Advanced coupled atmosphere-wave-ocean modeling for improving tropical cyclone prediction models

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LONG-TERM GOALS

The goals of this PI team are to understand the physical processes that control the air-sea interaction and their impacts on rapid intensity changes in tropical cyclones (TCs) and to develop a physically based and computationally efficient coupling at the air-sea interface for use in a multi-model system that can transition to the next generation of research and operational coupled atmosphere-wave-ocean-land models.

OBJECTIVES

The main objectives of this research are to 1) develop and implement a new, unified air-sea interface module for fully coupled atmosphere-wave-ocean modeling systems with a general coupling framework that can transition from research to operations, 2) implement the unified module into NOAA's HWRF and Navy's COAMPS-TC coupled systems, 3) develop new air-sea coupling parameterizations of the wind-wave-current interaction and sea spray effects and implement them in the unified module, 4) explore new physics in wind-wave-current coupling at the air-sea interface, including wave-breaking and spray and bubble processes, 5) test the generality of the air-sea interface coupling and sensitivity to various physical parameterizations in the atmosphere boundary layer (ABL) and the ocean mixed layer (OML) in the extreme wind conditions of TCs with multi-model components in the coupled modeling systems, 6) evaluate and validate the coupled modeling systems in relatively data rich regions in the Atlantic and Northwest Pacific, and 7) demonstrate the utility of the newly developed air-sea interface module (ASIM) for improving TC intensity forecasts in real-time.

APPROACH AND WORK PLAN

In this project, multiple atmosphere, wave, and ocean model components are used in the development and testing of physical coupling parameterizations, including the high-resolution, nonhydrostatic, multi-nested grid HWRF, COAMPS-TC models and nested-grid GFDL (atmosphere), WAVEWATCH III (wave), and POM and NCOM (ocean). At the heart of the coupled system is a computationally efficient, unified Air-Sea Interface Module (ASIM) that establishes a consistent, physically based representation of the air-sea interface. A key requirement for the ASIM is that it supports both technical and scientific interoperability over a range of models, parameterizations, and data resources. Model development effort under this proposal involves 1) improving physical parameterizations of the air-sea heat and momentum fluxes at and near the sea surface with fully coupled wind-wave-current interaction and sea spray effects and 2) forging a comprehensive, scientifically integrated, computationally efficient multi-model coupled system from individual components using the Earth System Modeling Framework (ESMF).

This research is conducted as a team with scientists at University of Rhode Island (URI), University of Miami (UM), University of Washington (UW), Nova Southeastern University (NSU), University of Hawaii (UH), NorthWest Research Associates, Inc. (NWRA), Naval Research Labs (NRL) at Monterey and the Stennis Space Center, National Center for Atmospheric Research (NCAR), NOAA/Earth Systems Research Laboratory (ESRL), and NOAA/Environmental Modeling Center (EMC). PIs Shuyi Chen of UM and Isaac Ginis of URI are responsible for overall coordination of all aspects of the research. Isaac Ginis and Tetsu Hara of URI are responsible for the development of the URI air-sea coupling parameterization and for implementing the URI parameterization into the unified air-sea interface module and carrying out model testing and TC simulations with the coupled HWRF-WAVEWATCH III-HYCOM system. Co-PIs Alexander Soloviev of NSU and Roger Lukas of UH are responsible for implementing the two-phase transition layer model into the URI parameterization and investigating the impact of the wave-induced form drag (including air-flow separation from waves) on the sea-state dependence of the drag coefficient at high wind speeds. Co-PIs Edgar Andreas of NWRA and Chris Fairall and Jian-Wen Bao of NOAA/ESRL are responsible for implementing an interfacial flux algorithm of the near-surface distribution of spray into the URI parameterization and calibrating the predicted spray concentration profile in the lower atmosphere against available measurements. Jian-Wen Bao and Chris Fairall of NOAA/ESRL are also responsible for development and implementation of the overall sea-spray parameterizations in the unified air-sea interface module (ASIM).

WORK COMPLETED

The main accomplishments during the third year of this project for the URI team and its collaborators are: 1) delivery the unified air-sea interface module (ASIM) to NCEP/EMC and assistance in its implementation into the HWRF-WAVEWATCH-POM and GFDL-WAVEWATCH-POM coupled models, 2) implementation of sea spray effects into the air-sea interface module, 3) a new algorithm for sea spray-mediated heat, moisture, and enthalpy flux across the air-sea interface, 4) a new approach to drag coefficient parameterization, 5) investigation of Stokes drift due to ocean surface waves and its effect on air-sea momentum flux budget under hurricane conditions, 6) investigation of the effects of sea states on the drag coefficient (air-sea momentum flux) using two different theoretical approaches, 7) completed documentation of the unified air-sea interface module for general applications, and 6) peer-reviewed publications.

Some of the results are briefly presented below. The work completed by the UM PI team is described in a separate report.

RESULTS

a) Implementation of unified air-sea interface module into the HWRF and GFDL coupled hurricane-wave-ocean models

The coupled atmosphere-wave-ocean modeling framework developed under the NOPP funding has been implemented into the NOAA's HWRF and GFDL hurricane prediction systems. Please note the implementation into the GFDL model was done instead of COAMPS-TC because the COAMPS-TC code has not been made available to our research group during the time of this project. In the coupled framework, which is based on a comprehensive, physics-based treatment of the wind-wave-current interaction, the bottom boundary condition of the atmospheric model incorporates sea-state dependent air-sea fluxes of momentum, heat, and humidity, and it includes the effect of sea-spray. The wave model is forced by the sea-state dependent wind stress and includes the ocean surface current effect. The ocean model is forced by the sea-state dependent wind stress and includes the ocean surface wave effects (i.e. Coriolis-Stokes effect, wave growth/decay effect, and Langmuir turbulence effect). Figure 1 shows the surface wind and significant wave height in a coupled HWRF-WAVEWATCH-POM simulation of Hurricane Irene (2010).

The new wind stress calculation parameterization includes 1) an updated URI wind stress calculation with a new tail parameterization (Reichl et al. 2012) and 2) the new University of Miami wind stress calculation (Donelan et al. 2012). Two additional modules implemented into the coupled air-sea interface calculate the momentum fluxes due to the Coriolis-Stokes and wave growth/decay effects. These fluxes are subtracted from the wind stress to calculate the momentum flux that drives the ocean model. Figure 2 shows the components of the new HWRF coupled air-sea interface: momentum flux in the atmospheric model (wind stress), momentum flux due to wave growth/decay (wave momentum budget), and momentum flux due to the Coriolis-Stokes effect. The results indicate that under tropical cyclone conditions, the effective wind forcing (momentum flux) on ocean currents may be significantly different from the wind stress because the surface wave field is typically underdeveloped and complex.

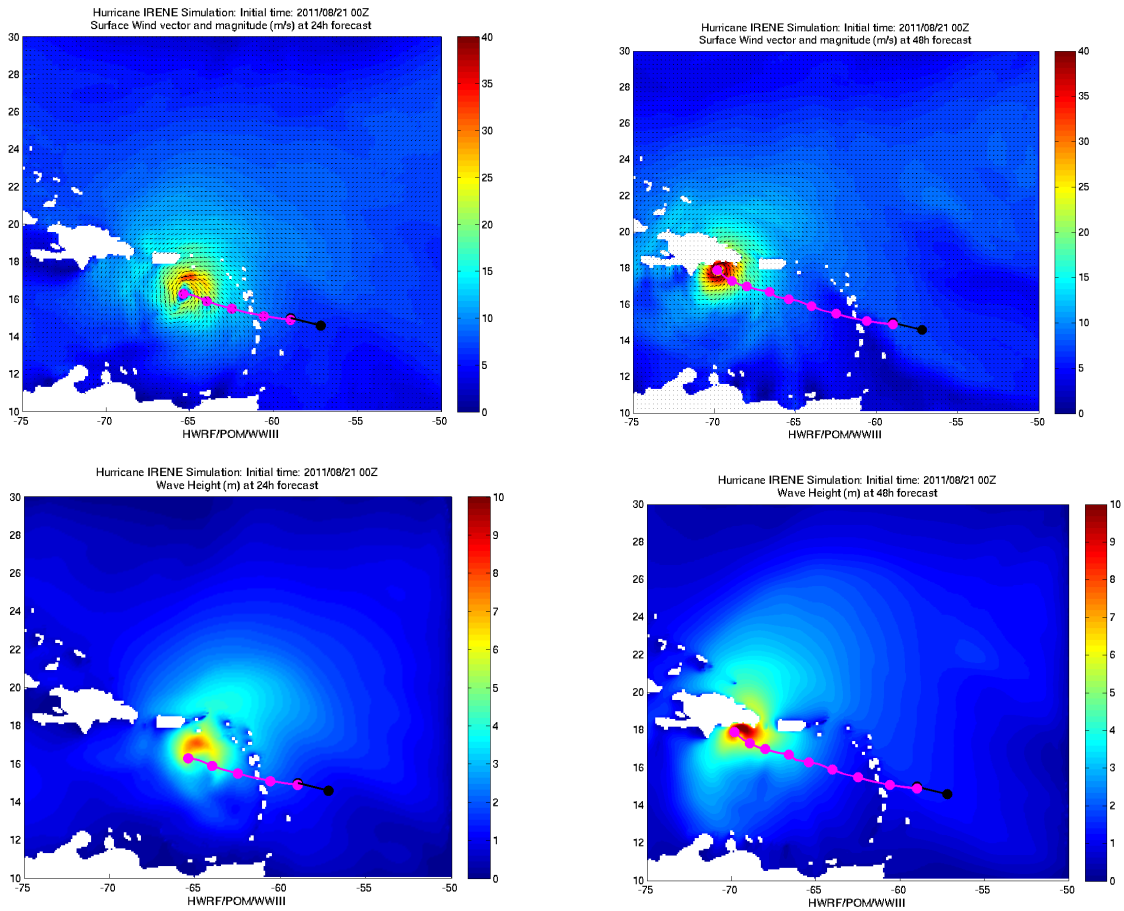

***Figure 1**. Surface wind (top) and significant wave height (bottom) at 24 h (left) and 48 h (right) in the coupled HWRF-WAVEWATCH simulation of Hurricane Irene. Initial time: 00 UTC 21 August 2012.*

b) Implementation of sea spray effects into the air-sea interface module

The new air-sea interface module includes the NOAA/ESRL sea spray parameterization scheme (Bao et al. 2011). The ESRL sea-spray scheme predicts that the overall impact of sea-spray droplets on the mean winds depends on the wind speed at the level of sea-spray generation. As the wind speed increases, the average droplet size and the total mass of droplets increases, leading to an increase in the overall wind speed in the surface layer above the level of sea-spray generation. Thermodynamically, the size of droplets at hurricane-intensity winds is so large that they do not have enough time to evaporate that much before falling back into the sea. When the large droplets are still in the air, they have sufficient time to release sensible heat to the ambient air and increase the buoyancy of the surface layer and enhancing the turbulent mixing. Mechanically, the suspension of sea-spray droplets reduces the buoyancy and makes the surface layer more stable. As a consequence, the friction velocity is lowered and the downward turbulent mixing of momentum is reduced.

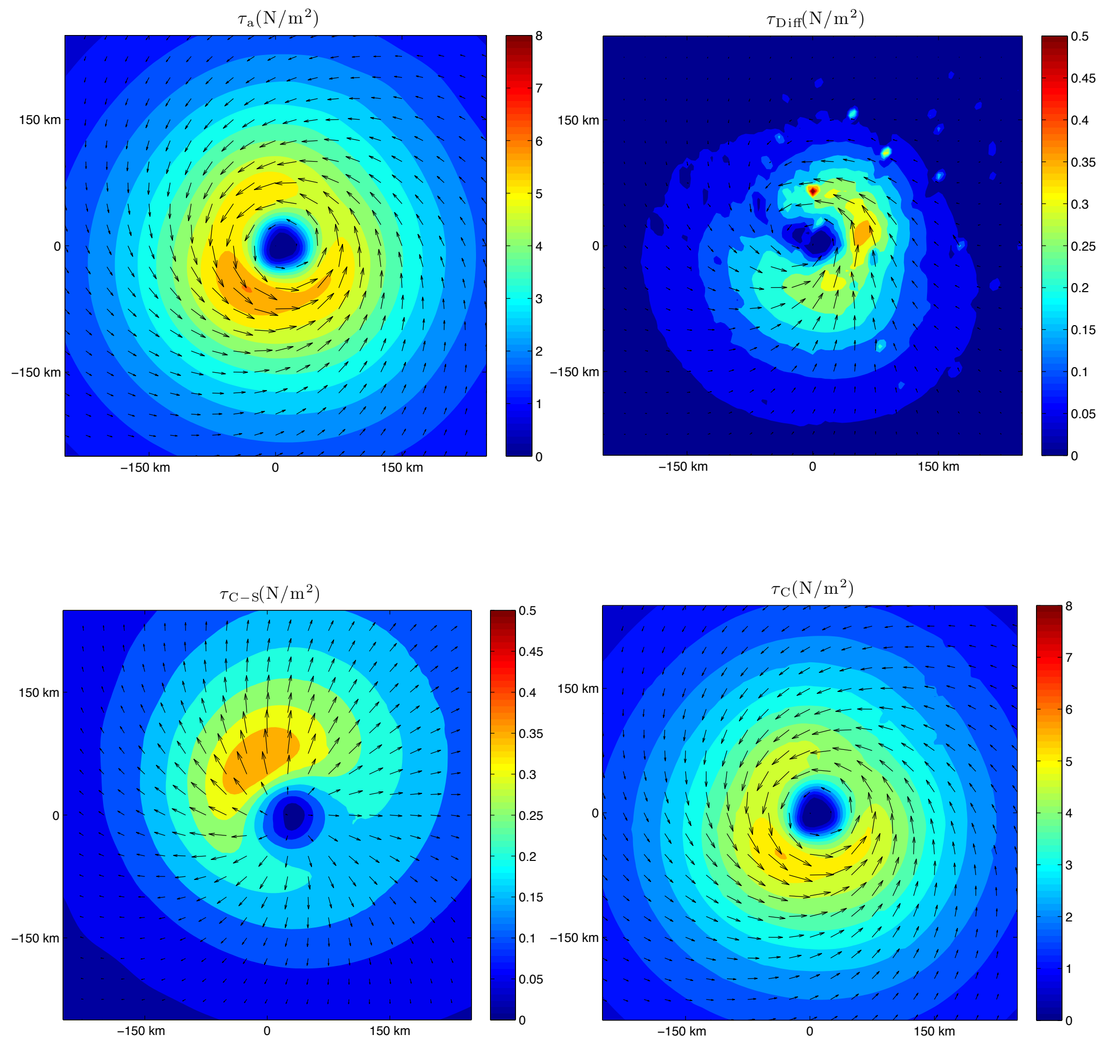

Figure 2*. Components of the new air-sea module in the HWRF coupled atmosphere-wave-ocean system: momentum flux in the atmospheric model (wind stress, upper left), momentum flux to the wave momentum budget (upper right), momentum flux due to the Coriolis-Stokes effect (lower left), and momentum flux into the ocean model (lower right). The hurricane is moving westward.*

As the cyclone continues intensifying, the reduced friction velocity, however, leads to an increased shear between the surface and the flow above the surface layer, which in turn increases the shear-induced vertical mixing in the surface layer. Also, enhanced air-sea enthalpy flux provides necessary energy to further intensify the cyclone, which in turn induces more vertical mixing. Figure 3 depicts the differences made in an idealized tropical vortex intensification case by including the ESRL sea-spray parameterization scheme in the GFDL atmosphere-wave-ocean coupled model. It is seen in the surface wind speed output that the inclusion of sea spray increases the maximum simulated surface wind speed and renders a more symmetric eyewall of the simulated vortex. The inclusion of sea spray also changes the azimuthally-averaged vertical structure of the simulated radial and tangential winds, resulting in a noticeable increase in both the tangential wind and the boundary-layer inflow.

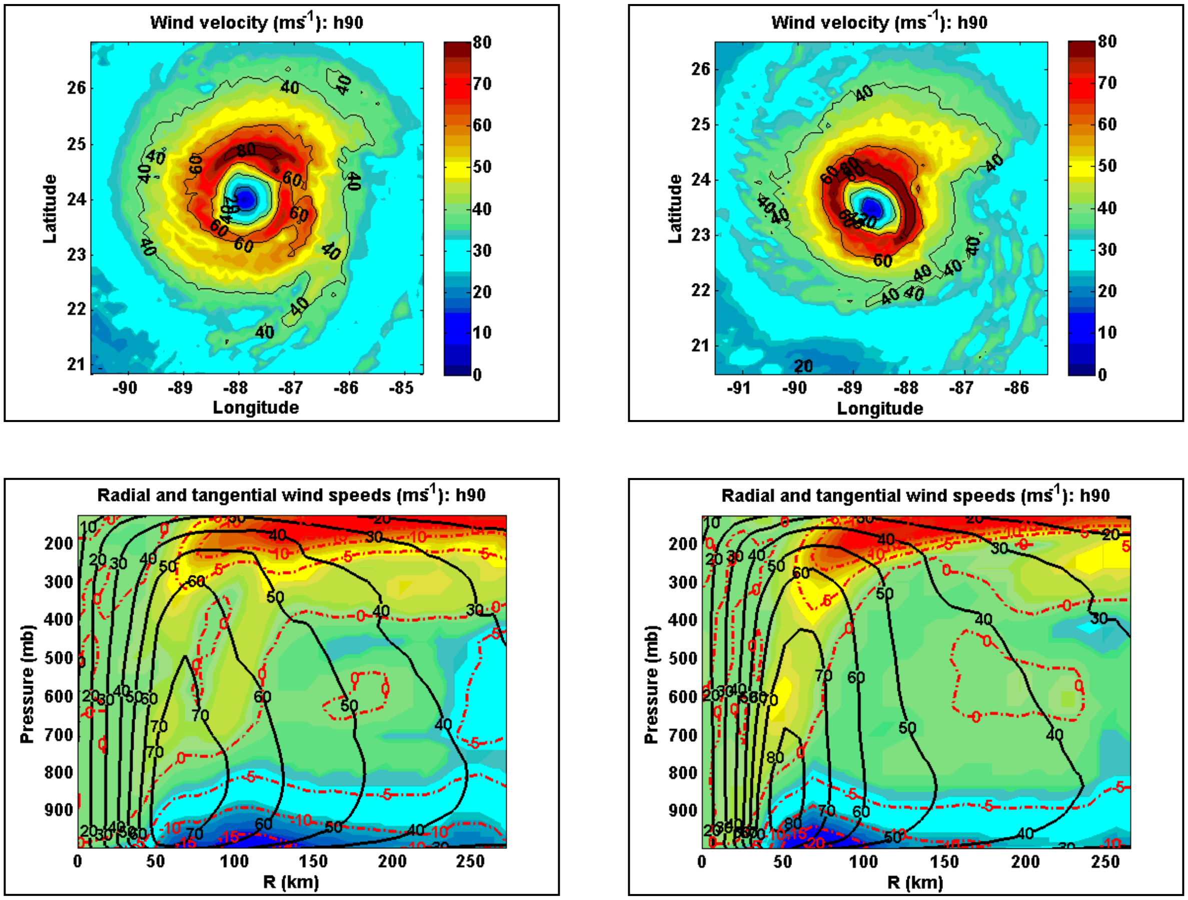

Figure 3. *Implementation of the ESRL sea spray module into the GFDL hurricane-wave-ocean coupled system. Upper panels: surface wind speed with (left) and without (right) sea spray. Low panels: azimuthally-averaged vertical structure of the simulated radial and tangential winds with (left) and without (right) sea spray.*

c) A new algorithm for sea spray-mediated heat, moisture, and enthalpy flux across the air-sea interface

One of the Co-PIs, Edgar Andreas, developed a theoretically based surface flux algorithm that accounts for both the interfacial and spray-mediated routes by which heat, moisture, and enthalpy cross the air-sea interface. For the sake of brevity, we write Andreas's surface flux algorithm in skeleton form as

$$H_{L,T} = H_L + \alpha Q_L, \tag{1a}$$

$$H_{s,T} = H_s + \beta Q_S - (\alpha - \gamma) Q_L, \tag{1b}$$

$$Q_{en,T} \equiv H_{L,T} + H_{s,T} = H_L + H_s + \beta Q_S + \gamma Q_L . \tag{1c}$$

Here, $H_{L,T}$, $H_{s,T}$, and $Q_{en,T}$ are the total air-sea fluxes of latent heat, sensible heat, and enthalpy. Each such flux has two components, an *interfacial* flux (H_L, H_s, and $H_L + H_s$, respectively) and a *spray-*

mediated flux (the remaining terms). Also in (1), Q_L and Q_S are "nominal" spray latent and sensible heat fluxes from Andreas's microphysical spray model. These terms account for the heat and moisture transfer facilitated by all sea spray droplets that are formed with radii between 1.6 and 500 μm. Although Q_L and Q_S are theoretically based, there are some uncertainties and some approximations in this microphysical model; hence, the α, β, and γ coefficients let us tune the model with data. Andreas and DeCosmo (2002) and Andreas et al. (2008, 2012) provide many more details.

With only three fitting coefficients, this algorithm can explain both the magnitude and the wind speed dependence of over 4000 flux observations collected from a variety of platforms at latitudes ranging from the equator to the Arctic Circle. Of special note is the fact that this algorithm accurately predicts the wind speed dependence in the measurements. This success justifies our extrapolating the algorithm to hurricane-strength winds, where we can use it to predict the crucial air-sea heat fluxes that power these storms.

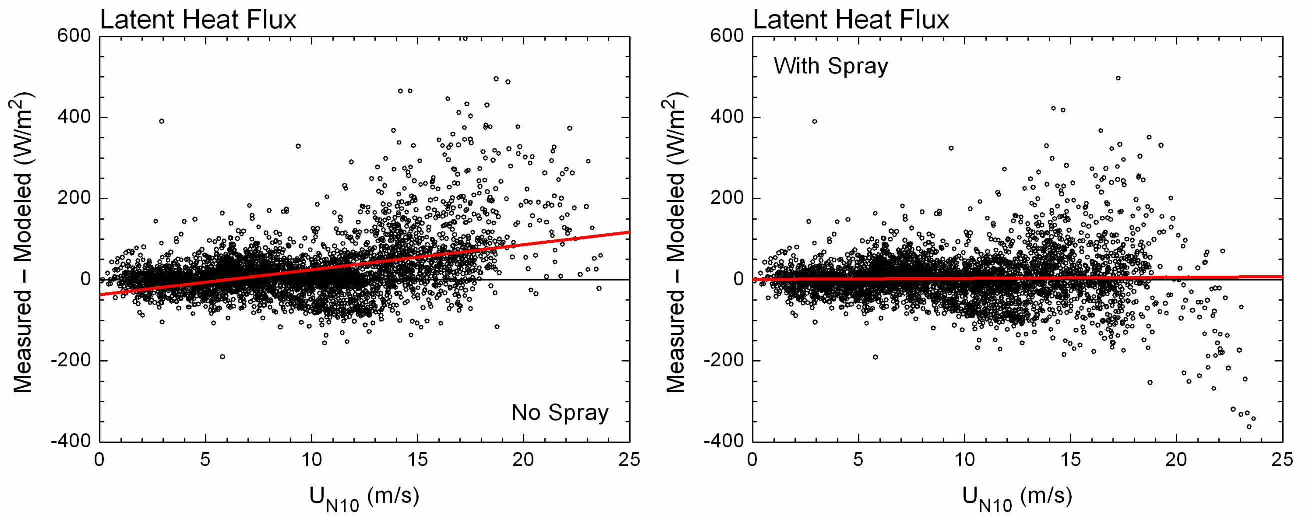

Figure 4. *Model estimates of the total air-sea flux of latent heat based on (1a) are subtracted from eddy-covariance measurements of the latent heat flux; this difference is plotted against the 10-meter, neutral-stability wind speed, U_{N10}. The left panel shows model values with no spray contribution; that is, $\alpha = 0$ in (1a). The right panel shows the full model that accounts for both spray and interfacial transfer. Here, $\alpha = 2.46$. In each panel, the red line is the least-square fit through the data. In the "No Spray" panel on the left, the best fit obviously increases with wind speed and suggests that the measurements are, on average, above the modeled flux when U_{N10} is above 12–13 m/s. This behavior is a signature of spray-mediated transfer. In the "With Spray" right panel, in contrast, by properly accounting for the spray-mediated transfer, (1a) is able to produce a modeled latent heat flux that has proper magnitude and wind speed dependence; that is, the "Measured – Modeled" values are, on average, zero for all wind speeds.*

d) A new approach to drag coefficient parameterization

Co-PIs Alex Soloviev and Roger Lukas have developed a unified modeling framework for the two-phase environment under very high wind speeds. It resulted in a parameterization for the drag coefficient, C_d, for situations where form-drag due to surface waves is negligible. The role of sea spray in this model framework is, however, completely different from existing models, in which the sea spray effect on the air-sea drag is due to the buoyancy suppressing turbulent friction. In our unified model, the two-phase environment developing at the air sea interface eliminates a portion of the wind-wave wavenumber spectrum, which is responsible for a substantial part of the air sea drag coefficient.

In order to investigate the mechanism of the breakup of the air-sea interface and dynamics of the two-phase transition layer, numerical experiments using the volume of fluid multiphase computational fluid dynamics model were conducted, which allowed us to simulate the air-sea interface including surface tension at the water surface. The results have demonstrated that the KH instability of the air-water interface takes place but predominantly near wave crests (Figure 5).

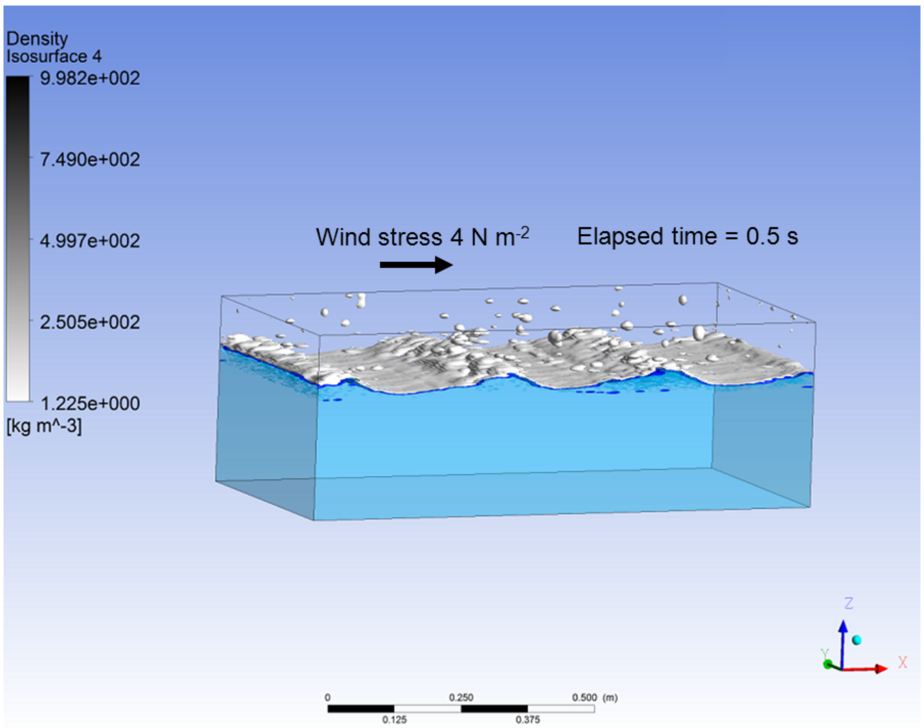

Figure 5. *Snapshot from a computational fluid dynamics experiment with imposed short waves demonstrates the tearing of wave crests, formation of water sheets and spume ejection into the air, 0.5 s after hurricane force wind stress is imposed at the top of the air layer. The two-phase mixture (density scale at left) of air and water covers the surface, and individual bubbles and spray droplets are also apparent. The length scale is indicated. From Soloviev et al. (2012a).*

We have developed an approach that unifies wave-form drag and two-phase turbulent drag parameterizations (Soloviev et al., 2012b). In order to represent hurricane conditions, we have extended the Farrell and Ioannou (2008) concept to the case of very high wind speeds by adding the effects of the two-phase environment on short gravity-capillary waves ("ultragravity waves", following Munk, 2009). While reaching saturation, the ultragravity wave spectrum is also progressively damped for higher wind speeds, and the wavenumber at which the curvature spectrum rolls off is correspondingly smaller as the thickness of the two-phase layer increases. The damping is justified by the increased turbulent dissipation, which affects the shortest waves. It is also justified by the fact that the two-phase layer of thickness *H* cannot support ultragravity waves that are shorter than a certain threshold. As a conservative estimate, we have selected a threshold condition $H = \lambda/2$, where λ is the wavelength. Comparison of the unified drag coefficient parameterization with laboratory and field measurements shows leveling off (or even some reduction) of the drag coefficient under hurricane conditions (Figure 6).

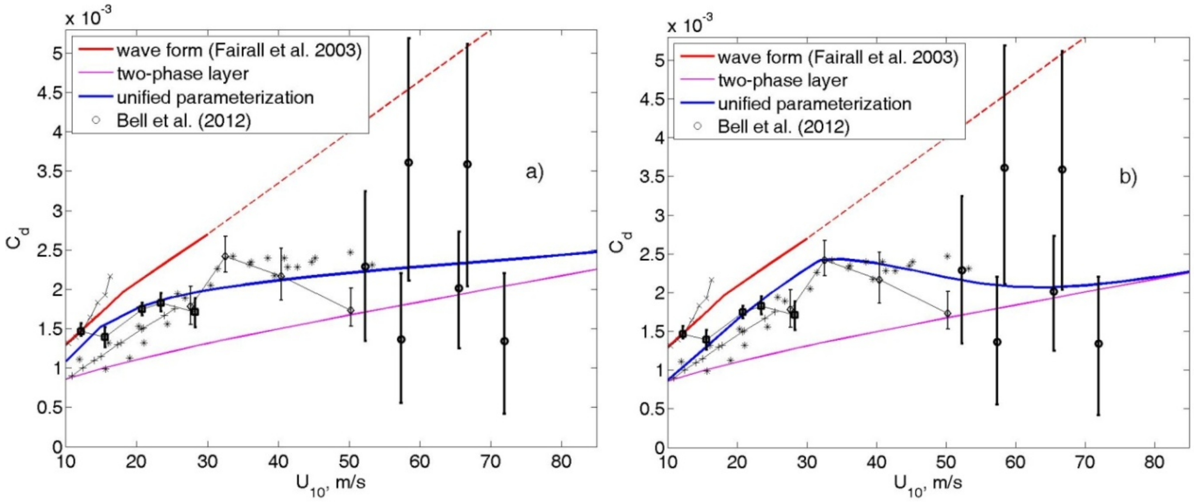

Figure 6. *Comparison of the new air-sea drag parameterization (blue) with the upper (wave form; red) and lower (two-phase layer; purple) bounds. The two panels use the exponential growth factor parameterization according to: (a) Donelan and Pierson (1987) parameterization and (b) Hsiao and Shemdin (1983). Available data from laboratory and field experiments by Donelan et al. (2004), Powell et al. (2003), Black et al. (2007) and Bell et al. (2012) are also shown.*

e) Investigation of stokes drift due to ocean surface waves and its effect on air-sea momentum flux budget under hurricane conditions

Recent studies suggest that upper ocean turbulent mixing may be significantly modified due to ocean surface waves. Surface waves introduce net mass transport called "Stokes drift" near the water surface. This Stokes drift interacts with turbulent eddies in a complex manner, depending on different wind and wave conditions (Langmuir turbulence). In addition, the combination of the Stokes drift and the Coriolis force modifies the upper part of the Ekman spiral (Coriolis-Stokes effect), and it effectively modifies the momentum flux into ocean currents below (Polton et al. 2005).

We have investigated how the Coriolis-Stokes effect modifies the air-sea momentum flux budget. Previously we have shown that the momentum flux into ocean currents can be significantly different from the momentum flux from wind (wind stress) when the surface wave field is evolving (Fan et al. 2010). This effect can be quantified accurately if the surface wave field is predicted in time and in space (e.g., by WAVEWATCH). In addition to the wave evolution effect, the momentum flux into currents is modified by the Coriolis-Stokes effect, such that

$$\tau_{cur\,\alpha} = \tau_{air\,\alpha} - \tau_{diff\,\alpha} + \tau_{c-s\alpha} \quad = \tau_{air\,\alpha} - \frac{\partial}{\partial t} M_\alpha - \frac{\partial}{\partial x_\beta} MF_{\alpha\beta} + \tau_{c-s\alpha}$$

$$M_{\alpha} = \int_{-\infty}^{\hat{\eta}} u_{s\alpha} dz, \qquad MF_{\alpha\beta} = \int_{-\infty}^{\hat{\eta}} S_{\alpha\beta} dz, \qquad \tau_{c-s\alpha} = \int_{-\infty}^{\hat{\eta}} \varepsilon_{\alpha\beta z} f u_{s\beta} dz$$

Here, τ_{cur} is the surface stress applied to ocean currents, τ_{air} is the wind stress, M is the wave momentum, MF is the horizontal wave momentum flux, u_s is the Stokes drift, S is the Radiation stress, and τ_{c-s} is the Coriolis-Stokes term. The subscripts α, β denotes horizontal directions. We have estimated the wave evolution effect τ_{diff} as well as the Coriolis-Stokes effect τ_{c-s} under stationary and translating tropical cyclone conditions.

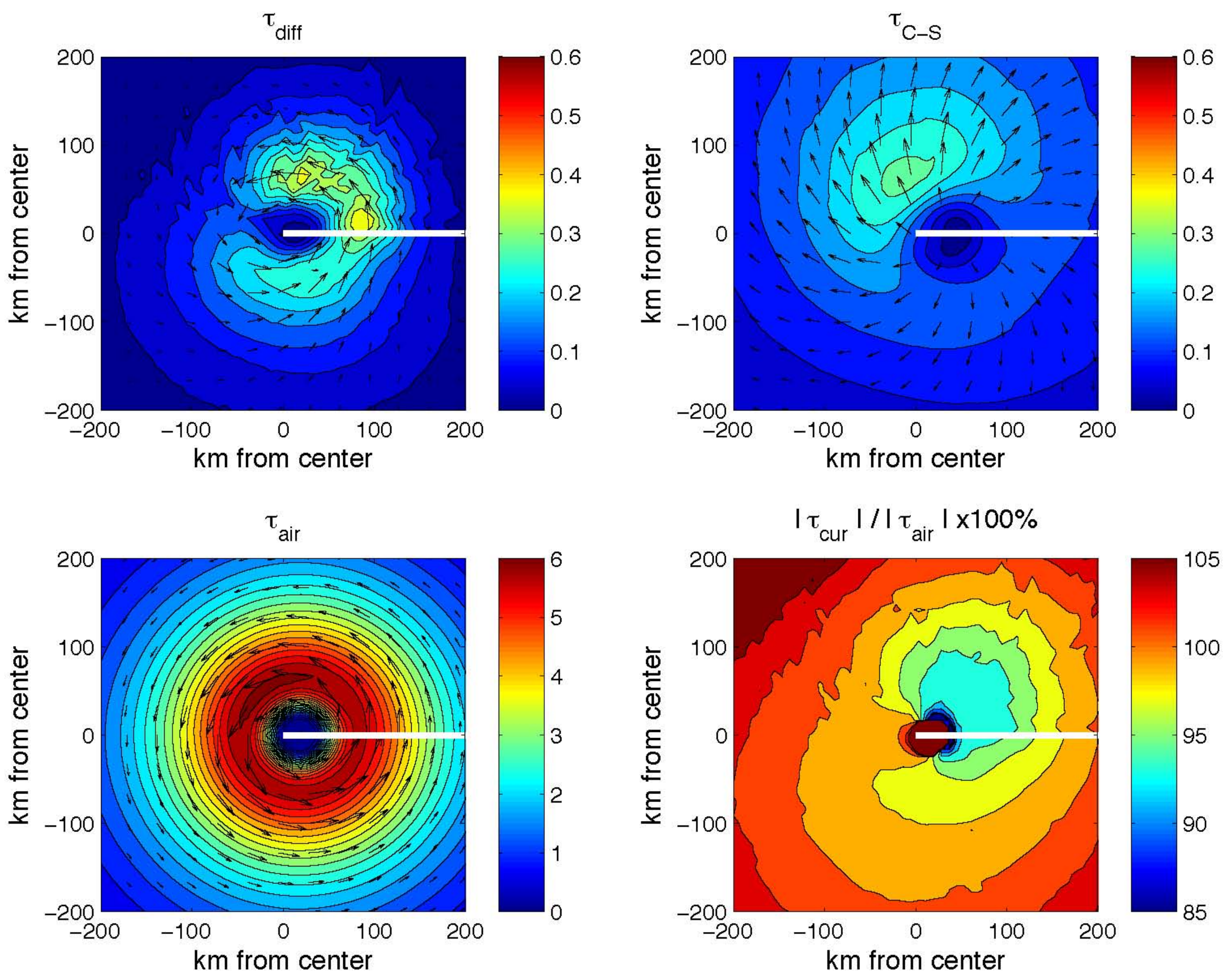

Figure 7. *Difference between momentum flux into ocean currents τ_{cur} and momentum flux from wind τ_{air} (wind stress), due to the wave evolution effect τ_{diff} and the Coriolis-Stokes effect τ_{c-s} under tropical cyclone condition. Maximum wind speed is 45 m/s, Radius of maximum wind is 70 km, and translation speed (to the left) is 5 m/s. In the first 3 panels the color scale shows the stress magnitude and the arrows show the stress direction.*

In Figure 7 we present τ_{diff} and τ_{c-s} under a tropical cyclone with a translation speed of 5 m/s. Although the magnitudes of τ_{diff} and τ_{c-s} are comparable, their directions are vastly different. In particular, on the right hand side of the storm track the wave evolution effect tends to reduce the magnitude of τ_{cur}, while the Coriolis-Stokes effect tends to modify the direction of τ_{cur}. When the both effects are combined, the magnitude of τ_{cur} is significantly reduced from the magnitude of τ_{air}, particularly in the rear right quadrant. This reduction of the momentum flux may decrease the upper ocean mixing and the resulting sea surface temperature cooling, hence, may increase the heat flux from ocean to the tropical cyclone.

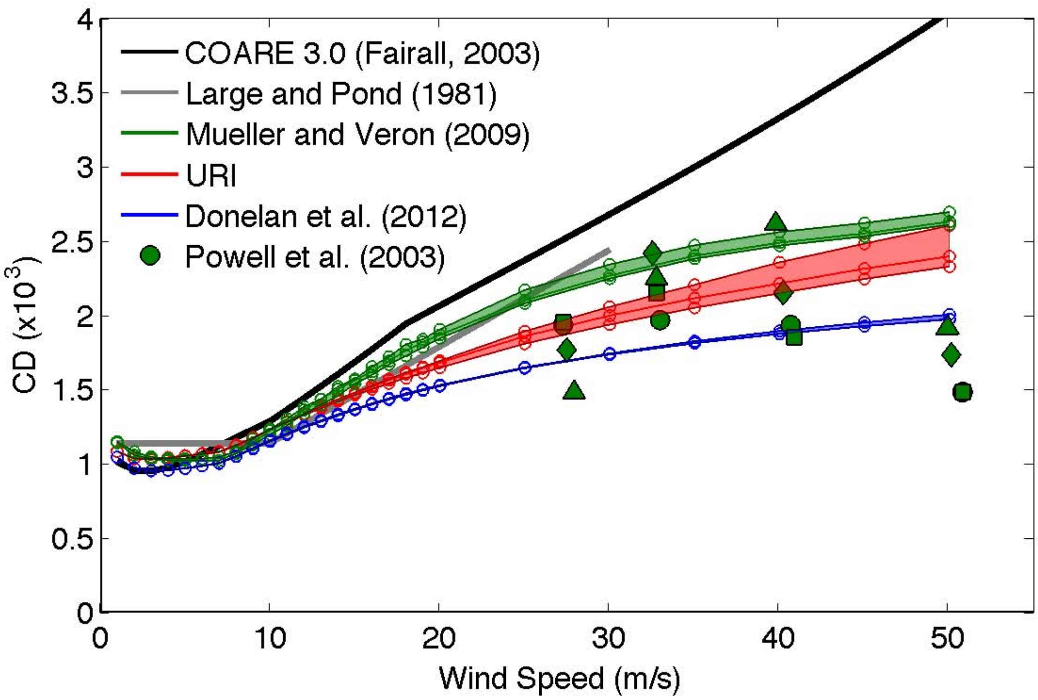

Figure 8. *Drag coefficient over fetch dependent (growing to fully developed) surface waves estimated using three different approaches. The wave spectrum is based on Elfouhaily et al. (1997). With each method, the upper bound is for younger seas and the lower bound is for the fully developed seas.*

f) Investigation of the effects of sea states on the air-sea momentum flux

The relationship between the 10 meter wind speed and the wind stress can be modified depending on different sea states. Normally, the directions of the wind speed and the wind stress are assumed identical, and the drag coefficient is defined as the ratio of the wind stress magnitude and the 10 meter wind speed squared. Previously, it has been suggested that the drag coefficient is larger for younger (less developed) seas at low to moderate wind speeds (e.g., Drennan et al. 2003). Moon et al. (2004) estimated the drag coefficient under high (tropical cyclone) wind speeds by explicitly estimating the form drag due to a spectrum of waves, and showed that the drag coefficient may not increase or even decrease with younger seas.

We have improved the estimation of the sea state dependent drag coefficient using two theoretical approaches that are recently developed. The first approach (URI) is an extension of the approach developed by Moon et al. (2004). It has been updated by improving the spectral tail parameterization (the unresolved high frequency part of the wave spectrum), based on recent observational and theoretical findings (Riechl et al, 2012). The second approach (UM) is developed by Donelan et al. (2012). The two approaches are different in the following two areas: (a) the growth rate is parameterized based on the wind stress in the URI approach and based on the wind speed in the UM approach, (b) inside the wave boundary layer, the mean wind profile is modified (i.e., it is not logarithmic and may rotate) in the URI approach but is logarithmic and does not rotate in the UM approach.

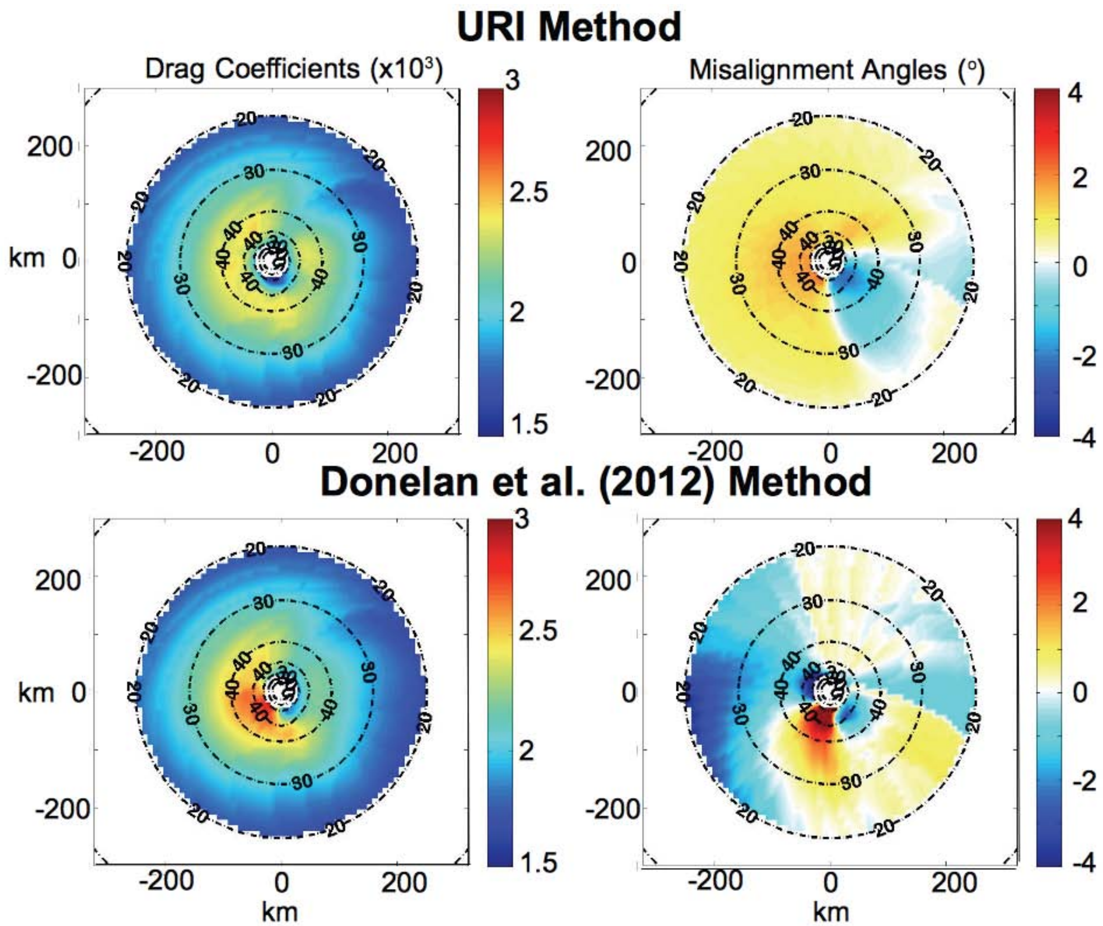

Figure 9. *The drag coefficient under a tropical cyclone estimated by two different approaches. Maximum wind speed is 45 m/s, Radius of maximum wind is 70 km, and translation speed (to the north) is 10 m/s. The right panels show misalignment angle between wind speed and wind stress.*

We have applied the two approaches using identical surface wave spectra and wind speed conditions under uniform wind forcing (fetch dependent seas) and under tropical cyclone conditions. Figure 8 shows the results of the drag coefficient with fetch dependent seas (fetch from 10 km to infinity) using the empirical wave spectrum of Elfouhaily et al. (1997). For reference, the results of Mueller and Veron (2009) are also shown. The overall results of the drag coefficient are quite similar even if the three approaches are significantly different. The drag coefficient levels off at high wind speeds. All three approaches show relatively weak sea state dependence of the drag coefficient.

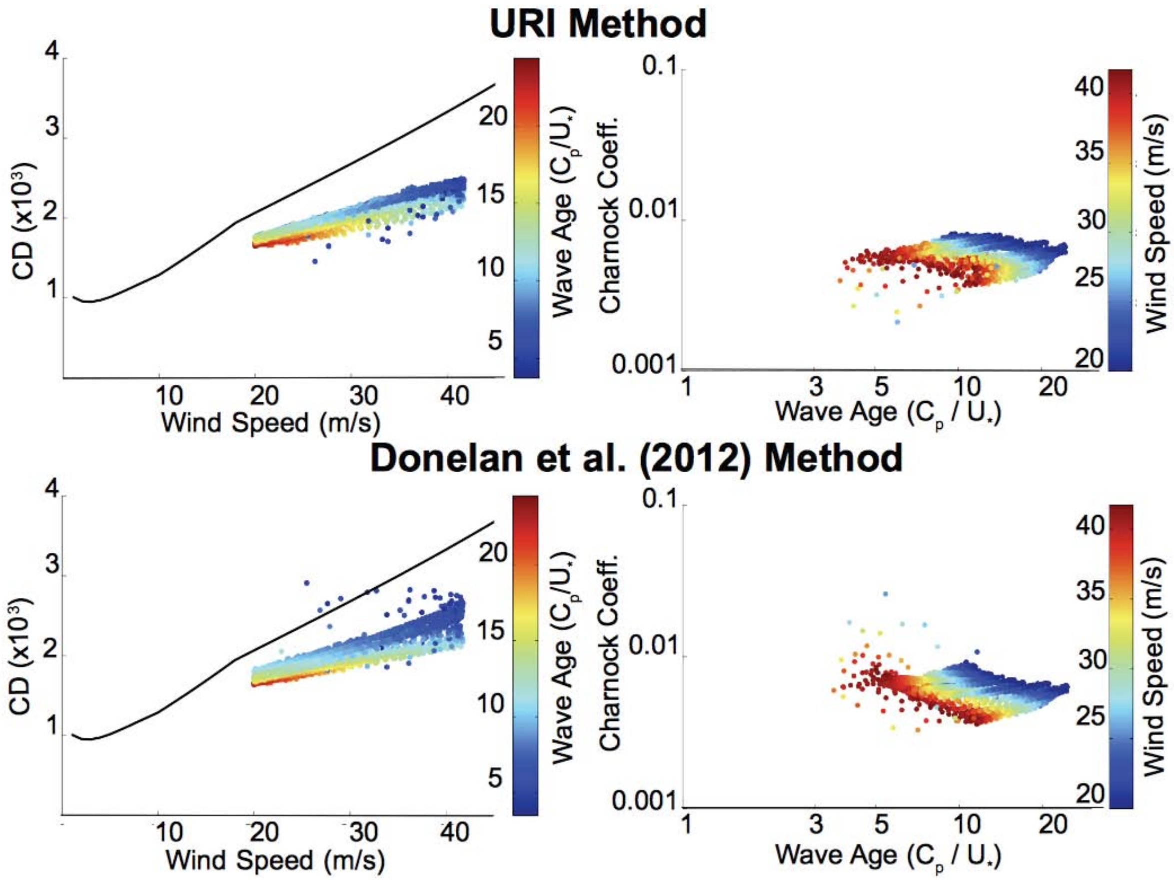

Figure 10*. The drag coefficient and the Charnock coefficient under a tropical cyclone. All parameters are the same as in Figure 9. Left panels show the wave age dependence of the drag coefficient at a fixed wind speed. Right panels show the dependence of the Charnock coefficient on the wave age.*

Next, we applied the URI and UM approaches with surface wave spectra simulated by WAVEWATCH under tropical cyclone conditions. Since WAVEWATCH does not resolve the high frequency part (tail) of the spectrum, we need to specify the spectral tail. Moon et al. (2004) used the theoretical tail spectrum of Hara and Belcher (2002), which was later found too high compared with observed values. We have therefore kept the spectral tail level low, being consistent with recent findings. Figure 9 shows the drag coefficient under a translating tropical cyclone calculated by the URI and the UM approaches. The drag coefficient values are quite similar and the sea state dependence is relatively weak in both approaches. The UM result shows a slight increase of the drag coefficient in the left real quadrant, where the sea is less developed. A notable difference between the two approaches is the misalignment angle between the 10 meter wind speed and the wind stress. While the URI approach always predicts small misalignment less than 2 degrees, the misalignment angle may exceed 4 degrees by the UM approach, particularly inside the radius of maximum wind. This difference is likely due to the different assumptions of the wind profile inside the wave boundary layer. The URI approach allows the wind speed vector to rotate inside the wave boundary layer, and the vertical wind shear is aligned with the wind stress direction above the wave boundary layer, i.e., the misalignment angle between the wind stress and the wind speed decreases with height. In contrast, the UM approach assumes that the wind direction (as well as the misalignment angle) is fixed from the surface to the 10 meter height. Figure 10 summarizes the drag coefficient and the Charnock coefficient (normalized equivalent roughness length) at all locations under a tropical cyclone. The figure further confirms that the both approaches yield similar values of the drag coefficient and that the sea state dependence is relatively weak.

IMPACT AND APPLICATIONS

Quality of Life

The results of this project will directly impact the U.S. coastal communities by improving the accuracy of hurricane track, intensity, and storm surge forecasts. It will lead to increased reliability of hurricane forecasts and thus confidence in the official hurricane warnings.

Science Education and Communication

The University of Rhode Island has developed a comprehensive educational website ***Hurricanes: Science and Society*** **(HSS; www.hurricanescience.org)**. The HSS website and its associated educational resources provide information on the science of hurricanes, methods of observing hurricanes, modeling and forecasting of hurricanes, how hurricanes impact society, and how people and communities can prepare for and mitigate the impacts of hurricanes. In addition to in-depth science content, the website includes educational resources, case studies, and a historical storm interactive. Although the primary funding for the website development has been provided by the National Science Foundation, the results of this NOPP project have contributed to the website sections related to the science of hurricanes.

RELATED PROJECTS

Andreas is in the second year of an ONR project funded by the Marine Meteorology Program: "Predicting the Turbulent Air-Sea Surface Fluxes, Including Spray Effects, from Weak to Strong Winds." In that project, he has been collaborating with Larry Mahrt and Dean Vickers to develop a unified bulk flux algorithm for all wind conditions. Part of that project is to assemble the large air-sea flux dataset that we already used in the current project for the analyses reported in Figures 1 and 2.

Andreas and Kathy Jones of the Army Cold Regions Research and Engineering Laboratory just started in FY12 a project to study spray icing that is funded under the new ONR Arctic program. We plan two field experiments during the three-year project and will measure sea spray size distributions and the associated meteorological conditions from off-shore platforms or at other well-exposed marine sites where we can expect high winds and sub-freezing temperatures. In particular, we will make eddy-covariance measurements of the momentum and sensible and latent heat fluxes and thus will add to the inventory of flux datasets that we have already assembled and analyzed under the current project. The observations of sea spray should also reduce some of the uncertainties that exist in Andreas's spray flux algorithm.

The URI research group is involved in several projects funded by NOAA and the U.S. Navy focusing on improving the performance of the operational GFDL and HWRF models at the NOAA's National Centers for Environmental Prediction (NCEP) and the operational GFDN model at the Navy's Fleet Numerical Meteorology and Oceanography Center; the URI group also provides assistance to NCEP and FNMOC in transitioning the model upgrades to operations.

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