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

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

Hurricane Size and Structure
Hurricane Michael 1857 UTC 18 October 2000

- 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
• 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

\( H_s > 55 \text{ m s}^{-1} \)

HWIND wind analysis (includes SFMR obs.)

Tri-modal

Bi-modal

Black et al. (2007)

Courtesy: Ed Walsh
Surface Waves Beneath TCs

SRA in Bonnie

Unimodal spectra
Short waves (~150-200 m) moving with wind

Bi- or Tri-modal spectra
Shift to longer $\lambda$ (~200-300 m) moving outward relative to winds up to 45°

Unimodal spectra with long $\lambda$ (~300-350 m) moving outward relative to winds by 60-90°

Wave steepness ($10^{-3}$)
Wave heights
Wave direction

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 drop sondes in 15 storms (of various intensities).
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.
• 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.
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)
• 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).

Haus et al. (2010)
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

• Mean value of the Stanton number $(1.09 \pm 0.11)$ agrees w/ HEXOS
• No dependence of the Stanton number on the surface wind speed.

Zhang et al. (2008)
New Boundary Layer Observations

Hurricane Boundary Layer Rolls

Doppler On Wheels (DOW)
Hurricane Fran

RADARSAT-1 Synthetic Aperture Radar imagery
Hurricane Floyd
Hurricane Isidore

Wurman and Winslow (1998) Science

• 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)
- 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.
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.
Several new parameterizations for sea spray have been developed including Fairall et al. (2009), Andreas (2010), Bianco et al. (2010). Bao et al. (2011) demonstrates large impact of spray on fluxes.
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 $C_d$
Numerical Modeling Issues
Spray Parameterizations

Transfer Coefficients in COAMPS-TC

- 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.

Wang et al. (2012)
Numerical Modeling Issues
Air-Sea Interface Physics in COAMPS-TC
Earth System Modeling Framework (ESMF)

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

- 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.

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.
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.