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 and COAMPS-TC models (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).

The main targets for the third year of this project for the URI team and its collaborators will be: 1) to deliver the unified air-sea interface module to NCEP and NRL and assist in its implementation into the HWRF and COAMPS-TC coupled models, 2) to fully test the multi-model coupled modeling system using COAMPS-TC-WAVEWATCH-NCOM and HWRF-WAVEWATCH-POM, 3) to investigate the impact of the air-sea coupling on the model-predicted structure and intensity change in tropical cyclones using the full multi-model system, 4) to conduct limited multi-model forecasting experiments with the fully coupled atmosphere-wave-ocean modeling systems in real-time or near real-time, 5) to complete the documentation of the unified air-sea interface module for general applications and submission to peer-reviewed publications, and 6) to provide assistance to the future potential transfer from research to operations effort if it becomes feasible.

WORK COMPLETED

The URI PI team completed the following tasks: 1) implementation of the unified air-sea interface module into the GFDL and HWRF hurricane models, 2) investigation of the impact of sea spray on the momentum and enthalpy fluxes in high wind conditions, 3) implementation of new methods for coupling the sea-spray parameterization with the surface wave properties in the wind-wave and wave-current coupling parameterizations, 4) investigation of the impact of rainfall on the momentum fluxes in hurricanes, 5) investigation of the upper and lower limits of the drag coefficient in high wind conditions, 6) evaluation of the new version of the WAVEWATCH wave model in hurricane conditions, 7) investigation of the mechanism of disruption of the air-sea interface and formation of the two phase transition layer in hurricane conditions and their effect on the sea-state dependence of the drag coefficient at high wind speeds, and 8) investigation of the Stokes drift due to ocean surface waves under hurricane conditions.

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 sea spray effects into the air-sea interface module

The URI PIs worked with Jian-Wen Bao and Chris Fairall at NOAA/ESRL to fully incorporate sea spray effects in the unified air-sea interaction module. In the implemented scheme, the mass-density effect of sea spray is considered as an additional modification to the stratification of the near-surface profiles of wind, temperature, and moisture in the marine surface boundary layer (MSBL) (Bao et at, 2011). The overall impact of sea-spray droplets on the mean profiles of wind, temperature, and moisture depends on the wind speed at the level of sea-spray generation. As the wind speed increases, the mean droplet size and the mass flux of sea-spray increase, rendering an increase of stability in the MSBL and the leveling-off of the surface drag. Sea spray also tends to increase the total air–sea sensible and latent heat fluxes at high winds. Our simulations with the GFDL hurricane-wave-ocean system with sea spray effects show significant impact of sea spray on the momentum and heat fluxes. An example of the drag coefficient with and without sea spray effect is shown in Fig. 1.

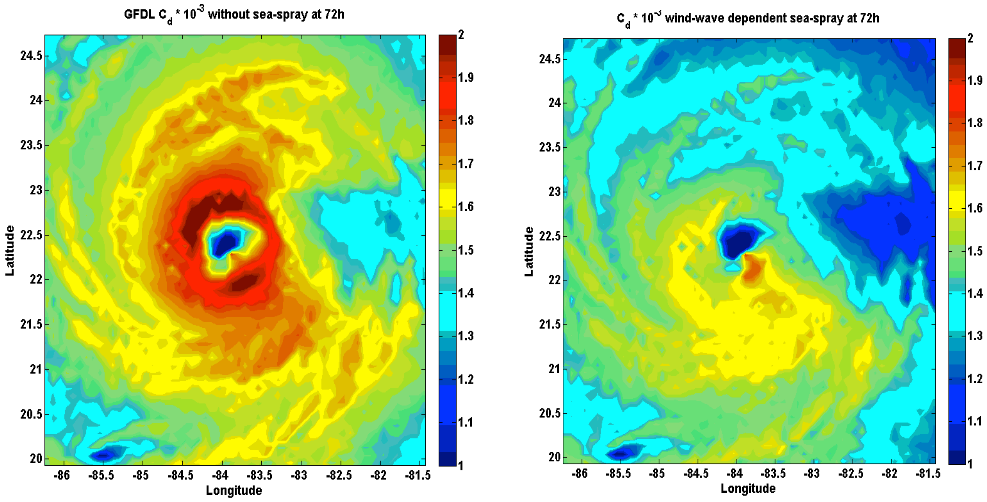

Figure 1. *Drag coefficient at 35-m height in the GFDL hurricane-wave-ocean coupled system without (left) and with (right) sea spray effects.*

One of the novel features implemented into the air-sea interaction module is the method of coupling between breaking waves and the sea spray generation model. Without wave coupling, the source function is parameterized in terms of energy lost to the wave breaking process, which is simply related to the wind speed. The effective droplet source height is related to the significant wave height. Within the framework of ASIM, the total energy lost to breaking is accurately estimated by explicitly accounting for the sea state dependence and the air-sea flux budget (Fan et al. 2010). The source height is determined not from the significant wave height but from the input wave age (wave age of the wind-forced part of the spectrum) and the wind stress. This modification is important under hurricanes because the dominant scale of breaking waves is related to the scale of the actively wind-forced waves – not related to the scale of swell generated elsewhere. An example of the effect of wave coupling on the sea spray mass flux is shown in Fig. 2.

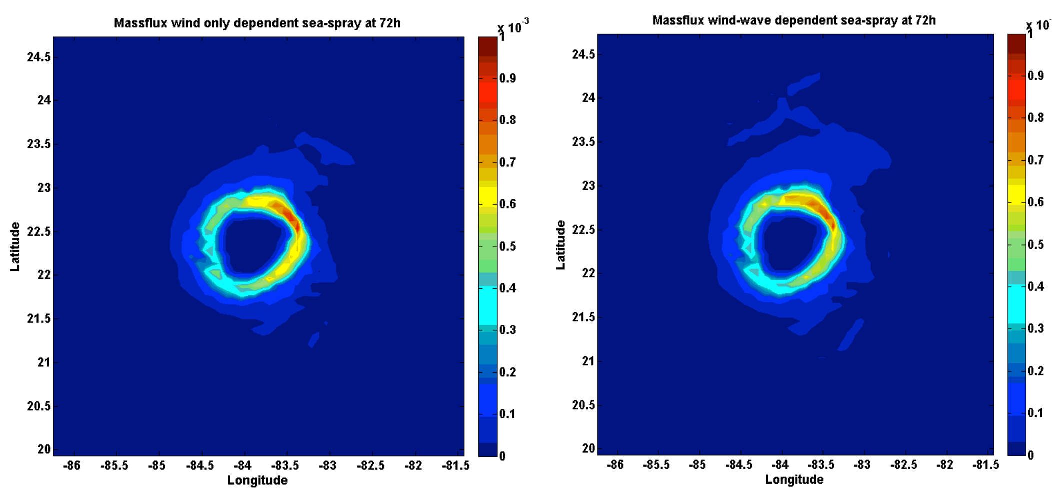

Figure 2. *Sea spray mass flux (kg m^{-2} s^{-1}) simulated in the GFDL coupled system in two sensitivity experiments: wind-only dependent sea spray source function (left) and sea-state dependent sea spray source function (right).*

b) Wave model evaluation

In preparation for the coupling with the hurricane models, the URI PIs have completed an in-depth evaluation of the performance of WWIII v. 3.14 recently released by NOAA/NCEP using field observations of the surface wave spectra from an airborne scanning radar altimeter, National Data Buoy Center (NDBC) time series, and satellite altimeter measurements during Hurricane Ivan (2004) (Fan et al. 2009b). WWIII v. 3.14 includes a number of significant improvements, including the ability to accurately simulate waves in shallow water (i.e. coastal) regions. In Fig. 3, the significant wave heights produced during two WWIII simulations of Hurricane Ivan (2004) reveals that only v. 3.14, not the previous version, v. 2.22, accurately represents waves in the shallow water on the continental shelf near the Gulf Coast. We will continue a comprehensive evaluation of WWIII v. 3.14 in shallow water in Year 3. Shallow water tests of WWIII v. 3.14 will include a variety of available field observations, including the scanning radar altimeter (SRA) measurements taken on 3 October 2002 during Hurricane Lili's landfall in Louisiana and any available buoy measurements.

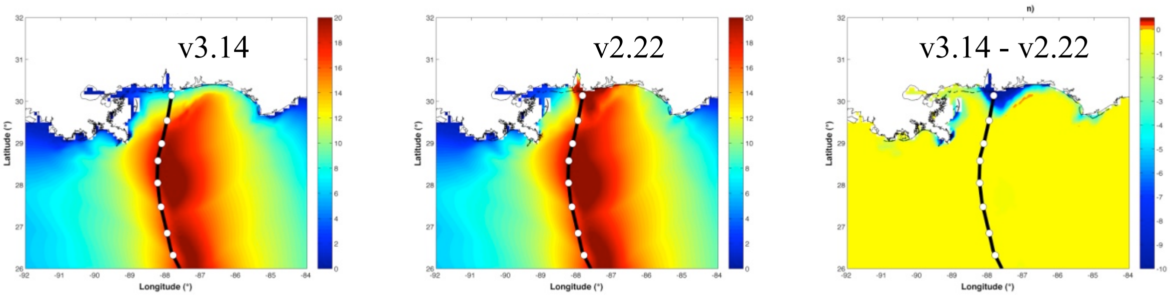

Figure 3. *Swaths of significant wave height (m) from WWIII simulations forced with the observed wind during Hurricane Ivan (2004). Swaths are from WWIII v. 3.14 (left), WWIII v. 2.22 (center), and the difference between WWIII v. 3.14 and v. 2.22 (right).*

c) A new drag coefficient formulation

One of the Co-PIs, Edgar Andreas, investigated a new way of formulating an air-sea drag relation that has several advantages over the traditional drag coefficient. Two large observational datasets were utilized. One dataset, hereafter 'original', comprises 778 eddy-covariance flux measurements over the ocean made from ships, towers, and low-flying aircraft. A second dataset, hereafter 'aircraft', comprises over 6000 flux measurements made by low-flying aircraft. Following the Foreman and Emeis (2010) suggestion

$$u_* = a U_{N10} + b \,, \tag{1}$$

where u_* is the friction velocity and U_{N10} is the neutral-stability wind speed at a reference height of 10 m. The surface stress τ is ρu_*^2, where ρ is the air density. Fig. 4 shows the two datasets plotted as u_* versus U_{N10}.

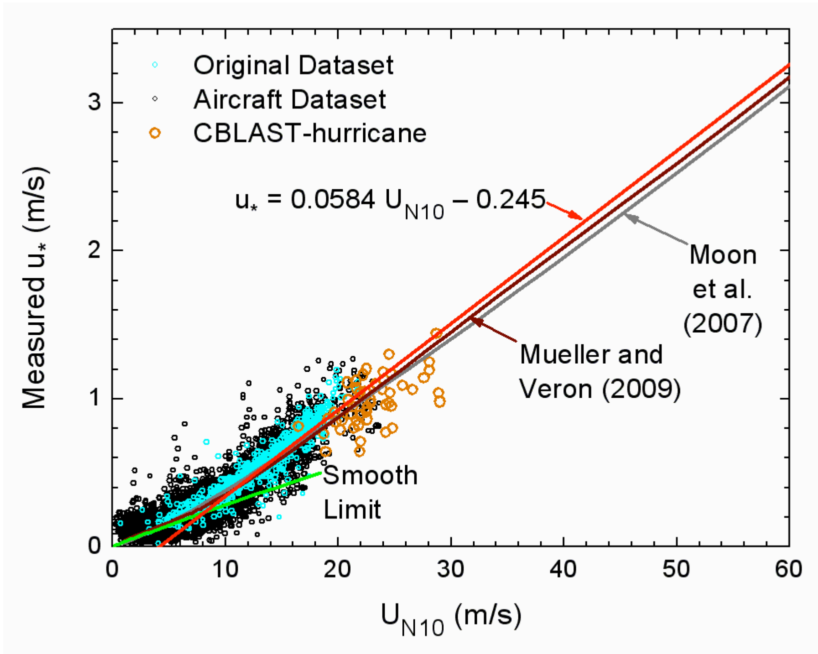

Figure 4. *The "original" and "aircraft" datasets are plotted as* u_* *versus* U_{N10}*. The plot also shows the CBLAST-hurricane data (French et al. 2007), which were ignored because they seem to be biased low. The best fit to the data in aerodynamically rough flow,* $U_{N10} \geq 9\,\mathrm{m\,s^{-1}}$ *(red line), is the straight line given by (2). The green line comes from (6) and shows aerodynamically smooth scaling. The two other curves are theoretical results from Moon et al. (2007) and Mueller and Veron (2009) for wind speeds up to at least 70 m* s^{-1}*; their similarity to (2) justifies extrapolating our fit to hurricane-strength winds.*

In the aerodynamically rough regime in Fig. 4, $U_{N10} \geq 9\,\mathrm{m\,s^{-1}}$, the data do, indeed, follow a straight-line relation; the least-squares fit is

$$u_* = 0.0584\,U_{N10} - 0.245\ , \tag{2}$$

where u_* and U_{N10} are in m s^{-1}.

Another significant result in Fig. 4 is that the theoretical models of Moon et al. (2007) and Mueller and Veron (2009) also produce essentially straight-line relations for U_{N10} above about 20 m s^{-1} when u_* is plotted against U_{N10}. Neither group evidently realized this behavior in their results. Both groups modeled the air-sea drag as a combination of skin friction, form drag over the waves, and reduced drag due to wave sheltering. The fact that these theoretical models, which were applied for winds up to major hurricane strength, yield straight-line relations close to (2) is justification for extrapolating (2) to hurricane-strength winds.

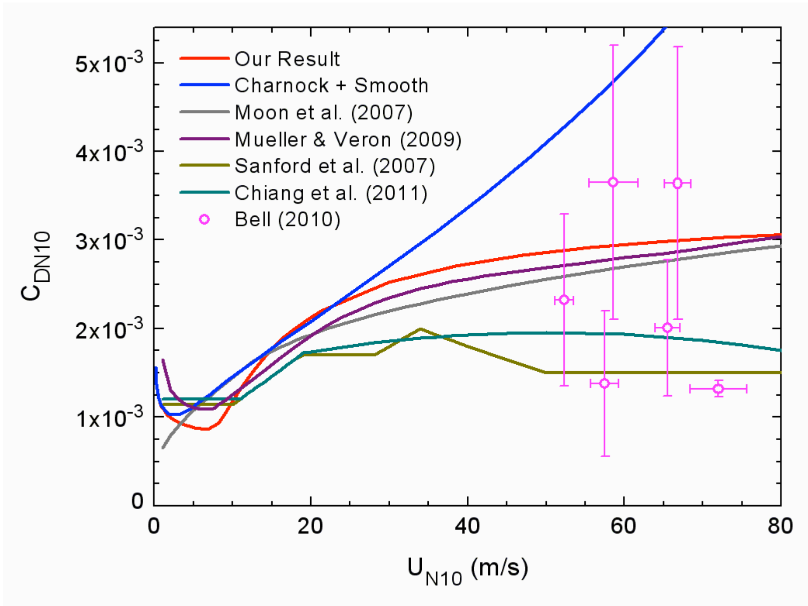

Figure 5. *Several opinions as to the 10-m, neutral-stability drag coefficient (C_{DN10}) as a function of U_{N10}. "Our Result" comes from (5)–(7). The Moon et al. (2007) and Mueller and Veron (2009) curves are just recast as drag coefficients from Fig. 4. The "Charnock + Smooth" curve comes from (7) with the Charnock relation substituted for z_{0r}. The Sanford et al. (2007) and Chiang et al. (2011) curves are their adaptations of the results from Powell et al. (2003). Bell's (2010) data come from estimates of the angular momentum budget in hurricanes Fabian and Isabel and are not useful is deciding among the various parameterization for C_{DN10} because they range so widely.*

Another feature that recommends (2) is that it naturally predicts a roll-off in the usual 10-m, neutral-stability drag coefficient, C_{DN10}, and an asymptotic limit of 3.41×10^{-3}. That is,

$$C_{DN10} = \left(\frac{u_*}{U_{N10}}\right)^2 = a^2\left(1 + \frac{b}{a\,U_{N10}}\right)^2 = 3.41\times10^{-3}\left(1 - \frac{4.20}{U_{N10}}\right)^2 . \tag{3}$$

From the comparable expression for C_{DN10},

$$C_{DN10} = \left[\frac{k}{\ln\left(10/z_0\right)}\right]^2 , \tag{4}$$

where k is the von Kármán constant and z_0 is the roughness length, we can obtain the roughness length in aerodynamically rough flow implied by (2):

$$z_{0r} = 10\exp\left[\frac{-k\left(u_* - b\right)}{a\,u_*}\right] , \tag{5}$$

where z_{0r} is in meters. Then, as is customary (e.g., Smith 1988), we can add the roughness length in aerodynamically smooth flow,

$$z_{0s} = 0.135 \frac{\nu}{u_*} , \tag{6}$$

to (5) to get an expression for the roughness length at all wind speeds:

$$z_0 = z_{0s} + z_{0r} . \tag{7}$$

In (6), ν is the kinematic viscosity of air. In turn, inserting (7) in (4) yields a drag coefficient for all wind speeds.

Fig. 5 shows the C_{DN10} function derived from (7) and several other opinions as to C_{DN10}. In particular, the "Charnock + Smooth" curve in Fig. 5 is the standard drag relation at lower wind speeds. It comes by using the Charnock relation, $\alpha u_*^2 / g$, where $\alpha = 0.0185$ and g is the acceleration of gravity, for z_{0r} in (7). Fig. 5 also shows the Moon et al. (2007) and Mueller and Veron (2009) results expressed as drag coefficients.

For their hurricane models, Sanford et al. (2007) and Chiang et al. (2011) developed functions for C_{DN10} that approximated the data from Powell et al. (2003) at high wind speeds. Because their functions are continuous, like the other functions in Fig. 5, and because the Powell et al. results are the smallest lower bound on C_{DN10} in high winds, we include the Sanford et al. and Chiang et al. expressions in Fig. 5 for comparison.

Lastly, Fig. 5 also shows drag coefficients that Bell (2010) estimated from the angular momentum budget that he computed based on dropsondes released in hurricanes Fabian and Isabel in (2003). Unfortunately, Bell's results provide no guidance on how to choose among the functions depicted in Fig. 5; his data range from below the smallest reasonable C_{DN10} to above the level based on (2), which can be viewed as a reasonable upper bound on C_{DN10}.

d) Effect of rainfall on the momentum fluxes in hurricanes

One of the Co-PIs, Roger Lukas, investigated the effect of rainfall on the momentum fluxes. The impacts of rainfall on relatively short surface waves ("ultragravity waves"; Munk 2009) and near-surface turbulence are well known to be significant (Houk and Green, 1976; Tsimplis and Thorpe 1989; Tsimplis 1992; Le Mehaute 1988; Le Mehaute and Khangaonkar 1990; Nystuen 1990; Schlussel et al. 1997; Craeye and Schlussel 1998; Ho et al. 1998; Soloviev and Lukas 2006; Zappa et al. 2009). In thinking about the modifications of the wave spectrum by spray, he realized that rainfall should be included in the roughness length and turbulent stress parameterizations on the air side. He then realized that the direct transport of momentum from the top of the hurricane boundary layer into the ocean by the rainfall also needs to be included. Caldwell and Elliott (1971, 1972), hereafter C&E, modeled the momentum transferred to the ocean by rainfall and the additional shear stress in the logarithmic layer. Their results depended on rain drop size, rain rate, and wind speed.

A rough estimate of the ratio of rain stress to wind stress is

$$\tau_r / \tau_w = (\rho_r / \rho_a)(0.85R)/(Cd_{10}{*}U_{10}),$$

which assumes that the rain drops lose about 15% of their horizontal speed below 10 m on average. Assuming a constant $Cd_{10} = 1.2 \times 10^{-3}$,

$$\tau_r / \tau_w = 0.16R/U_{10}$$

for R in mm/hr and wind in m/s. Of course, we know that Cd_{10} is not a constant, being a function of the wave field (which is affected by the rainfall; see below.)

Schlussel et al., (1997) point out that C&E assumed that wind varies with height only in the log layer, which does not take into account the stronger winds at the top of the hurricane boundary layer, well above the log layer. Thus, parameterizing the rain stress as a function of U_{10} probably underestimates actual values in storms. In their analysis, C&E did not account for the effects of the rain on z_0. Schlussel et al. (1997) show that roughness due to rain increases rapidly up to a rain rate of 2 mm/hr, and that for $u^* > 0.15$ m/s, the wind-induced roughness is greater than the rain roughness. Thus, for the turbulent stress of the wind on the ocean, rain roughness needs to be considered for winds of 20 m/s or less and can safely be ignored for winds greater than 30 m/s.

The freshwater and sensible heat fluxes were included by Jacobs and Koblinksky (2007) in their forced ocean simulation of Hurricane Gilbert. They did not include any effects of rainfall on the momentum flux, however. It is suggested that some drag coefficient estimates from wind profile observations in hurricanes may be affected by rainfall. Within the assumptions used by C&E, they estimated O(10%) changes in U_{10} due to the distortion of the log layer; these differences would be hard to separate from stability effects.

Rainfall in the eyewall and outer rain bands may be enhancing the flux of horizontal momentum to the ocean significantly. For a 20 mm/hr average rainfall rate in a rain band, with wind 30 m/s, the rain stress from the C&E model is about 10% of the wind stress. The 50 mm/hr peak rainfall with 25 m/s observed in Typhoon Bilis yields 30% of the wind stress. Transients may produce peak rain stresses that are considerably more than 30% of the wind stress. Because the rain stress is in the direction of the wind, these are significant biases, but the magnitude depends on the wind speed, and thus varies radially. Accounting for the ocean momentum budget without rainfall likely leads to a radially-dependent overestimate of the drag coefficient in storms.

We conclude that rainfall momentum fluxes likely play an important role in forcing the ocean during the cyclogenesis phase, in the bulk of mature storms (outside the radius of maximum winds), and in the vertical divergence of upper ocean flow near the eyewall. Determining whether these effects are actually important for hurricane intensity changes requires coupled hurricane model experiments. This will require retuning of models to give a realistic result with rainfall momentum fluxes included. A review of the literature regarding air-sea momentum fluxes and rainfall on the ocean is being prepared.

e) The mechanism of the air-sea interface breakup and dynamics of the two-phase transition layer

One of the Co-PIs, Alex Soloviev, has focused on understanding the basic physics of the effect of the two-phase environment on the drag coefficient and developing a framework for combining the effects of the two-phase environment with the contribution to the drag from waves. Our working hypothesis is that the change of the air-sea interaction regime in hurricane conditions is associated with the mechanism of direct disruption of the interface (Soloviev and Lukas 2010). Direct disruption of the interface between air and water can be achieved through the Kelvin-Helmholtz (KH) instability. In addition, the Tollmien-Schlichting (TS) instability of viscous sublayers from the air and/or water side is potentially another important process taking place at the air-sea interface under hurricane conditions. Similar processes take place at the atomization of liquid fuels in cryogenic and diesel engines (Yecko et al., 2002). Under hurricane conditions, such instabilities initiate disruption of the air-sea interface, the tearing of short wavelet crests, and ejection of spume into the air. The associated smoothing of the sea surface in the direction of the airflow affects the drag coefficient, an effect observed in the field and laboratory experiments (Powell et al. 2003; Donelan et al. 2004; Black et al. 2007; Troitskaya et al. 2010).

In order to investigate the mechanism of the breakup of the air-sea interface and dynamics of the two-phase transition layer, we conducted numerical experiments using the volume of fluid multiphase computational fluid dynamics model, which allowed us to simulate the air-sea interface including surface tension at the water surface. The large eddy simulation Wall-Adapting Local Eddy-Viscosity turbulence model (Nicoud and Ducros 1999) was used for all numerical experiments.

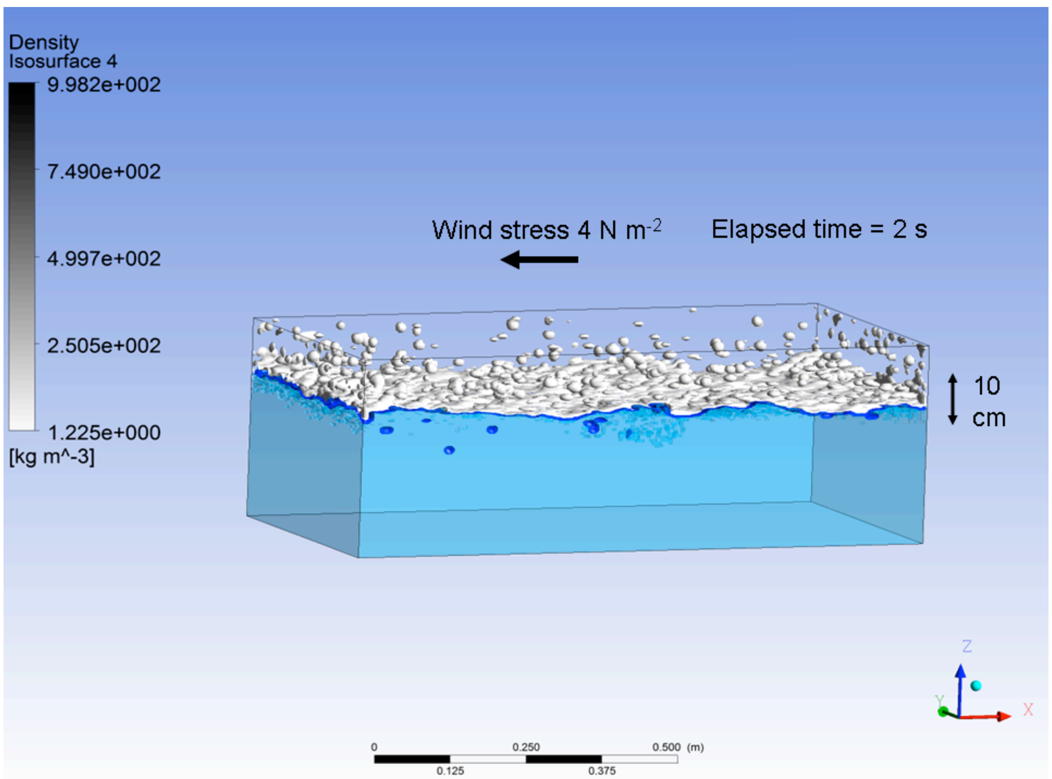

Figure 6. *The numerical experiment with an initially flat interface illustrates the possibility of the direct disruption of the air-water interface and formation of the two-phase environment under hurricane force wind.*

For the case shown in Fig. 6, the wind stress, 4 N m^{-2}, was applied at the upper boundary of the air layer. The disruption of the air-water interface resembled an 'explosive' type of instability. The Koga number, $K = u_{*a} / \left(g\sigma_s \rho_w / \rho_a^2 \right)^{1/4}$, introduced by Soloviev and Lukas (*2010*), was equal to $K = 0.38$, exceeding its critical value $K_{cr} \approx 0.26$, which satisfied the condition for the development of the KH type instability at the air-sea interface. The formation of a two-phase environment, as a result of the interface disruption, was observed before any significant waves could be generated by wind.

The average density and velocity profiles over the entire model domain (excluding near-wall areas) provided an estimate for the critical value of the global Richardson number. Under the assumption of the regime of marginal stability in the two-phase transition layer, the lower boundary on the drag coefficient is shown in Fig. 7 in comparison with a wave resistance parameterization.

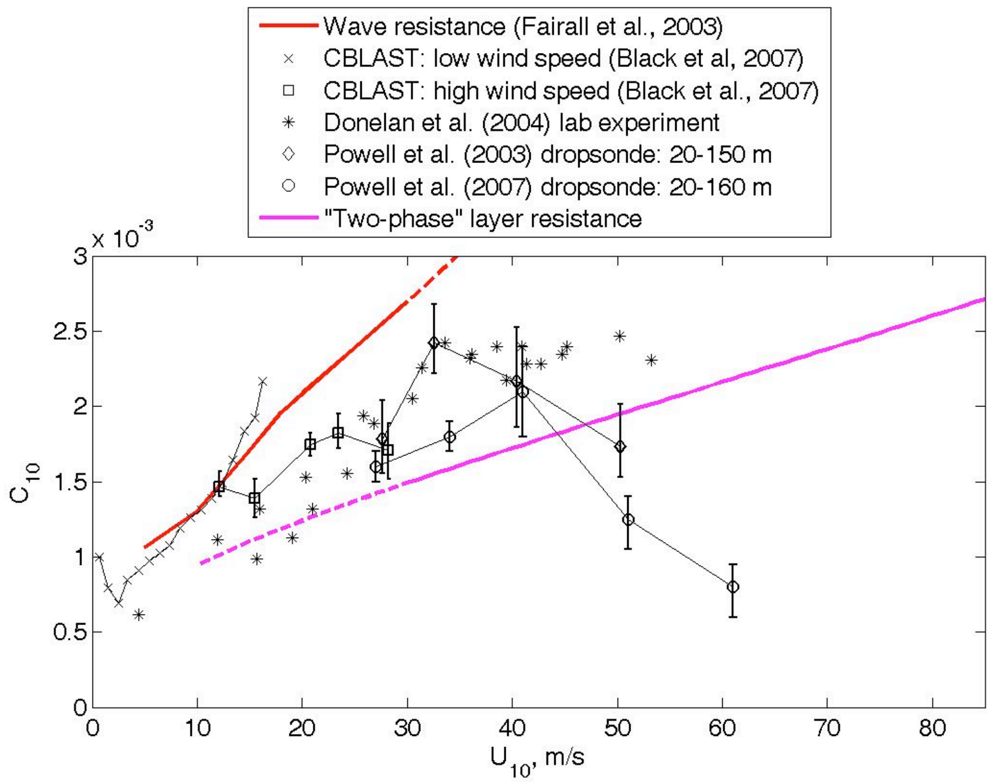

Figure 7. *The two-phase layer resistance and wave resistance parameterizations in comparison with available laboratory and field data.*

Laboratory data fall between the two-phase layer resistance parameterization from below and wave resistance parameterization from above (Fig. 7). The field data fall between these two parameterizations but only up to 50 m s^{-1} wind speed. A few points from the dropsonde data, obtained at very high wind speeds, are below the lower limit on the drag coefficient. The state of the sea surface in hurricane conditions varies in azimuth and distance from the hurricane center because of the variation in swell characteristics relative to the wind (Powell et al., 2003). The relative contribution of the wave and two-phase layer mechanisms to the drag coefficient is also expected to vary. In certain wind-wave interaction regimes, or because of suppression of short surface waves by the two-phase environment, the wave drag may become inefficient. In this case, the air-sea drag is due to the two-phase transition layer and the drag coefficient drops to its lower limit shown in Fig. 7.

As noticed in Soloviev and Lukas (2010) and evident from Fig. 7, the lower limit on the drag coefficient slowly increases with wind. This is because the two-phase transition layer takes a part of its momentum from the wind, which results in an increase of the drag coefficient with wind. Andreas (1998) anticipated a similar effect, considering additional resistance due to the transfer of a part of the wind momentum to the sea spray. Note that the role of sea spray in this process is to increase the air-sea drag coefficient rather to reduce it.

Development of a parameterization taking into account the impact of both waves and the two-phase environment in the air-sea drag is important for the realistic representation of the air-sea interface in hurricane models. For this purpose, we conducted a series of numerical experiments aimed at understanding physics of the two-phase environment in the presence of surface waves. The numerical experiments with imposed short waves demonstrated the tearing of wave crests, formation of water sheets and spume ejected into the air, and smoothing of the water surface in the direction of the air flow (Fig. 8).

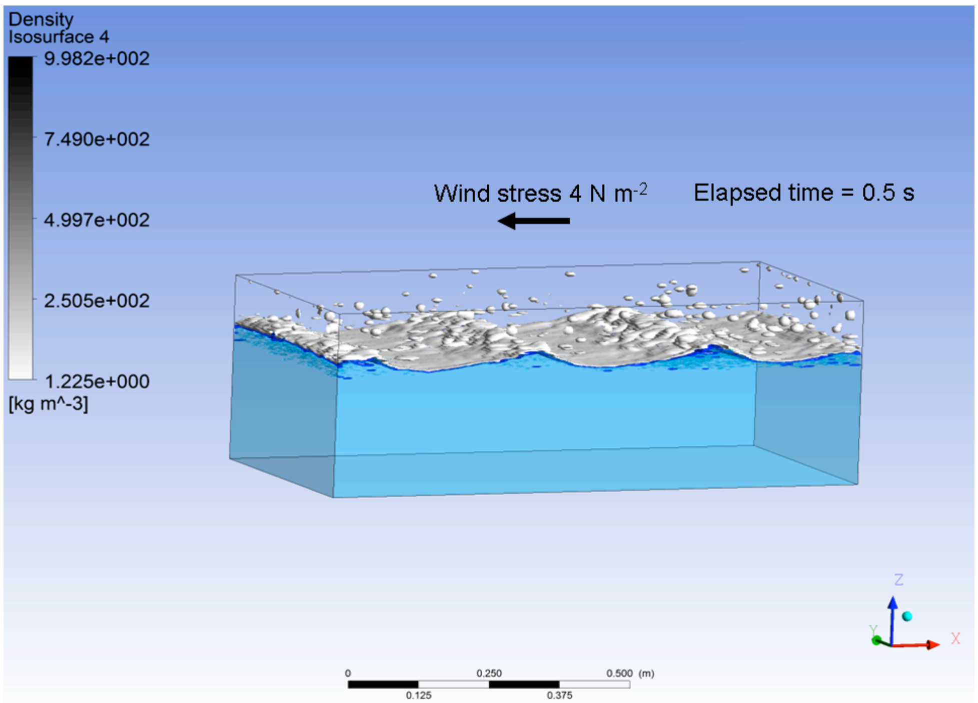

Figure 8. *Numerical experiment with imposed short waves demonstrates the tearing of wave crests, formation of water sheets and spume ejection into the air.*

Based on the results of numerical simulations, we have come up an improved estimate of the lower limit on the drag coefficient under hurricane conditions. This limit is associated with the presence of two-phase transition layer and is appreciably lower than the wave resistance law; though, it was gradually increasing with wind speed (Soloviev et al. 2011). Merging the two-phase layer parameterization with the wave parameterizations is the subject of the third year work, which will be done by the URI PIs.

f) Stokes drift due to ocean surface waves 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).

As a first step to study the effect of Langmuir turbulence, the URI PIs investigated the vertical profile of Stokes drift under a wide range of wind and wave conditions. First, investigations were made with growing and fully-grown wave fields generated by uniform wind speeds from 10 to 50 m s^{-1}. The results show that the vertical profile of the Stokes drift is well described by two parameters: a depth that is inverse of the peak wave number (wave number at the wave spectral peak) and the Stokes drift value at that depth. Next, the Stokes drift calculations were performed for more complex wave fields under a stationary tropical cyclone, as well as storms moving at 5 and 10 m s^{-1} translation speeds. Such simulations demonstrate good directional agreement between wind and surface Stokes drift vectors as well as between dominant wave direction and deep Stokes drift vectors. For the translating tropical cyclones, strong asymmetries were present in the Stokes drift field. Both cases showed significant regions where the wind and the deep Stokes drift were misaligned by more than 90° (Fig. 9), suggesting significant weakening of near surface turbulence due to surface waves. Such regions, in both simulations, occur to the left of the storm translation direction both within and outside of the radius of maximum winds. Such finding lends merit to further investigation of its effect on the Langmuir turbulence.

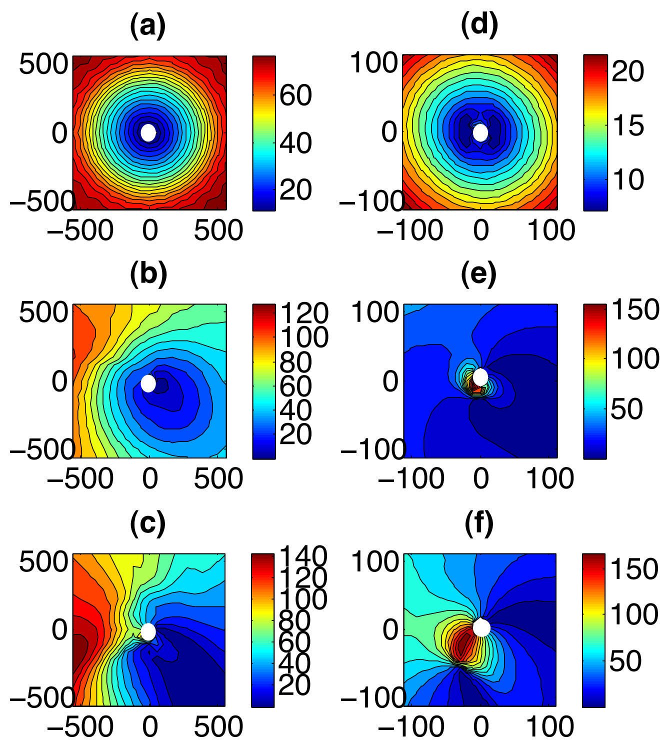

Figure 9. *Angle difference (Δθ) between wind direction and the direction of the Stokes drift (k_{peak}^{-1}), for wave fields under stationary (a) as well as 5 m s^{-1} (b) and 10 m s^{-1} (c) translating hurricane wind conditions. Right panels show higher resolution regions sampled at 1/12° intervals. The hurricane is moving northward.*

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

In 2011, ONR started funding Andreas and Larry Mahrt (also of NWRA) under a project entitled "Predicting the Turbulent Air-Sea Surface Fluxes, Including Spray Effects, from Weak to Strong Winds." While the current project focuses on hurricanes, this new project is complementary because Andreas and Mahrt will be developing parameterizations for all wind speeds. Mahrt and Dean Vickers of Oregon State University provided Andreas the "aircraft" data in Fig. 1.

Duennebier et al. (2011, JGR submitted) developed an improved model of the short gravity and capillary wave portion of the surface wave spectrum through inversion of a long seafloor acoustics record. This model excludes the effects of rainfall, but ongoing analysis with the acoustic data may allow us to better model the modifications of the wave spectrum associated with rain.

The CFD model used for the numerical simulation of the air-water interface in hurricane conditions is based on the model developed as a part of the project "Hydrodynamics and Remote Sensing of Far Wakes of Ships" funded by the US Federal Government (PI Dr. Alex Soloviev). A similar numerical model will be used as a prototype model for studying dispersion of oil spills under hurricane conditions as a part of the "Consortium for Advanced Research on Hydrocarbon Transport in the Environment (CARHTE)" project funded via an NSU subcontract to UM RSMAS/BP (PI Dr. Alex Soloviev).

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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