Impacts of Shoaling Ocean Surface Waves on Wind Stress and Drag Coefficient

COASTAL RESILIENCE CENTER
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Homeland Security Challenge

Wind stress is a key parameter in storm surge modeling as it determines the capacity of wind to move water. In storm surge models, it is usually

- parameterized using the drag coefficient (Cd) that is a function of the 10-meter neutral wind speed;
- assumed to be in the same direction as the wind speed direction;
- assumed to be the same in open ocean and in coastal waters.

In this study, we use a numerical wave model to investigate how wind stress and Cd are modified by the wave shoaling during hurricane landfall.

Approach / Methodology

A. Sea-state dependent wind stress ($\vec{\tau}$)

- WAVEWATCH III (v5.16) simulated shoaling wave spectrum + two spectrum-based wind stress calculation methods (Miami[1], URI[2]);
  (only results from URI method are shown in this poster)

$$\vec{\tau} = \vec{\tau}_v + \vec{\tau}_f$$

$$\vec{\tau}_f = \int_{k_{min}}^{k_{max}} \int_{-\pi}^{\pi} \frac{\rho_w g \beta_g(k,\theta) \Psi(k,\theta)}{c} d\theta \vec{k} dk$$

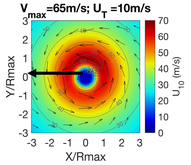
$$C_d = |\vec{\tau}| / (\rho_a |\vec{U}_{10}|^2)$$

$\vec{\tau}_v$: surface viscous stress
$\vec{\tau}_f$: wave-induced (form) stress

β_g: wave growth rate
Ψ: wave spectrum

B. Experimental Design

- Parametric wind field (Holland 1980) with following TC characteristics:
  - maximum wind speed (V_{max}): 35m/s, 65m/s
  - translation speed (U_T): 5m/s, 10m/s
  - Radius of maximum wind (R_{max}): 70km
  - translation direction: normal to the shoreline
- Bottom Slope: 1:2000, 1:200



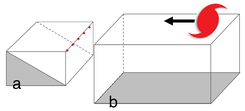


Figure 2.1 Schematics of two simulation domains.
a) sloping bottom (0~500m depth): simulate wave shoaling
b) deep water (4km depth): generate deep water TC waves in quasi-steady state

Outcomes / Results

Spatial-temporal map of shoaling effects

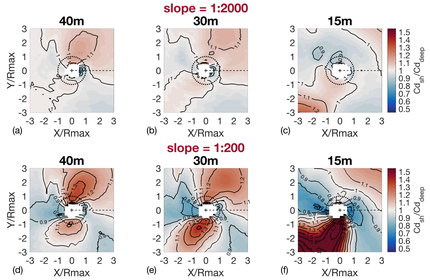


Figure 3.1 Relative change of Cd by shoaling TC waves at different depths to its deep-water counterpart .

- *As a TC passes over an isobath, Cd is increased in right toward right-rear and in left toward left-front sectors.*
- *Shoaling effects are enhanced with shallower water depths and steeper bottom slopes.*

Variability in the Cd-U_{10} relation

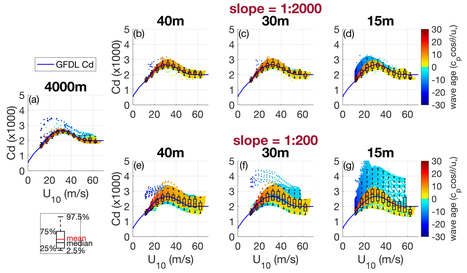


Figure 3.2 Cd-U_{10} scatter plots at different water depths.
Warm (cold) colors: angle between wind and dominant waves is less (more) than 90 degrees. Rectangular box: interquartile range.

- *As depth decreases, Cd variability at a given wind speed increases, more significant with a steep sloping bottom.*

References

[1] Donelan, M. A., Curcic, M., Chen, S. S., & Magnusson, A. K. (2012). Modeling waves and wind stress. JGR: Oceans, 117(7);

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[3] Ginis I., M. Bender, B. Thomas, M. Morin, V. Tallapragada, and A. Soloviev, 2015: A new drag coefficient formulation and its impact on the GFDL and HWRF hurricane model predictions, 19th Conference on Air-Sea Interaction, Phoenix, AZ, January 4-8, 2015

[4] Chen, X., Ginis, I., & Hara, T. (2020). Impact of Shoaling Ocean Surface Waves on Wind Stress and Drag Coefficient in Coastal Waters: 2. Tropical Cyclones. Journal of Geophysical Research: Oceans, 125(7), e2020JC016223. https://doi.org/10.1029/2020JC016223

Conclusions

- Compared to its deep-water value, Cd is
  - enhanced in the right (toward right- rear) TC quadrant due to shoaling fetch-dependent waves
  - enhanced in the left (toward left-front) TC quadrant due to swell opposing wind.
  - reduced in the front/rear quadrants due to weaker wind seas.
- The variability of wind stress magnitude (or Cd) significantly increases in shallow water at a given wind speed
- The misalignment angle between wind speed vector and wind stress vector is enhanced as water depth decreases.
- In general, the effects of shoaling TC wave on the wind stress and Cd are much stronger on a steeper bottom slope and is further enhanced with a faster propagating storm.
- This study suggests that the wind stress and Cd can be significantly modified under landfalling TCs in shallow water which can affect predictions of landfalling TCs and their impacts (e.g., storm surge).

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