Effects of surface waves on air-sea momentum and energy fluxes and ocean response to hurricanes

Isaac Ginis
University of Rhode Island

Collaborators: Yalin Fan and Tetsu Hara

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Outline

1. Energy and momentum flux budget across air-sea interface
   - Uniform wind
   - Hurricanes

2. Wind-wave-current interaction in hurricanes

Wind-Wave-Current Interaction

Wind stress
(momentum flux from air)

Surface waves
Ocean currents

Atmosphere
Ocean
URI Coupled Wave-Wind (CWW) Model

- **Near the peak**: WAVEWATCH III (WW3) model.
- **High frequency part**: Equilibrium Spectrum model of Hara and Belcher (JFM, 2002)

- Explicitly calculates wave-induced stress
- Wind profile and drag coefficient over any given seas
Drag Coefficient in the CWW model

- At high wind speeds, $C_d$ levels off and even decrease with wind speed.

GPS sonde observation under various hurricanes (Powell et al., 2003).
Roughness Length and Drag Coefficients

Parameterizations based on CWW

(a) Roughness Length vs. Wind Speed
- Operational model
- CWW model
- New formula

(b) Drag Coefficient vs. Wind Speed
- Powell et al. (2003)
- Large & Pond (1982)
- Donelan et al. (2004)
- Wu (1982)
- Operational model
- New formula
1. Modeling of air-sea fluxes in hurricanes

- **Effect of surface gravity waves on air-sea fluxes**

\[
\text{EF}_{\text{air}} = \text{EF}_{c} + (\text{EF}_{\text{growth}} + \text{EF}_{\text{divergence}})
\]

\[
\vec{\tau}_{\text{air}} = \vec{\tau}_{c} + (\vec{\tau}_{\text{growth}} + \vec{\tau}_{\text{divergence}})
\]
1. Modeling of air-sea fluxes in hurricanes

Air-sea flux calculations

Atmospheric observations (wind speed, $U_w$)

Traditional parameterization
Momentum flux ($\tau_{\text{air}} = \rho_{\text{air}} C_p |U_w| \theta$)
Energy flux ($E_{\text{fair}}$)

Ocean Model

Wind Field

Coupled Wind-Wave Boundary Layer Model

Wave information $\psi(\theta,k), H_s, L, T, \ldots$

Momentum & energy flux $\tau_{\text{air}} = f(\psi(\theta,k), \beta(\theta,k))$
$E_{\text{fair}} = f(\psi(\theta,k), \beta(\theta,k))$

Downward Energy and Momentum Flux Budget Model

$\tau_c = \tau_{\text{air}} - \tau_w$
$E_{\text{fc}} = E_{\text{fair}} - E_{\text{fw}}$

Ocean Model

Ocean Response $U, T, \ldots$
2. Energy and momentum flux budget across air-sea interface

- **Uniform wind experiments**

Fetch limited (space variation) experiment

- Study section
- Steady and homogenous wind: 10, 20, 30, 40, 50 m/s

Duration limited (time variation) experiment

- Study point
- Steady and homogenous wind: 10, 20, 30, 40, 50 m/s
2. Energy and momentum flux budget across air-sea interface

**Uniform Wind experiments: Momentum and energy fluxes**

Time Dependent

- $|\tau_c| / |\tau_{air}| \times 100\%$
- $\frac{E_{F_c}}{E_{F_{air}}} \times 100\%$

Fetch Dependent

- $|\tau_c| / |\tau_{air}| \times 100\%$
- $\frac{E_{F_c}}{E_{F_{air}}} \times 100\%$
2. Energy and momentum flux budget across air-sea interface

- Uniform wind: Energy flux into currents ($EF_c$) as a function of $u_*$

Previous studies: $EF_c \sim \rho_{air} |u_*|^3$

This study: $EF_c \sim \rho_{air} |u_*|^{3.5}$
2. Energy and momentum flux budget across air-sea interface

- Hurricane experiments

Holland Hurricane Wind Model

**Input parameters:**
- Maximum wind speed (MWS)
- Radius of MWS (RMW)
- Central & environmental sea-level pressure

Wind Field (m/s)

0m/s
TSP = 5m/s
10m/s

Latitude

Longitude

Wind speed (m/s)
2. Energy and momentum flux budget across air-sea interface

- Hurricane experiments
  - Wave Field
  - Group Velocity

![Wave Field and Group Velocity Diagrams](image.png)
2. Energy and momentum flux budget across air-sea interface

- Hurricane experiments: Stationary Case (TSP = 0 m/s)
2. Energy and momentum flux budget across air-sea interface

- Hurricane experiments: Moving cases (TCP = 5 m/s and 10 m/s)

### TSP = 5 m/s

- $\tau_{\text{air}}$
- $\tau_c$

### TSP = 10 m/s

- $\tau_{\text{air}}$
- $\tau_c$

Latitude

Longitude

$7\text{Nm}^{-2}$
2. Energy and momentum flux budget across air-sea interface

- Hurricane experiments: Moving cases (TCP = 5 m/s and 10 m/s)
2. Energy and momentum flux budget across air-sea interface

- Hurricane experiments: Moving cases (TCP = 5 m/s and 10 m/s)

![TSP = 5 m/s](image1)

![TSP = 10 m/s](image2)
3. Wind-wave-current interaction in hurricanes

Momentum & energy flux
\[ \tau_{\text{air}} = f(\psi(\theta,k), \beta(\theta,k)) \]
\[ EF_{\text{air}} = f(\psi(\theta,k), \beta(\theta,k)) \]
3. Wind-wave-current interaction in hurricanes

- Ocean response in Control Experiment
3. Wind-wave-current interaction in hurricanes

Ocean response in Control Experiment

Sea Surface Temperature anomaly

Temperature, TKE profile

Initial T profile
3. Wind-wave-current interaction in hurricanes

- **Momentum Flux ratio**
  - $\tau_c$ in A / $\tau_{air}$ in Control
  - $\tau_{air}$ in B / $\tau_{air}$ in Control
  - $\tau_{air}$ in C / $\tau_{air}$ in Control
  - $\tau_c$ in D / $\tau_{air}$ in Control

Exp A (one way)

Exp B (two way)

Exp C (two way Partial)

Exp D (fully coupled)
3. Wind-wave-current interaction in hurricanes

- **Differences in surface current**

**Exp A** (one way)

**Exp B** (two way)

**Exp C** (two way Partial)

**Exp D** (fully coupled)
3. Wind-wave-current interaction in hurricanes

- Differences in the Sea Surface Temperature cooling

Exp A (one way)

Exp B (two way)

Exp C (two way Partial)

Exp D (fully coupled)
3. Wind-wave-current interaction in hurricanes

- **Temperature and TKE profiles**

  (a) T profile at a

  (b) $q^2$ profile at a

  (c) T profile at b

  (d) $q^2$ profile at b
3. Wind-wave-current interaction in hurricanes

- Impact of wind-wave-current interaction on the wave field

![Graphs and diagrams showing wind-wave-current interaction in hurricanes]
3. Wind-wave-current interaction in hurricanes

- Frequency spectrum for different experiments

![Graphs showing frequency spectrum for different experiments](image)
3. Wind-wave-current interaction in hurricanes

- **WW3 2-D spectrum in two locations**

![Diagram showing WW3 2-D spectrum in two locations](image)

**L1**:
- **(a)**: Contr & A
  - East Wave Number (rad m⁻¹)
  - North Wave Number (rad m⁻¹)
  - Wave heights: 17.05 m, 358.69 m

- **(b)**: B
  - East Wave Number (rad m⁻¹)
  - North Wave Number (rad m⁻¹)
  - Wave heights: 14.58 m, 304.22 m

**L2**:
- **(c)**: Contr & A
  - East Wave Number (rad m⁻¹)
  - North Wave Number (rad m⁻¹)
  - Wave heights: 16.82 m, 365.78 m

- **(d)**: B
  - East Wave Number (rad m⁻¹)
  - North Wave Number (rad m⁻¹)
  - Wave heights: 14.74 m, 316.81 m
3. Wind-wave-current interaction in hurricanes

Explanation of the ocean current effect on wave spectrum

Steady state equation of wave action conservation:

\[
\frac{\partial N}{\partial x} \left( U + C_g - U_i \right) - k \frac{\partial N}{\partial k} \frac{\partial U}{\partial x} = 0
\]

\[
\frac{\partial U}{\partial x} > 0 \quad \text{for } x < 0
\]

\[
\frac{\partial U}{\partial x} < 0 \quad \text{for } x > 0.
\]

\[
k \frac{\partial N}{\partial k} \quad \text{is always negative}
\]

- Ivan track and reconnaissance flight tracks

Exp. A: WAVEWATCH III wave model (operational model)
Exp. B: Coupled wind-wave model
Exp. C: Coupled wind-wave-current model

- Scanning Radar Altimeter (SRA) measurements

- **HRD H*wind**

(a) HRD wind at 09/09 13:30 UTC (ms\(^{-1}\))

(b) HRD wind at 09/09 19:30 UTC (ms\(^{-1}\))

(c) Interpolated wind at 09/09 18:00 UTC (ms\(^{-1}\))

- Wind swath and sea surface temperature

(a) Wind Speed Swath

(b) Sea Surface Temperature

- **Significant Wave Height Swaths**

![Wave Height Maps for Experiments A, B, and C](image)

- **Exp. A**: WAVEWATCH III wave model (operational model)
- **Exp. B**: Coupled wind-wave model
- **Exp. C**: Coupled wind-wave-current model

- Surface wave field & flight track

September 9 18:00 UTC

- Wave parameter comparisons between model and SRA data

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**Vertical velocity**

![Vertical velocity plot](image)

**Wave Direction**

![Wave Direction plot](image)

**Dominant Wave Length**

![Dominant Wave Length plot](image)

**Significant Wave Height**

![Significant Wave Height plot](image)

Wave spectrum comparisons

- **SRA**
  - East Wave Number (rad m\(^{-1}\))
  - North Wave Number (rad m\(^{-1}\))
  - Location: 7.32 m, 261 m
  - Date: Sept. 09, 71067
  - Latitude: 15.5N
  - Longitude: -72.14W

- **Exp. C**
  - East Wave Number (rad m\(^{-1}\))
  - North Wave Number (rad m\(^{-1}\))
  - Location: 9.04 m, 222.1 m

- **Exp. B**
  - East Wave Number (rad m\(^{-1}\))
  - North Wave Number (rad m\(^{-1}\))
  - Location: 10.77 m, 261.4 m

- **Exp. A**
  - East Wave Number (rad m\(^{-1}\))
  - North Wave Number (rad m\(^{-1}\))
  - Location: 11.81 m, 295.6 m
Conclusions

• For momentum flux calculations at the air-sea interface, the effect of time variation of the wave field is small but the effect of spatial variation is important. Both effects, however, are important for energy flux calculations.

• The surface wave effects on the air-sea fluxes are most significant in the rear-right quadrant of the hurricane and consequently reduce the magnitude of subsurface currents and sea surface temperature cooling to the right of the storm track.

• Wave-current interaction reduces the momentum flux into currents mainly due to the reduction of wind speed input into the wave model relative to the ocean currents.

• The improved momentum flux parameterization, together with wave-current interaction is shown to improve forecast of significant wave height and wave energy in Hurricane Ivan.
Energy and Momentum Flux Budget Model

Energy Flux Budget

\[ E = \iint \rho_w g \psi(\omega, \theta) d\theta d\omega \]
\[ EF_x = \iint \rho_w g C_g \psi(\omega, \theta) \cos \theta \cdot d\theta \cdot d\omega \]
\[ EF_y = \iint \rho_w g C_g \psi(\omega, \theta) \sin \theta \cdot d\theta \cdot d\omega \]
\[ EF_c = EF_{air} - \left[ \left( \frac{\partial EF_x}{\partial x} + \frac{\partial EF_y}{\partial y} \right) + \frac{\partial E}{\partial t} \right] \text{ Wave component} \]

\( \psi(\omega, \theta) \) wave spectrum
\( C_g \) group velocity
\( \rho_w \) water density

Momentum Flux budget

\[ M_x = \iint \rho_w \omega \psi(\omega, \theta) \cos \theta \cdot d\theta \cdot d\omega \]
\[ M_y = \iint \rho_w \omega \psi(\omega, \theta) \sin \theta \cdot d\theta \cdot d\omega \]
\[ MF_{xx} = \iint \rho_w \omega C_g \psi(\omega, \theta) \cos^2 \theta \cdot d\theta \cdot d\omega \]
\[ MF_{xy} = \iint \rho_w \omega C_g \psi(\omega, \theta) \cos \theta \sin \theta \cdot d\theta \cdot d\omega \]
\[ MF_{yy} = \iint \rho_w \omega C_g \psi(\omega, \theta) \sin^2 \theta \cdot d\theta \cdot d\omega \]
\[ MF_{yx} = \iint \rho_w \omega C_g \psi(\omega, \theta) \sin \theta \cos \theta \cdot d\theta \cdot d\omega \]

\[ \tau_{c_x} = \tau_{air_x} - \left[ \left( \frac{\partial MF_{xx}}{\partial x} + \frac{\partial MF_{xy}}{\partial y} \right) + \frac{\partial M_x}{\partial t} \right] \]
\[ \tau_{c_y} = \tau_{air_y} - \left[ \left( \frac{\partial MF_{yx}}{\partial x} + \frac{\partial MF_{yy}}{\partial y} \right) + \frac{\partial M_y}{\partial t} \right] \]