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, at least two different 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, WAVEWATCH III, and HYCOM. 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 improving physical parameterizations of the air-sea heat and momentum fluxes at and near the sea surface that involve fully coupled wind-wave-current interaction and sea spray effects and 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, the National Center for Atmospheric Research (NCAR), the NOAA/Earth Systems Research Laboratory (ESRL), and the 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 second year of this project for the URI team and its collaborators will be: 1) to complete the initial development of the wave-current coupling parameterization; 2) to investigate the impact of sea-spray on the sea-state dependent air-sea heat and momentum fluxes; 3) to refine the sea spray parameterizations based on available observations and additional theoretical analysis; 4) to investigate how surface gravity waves modify the momentum flux to subsurface currents via three mechanisms (the Coriolis-Stokes effect, the air-sea momentum budget, and the wave- current interaction); 5) to analyze the in situ observations from the specially hardened pressure-sphere turbulent stress sensor and an optical array spray droplet imager that will be deployed on buoys in 2010 and the airborne observations, including the scanning radar altimeter (WSRA) for wave parameters and a W-band Doppler radar for profiling sea spray for possible improvements of the sea spray models; 6) to implement the improved sea-spray and wind-wave-current coupled parameterizations in the unified air-sea interface module (ASIM); 7) to fully test the multi-model coupled modeling system with coupled model TC simulations using COAMPS TC-WAVEWATCH III-NCOM and HWRF-WAVEWATCH III-HYCOM; and 8) to evaluate and verify coupled model performance in prediction of TC structure and intensity.

WORK COMPLETED

The URI PI team completed the following tasks: 1) initial development of basic model structure for the unified air-sea interface module, 2) implementation and initial testing of the unified air-sea interface module with URI air-sea coupling parameterizations into research versions of the GFDL and HWRF coupled hurricane-wave-ocean models, 3) exploration 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 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, 5) investigation of the effects of sea spray on the momentum and enthalpy fluxes in high wind conditions, 6) implementation of ESRL’s and Andreas’ interfacial flux algorithms and the predicted near-surface distributions of sea spray into the URI parameterization and calibration of the predicted spray concentration profile in the lower atmosphere using available measurements, and 7) investigation of the link between wave generation and sea spray and their impact on surface momentum flux.

The work completed by the UM PI team is described in a separate report.

RESULTS

The key elements of the new URI air-sea interface module (ASIM) developed in this project are shown in Fig. 1. In this module, we have implemented coupled modeling strategies that include the following: 1) in the hurricane model, the parameterizations of the air-sea heat and momentum fluxes and the spray source functions explicitly includes the sea state dependence and ocean currents; 2) the wave model is forced by the sea-state dependent momentum flux and will include the ocean current effects; 3) the ocean model is forced by the sea-state dependent momentum flux that accounts for the air-sea flux budget. The ocean current can affect the air-sea fluxes in two ways: a) by modifying the surface wave properties (wave spectra, propagation speed, etc.) and thus surface roughness, and b) by using the relative wind speed (wind speed minus current) in determining the wind stress and heat and moisture fluxes.

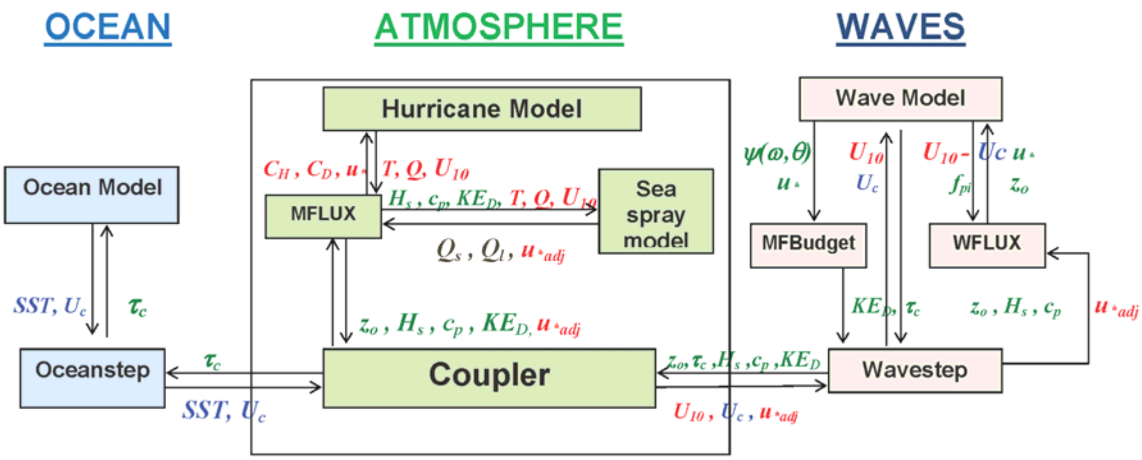

Figure 1. *A schematic diagram of the coupled wind-wave-current modeling system and the air-sea interface module (ASIM) represented by the following components: MFLUX, Sea spray model, MFBudget, and WFLUX. The arrows indicate the prognostic variables that are passed between the model components.*

ASIM consists of 1) the URI coupled wind-wave (CWW) boundary layer model of Moon et al. (2004 a,b) (sub-module "MFLUX" in Fig. 1); 2) an air-sea energy and momentum flux budget model of Fan et al. (2009a) and Fan et al. (2010) (sub-modules "MFBudget" and "WFlux" in Fig. 1) the sea spray model due to breaking waves model of Fairall et al. (2009) and Andreas et al. (2009) (sub-module "sea spray model" in Fig. 1). One of the novel features implemented in ASIM is the method of coupling between breaking waves and the sea spray generation model. In the present sea-spray models, the source function is parameterized in terms of energy lost to the wave breaking process, EF_c, which is simply related to the wind speed. The effective droplet source height h is related to the significant wave height. Within the framework of ASIM, the total energy lost to breaking (EF_c) 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 tropical cyclones 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.

The GFDL and HWRF hurricane models have been successfully coupled with NOAA's WAVEWATCH wave model. The air-sea coupler has been designed to handle the wind-wave-current interaction processes. We are in the process of conducting idealized simulations in a hurricane embedded in specific environmental zonal flows of various strengths. Figure 2 shows surface wind, significant wave height, and energy dissipation at 72 hours in the simulation with a 5 m/s zonal flow. The asymmetries in the wave parameters relative to the storm center are clearly seen and consistent with observed patterns. We are in the process of conducting various sensitivity experiments to evaluate the impact of wave coupling and will present the results in the next report. The wave model performance for hurricane conditions has been extensively tested by Fan et al. (2009a).

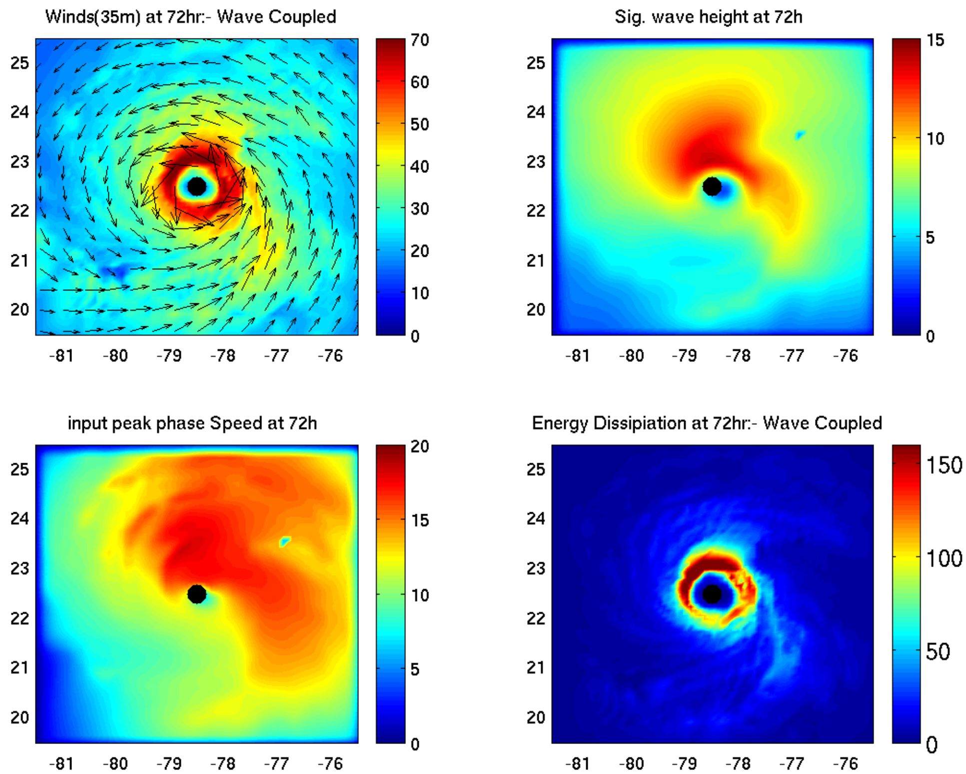

Figure 2. *Surface wind, significant wave height, peak phase speed and energy dissipation due to wave breaking at t=72 h in an idealized experiment using the GFDL coupled hurricane-wave-ocean system.*

We investigated the sensitivity of the track and intensity predictions and wind structure to the wave coupling and the ocean current effects in a series of idealized experiments. In these experiments, a hurricane of Category 3 intensity (the Hurricane Fran (1996) parameters were used to initialize the vortex) is embedded in a horizontally uniform 2.5 m/s steering wind directed eastward. The ocean was initially horizontally uniform with the initial vertical temperature profile typical for common water in the Gulf of Mexico. We present here the results of four experiments: 1 - (control) no wave coupling/no ocean current; 2 – wave coupling/no ocean current, 3 - no wave coupling/ocean current, and 4 – (full coupling) wave coupling/ocean current. While the impact on the track is quite small (not shown), the intensity prediction (especially the maximum wind speed) is found to be very sensitive to the different coupling effects (Fig. 3). The main reason for such sensitivity is the modulation of the drag coefficient due to the wave coupling and current effect. We found that the wave coupling can either increase or decrease the drag coefficient at high winds, depending on a specific location relative to the storm's track (Fig. 4). The effect of ocean currents generally tends to decrease the drag in high wind conditions.

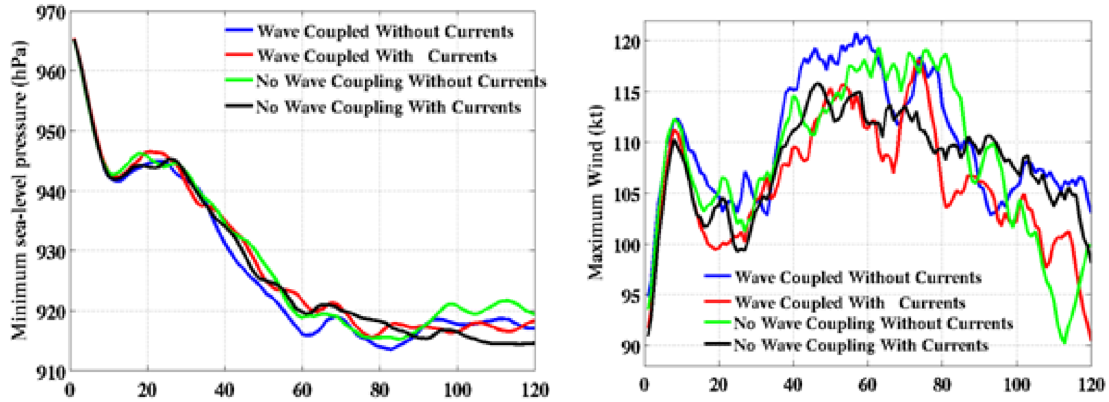

Figure 3. *Five-day (120-hr) simulations of central pressure (left) and maximum wind speed (right) in the four different sensitivity experiments described in the text.*

Figure 5 compares spatial distributions of surface winds and drag coefficient in the control experiment and in the experiment with wave coupling and current effects after 72 hours of model integration. It is evident that the maximum drag coefficient is reduced and the maximum wind speed is increased due to wave coupling. Also, the spatial patterns are notably affected. For example, the wind speeds to the left of the track are significantly reduced in the experiment with wave coupling. Thus the hurricane wind structure is modified due to the effects of wind-wave-current interaction.

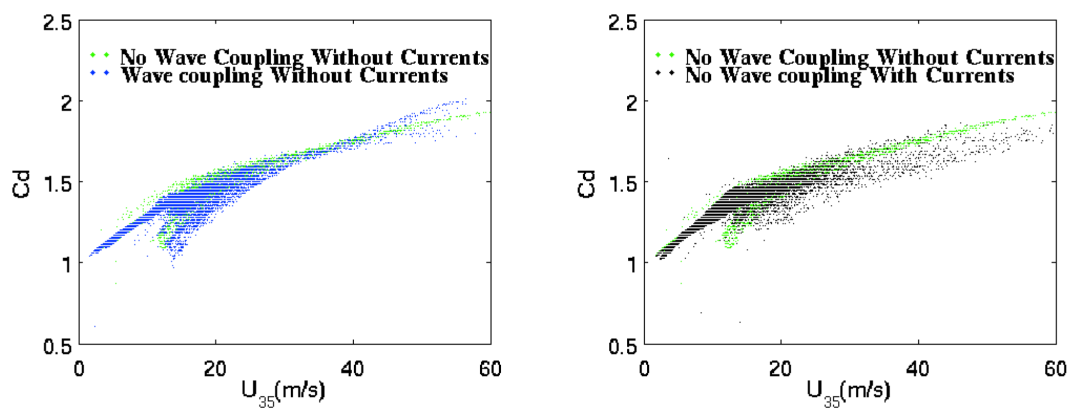

Figure 4. *Drag coefficient vs. wind speed at 35 m in the coupled model experiments described in the text. Green dots are for no wave coupling/no current (control), blue dots are for wave coupling/without current, black dots are for no wave coupling/with current.*

Figure 6 illustrates the impact of wave coupling and ocean currents on the spatial distribution and magnitude of the surface momentum flux. The location of maximum momentum flux has shifted from the hurricane rear in the control experiment to the right in the experiments with wave coupling. Note that the maximum flux value is the highest when both wave coupling and current effects are included.

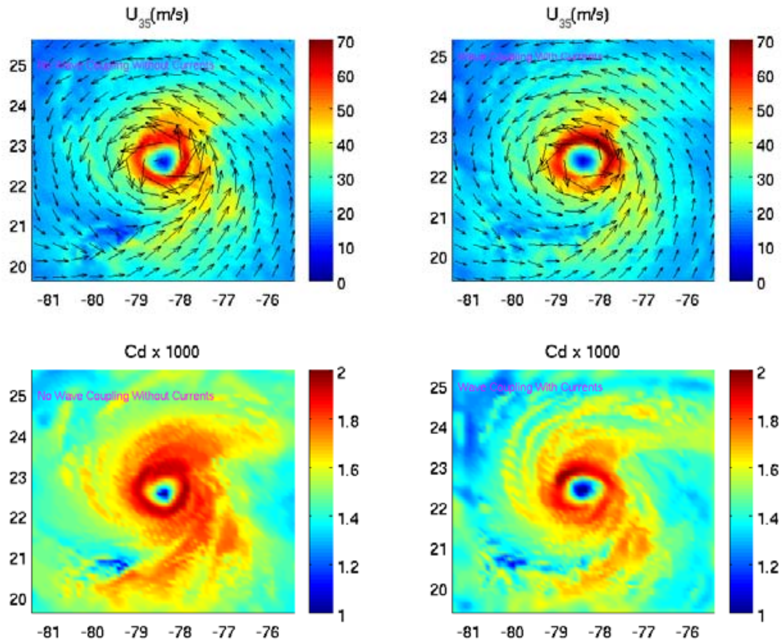

Figure 5. *Wind speed at 35 m (the lowest model level) and drag coefficient in the control experiment (no wave coupling, no current effects) (top and bottom left) and with wave coupling and current effects (top and bottom right) at t=72 hr.*

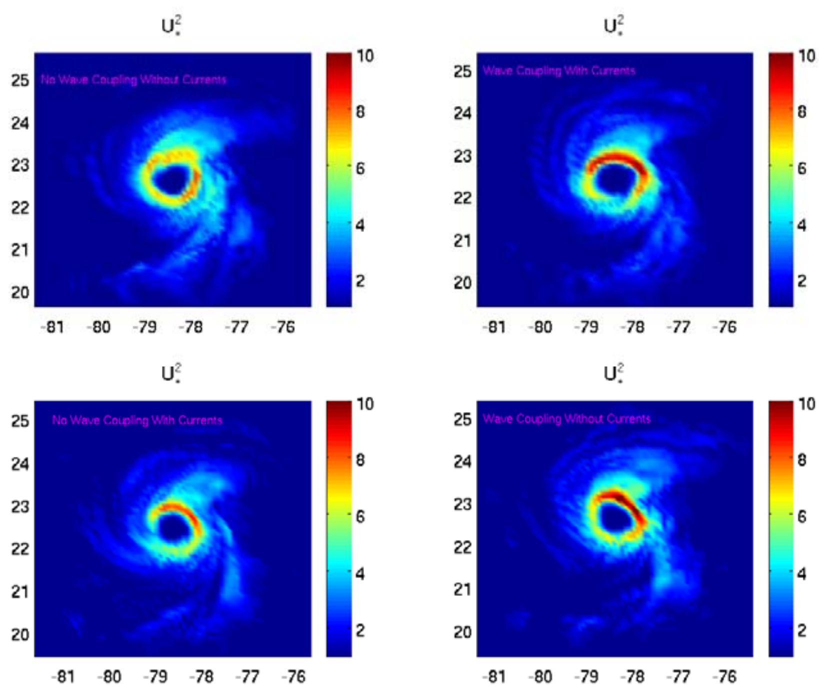

Figure 6. *Normalized momentum flux (m^2/s^2) in four sensitivity experiments: a) no wave coupling without current effects (top left), no wave coupling with current effect (bottom left), with wave coupling and with current effects (top right), and with wave coupling and without currents (bottom right) at t=72 hr.*

Andreas's air-sea flux algorithm (Andreas 2010a-c) quantifies both the interfacial and spray routes by which enthalpy, heat, and moisture cross the air-sea interface. With Fig. 7, we demonstrate the importance of the spray route in exchanging enthalpy in high winds. The main conclusion here is that the air-sea enthalpy flux cannot be parameterized as a simple function of an enthalpy transfer coefficient, C_{KN10}. When spray processes contribute to the flux, C_{KN10} is not a single-valued function of wind speed because interfacial and spray-mediated transfers scale differently. It is, thus, time to move beyond the common practice of trying to model storm intensity with an enthalpy transfer coefficient; implementing new practices that specifically account for spray-mediated transfer is an objective of this project.

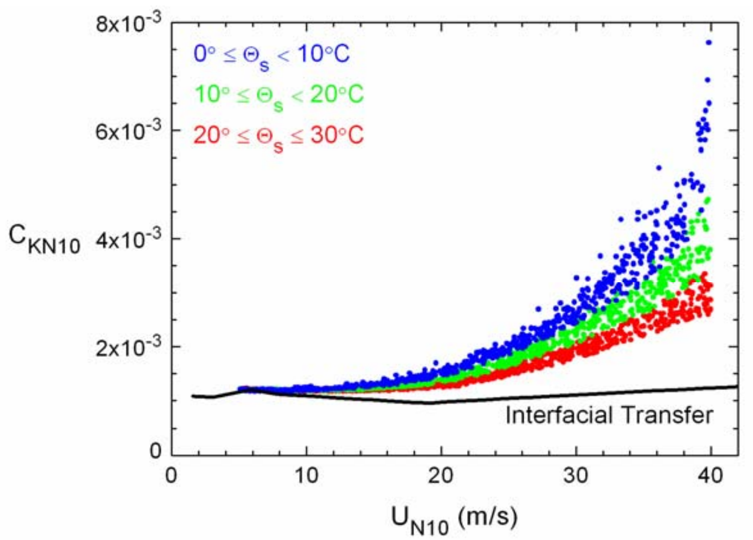

Figure 7. *The neutral-stability, 10-m enthalpy transfer coefficient, C_{KN10}, computed from the artificial dataset and plotted as a function of the neutral-stability, 10-m wind speed, U_{N10}. The solid curve shows what C_{KN10} would be if only interfacial transfer operated. Θ_s is the sea surface temperature. C_{KN10} is always above the curve for interfacial transfer: Spray-mediated processes augment the interfacial transfer. Moreover, the spread in the C_{KN10} values increases with increasing wind speed; and the values cluster according to sea surface temperature, where the coolest temperatures (0° to 10°C) produce the largest C_{KN10} values.*

Two-dimensional numerical simulations using computational fluid dynamics (CFD) software *ANSIS/Fluent* revealed the effect of the Kelvin-Helmholtz type instability and disruption of the air-water interface under hurricane force wind (Fig. 8). These results have qualitatively demonstrated the mechanism of the Kelvin-Helmholtz type instability developing at the air-sea interface under the hurricane force winds, which was previously hypothesized in Soloviev and Lukas (2010).

The subsequent series of 3D experiments has included the initial condition in the form of a short wavelet. Figure 9 shows a contour plot of the density field at the air-water interface in an experiment in which the wind stress was ranging from zero stress to hurricane force stress. The results suggest that tearing of the wave crests due to the Kelvin-Helmholtz type instability may result in smoothing of the water surface and therefore lead to the reduction of the drag coefficient. This mechanism is presumably associated with air-flow separation from waves, previously observed in laboratory conditions (e.g., Donelan et al. 2004), and it is expected to provide a new approach to merging the effects of the two phase environment with the contributions of the drag from waves.

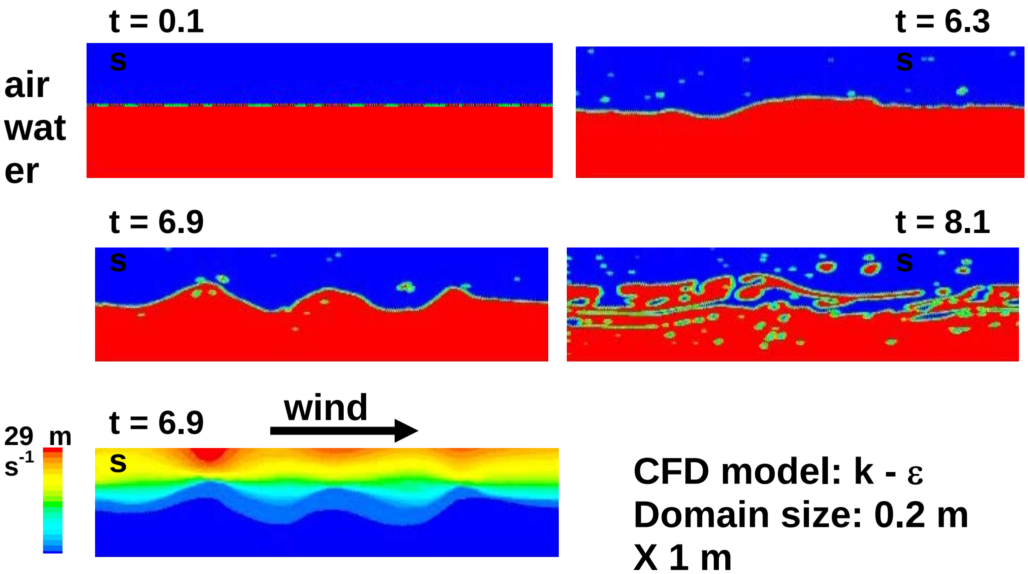

Figure 8. *2D simulation of the disruption of the air-sea interface and formation of a two-phase transition layer under hurricane force wind (Soloviev and Lukas 2010b).*

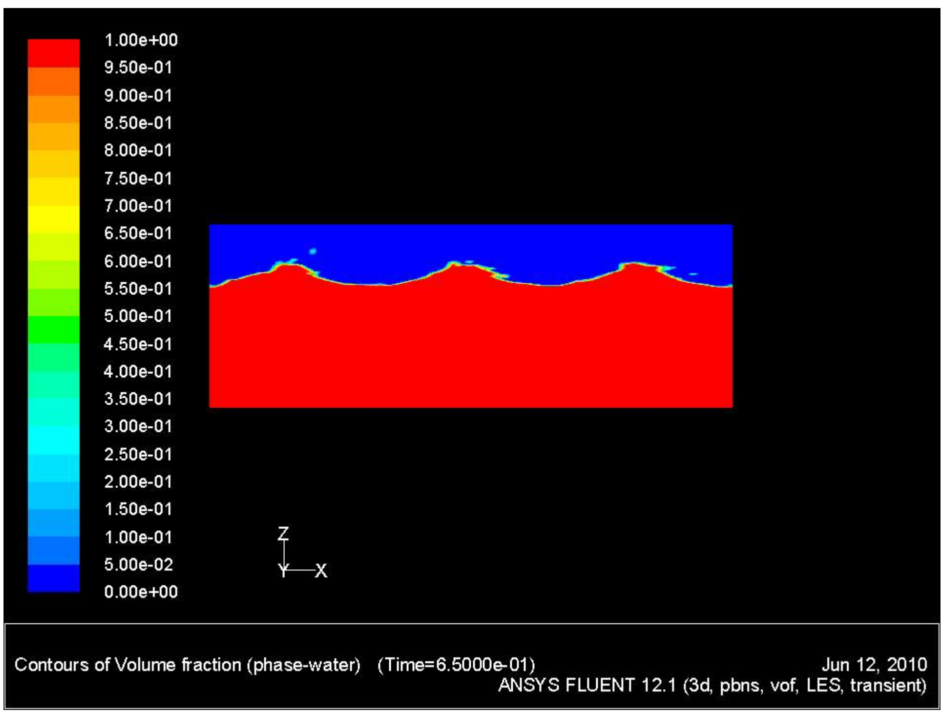

Figure 9. *3D simulation of the disruption of the air-sea interface and tearing of the wave crests due to the Kelvin-Helmholtz type instability at 4 N/m*^{2} *wind stress (side view).*

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

At the end of 2010, Andreas will finish a three-year ONR project on "Turbulent Air-Sea Exchange in Extreme Winds and Its Effect on Storm Structure." Under this project, he developed and validated his bulk flux algorithm for spray-mediated heat fluxes (Andreas et al. 2008; Andreas 2010a) but has also been working on how to parameterize air-sea momentum exchange (Andreas 2009; 2010b)—another crucial issue in modeling hurricane intensity.

The hydrophone in the proof module of the ALOHA Cabled Observatory north of Oahu, Hawaii provided 20 months of acoustic data sampled at 98 kHz. The co-located WHOTS surface mooring at this site provided high-quality meteorological data from which wind, friction velocity and wind stress have been derived. Spectral statistics were stratified by observed wind speeds (up to 15 m/s) and inverted with surface wave elevation models to estimate the spreading integral as a function of wavenumber and wind speed. A modified version of the unified wave spectral model of Elfouhaily et al. (1997) provides the best fit to the data within general constraints on the spreading function. The structure of the directional wave elevation spectrum in the short gravity-capillary wave regime is still not well determined observationally, and this is the region of the wavenumber spectrum where direct transfer of momentum from the wind to the wave field is dominant. Accounting for the effects of wave-breaking and spray on momentum transfer depends on knowledge of the directional wave field.

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".

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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