Importance of air-sea interaction on the coupled typhoon-wave-ocean modeling

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Air-Sea Fluxes
(Bulk Parameterization)

The vertical fluxes of any variable (c, i.e., wind speed) are assumed to be driven by the difference in variable across the air-sea interface with transport velocity, $U_T$. 

$$[Flux] = -U_T \times ([c]_{\text{air}} - [c]_{\text{water}})$$
Air-Sea Momentum Flux (Wind Stress)

- Air side controlled flux

\[ \text{Flux} = -U_T \times (U_{\text{air}} - U_{\text{surface}}) \]

- The transport velocity is usually parameterized as

\[ U_T = C_D U_{10} \]

where \( U_{10} \) is the mean horizontal wind speed at height 10m and \( C_D \) is the bulk transfer coefficient (or drag coefficient).
Drag Coefficient ($C_d$) & Roughness Length ($z_0$)

Using the logarithmic wind profile in neutral condition,

$$U(z) = \frac{u_\ast \ln \frac{z}{z_0}}{\kappa}$$

where $z_0$ is the surface roughness length and $u_\ast$ is the friction velocity, $u_\ast = \sqrt{C_D U_{10}}$

we obtain

$$C_D = \left( \frac{1}{\kappa} \ln \frac{z}{z_0} \right)_{z=10m}^{-2}$$

A non-dimensional roughness length, called the Charnock Coefficient, is widely used in atmospheric models

$$z_{ch} = \frac{g z_0}{u_\ast} = \text{Charnock coefficient}$$

While the $C_D$ is widely used in the ocean modeling, the $z_0$ & $z_{ch}$ is mostly used in atmospheric models
Why do we care about air-sea momentum fluxes (or Wind Stress, Drag Coefficient Cd, Roughness Length)?

- A crucial subject in atmospheric modeling and weather forecasting

- It provides the boundary conditions for atmospheric and oceanic models, including typhoon, wind waves, storm surge prediction models.

How do we estimate the air-sea momentum fluxes?
1. Simplest Way (Bulk formula)

- Drag coefficient is a function of wind speed
- Charnock coefficient (i.e. non-dimensional roughness length) is constant

\[ \frac{g z_0}{u^*} = \text{const.} \approx 0.0185 \]

Most widely used in atmospheric and oceanic models

\[ C_d = (0.8 + 0.065 \times U) \times 10^{-3} \]

Large & Pond (1981)

- Both formulas show a monotonic increase of drag with wind speed.
- Observations support that this is a good approximation, especially at low wind conditions.
For high wind speed?

- No field observations
- Extrapolated from field measurements in low wind conditions

Drennan et al. (2003)
2. Using relationships between Charnock coefficient and wave age

Charnock Coefficient = \( \frac{g z_0}{u_*} \)  
Wave age = \( \frac{c_p}{u_*} \)

- \( c_p \) is the phase speed of dominant waves (at the spectral peak)
- \( u_* \) is the friction velocity and \( z_0 \) is roughness length
- The state of growth of wind waves relative to local wind forcing
- small (young sea or growing sea), large (old sea or mature sea)

What is the relationship between Charnock coefficient and wave age?
The relationship is far from conclusive so far. There are many relationships that are proposed based on the different observations. Data: two sources.

Charnock coefficient vs Wave age

old  Wave age  young

100  10  1  0.1

Swell  Wind waves

Discontinuous

NOAA operational wave prediction model, WAVEWATCH III

GFDL operational Hurricane Model

Adapted by Jones & Toba (2001)
CD behavior of GFDL & WW3 at high winds (>20m/s)

- Internal Calculations of WAVEWATCH III under hurricane wind forcing
- GFDL operational hurricane model: Constant Zch, 0.0185

- Cd increases as wind speed increases at high winds
- WAVEWATCH III shows even much higher drag

Is this trend realistic?
Can we use these formulas for high wind speeds?

No !!!!
There is general consensus that the Cd ceases to increase with wind speed at high wind speeds, although their physical explanations vary and are not conclusive.

Recent studies

- Alamaro et al. (2002) and Donelan et al. (2004) : Laboratory experiments
- Powell et al. (2003) : Indirect estimates from GPS sonde observations
- Emanuel (2003) and Makin (2005) : Theoretical studies
- Moon et al. (2004a, 2004b, and 2004c) : Model experiments
Comparison of widely-used Cd formulas with recent results

- WAVEWATCH III (wave models)
- Most atmospheric models (GFDL) $z_{ch} = 0.0185$
- Most ocean models, Large & Pond
- Moon et al (2004,a,b,c) from Coupled Wave-Wind model experiments
- Donelan et al (2004) from wave tank experiments
- Powell et al (2003) from GPS sonde measurements

Cd is leveling off at high wind speeds

These trends are very different from those used in the most atmospheric and oceanic models
Coupled Wave-Wind (CWW) Model

Two dimensional wave spectrum

- Near the peak: WAVEWATCH III (WW3) model.

Full wave spectrum

Wave Boundary Layer (WBL) model of Hara and Belcher (2004)

To explicitly calculate wave-induced stress

Wind profile and drag coefficient over any given seas

Moon et al., (2004a & 2004b, JAS)
Moon et al. (2004, GRL)
Tracks of 10 hurricanes occurred in the western Atlantic Ocean during 1998-2003:
Because of large scatter, it is difficult to find a unique relationship between $z_{ch}$ and wave age. Toba et al. (1990) and Donelan (1990) found that the relationship between Charnock coefficient and wave age is not unique, but strongly depends on wind speed. For example, at low winds, younger waves produce higher $C_d$. But, at high winds, lower $C_d$.

- Different color symbols according to wind speed in 5-m/s intervals
- There is a strong correlation between $z_{ch}$ and $w_{age}$ for each wind speed group

The best fits of each wind speed group

All data grid points of ten hurricanes every 6-h interval

The relationship between Charnock coefficient and wave age is not unique, but strongly depends on wind speed! For example, at low winds, younger wave produce higher $C_d$. But, at high winds lower $C_d$. 

Donelan (1990)
Open ocean

Donelan (1990)
Laboratory

Moon et al. (2006, MWR)
Reduced drag coefficient at high wind speed

- Drag coefficient levels off at high wind speeds

- Under strong hurricane wind regimes, waves are extremely young and the young waves produce small drag.

- This explains why our drag coefficient levels off at high wind speed.

- The CWW model results affect not only the magnitude of $C_d$ but also spatial distribution

Scatterplot of $C_d$ as a function of wind speed for ten hurricanes.

CWW results for 10 hurricanes

GPS sonde observations

- Large & Pond [1981]

- Charnock Coefficient = 0.0185 (non-$d$ $z_o$)

- Powell et al. [2003]
Symmetric Wind Field

Asymmetric Wave & Drag coefficient
(Moon et al., 2003, JPO; Moon et al., 2004, JAS)

Any drag formula expressed as a function of wind speed cannot generate this asymmetric drag distribution!

Wave coupling is necessary !!!
A Coupled Hurricane-Wave-Ocean Model
The NCEP operational GFDL-POM Coupled Model

The Coupled Hurricane-Wave-Ocean Model

Future replacement plan: GFDL->WRF, POM->HYCOM
Model Domains for the Coupled Hurricane-Wave-Ocean Model in the Atlantic Basin

- GFDL model: C, M, F
- POM: OW, OE
- WAVEWATCH-III: WL, WS
Model Domains for the Coupled Hurricane-Wave-Ocean Model in the Northwestern Pacific

- GFDL: C, M, F (WRF)
- WAVEWTCH III: WW (SWAN)
- POM: OM (ROMS)
Coupled model simulations for hurricane Katrina (2005)

Sea Surface Temperature

Significant Wave Height
The Ocean Response to Typhoon Ewiniar (2006)

- First, MLD became deep and then shallow, periodically varying.
- During the strong SST cooling, upwelling is dominant, intensity became weak.
Effects of the wave coupling on

1. Hurricane Intensity and Structure Predictions
2. Hurricane Wave Simulation
3. Storm Surge Simulation
Comparison between operational model and the coupled model for hurricane Ivan (Initial time: 00Z 12 Sep)

- **Operational**: NCEP operational GFDL-POM coupled model
- **Coupled**: Coupled hurricane-wave-ocean model

- Operational model uses a constant Charnock coeff. (0.0185)
- Cd in the coupled model levels off at high wind speeds and the difference between two models become bigger as wind speeds increase.

![Graphs showing Roughness Length vs. Wind Speed and Drag Coefficient vs. Wind Speed for Ivan](image)
Spatial Distribution of Drag Coefficient

Wave Fields

- The coupled model: $C_d$ is clearly asymmetry relative to the storm center, which is produced by the asymmetric wave field.
- The operational model: $C_d$ is simply determined by wind fields regardless of wave field. So, the difference is large.
Surface Wind Fields

In the coupled model, the wind structure, in shape and location of strong wind regime, is in a better agreement with HRD wind.
**Improvement of hurricane intensity forecast**

**Maximum Wind Speed**

<table>
<thead>
<tr>
<th>Time [hour]</th>
<th>Wind speed [m/s]</th>
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<tbody>
<tr>
<td>0</td>
<td>80</td>
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<tr>
<td>12</td>
<td>70</td>
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<tr>
<td>108</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td></td>
</tr>
</tbody>
</table>

**Minimum Pressure**

<table>
<thead>
<tr>
<th>Time [hour]</th>
<th>Pressure [hPa]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1000</td>
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<tr>
<td>12</td>
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<td>108</td>
<td>820</td>
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<tr>
<td>120</td>
<td>800</td>
</tr>
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**Hurricane Track**

**Forecast comparisons between two models for hurricane Ivan**

- Track forecast of two models are almost identical, but the intensity forecast is much improved by the wave coupling.
2. Impact of the coupling on wind wave modeling under hurricane conditions

Moon et al. 2008 (Mon. Wea. Rev.)
Original parameterization of Cd used in WAVEWATCH III Model (WW3)

\[ C_d = 10^{-3} \left( 0.021 + \frac{10.4}{R^{1.23} + 1.85} \right) \]

\[ R = \ln \left( \frac{10g}{\chi \sqrt{\alpha u^2_{e10}}} \right) \]

\[ \alpha = 0.57 \left( \frac{c_p}{u_*} \right)^{-3/2} \]

Drag coefficient is a function of wave age

Young waves produce high drags, which is very different from CWW
Comparisons between original and CWW parameterization in WW3

Because of the difference, the Cd at high wind speeds are very different.

WW3 have used a unrealistically high drag at high winds.

Although WW3 used very high drag, wave simulations showed good performance so far.

We found that this is because WW3 used to use underestimated typhoon wind inputs, due to low grid resolution of atmospheric model under hurricane conditions.
Comparisons of two model results with buoy measurements for hurricane Katrina

When we use accurate wind inputs, the original WW3 overestimates Hs. The CWW model shows better agreement with observations.
Mean and rms errors between buoy and models (original and CWW parameterizations) for wind speed, wind direction, and significant wave heights. Comparisons are made at five locations along the track of hurricane Katrina

<table>
<thead>
<tr>
<th></th>
<th>Mean error</th>
<th>Rms error</th>
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<tbody>
<tr>
<td>wind</td>
<td>Speed (m/s)</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Direction (°)</td>
<td>-1.84</td>
</tr>
<tr>
<td>Significant wave height</td>
<td>Original (m)</td>
<td>-1.51</td>
</tr>
<tr>
<td></td>
<td>CWW (m)</td>
<td>-0.37</td>
</tr>
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Statistically, the mean and rms errors are reduced by the coupled model
3. Effect of coupling on the storm surge modeling

Moon et al. 2009 (Ocean Modeling)
1. Three types of wind stress parameterizations

(i) The linear relationship by Wu (1981)

(ii) A fast-increasing $C_d$ used in WAVEWATCH III (WW3)

(iii) A leveling-off $C_d$ by Coupled Wave-Wind (CWW) model (Moon et al., 2004), which is consistent with recent measurements at high winds
2. Three domains to investigate effects of model grid resolution

(i) Large domain: Coarse resolution (1/12°) grid

(ii) First nested domain: High resolution (1/60°) grid

(iii) Second nested domain: Very high resolution (1/360°, 300m)
A Selected Typhoon for Experiments

Typhoon Maemi (2003)

The strongest typhoon that ever hit Korean coasts

Produced a lot of storm surge damage
Storm Surge Model

KORDI-S (Lee et al., 2007)

: A depth-averaged hydrodynamics model developed by KORDI

Spatial distributions of computed surge level for typhoon Maemi
Maximum surge about 2m occurs at southern coasts of Korea
Effects of model resolution on the surge prediction

- In this experiment, all conditions are same except model resolution
- Used three model grid resolution: 1/12°, 1/60°, 1/360°

Higher resolution grids produce higher surge level
In the past, many storm surge model could not have sufficient grid resolution!!
As a result, storm surge was underestimated in many models.
To compensate this, it seems that model requires higher wind stress
Experiment 2

Effects of wind stress parameterization

- If we use very accurate wind input and high resolution grid, the Wu and WW3 with high drag at high wind speed produce overestimated surge.

- The CWW with the reduced Cd at high wind speeds produces the most accurate surge height.
For the case when the wave-coupled model is not available

A New Empirical Formula of $Z_0$

$Z_0$ is expressed by a function of wind speed

Ignoring sea state dependence

Overcome the big difference

Based on the CWW model simulations for 10 hurricanes

Regression coeff. = 0.99

Moon et al. (2007, Mon Wea Rev)

\[
Z_0 = \begin{cases} 
\frac{0.0185}{g} (0.001W^2 + 0.028W)^2, & W \leq 12.5 \text{ m/s} \\
(0.085W - 0.58) \times 10^{-3}, & W > 12.5 \text{ m/s}
\end{cases}
\]
Drag Coefficients

$\frac{Z_{ch}}{\kappa} = 0.0185$

$C_d = \kappa^2 \left( \ln \frac{10}{z_0} \right)^{-2}$

Drag coefficient relationship as a function of wind speed

- For $W \leq 12.5$ m/s, the new $C_d$ represents a monotonic increase with wind speed as in the operational GFDL model. But for $W > 12.5$ m/s, the new $C_d$ tends to level off between 2 and 3. This is similar to the trend observed by Donelan et al. (2004) and is within the error bars estimated by Powell et al. (2003)
Test of the new momentum flux parameterization for the GFDL model hurricane predictions

Moon et al. 2007 (Mon. Wea. Rev.)

Five-day Forecasts Experiments
Eleven cases during five hurricanes

- **Isabel** (00 UTC 10 September, 18 UTC 18 September, 00 UTC 12 September, 00 UTC 12 September),
- **Ivan** (00 UTC 10 September, 06 UTC 10 September, 00 UTC 11 September, 00 UTC 12 September),
- **Frances** (06 UTC 1 September),
- **Jeanne** (00 UTC 19 September)
- **Charley** (18 UTC 11 August)
The skill of empirical parameterization is comparable to that of the full wave-coupled model.
Limitation of predicting hurricane wind structure

**Operational**
Wind Field: Isabel, Initial time: 06Z 12 Sep

**Uncoupled**
06Z 14 Sep 2003

**Coupled**
06Z 14 Sep 2003

**Wave-Coupled**

**Empirical Zo**
(b) Wind Field: Isabel, Initial time: 06 UTC 12 Sep

CHOM Z0MOD
06 UTC 14 Sep 2003

**HRD**

HRD Wind Field at 7:30Z 14 Sep.

**HRD**

Because we ignore the wave dependency
• Air-sea momentum flux is strongly wave-dependent. The behaviors of drag coefficient at high wind speeds are very different from those at low winds.

• Simulation results from the coupled wave-wind model show that drag ceases to increase with wind speed at high winds, which is consistent with recent observational and theoretical trends.

• From the experiment of the coupled hurricane-wave-ocean model, it is demonstrated that hurricane intensity and wind structure as well as wind wave and storm surge predictions can be improved by the wave coupling.

• A new parameterization can be used for the case when the wave model is not available.
International Workshop on Tropical Cyclone-Ocean Interaction in the Northwest Pacific (TCOI 2009)

April 27 ~ 29, 2009
Jeju, Korea

http://www.tcoi.kr/
THE END

pdf files of references
http://mml.cheju.ac.kr/