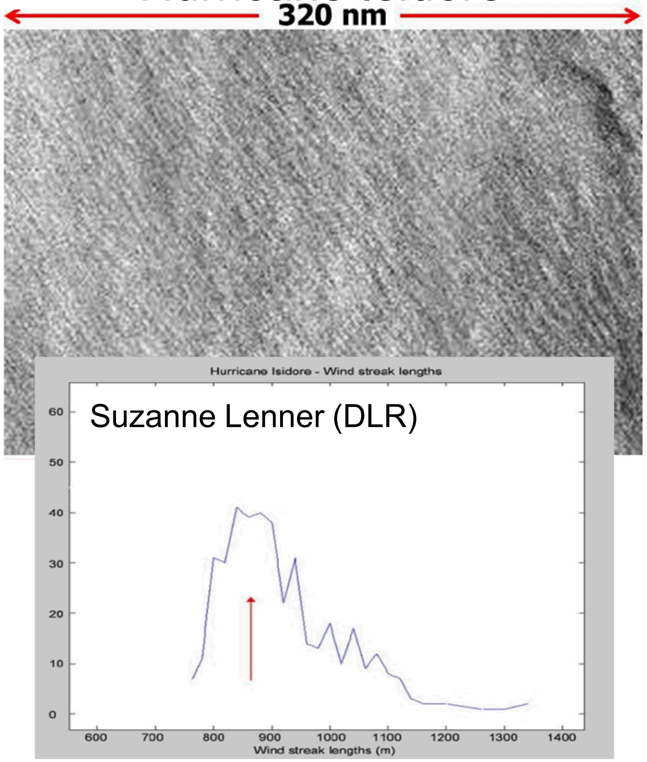


Wurman and Winslow (1998) Science

Hurricane Floyd



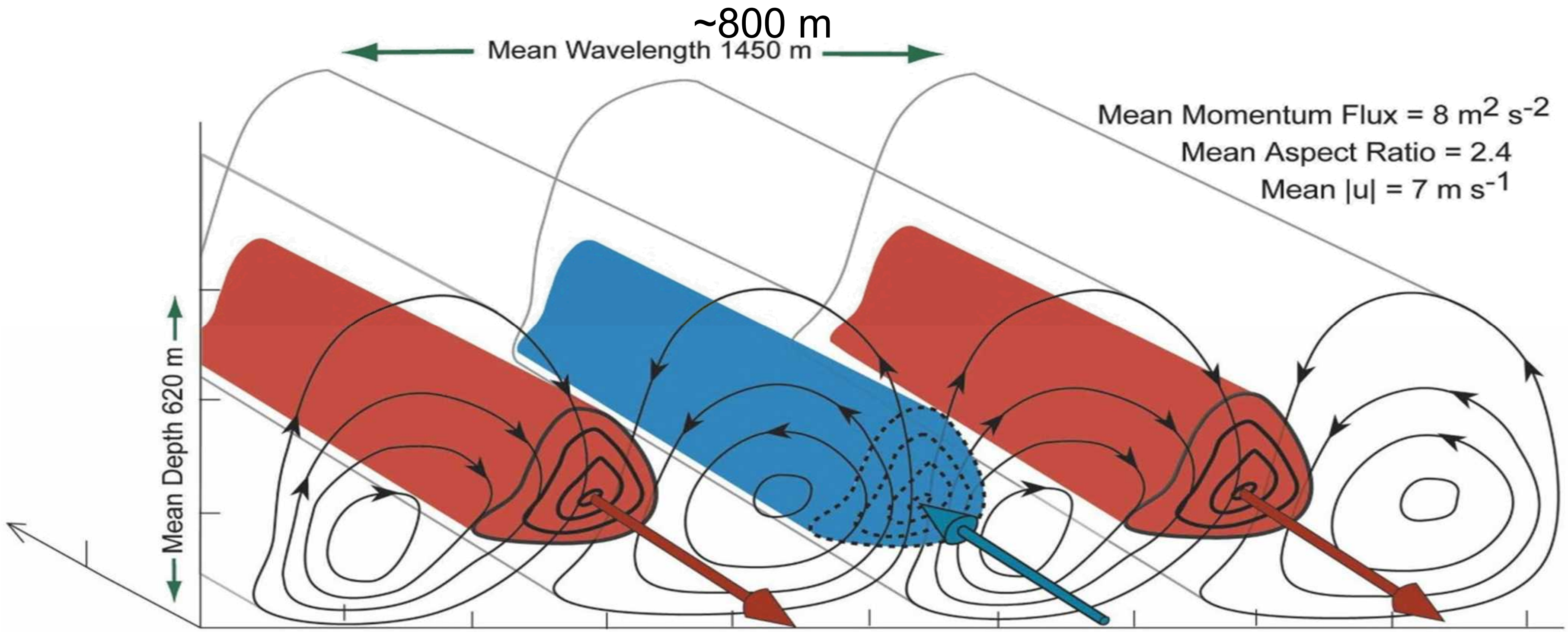
Hurricane Isidore



- **DOW indicates ~30 m/s mean +/- 15 m/s across-roll variation in low-level wind for Hurricane Fran**
- **SAR wind streaks for hurricane Floyd and Isidore have a wavelength of ~900 m, and an aspect ratio of about a 2:1 (x-z)**

New Boundary Layer Observations

Hurricane Boundary Layer Rolls



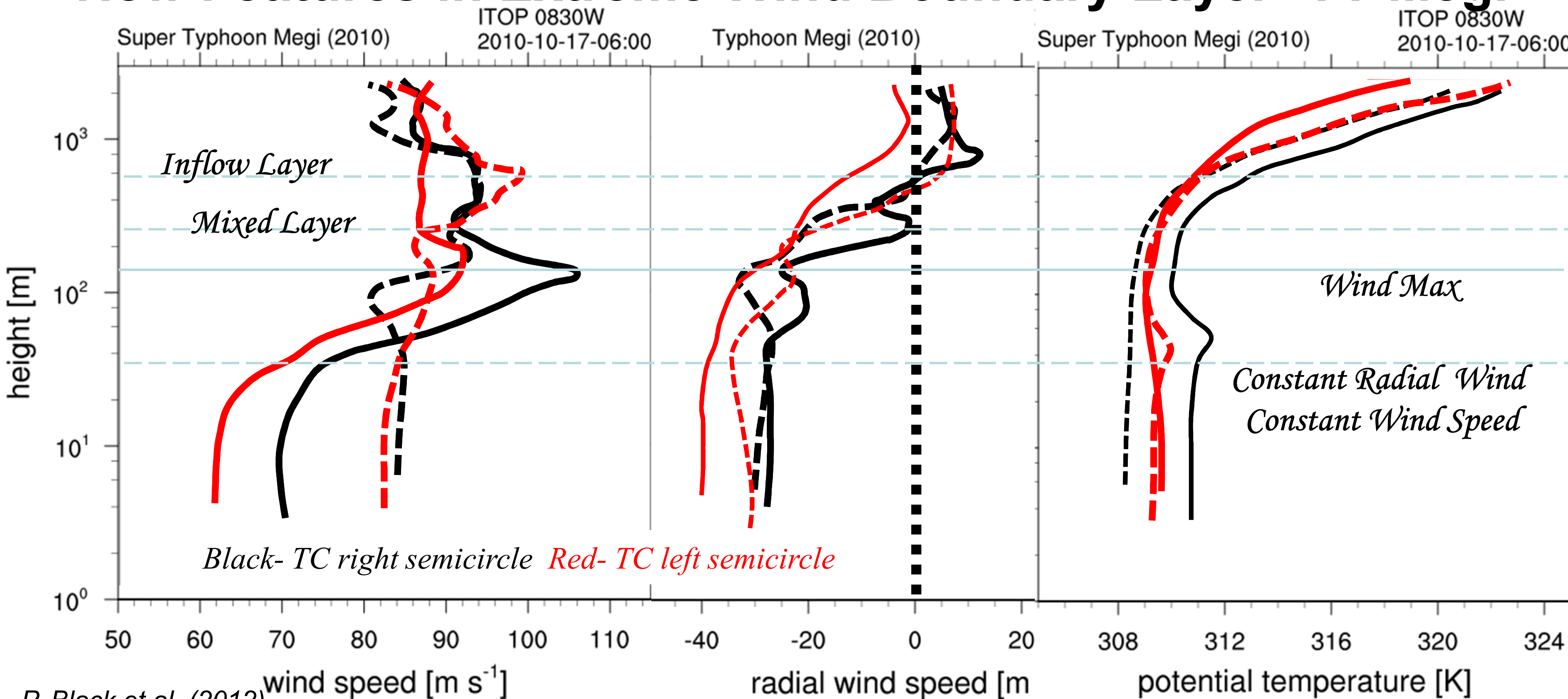
Morrison et al. (2005) JAS

- **Schematic for hurricane boundary layer rolls (four hurricanes).**
- **Streamline arrows indicate transverse flow, with high (low) momentum air being transported downward (upward). Shaded arrows and bold contours indicate the positive (red) and negative (blue) residual velocities [R. Foster 2004; Brown (1974), WW98].**
- **Important implications for BL parameterizations and wave generation.**

New Boundary Layer Observations

Results from ITOP

New Features in Extreme Wind Boundary Layer- TY Megi



P. Black et al. (2012)

- Simultaneous sonde pairs reveal strong/weak shear couplets - mesoscale influence
- Constant wind layer (30 m) violates 'log' law: air/water (spray) slurry acts as no-slip layer
- Wind max (210 m) below top of mixed layer (250 m) in contrast to reverse at larger radii
- Shallow inflow layer (600 m)
- Implications for boundary layer parameterizations, winds, and wave generation.

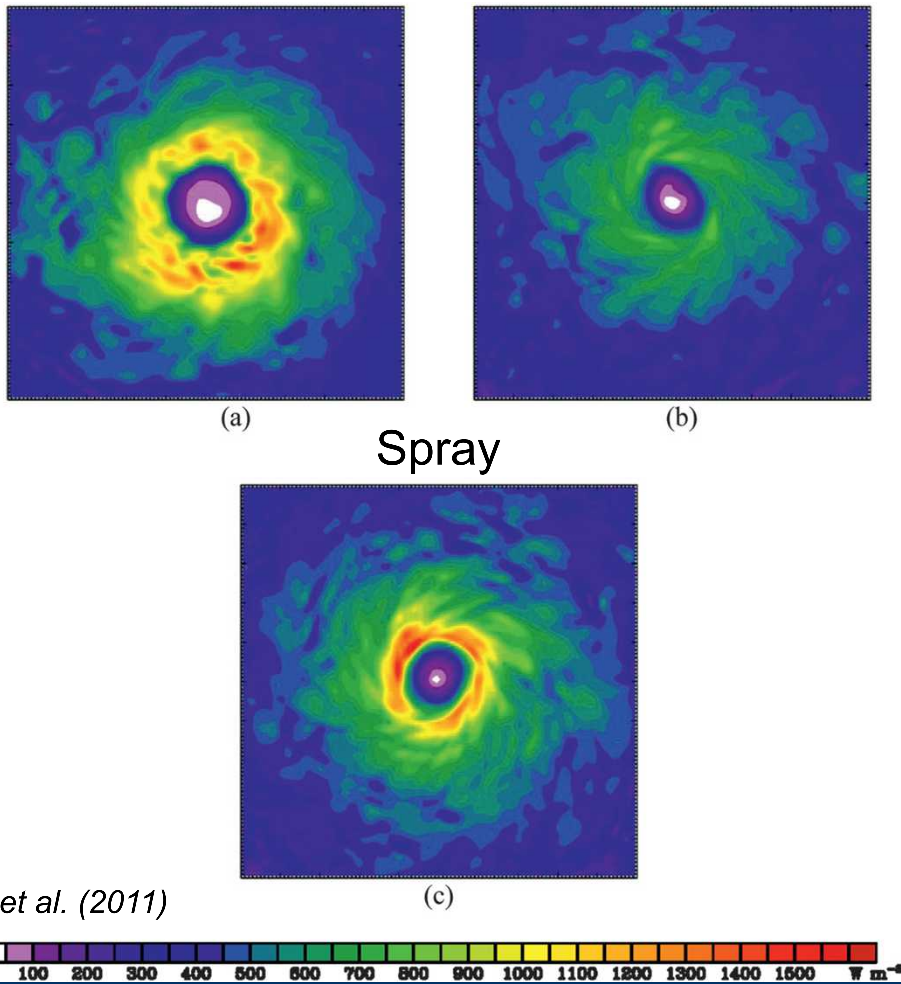
Numerical Modeling Issues

Spray Parameterizations

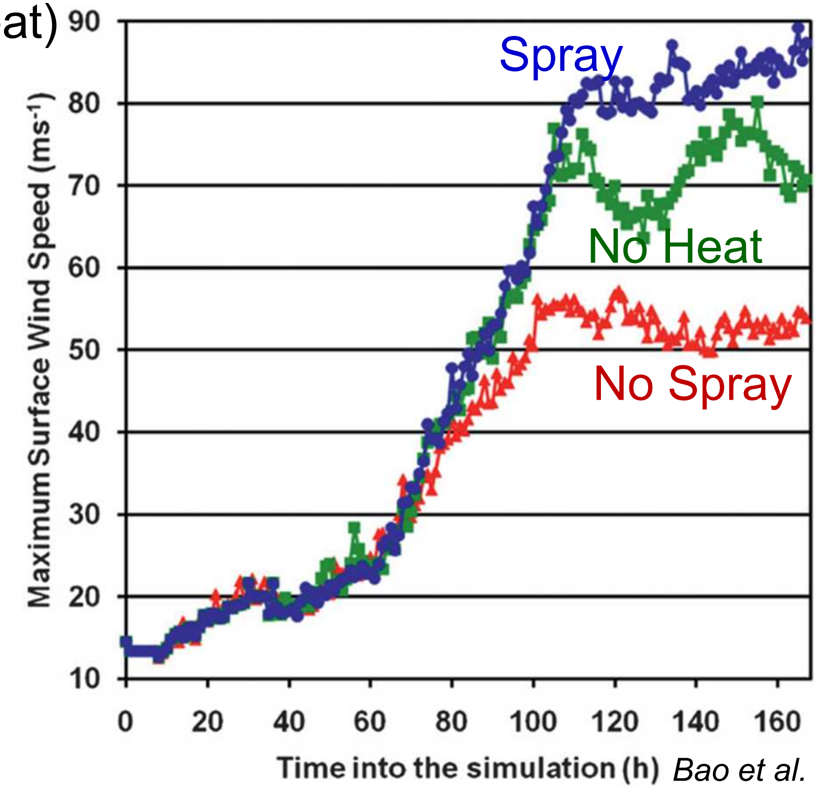
Latent Heat Flux

No Spray   Spray (no impact on heat)

Spray



Bao et al. (2011)



Bao et al. (2011)

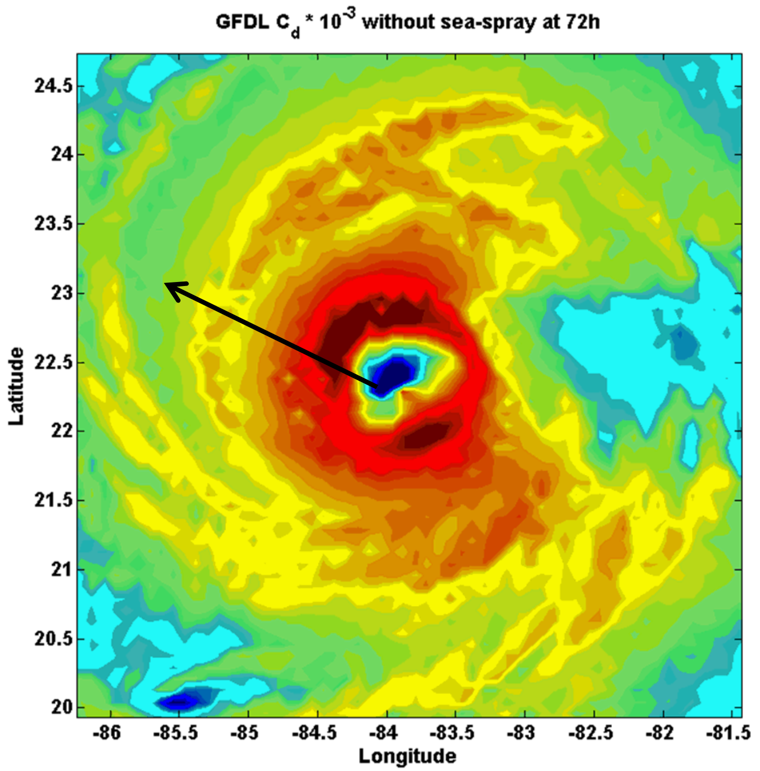
Bao et al. (2011) demonstrates large impact of spray on fluxes

Several new parameterizations for sea spray have been developed including Fairall et al. (2009), Andreas (2010), Bianco et al. (2010).

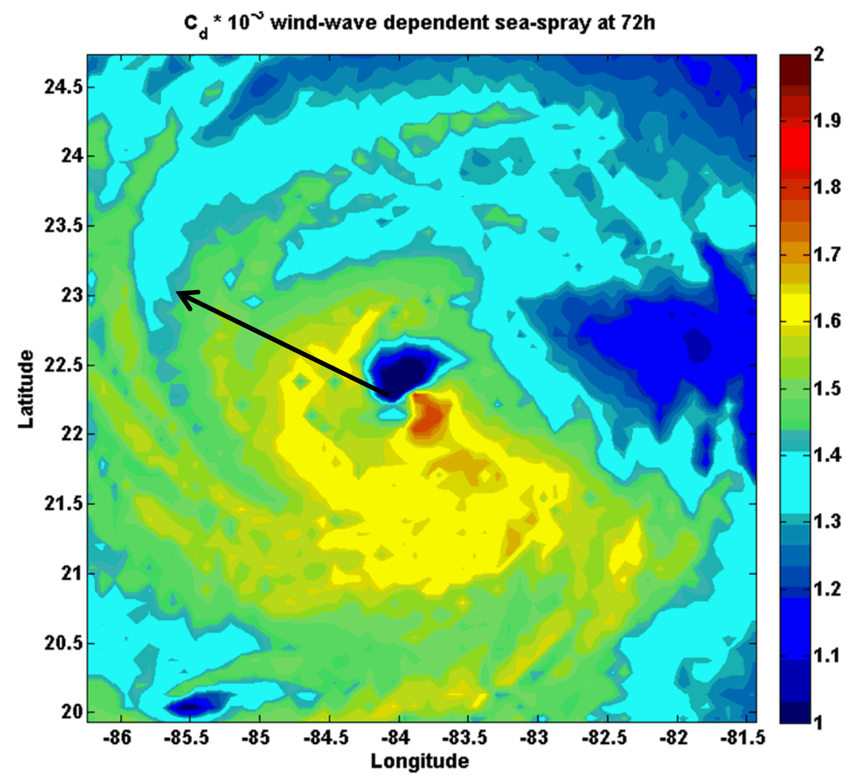
Numerical Modeling Issues

Spray Effect on Drag using NOAA/ESRL Model

Without sea spray



With sea spray

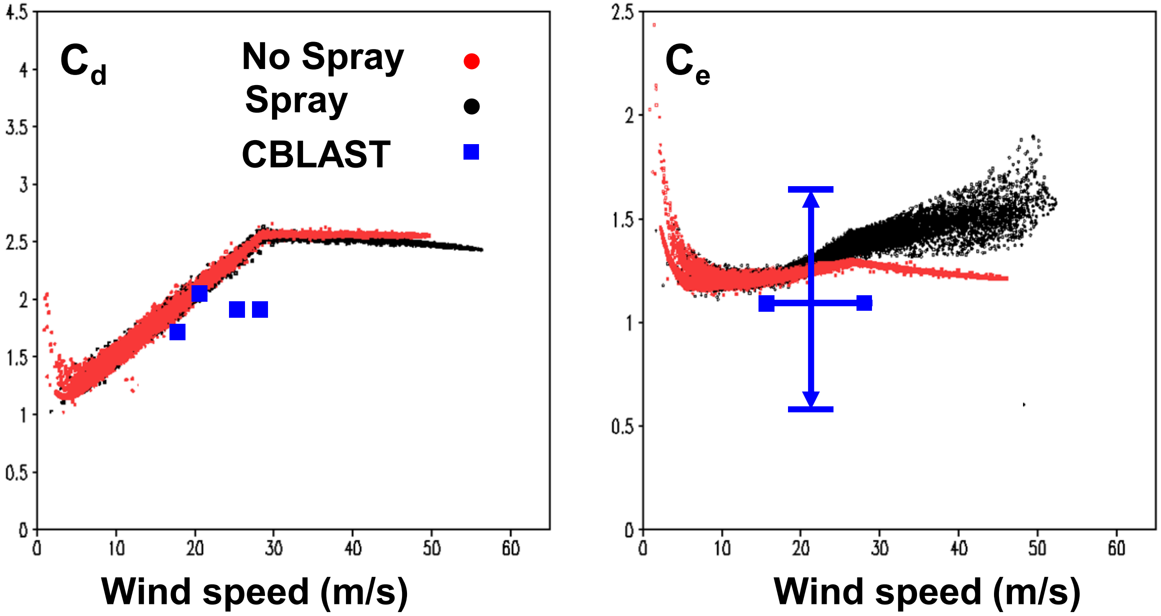


- **Sea spray sensitivity tests carried out using NOAA/ESRL model (Bao).**
- **Latest sea spray representation (Fairall et al.) has a large impact on C_d**

Courtesy of Isaac Ginnis

Numerical Modeling Issues
Spray Parameterizations

Transfer Coefficients in COAMPS-TC

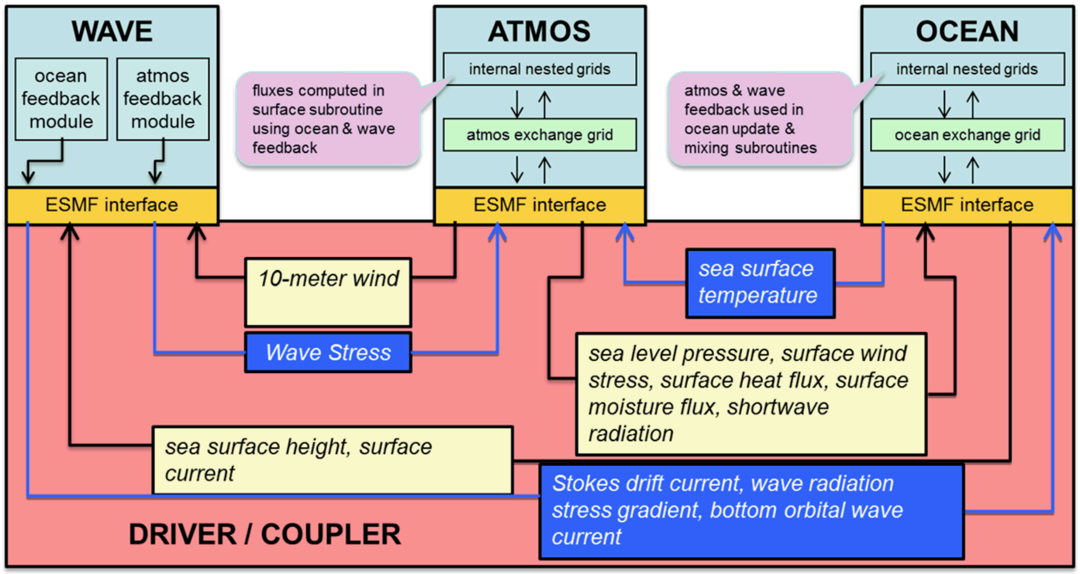


Wang et al. (2012)

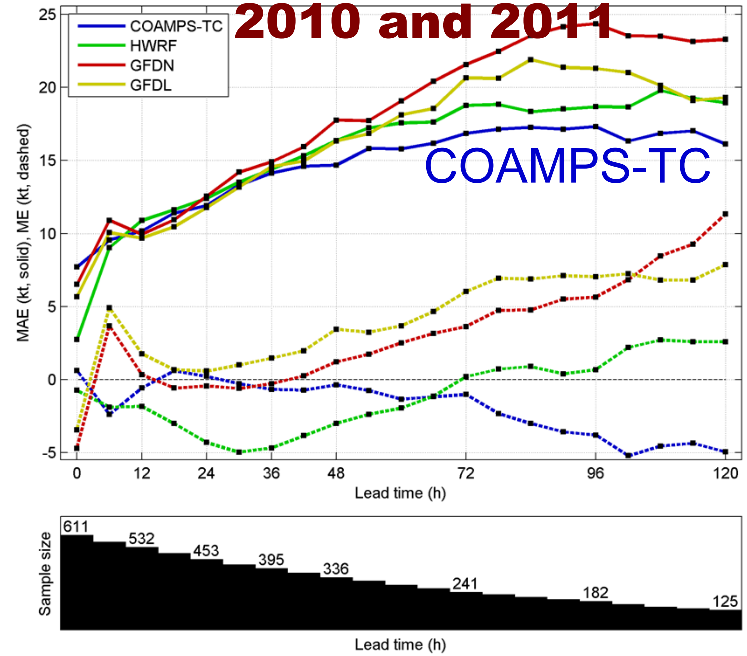
- Sea spray (Fairall and Bao, 2009) included in US Navy's COAMPS-TC
- C_D slightly decreases when the sea spray effect is enhanced.
- C_E increases for wind speed greater than 30 m/s.

Numerical Modeling Issues

Air-Sea Interface Physics in COAMPS-TC
Earth System Modeling Framework (ESMF)



W. Atlantic Intensity Error 2010 and 2011

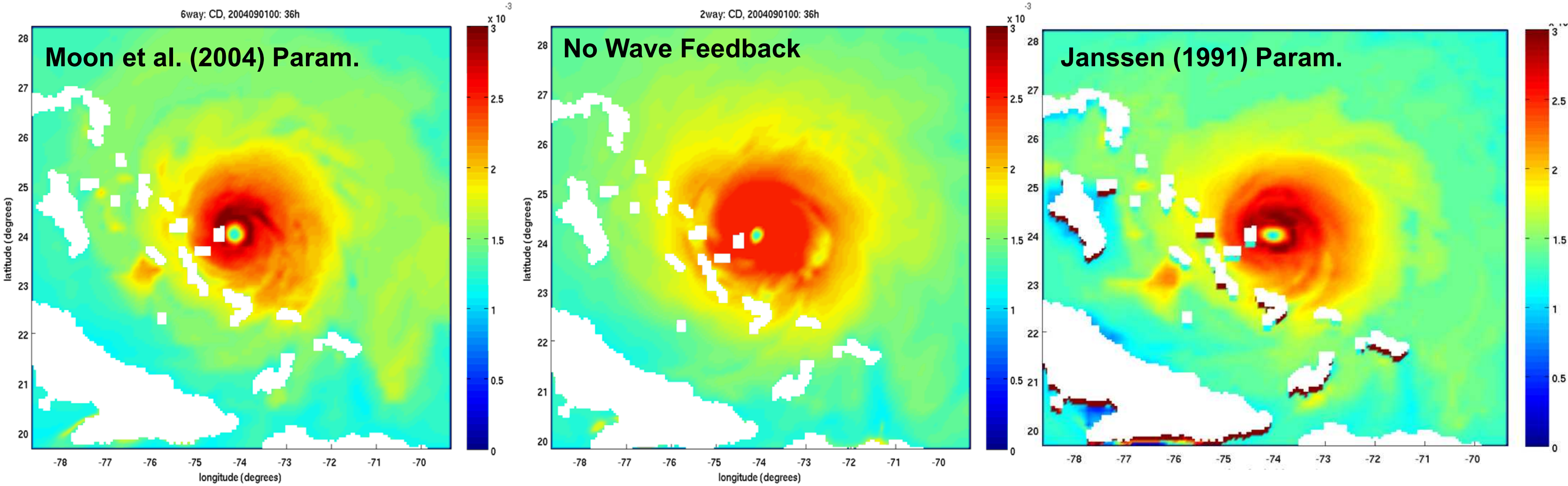


COAMPS-TC Had a Lower Intensity Error for Intensity Forecasts Than Other Models

COAMPS contains a community based (ESMF) coupler to facilitate flexible and generalized exchange between components.

Numerical Modeling Issues
Wind-Wave Interactions (COAMPS-TC)

COAMPS-TC Atmospheric Momentum Drag (Francis)

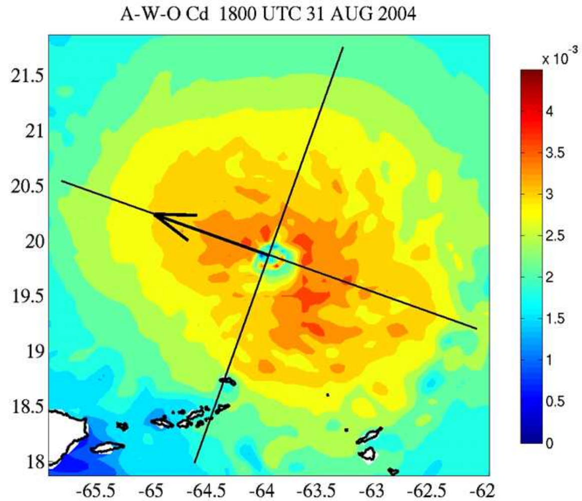


- COAMPS-TC is coupled to SWAN and WWIII.
- Including the wave feedback to the atmosphere produces stronger drag near the eyewall and changes the storm structure.

Numerical Modeling Issues

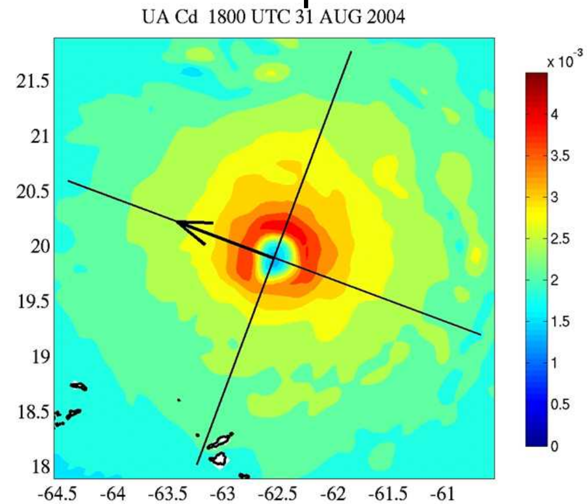
Wind-Wave Interactions (U. Miami)

Coupled (A-W-O)



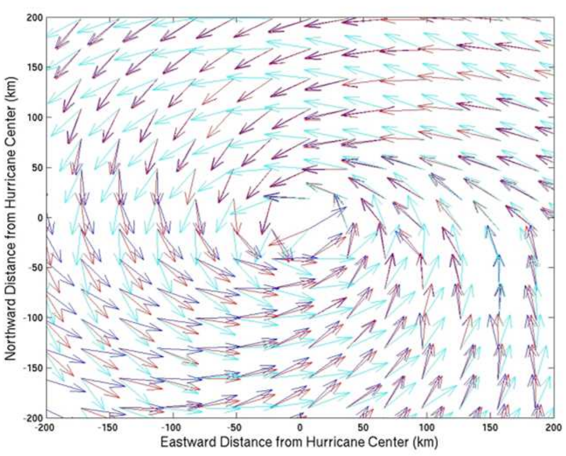
A-W-O Exchange Coefficient (10^{-3}) 1800 UTC 31 AUG 04

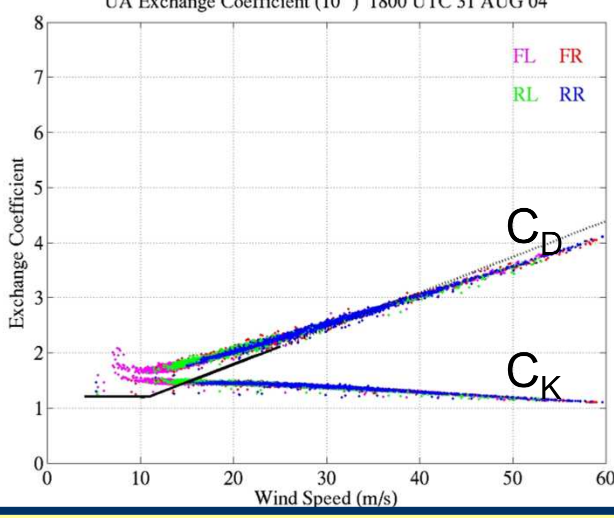
Uncoupled



UA Exchange Coefficient (10^{-3}) 1800 UTC 31 AUG 04

Stress
Wind
Waves





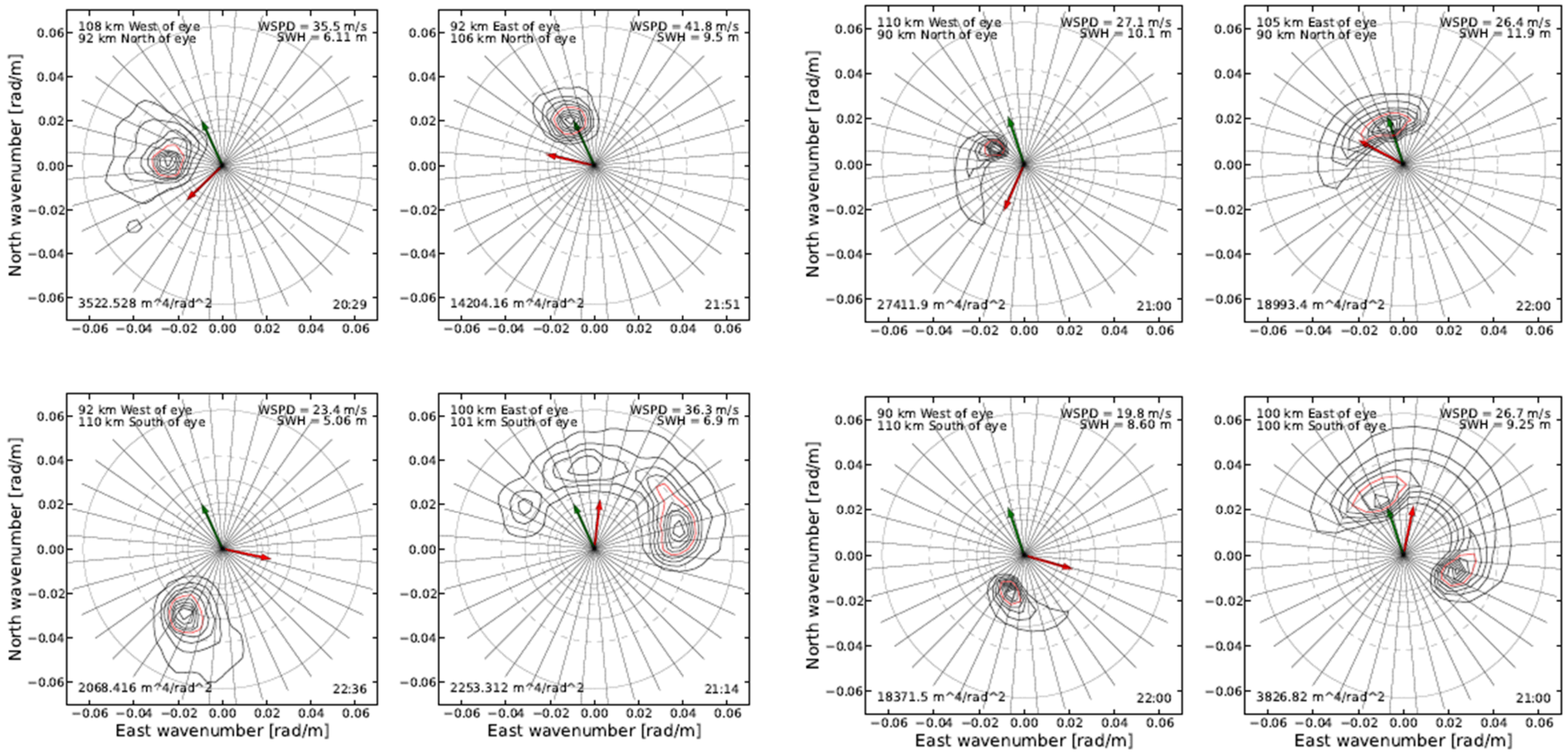
Chen et al. (2012)

Chen et al. (2012) uses a directional wind-wave coupling method to include winds and waves directionality effects.

Numerical Modeling Issues

Wind-Wave Interactions (UMWM)

Observed SRA **Hurricane Bonnie** Model



Donelan et al. (2012)

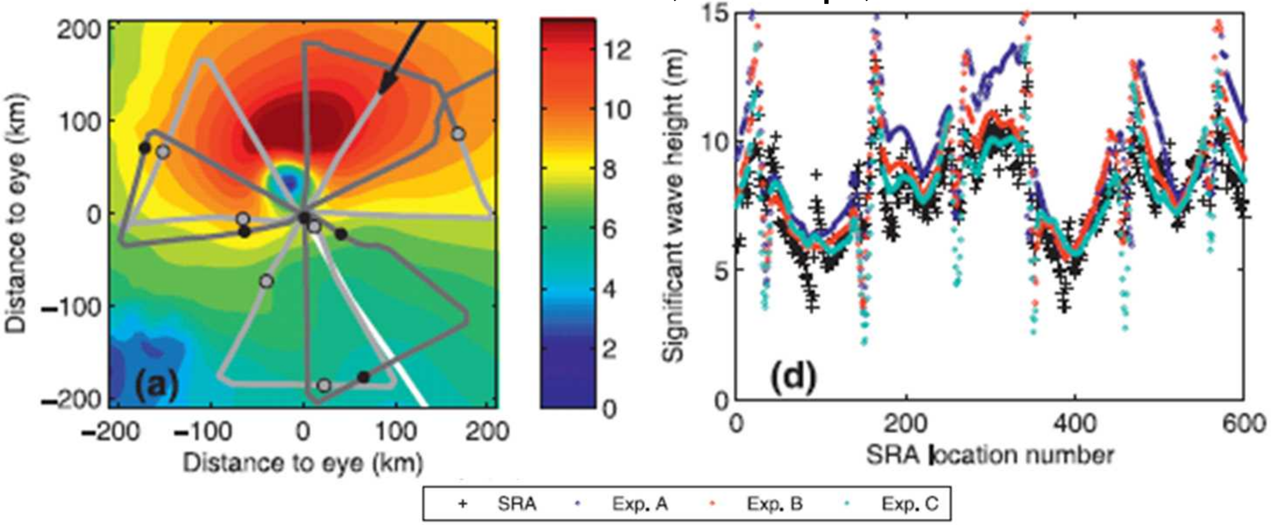
A new spectral model developed by Donelan et al. (2012) (U. Miami Wave Model, UMWM) is validated against the aircraft wavenumber spectra in the 4 quadrants around Bonnie (1998).

Numerical Modeling Issues

Wind-Wave-Current Interactions (GFDL)

WAVEWATCH III can accurately reproduce observed hurricane surface wave fields if:
- **Wind forcing is reduced at very high wind speeds.**
- **Ocean current is explicitly included in simulation.**

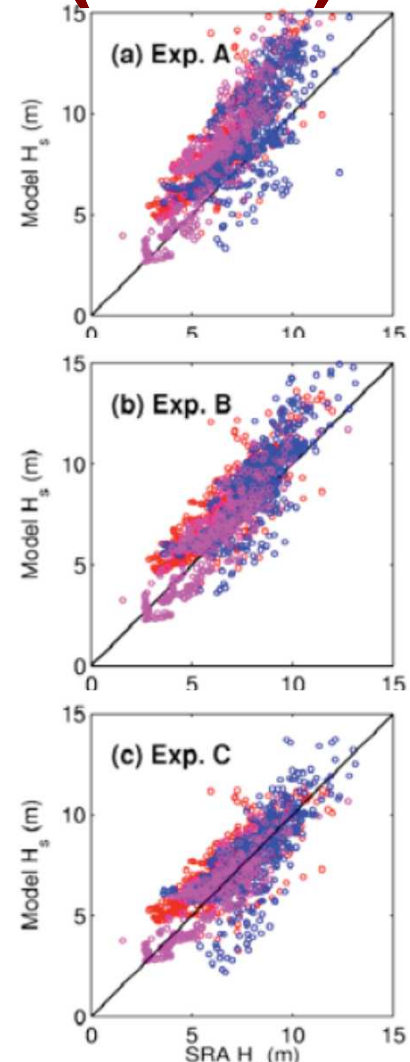
Hurricane Ivan, 15 Sept, 2004



WW3 significant wave height field (color) at Sept. 15 2:00 UTC. The thick gray line is the flight track.

Fan, Ginis, Hara, Wright, Walsh (2009)

Significant wave height comparison between SRA measurements (during this flight) and WW3 results from experiments A, B (with modified wind stress) and C (with modified wind stress and including ocean currents).

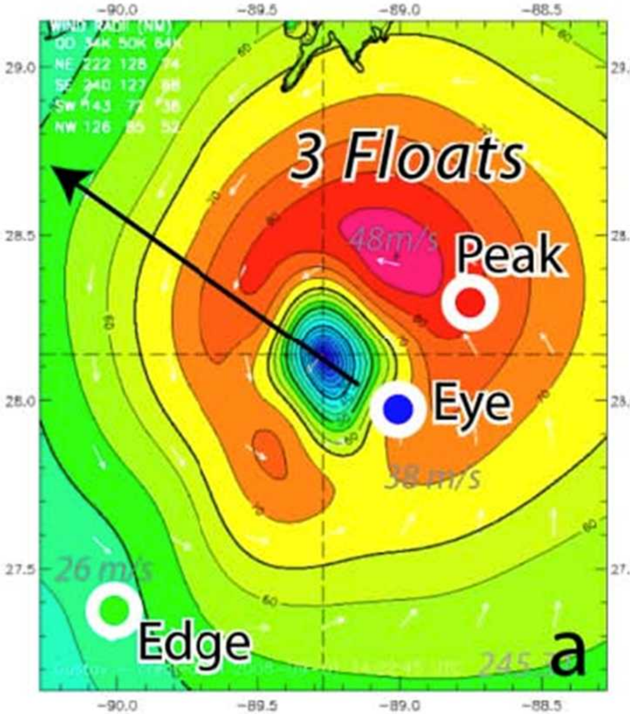


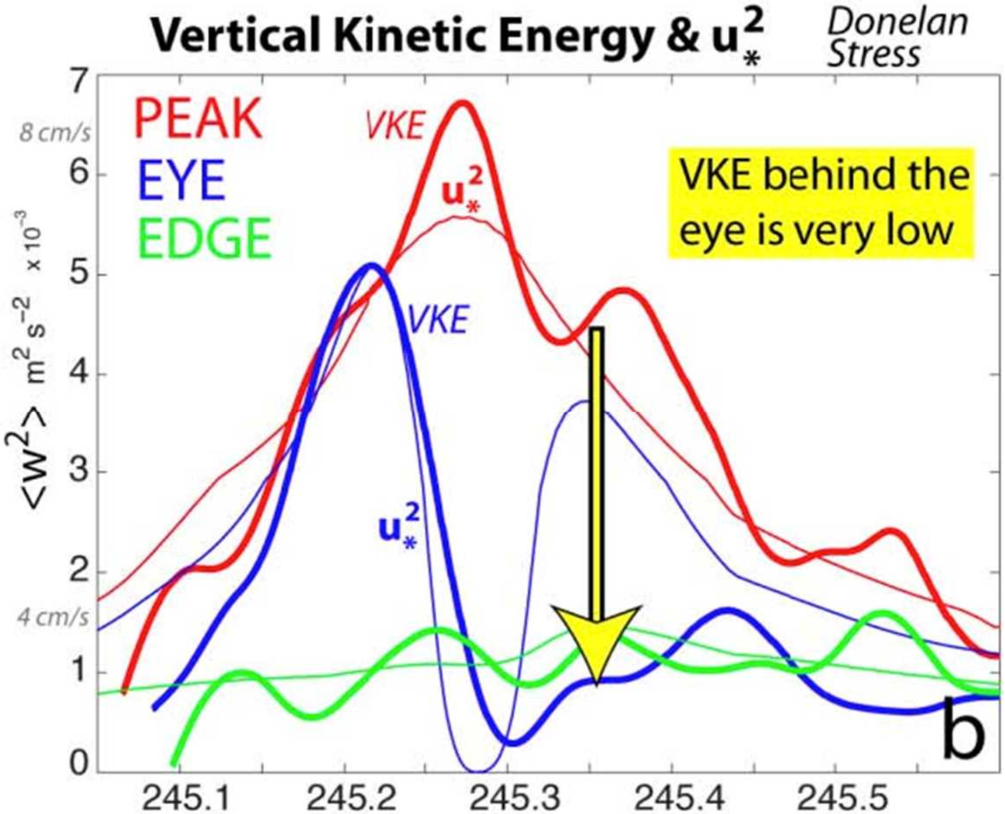
Comparison between modeled and measured significant wave heights from all flights.

Courtesy of Isaac Ginnis (URI)

Air-Wave-Ocean Coupling

Langmuir Turbulence Under Hurricanes





D'Asaro, E. A., R. R. Harcourt, A. Shcherbina (2010)

- **Surface wave motions induce net mass transport, "Stokes drift", which tilts and organizes upper ocean turbulent eddies, referred to as "Langmuir turbulence".**
- **D'Asaro et al. find that near surface turbulence & upper ocean mixing may be greatly reduced when surface waves oppose the wind and suppress Langmuir turbulence.**

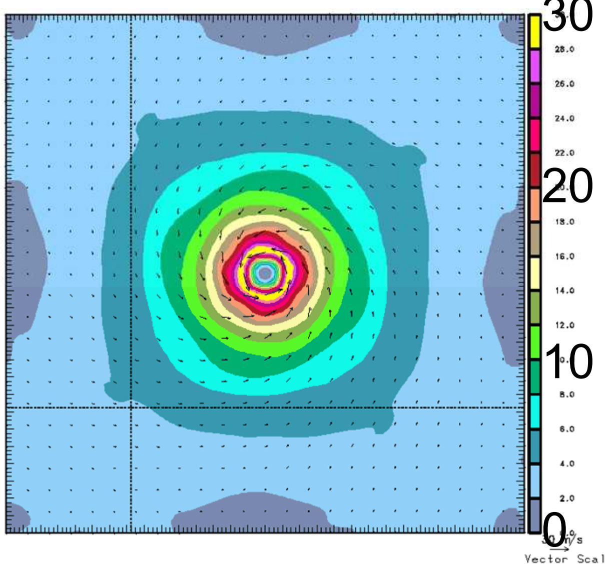
Courtesy of Eric D'Asaro via Isaac Ginnis

Numerical Modeling Issues

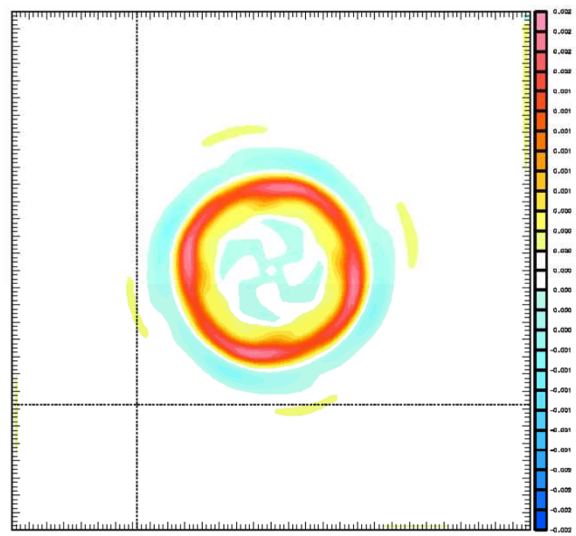
Sensitivity

High-resolution COAMPS-TC adjoint (5 km) (w/ microphysics) is used to quantify where the flux sensitivity is largest for an idealized storm

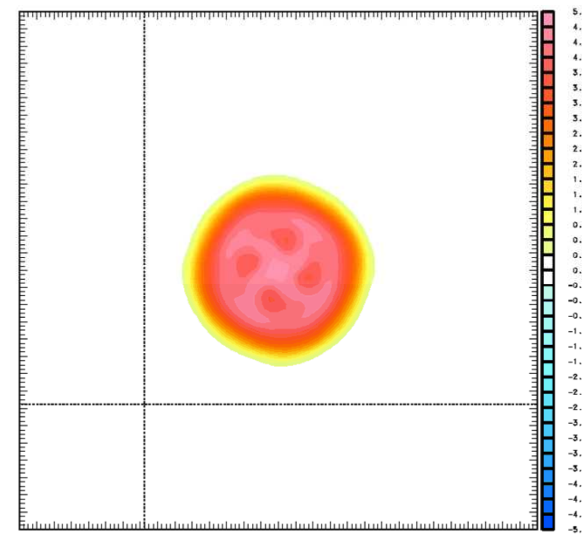
10-m Winds (69 h)



Momentum Flux Sensitivity



Latent Heat Flux Sensitivity



Adjoint sensitivity (69-72 h) computed during a period of rapid intensification (30-39 m s^{-1} in 3 h). Further intensification occurs with:

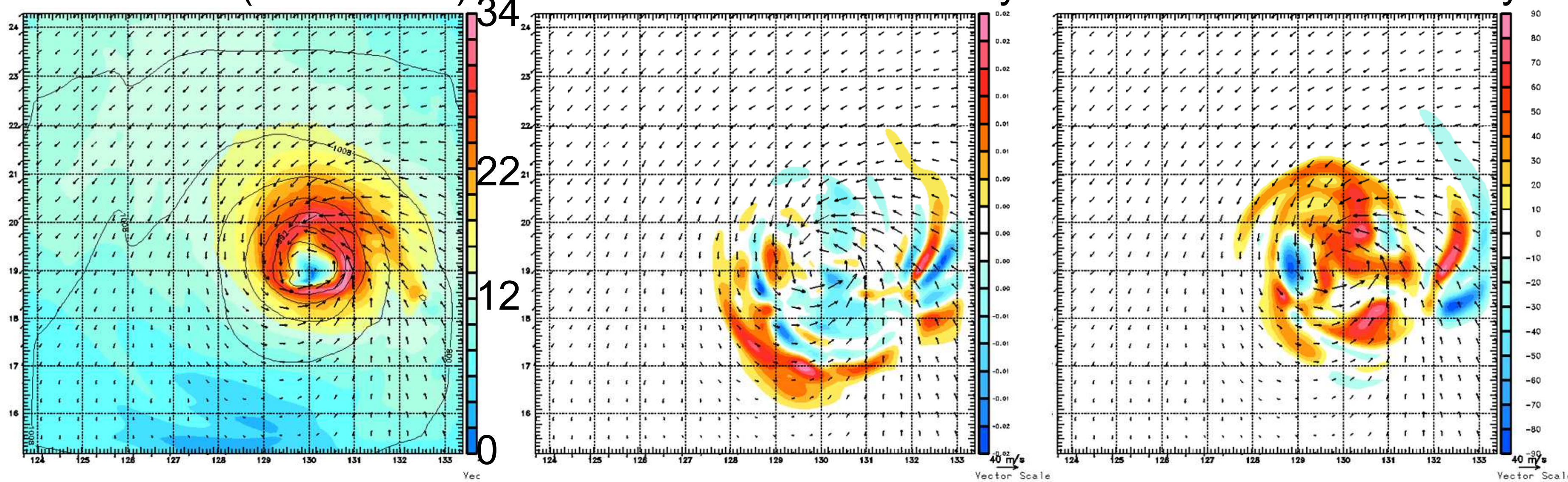
- **Momentum flux reduction in banded regions in core.**
- **Momentum flux increase in annulus around storm at ~100 km radius.**
- **Latent heat increase in the inner core of the storm.**

Numerical Modeling Issues

Sensitivity

High-resolution COAMPS-TC adjoint (9 km) (w/ microphysics) is used to quantify where the flux sensitivity is largest for TY Megi

10-m Winds (12Z 16 Oct) | Momentum Flux Sensitivity | Moisture Flux Sensitivity



Adjoint sensitivity (12-18 h) computed for super typhoon Megi (2010). Further intensification occurs with:

- **Momentum flux reduction in core; banded regions in NE/SW quadrants**
- **Moisture flux increase in core; isolated negative sensitivity to west.**
- **Overall interaction of fluxes with convection and dynamics is complex.**

Wind-Wave Interaction Under Hurricane Conditions
Summary and Future Directions

➢ **New Observations of Hurricanes that show:**

- Marked asymmetries in the directional wave spectra.
- Reduced drag coefficient in the high wind regime.
- Importance of spray and its impact on C_K.
- C_K/C_d does not increase above 30 m s^{-1}.
- Boundary layer rolls & log-law departures

➢ **New Modeling Capabilities:**

- Convective permitting resolution (~5 km) needed for intensity forecasts.
- New generation of coupled models (one includes directional dependence).
- Large model sensitivity to both C_K and C_D exchange coefficients.
- Spray parameterizations can impact the intensity.

➢ **Future Directions:**

- New observational & laboratory studies needed ($U > 35$ m s^{-1})
- Mechanism for reduced drag at high winds is still unknown.
- Consistent fluxes, and approaches are needed across air-sea interface.
- Partitioning of stress into waves and current remains an unresolved issue.
- Significance of BL rolls and log-law departures yet to be established.