Modeling of Wind-Wave-Current Coupled Processes in Hurricanes

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Wind-Wave-Current Interaction

Wind

Sea state, Sea spray

Surface waves

Current

Sea state, Sea spray

Current

Ocean currents

Atmosphere

Ocean

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Surface waves

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Key Air-Sea Physical Processes in the Coupled Tropical Cyclone-Ocean System
2D LES BL Model for Roll Vortices

3.0 km, 61 levels

2-4 km

8.0 km, 40 m resolution

"Cloud streets"
2D LES BL Model for Roll Vortices

Graph showing wind departure (m/s) vs. height (km) for 'With Rolls' and 'No Rolls' conditions.
Wave BL Model: Drag Coefficient Sea State Dependence

Wave BL Model: Drag Coefficient Sea State Dependence
\[ \vec{\tau}_{air} = \vec{\tau}_{c} + (\vec{\tau}_{growth} + \vec{\tau}_{\text{divergence}}) \]

M - total momentum
MF - total momentum flux

Momentum Flux from Atmosphere
\( (\vec{\tau}_{air}) \)

Horizontal wave propagation
\( (\vec{\tau}_{\text{divergence}} = \nabla MF) \)

Wave growth
\( (\vec{\tau}_{growth} = \frac{\partial M}{\partial t}) \)

Momentum Flux into Currents
\( (\vec{\tau}_{c}) \)

Flux Budget Model

Atmosphere
Ocean
Surface Waves
Ocean Currents
Flux Budget Model

- Idealized 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)

TSP = 5m/s
Flux Budget Model

Wind Model

\[ \vec{U}_{\infty} \]

Wave Boundary Layer Model

\[ \vec{\tau}_{\text{av}} \Psi(k,\theta) \]

Flux Budget Model

\[ \vec{\tau}_{c} \]

Ocean Model

\[
\frac{\vec{\tau}_{c}}{\vec{\tau}_{\text{air}}} \times 100\%
\]

3D model showing wave patterns with color coding and arrow vectors indicating wind direction.
Wind-wave-current Interaction

Wind Model

\[ \vec{U}_0 \]

\[ \vec{\tau}_w \]

\[ \psi_{\text{peak}}(k, \theta), f_W \]

Wave Boundary Layer Model

\[ \vec{\tau}_c \]

\[ \vec{U}_c \]

Flux Budget Model

\[ \vec{U}_c \]

Ocean Model

\[ \vec{\tau}_c / \vec{\tau}_{\text{air}} \times 100\% \]

\[ W \text{ at } 90 \text{ m} \]

\[ x \times 10^3 \]

\[ 3 \]

\[ 2.5 \]

\[ 2 \]

\[ 1.5 \]

\[ 1 \]

\[ 0.5 \]

\[ 0 \]

\[ -0.5 \]

\[ -1 \]

\[ -1.5 \]

Currents

\[ \text{Latitude} \]

\[ \text{Longitude} \]

\[ 25 \]

\[ 26 \]

\[ 27 \]

\[ 28 \]

\[ 29 \]

\[ 30 \]

\[ 31 \]

\[ 32 \]

\[ 33 \]

\[ \text{Longitude} \]

\[ 6 \]

\[ 8 \]

\[ 10 \]

\[ 12 \text{(ms}^{-1}) \]

\[ 80 \]

\[ 85 \]

\[ 90 \]

\[ 95 \]

\[ 100 \]

\[ 105 \]

\[ 110 \]

\[ 115 \]

\[ 120 \]
Impact Wind-Wave-Current Interaction on Ocean Cooling

SST anomaly when $\vec{\tau}_{\text{air}}$ as forcing (Control Exp.)

SST anomaly in Fully Coupled Exp.

— SST anomaly in Control Exp.
Impact Wind-Wave-Current Interaction on Waves

- Hurricane Ivan (2005) track and reconnaissance flight tracks

Flight tracks/Scanning Radar Altimeter measurements
NASA/Goddard space flight center & NOAA/HRD

Sept. 09 1800 UTC

Sept. 06 00 UTC

Wind (ms⁻¹)
Impact Wind-Wave-Current Interaction on Waves

- **Significant Wave Height Swaths**

(a) Exp. A

Exp. A: WAVEWATCH III wave model (operational model)

(b) Exp. B

Exp. B: Coupled wind-wave model

(c) Exp. C

Exp. C: Coupled wind-wave-current model
Impact Wind-Wave-Current Interaction on Waves

Wave parameters comparison between model and SRA (Courtesy of Ed Walsh)
Air-Sea Coupling Strategies for Tropical Models

- **In the TC model**, the parameterizations of the air-sea heat and momentum explicitly include the a) *sea state dependence*, b) *SST* and c) ocean current effects.

- **The wave model** is forced by a) *the sea-state dependent momentum flux* and b) includes the *ocean current effects*.

- **The ocean model** is forced by a) *the sea-state dependent momentum and energy fluxes* calculated from the air-sea flux budget.