A Unified Air-Sea Interface for Fully Coupled Atmosphere-Wave-Ocean Models for Improving Intensity Prediction of Tropical Cyclones

Annual Progress Report 2011

PI: Shuyi S. Chen
Rosenstiel School of Marine and Atmospheric Science
University of Miami
4600 Rickenbacker Causeway, Miami, FL 33149
Phone: (305) 421-4048 FAX: (305) 421-4696 E-mail: schen@rsmas.miami.edu

Co-PIs: Mark A. Donelan and Ashwanth Srinivasan, RSMAS/University of Miami
Rick Allard, Tim Campbell, and Travis Smith, Naval Research Lab, Stennis Space Center
Sue Chen, Hao Jin, Shouping Wang, and James Doyle, Naval Research Lab, Monterey
John Michalakes, NCAR/MMM
Hendrick Tolman, NOAA/EMC

Award Number: N00014-10-1-0162
http://orca.rsmas.miami.edu

LONG-TERM GOALS

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

OBJECTIVES

The main science and technology development objectives are to

- develop a 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,
- develop new air-sea coupling parameterizations of the wind-wave-current interaction and sea spray effects and implement them in the unified module,
- implement the unified module into both research and operational coupled model systems,
- examine and constrain the budgets of momentum and enthalpy fluxes as well as the energetic balance of the fully coupled system,
- explore new physics in wind-wave-current coupling at the air-sea interface including wave-breaking and spray and bubble processes using both field observations and the air-sea wave tank at UM,
- test the generality of the air-sea interface coupling and sensitivity to 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,

- evaluate and validate the coupled modeling systems in relatively data rich regions of the Gulf of Mexico and US coastal regions where data are collected regularly by the NOAA research and operational aircraft missions, and through the ONR-supported field programs over the West Pacific (i.e., TCS-08 and ITOP), and
- demonstrate the utility of the newly developed air-sea interface module for improving TC intensity forecasts in real-time.

APPROACH AND WORK PLAN

Scientific and technical approaches over the last two years have been consistent with the proposal. The focus is to develop and test the air-sea interface module in a multi-model, fully coupled framework that is general and flexible for future transition and applications in research and operational models. To ensure the generality and utility of the unified air-sea interface module, two models from each component, i.e., the atmosphere, the surface waves, and the ocean are included in the development. The current component models are COAMPS, WRF, NCOM, HYCOM, SWAN and UMWM. The NOAA WAVEWATCH III is the third wave model that will be included in the coupled system. One of the goals is to make the transition of the air-sea coupling parameterizations developed under this project and others in the community to the operational coupled models. We will continue to take advantage of the recent advancement in the applications of the Earth System Modeling Framework (ESMF) Version 5 in the multi-model system.

One of the most critical components in the air-sea interface module is the energy balance. Coupling at the air-sea interface with surface waves is essential, which needs the level of flexibility and computational efficiency that current wave models are lacking. To address issues related to computational efficiency, a new wave model has been developed. Shuyi Chen and M. Donelan have been working with a graduate student Milan Curcic at RSMAS in developing and testing the new UMWM. A. Srinivasan works in collaboration with Chen at RSMAS and scientists at NRL-SSC on HYCOM related data assimilation and ESMF capabilities. R. Allard leads the efforts at NRL-SSC in wave-ocean coupling using SWAN and NCOM. He and T. Smith work with their colleagues at NRL-MRY on testing new air-sea physical parameterizations in COAMPS-TC. Sue Chen is responsible for the overall development related to COAMPS-TC. She works closely with her colleagues at NRL-MRY (H. Jin, S. Wang and J. Doyle) and NRL-SSC on the implementation of new air-sea interface module in COAMPS-TC. T. Campbell of NRL-SSC, J. Michalakes of NCAR, and H. Tolman of NOAA/EMC are responsible for the ESMF implementation and testing the interface module in the coupled modeling system.

The PI team of the NOPP project has met in February 2011 at RSMAS/UM. A detailed model development and implementation plan was the main outcome of the meeting. The work completed during the second year is summarized in the following sections. The work plan for the coming year (FY12-13) will be: 1) to complete the development of the wave-current coupling parameterization in collaboration with researchers working with the UM air-sea wave tank, 2) to improve the unified air-sea interface module developed during the last two year with multiple air-sea coupling parameterizations developed by this and other NOPP science teams, 3) investigating 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), 4) to complete the implementation of the unified air-sea interface based on the NUOPC interoperability software layer,
and 5) full testing of the multi-model coupled modeling system with the unified air-sea interface module in coupled model TC simulations and forecasts.

WORK COMPLETED

During the second year of this NOPP project (December 2010-Novemver 2011), the PI team have completed the following tasks: 1) initial implementation of the unified air-sea interface coupler using ESMF has been completed; 2) UMWM have been fully tested in both the Northern Sea moderate-high wind conditions and in extreme wind conditions in hurricanes. The results have been summarized in a manuscript submitted to JGR by Donelan et al. (2011); 3) implementation of a wave-state dependent momentum drag and sea spray parameterizations in COAMPS-TC, 4) COAMPS-TC coupling sensitivity experiments and comparisons with observations in Typhoon Fanapi (2010), 5) an improved turbulence kinetic energy (TKE) prognostic calculation of the dissipative heating rate interacting with the sea spray, 6) implementation of ESMF in HYCOM, 7) implement of ESMF interface layer in WAVEWATCH III and integrated WAVEWATCH III into the COAMPS build system, 8) integrated the 3D variational atmospheric data assimilation model NAVDAS and the ocean data assimilation model NCODA into COAMPS.

RESULTS

1. Unified Air-Sea Interface Module with ESMF

The initial development and testing of the unified interface module framework have been completed. We now have two sets of coupled models run under the same ESMF code, i.e., COAMPS-SWAM-NCOM and WRF-UMCM-HYCOM. The NOPP team with PIs from NRL-MRY, NRL-SSC, NREL, and UM have developed a prototype air-sea interface module that comprises of many current existing and new air-wave coupling physics provided by the research team. In the new prototype coupler, we separated the current surface physics for water and land. The new sea surface sub-module that only contains surface flux and sea spray parameterizations over water was then implemented into the prototype air-sea interface module. An I/O subroutine to read in full wave spectrum into the prototype was also implemented. We plan to add a second I/O subroutine to read in the atmospheric model output to begin the test of integrating the momentum fluxes between the air and wave components.

2. Fully Coupled Model with UMWM

The UMWM have been test in moderate to relatively high wind conditions in the northern sea as well as the extreme high wind conditions in hurricanes. Donelan et al. (2011) provide a detailed description of the model and key results of model simulated wave fields compared with observations. The observations are for the month of January 2005 and are derived from an array of laser rangefinders mounted on a bridge between two platforms in the Ekofisk oil field in the North Sea. The model calculates the form stress on the waves and adds it vectorially to the sheltering-modified skin stress. The resulting drag coefficient versus wind speed is shown to have the observed structure – low in light winds; increasing in moderate winds; and leveling out to a limiting value in very strong winds. Modeled spectral properties in Hurricane Bonnie (1998) are compared against NDBC buoys and scanning radar altimeter estimates with acceptable results. Drag coefficients in the mixed seas produced by hurricanes show strong dependence on wave age of the windsea, swell propagation direction and water depth. The need for wave and stress modeling for atmosphere-ocean coupling is emphasized.

UMWM has also been implemented and tested in the unified air-sea interface module. The module has been used in the fully coupled model simulation of Hurricane Ike (2008). Various configurations model resolution and coupling physics have been experimented. One of the results that is relevant in comparison of previous studies of Donelan et al. (2004) and Chen et al. (2007) is the drag coefficient in the coupled model simulation as shown in Fig. 1. The general characteristics is similar to that observed by Donelan et al. (2004). Increase grid resolution has improved the model results substantially (Fig. 1).

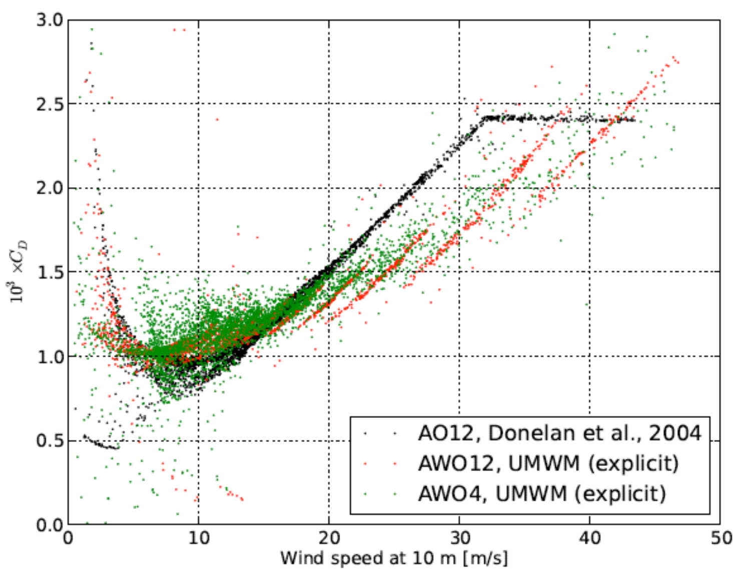

Fig. 1 Drag coefficient of coupled WRF-UMWM-HYCOM simulations of Hurricane Ike (2008) with AO, AWO, 12-km and 4-km grid resolution in all three component models.

3. NRL-MRY Results

In addition to development of the prototype air-sea coupler, we have implemented and tested the new air-sea interaction physics from URI and NOAA within the current coupled COAMPS-TC framework. The new physics include an improved URI wind-wave algorithm that relates Charnock to wave age and wind speed using a set of empirical regression functions. The new URI scheme is similar to the Moon (2004) scheme that has been tested in coupled COAMPS in prior year. As shown in COAMPS hurricane Ivan (2004) simulation (Fig.2a), the momentum drag coefficients from the new URI scheme is larger than the Moon scheme for wind speed greater than 40 m/s. The Ivan simulation has a horizontal grid resolution of 2 km for the atmospheric, 5 km for the ocean, and 10 km for the wave models. Compare to the uncoupled bulk scheme with drag (0.025) level-off at 35 m/s, both the new URI and Moon schemes provides a higher drag (0.003) at high wind speed. Overall, the URI scheme is also less scattered than the Moon scheme for all wind speed range. The azimuthally column-averaged vorticity between 24 and 48 hours showed the URI scheme gives a tighter vortex in the TC core region with a slightly greater relative vorticity than the Moon scheme. The intensity and track forecasts using these two schemes are similar up to 36 hour. The run uses the URI scheme has a 5 nm smaller track error at 48 hour. Because of the wind stress difference between these two runs, the maximum SST cooling difference is about 0.4 C at 48 h.

We also performed tests with COAMPS current spray parameterization follows that of Fariall et al. (2009). The uncoupled COAMPS-TC results showed Fariall (2009) sea spray parameterization provides only moderate impacts in Typhoon Mellor (2009) simulations. The inclusion of spray increases the enthalpy transfer coefficient while it improves slightly on the wind-pressure relationship when comparing with the JMA relationship (Fig. 3).

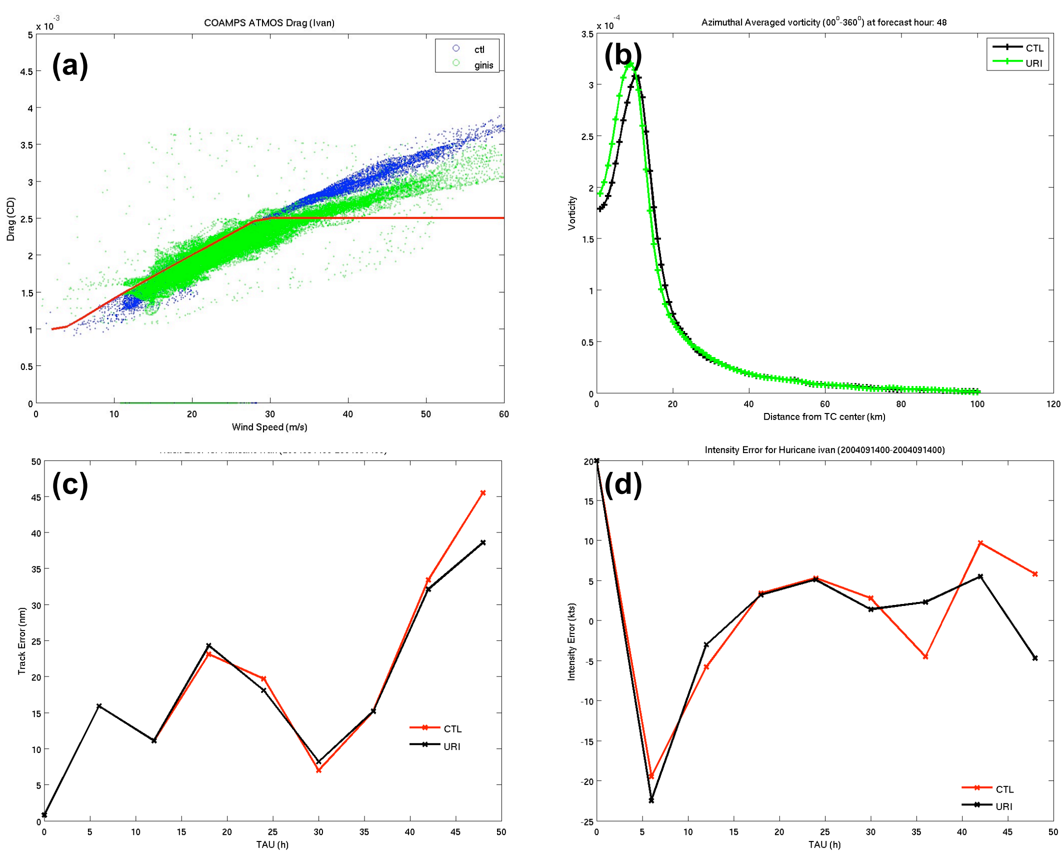

Fig.2 Comparisons of COAMPS Ivan (2004) simulation of (a) drag coefficient, (b) azimuthally column-averaged relative vorticity (s^{-1}), (c) forecast track error (nm), and (d) intensity error (knots) between the new URI and Moon (CTL) wind-wave coupling schemes.

COAMPS-TC Typhoon Melor 2009 Simulations

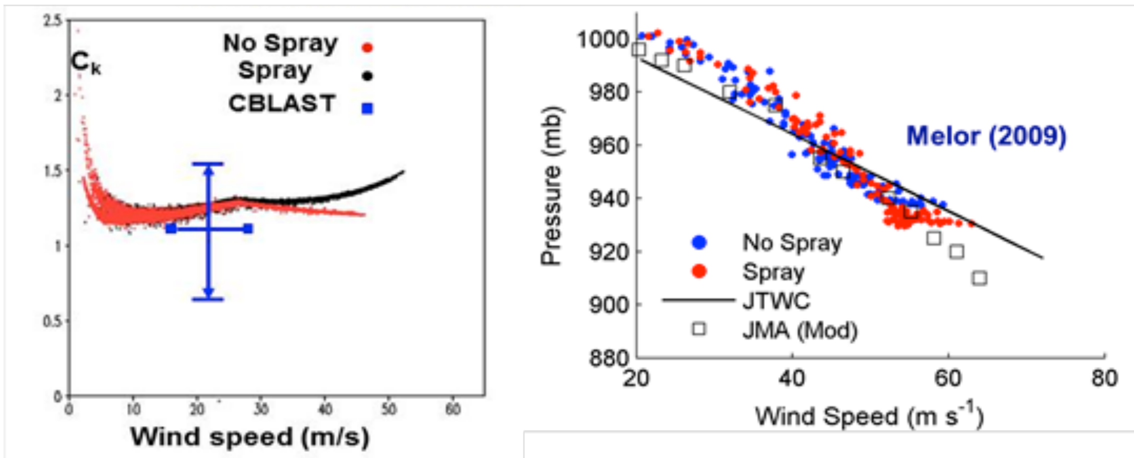

Fig. 3. Impacts of sea spray parameterization on COAMPS-TC Typhoon Mellor (2009) simulations. Left: comparison of enthalpy transfer coefficient and CBLAST observations; right: maximum wind speed-pressure relationship derived from No-Spray and Spray simulations.

We are in the process of implementing the latest version of the spray parameterization developed by NOAA/ETL (Bao et al., 2011), which has an option to couple the spray module to the wave model. The wave parameters used in the new sea spray scheme include the significant wave height, the dominant wave phase speed, and the energy dissipation of breaking waves.

In order to access the impact of air-sea coupling physics in different ocean basin, we added the ITOP cases Fanapi and Megi as additional test cases. We performed a high-resolution air-sea-wave coupled COAMPS control simulation of Fanapi that spin-up from Sep 8, 2010. The model setup for Fanapi includes a 27x9x3 km atmospheric model, a 9x3 km ocean model, and 1/6 degree wave model. The COAMPS forecast track bias is small in the cross track direction. The along track error occurred in the first 12 h forecast time with overall storm movement of being six hour too slow. The intensity forecast for this case is lower than the observation (Fig.3a). A large east-west oriented ocean SST anomaly with maximum of 5.8 C (Fig. 3b) cooling was created as simulated Fanapi traveled westward toward Taiwan and made landfall in east-central Taiwan. The significant wave height forecast agreed well with the JASON2 altimeter observation if considered the 6 h time leg of model forecast typhoon position. We plan to conduct sensitivity runs to access the air-sea coupling physics as well as the new atmospheric physics and their impact to TC intensity and structure change.

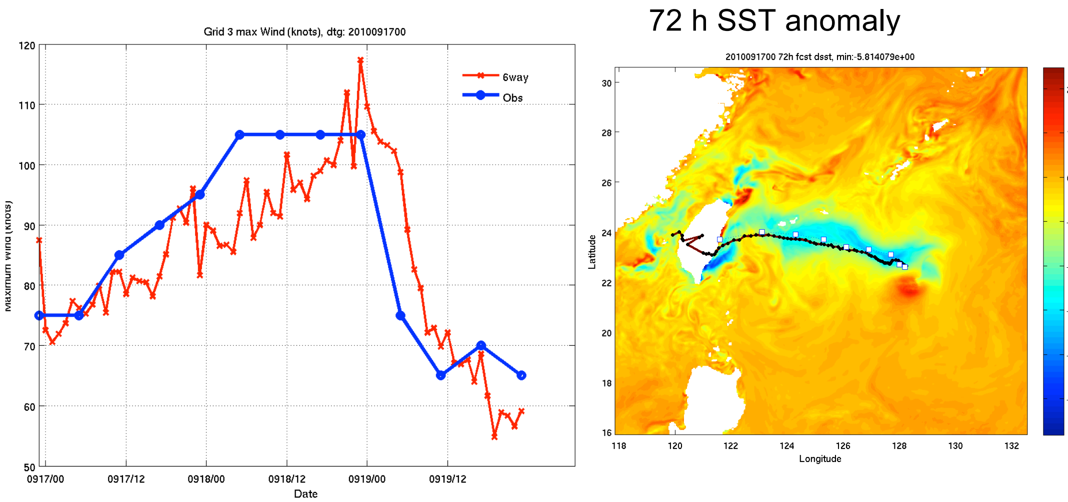

Fig. 4 COAMPS simulation of typhoon Fanapi (2010). (a) Comparisons of forecast intensity with observation and (b) COAMPS forecast SST anomaly.

4. NRL-SSC Results

NCODA 3DVAR and setup programs for SWAN and WaveWatch-III have been integrated into COAMPS. COAMPS has been updated to the ESMF 5.x API. Initial implementation of air-sea coupling in COAMPS based on the NUOPC interoperability software layer is completed. The NUOPC interoperability layer consists of two main elements: a collection of generic code and a catalog of very specific technical rules. The technical rules form the underpinning of the architecture, while the generic code collection implements the rules and provides tangible pieces of software. Applications that leverage the generic code collection immediately start adopting the common model architecture and profit from the benefits of increased interoperability and compatibility checking.

Fully-coupled and uncoupled COAMPS-TC (COAMPS-SWAN-NCOM) simulations for Hurricane Ivan (2004) were tested with a new SWAN wave dissipation and input parameterization from Rogers et al. (2011), a new wave drag formulation from Hwang (submitted, 2011) based on observational data, and a wave age formulation for the Charnock coefficient from Moon et al. (2004). The focus for FY11 included a fully-coupled, 6-way, air-sea-wave simulation for Hurricane Ivan in the Gulf of Mexico (GOM) (September 2004) that yielded improved results for tropical cyclone (TC) intensity and ocean-wave response based on these new wave physics. The fully-coupled model was also compared to an uncoupled model (no ocean to wave or wave to ocean feedback) with satisfactory results. Both simulations included wave to atmospheric feedback that significantly improved the intensity of Hurricane Ivan that included updated atmospheric physics from NRL-MRY, such as an updated radiation scheme and sea spray module. These improved wave and atmospheric model physics will allow for further testing of the unified interface that will be completed in FY12.

A. SWAN Results

Several NBDC (National Data Buoy Center) buoys provided wave observational data during Hurricane Ivan's passage over the eastern and central GOM. The track of Hurricane Ivan was such that several buoys were located both east and west of the storm's central core on the outer fringes of the tropical storm force (greater than 34 kts) wind field; however, buoy 42040 was directly in the path of Ivan (Fig. 1). The model track for the simulations are very good (track error less than 20 nm), although there is about a 6 hr lag in the modeled TC when compared to observations. Regardless, there is good agreement in the SWH at this buoy for the fully-coupled model (Fig. 2). The uncoupled model (no NCOM currents passed to SWAN) yielded SWH that were too large when compared to the buoy. Similar results were noted at other buoys in the Gulf of Mexico.

Although useful in point comparisons, the array of NDBC buoys in the GOM could not adequately capture the evolving wave field in each quadrant of a tropical cyclone. As a TC translates in a certain direction, it is unlikely that fixed buoys would provide enough information about the wave field in each quadrant relative to the TC's center. In addition, not all buoys provide directional wave spectra, which further reduce the quantification of the wave field. The Scanning Radar Altimeter (SRA), on the other hand, is an airborne instrument with high spatial and temporal resolution along the flight tracks. SRA has been successfully used to observe the wave field in the vicinity of a TC (Wright et al. 2001).

For the fully-coupled 72-hour 0000 UTC 14 September forecast, the preliminary comparison of the significant wave height between SRA and SWAN indicated that the wave model slightly overpredicted the SWH (Fig. 3). For the fully-coupled run, the mean error (ME) was 1.62 m, while RMSE is 2.55 m. However, this result was a significant improvement over the classic SWAN wave physics parameterizations where wave heights were consistently well above observational values. The simulated mean wave propagation direction was very close to the observed value (Fig. 3). The bias was very small, approximately -7^{o}, and the RMSE was 37.9^{o}. The propagation direction was captured very well, with only minor differences to the observations.

Additionally, several satellite altimeter data sets were available for comparison to SWAN during Hurricane Ivan's trek across the GOM. Figure 4 shows statistics for all 806 measurements taken by satellite altimeter compared to the 1200 UTC 14 September 72-hour forecast for the coupled and uncoupled simulations. The coupled model RMSE was lower than the uncoupled model for the SWH although the winds measured during this pass were similar. The specific ERS-2 pass of 15 September 2004 was nearest to the core of the hurricane as Ivan traversed the GOM. The position and intensity of Ivan in both model simulations for the 72-hour forecast were very similar during the ERS-2 pass. For both the uncoupled and coupled model, the COAMPS winds were slightly lower when compared to the altimeter data which is primarily attributed to the more compact structure of the cyclone in COAMPS-TC when compared to the larger observed cyclone wind field. However, the SWH in the coupled model was much lower and more representative of the observed wave field when compared to the uncoupled model. Overall, the combination of both the new wave physics and ocean to wave coupling markedly improved the SWAN results.

B. NCOM Results

NCOM was allowed to spin-up with data assimilation for several weeks prior to the arrival of Hurricane Ivan into the GOM to allow pertinent ocean circulation and surface features to develop, which would provide a good initial state for the cyclone's passage in the model. The 1200 UTC 14 September 2004 72-hour forecast track of Hurricane Ivan brought the cyclone directly over the 14 ADCP current profilers deployed along the outer continental shelf and upper slope of the GOM just south of the Mississippi and Alabama coasts (Fig. 1). The ADCP data showed that shelf currents followed Ekman dynamics with overlapping surface and bottom layers during Ivan's approach and transitioned to a dominant surface boundary layer as the wind stress peaked with Ivan's passage (Teague et al. 2007). In addition, Hurricane Ivan generated very strong currents on the shelf and slope. For example, the M1 ADCP measured currents in excess of 200 cm s^{-1} during the forced stage response, while currents on the slope at 50 m and greater depths commonly exceeded 50 cm s^{-1}.

Table 1 summarizes the statistical results at each of the ADCP moorings in Fig. 1. Each calculation was made at the closest possible grid point to the moorings, paying close attention to the model bathymetry. For each ADCP, there were 13 or 14 bins directly comparable to NCOM's vertical depth levels. The M1-M6 ADCPs were shallow-depth moorings that were located either on the shelf or slope while the M7-M14 ADCPs were located off the shelf in much deeper waters. To accurately and directly gauge the physical ocean forced response to Hurricane Ivan, the lag time within the forecast is factored into each calculation. It is important to note that these calculations are very sensitive to along and cross track errors, whether in distance and/or time, and the lag time adjustments were necessary to reduce error in lag as much as possible. Current research involves reducing the lag time in future versions of COAMPS-TC.

To compare the observed ocean current response near and below the surface to the COAMPS-TC runs, we followed Kuzmic et al. (2006) for calculations of the magnitude of the complex correlation coefficient(s) (CCC, Eq. 1) and the angular displacement, or mean directional error (MDE, Eq. 2), between the measured ADCP and NCOM model currents in the fully-coupled model (Kundu 1976). NCOM currents were directly compared to the ADCP currents hourly throughout the 72-hour 1200 UTC September 14 forecast (N = 72). To further evaluate the COAMPS-TC wave to ocean coupled response to the extreme wind forcing of Hurricane Ivan, the MDE was also calculated with and without the Stokes' drift current (SDC) that is provided by SWAN and passed to NCOM currents.

The SDC was calculated to be approximately 10-15% of the total current near the surface of each shallow ADCP mooring. The SDC was found to be negligible in ocean depths of greater than 50 m, therefore the MDE calculation with SDC was not necessary for the deep-water ADCPs. The lag adjusted CCC and MDE for the shallow ADCPs were very good when compared to the model results. The statistics for the period encompassing the forced ocean response to Hurricane Ivan indicated mean CCC values of greater than 0.8 and mean MDE values of less than 15 degrees throughout the water column for almost all of the shallow ADCPs. In fact, the MDE calculations for the top 3-4 bins nearest the surface were primarily less than 10 degrees for all the shallow ADCPs, indicating a very good ocean response to the intense wind forcing near the surface.

Ivan's extreme wind forcing was felt throughout the entire water column in the shallow-water ADCPs. Calculations showed that the SDC during the time of greatest wind forcing was approximately 10-20% of the total current velocity near the surface in each of the shallow ADCP moorings. The addition of the SDC currents from SWAN slightly improved the MDE for all of the shallow ADCPs. A small, but non-negligible, mean MDE improvement of 2-8.5% was calculated throughout the water column for each shallow ADCP; however, nearest the surface (with the greatest wind forcing), improvements of greater than 15% were noted. SWAN SDC feedback to the ocean certainly improved the mean current direction and velocity at each of the shallow ADCPs over the uncoupled model without SDC.

For the deep M7-M14 ADCPs, the mean CCC and MDE were comparable to shallow ADCPs, although the forcing effects of Ivan were negligible below 60-80 m. In fact, the largest errors in MDE for the deep ADCPs occurred due to the model overestimating the depth at which direct effects of the surface forcing were being felt. At some of the deep ADCPs, the forcing in the model registered at least 20 m below what the ADCP current observations were indicating. This equated to MDE values of less than 10 degrees in the topmost bins of the deep ADCPs, while some of the ADCP bins just below the top few bins had MDE values greater than 20 degrees, which in turn increased the overall mean MDE for some of the deep-water ADCPs.

An example vertical profile of ocean currents for ADCP M1 is displayed in Fig. 5. There was an overall good agreement in the magnitude of the ocean currents with depth including the duration of the forced ocean response as Ivan passed over M1. The strongest ocean currents extended about 10 m deeper in the model than in the observations. Also, the model lag time is easily discernable in the vertical profile ocean response when compared to the observations (about 6 hours). Fig. 6 shows an example of the vertical temperature response at M1 for the same period. In terms of vertical ocean mixing, complete mixing was observed in the water column at M1 as Ivan passed along with the quick upwelling and entrainment of colder waters from off the continental shelf after the hurricane's passage. There is remarkable agreement in the bottom temperature measured at M1 and the bottom temperature predicted by NCOM at the location of M1. Overall, the agreement pertaining to the oceanic response at M1 was on par with the observations in both the magnitude and direction of ocean currents and the vertical mixing profile. Similar results were noted at the other ADCPs.

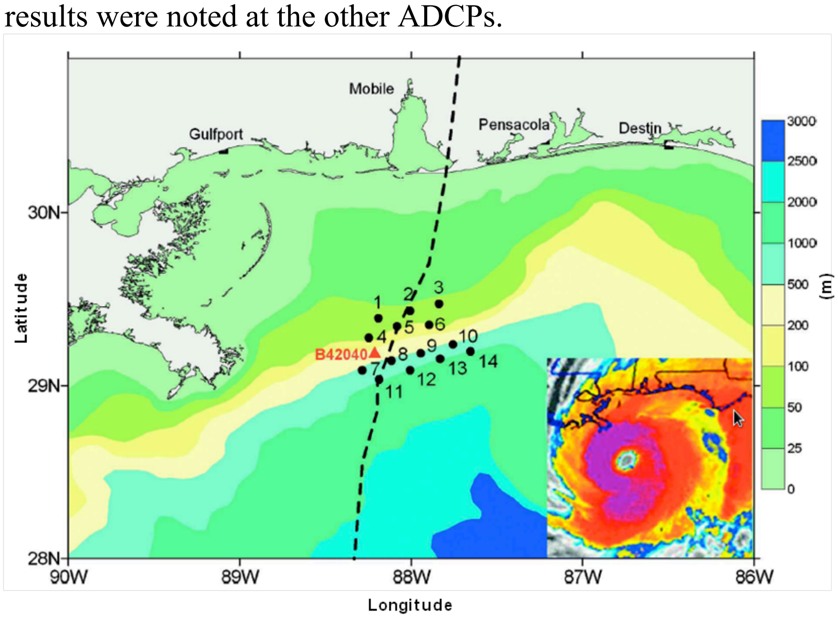

Figure 1. ADCP array in northern Gulf of Mexico in September 2004 (adapted from Teague et al. 2007). Bathymetry contours, the location of NDBC buoy 42040, and best track of Hurricane Ivan are shown. Inset: Infrared satellite picture of Hurricane Ivan as the hurricane approaches the northern GOM coast on 15 September 2004.

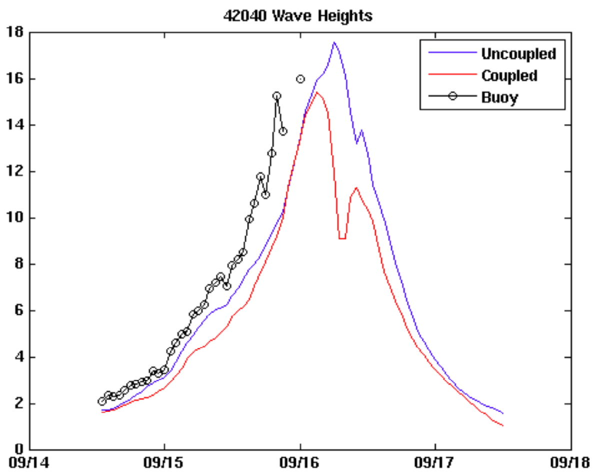

Figure 2. SWH observations (circles) at NBDC Buoy 42040 for 2004091412 72-hour forecast for the uncoupled (blue) and coupled runs (red).

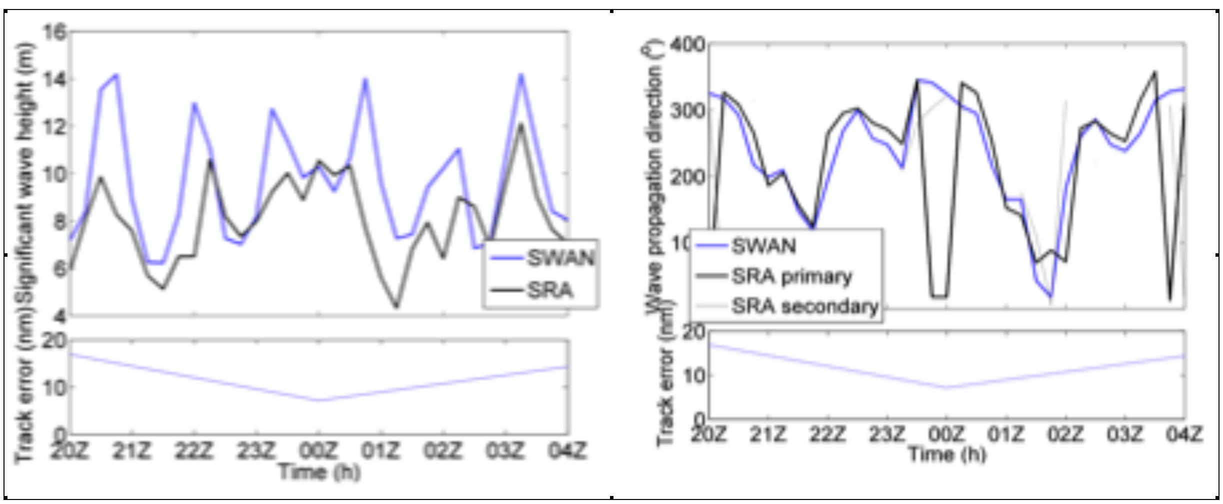

Figure 3: The airborne SRA measurements of significant wave height as a function of time (top panel) and track error (bottom panel), starting on 2000 UTC 14 September 2004 and ending on 0400 UTC 15 September 2004.

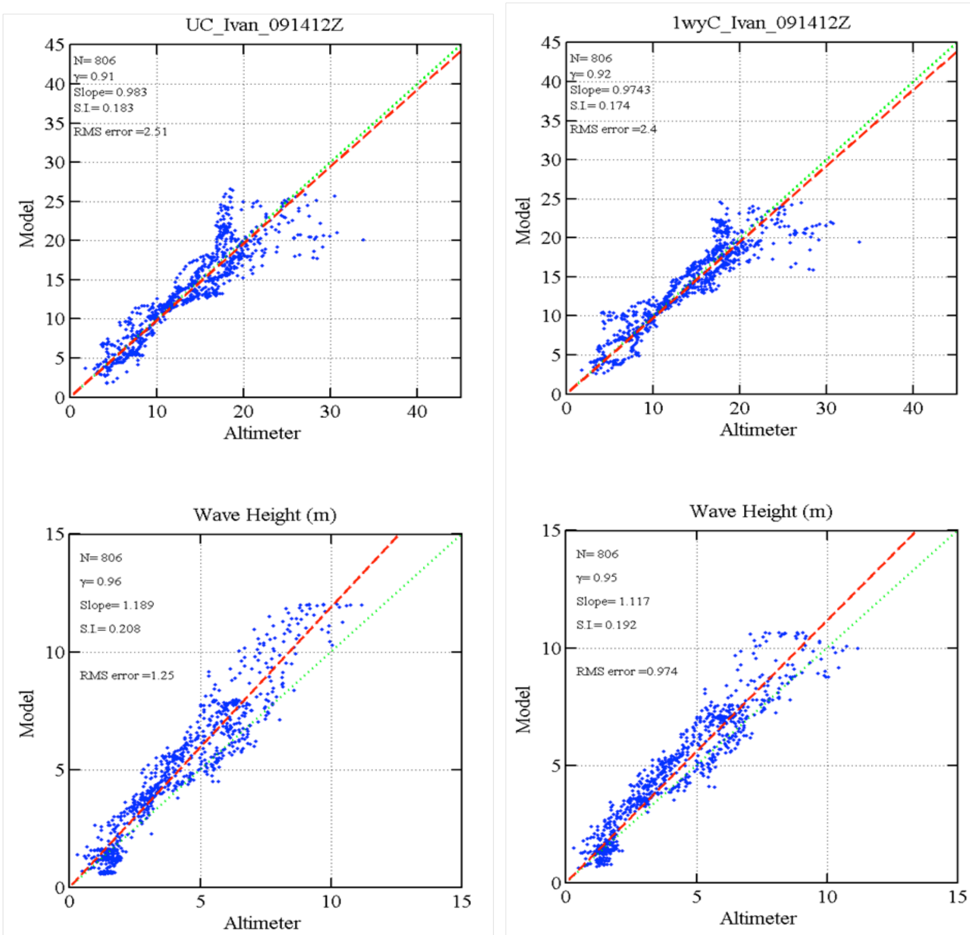

Figure 4. Statistical analysis of satellite altimeter wave height data for all N=806 observations for left column: uncoupled (top: surface winds, bottom: SWH) and right column: coupled (top: surface winds, bottom: SWH).

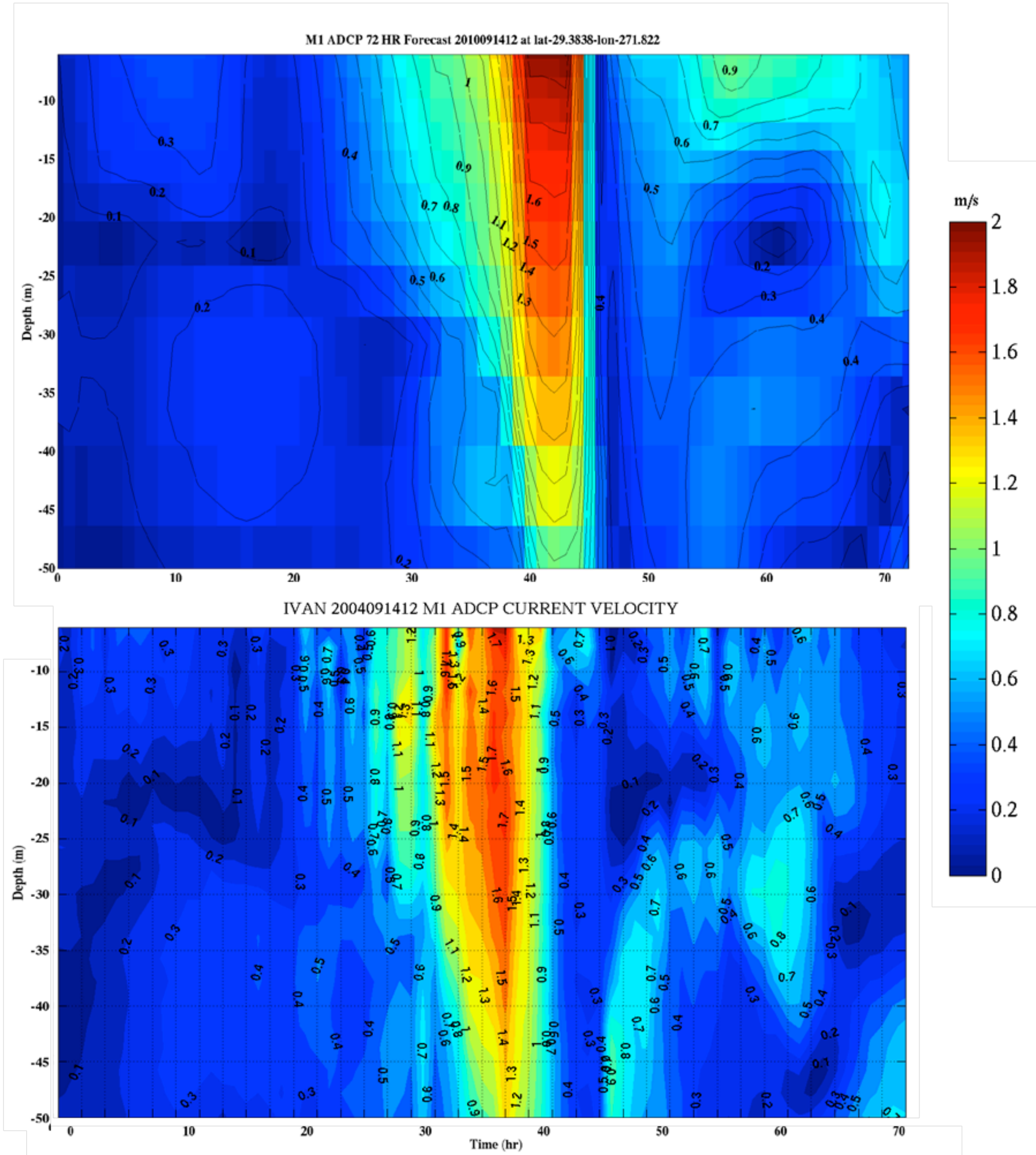

Figure 5. ADCP M1 vertical profile of ocean current velocity. COAMPS-TC (top) and observed (bottom) profiles are shown. Note time lag in the model is approximately 6 hours as Ivan passes near M1.

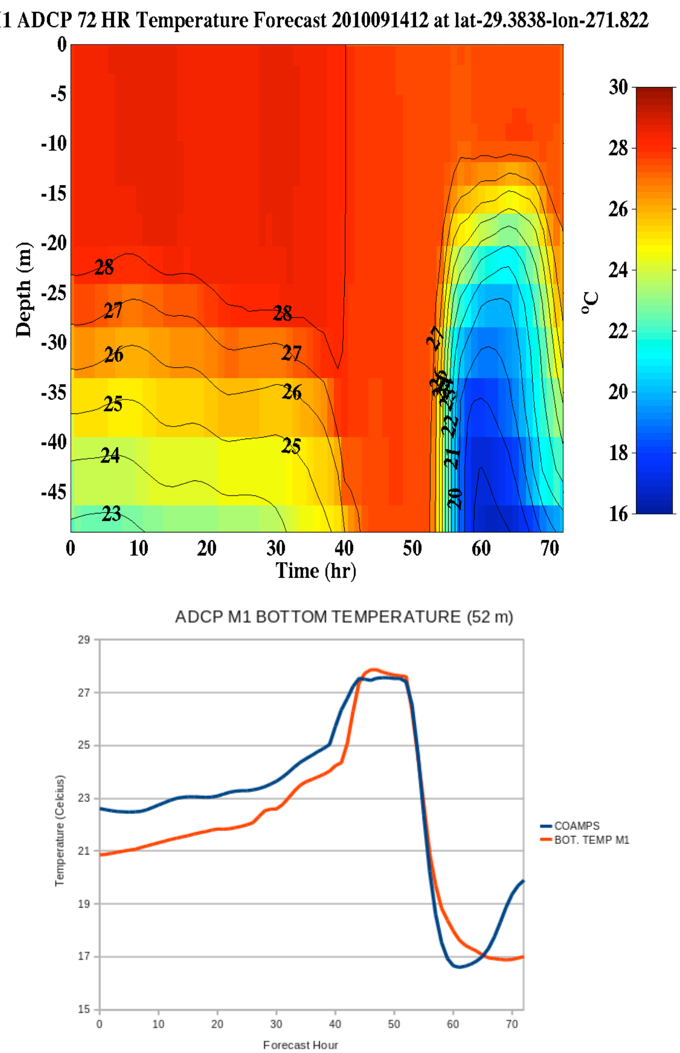

Figure 6. Top: Vertical temperature profile at ADCP M1. Bottom: COAMPS-TC and observed bottom temperature time series. Time lag is factored into the time series plot.

SHALLOW ADCPs	# COMP. BINS	TOP BIN DEPTH	BOTTOM BIN DEPTH	CCC	MDE with SDC (deg)	MDE w/o SDC (deg)	% improvement
M1	13	6	52	0.86	6.21	6.72	7.59
M2	14	4	54	0.87	10.35	11.31	8.49
M3	13	6	54	0.78	10.93	11.52	5.12
M4	13	10	82	0.80	11.10	11.38	2.46
M5	13	11	83	0.81	14.24	14.53	2.00
M6	14	9	81	0.82	15.60	16.22	3.82
ALL SHALLOW AVC				0.82	11.41	11.95	4.53
DEEP ADCPs							
M7	13	52	492	0.73	4.68	N/A	N/A
M8	13	52	492	0.88	10.65	N/A	N/A
M9	13	50	492	0.80	7.65	N/A	N/A
M10	13	50	500	0.87	15.87	N/A	N/A
M11	13	53	493	0.86	15.26	N/A	N/A
M12	13	53	513	0.73	17.92	N/A	N/A
M13	13	50	500	0.76	12.53	N/A	N/A
M14	13	52	502	0.81	11.38	N/A	N/A
ALL DEEP AVG.				0.81	11.99	N/A	N/A

Table 1. ADCP array ocean current statistical comparisons for coupled model configuration. The complex correlation coefficient (CCC) and mean directional error (MDE) are computed. The MDE is computed with and without the Stokes' drift current. Time lag is factored into each calculation.

IMPACT AND APPLICATIONS

Economic Development

Landfalling hurricanes are one of the most costly natural disasters in the US and worldwide. The wave model and fully coupled modeling system developed from this NOPP project will be used in a coastal planning program in South Florida for estimation of hurricane impacts on the local community.

Quality of Life

Improved hurricane intensity forecasts can potentially save lives through a more effective warning and response system. We have been working with social scientists at the University of Miami to conduct idealized online and field survey using the coupled model hurricane simulations to study human behavior and decision making process.

Science Education and Communication

Hurricane forecast products from the NOPP supported high-resolution coupled model, such as the detailed rainfall, winds, waves, and currents have been incorporated in a new course at the University of Miami: ***MSC 106: Hurricane and Society***. It is an interdisciplinary course on the meteorology of hurricanes, forecasting methods, and the societal and economic impact of the storms.

RELATED PROJECTS

The PIs from RSMAS/UM (Shuyi Chen and M. Donelan) and NRL-MRY (Sue Chen, H. Jin, S. Wang, and J. Doyle) are on the science team for the Impact of Typhoons on Ocean over the Pacific (ITOP) that collected unprecedent air-sea data including airborne dropsondes, AXBTs/ACDTs, EX-APEX floats, surface drafters and sea gliders, over the West Pacific during the ITOP field campaign from August-October 2010. These data will be used to evaluate and validate coupled model results.

The research group led by Shuyi Chen at RSMAS/UM is working on a project supported by NOAA/NWS on the development toward the next-generation hurricane impact forecast models. It explore the ultility of multi-scale models, from the global mid-range forecasts (2-4 weeks) to local impact forecasts (hours), with a special focus on hurricane intensity forecast verification.

Shuyi Chen is a Co-PI on a NSF supported research project Understanding Dynamic Responses to Hurricane Warnings - Implications for Communication and Research. It uses the coupled model forecasts from the NOPP project to better understand how the forecast information is communicated and used in decision making process.

REFERENCES

Bao, J.-W., C.W. Fairall, S. A. Michelson, L. Bianco, 2011: Parameterizations of sea-spray impact on the air-sea momentum and heat fluxes, *Mon. Wea. Rev.*, early release.

Chen, S. S., J. F. Price, W. Zhao, M. A. Donelan, and E. J. Walsh, 2007: The CBLAST-Hurricane Program and the next-generation fully coupled atmosphere-wave-ocean models for hurricane research and prediction. *Bull. Amer. Meteor. Soc.*, **88**, 311-317.

Donelan, M. A., 1999: Wind-induced growth and attenuation of laboratory waves. Proceedings edited by S. G. Sajjadi, N. H. Thomas and J. C. R. Hunt, Wind-over-Wave Couplings, *Clarendon Press*, 183-194.

Donelan, M. A., 2001: A nonlinear dissipation function due to wave breaking. Proceedings of the ECMWF workshop on Ocean Wave Forecasting, edited by P.A.E.M. Janssen, *European Centre for Medium-Range Weather Forecasts*, Reading, 87-94.

Fairall, C. W., M. L. Banner, W. L. Peirson, W. Asher, and R. P. Morison, 2009: Investigation of the physical scaling of sea spray spume droplet production. *J. Geophys. Res.*, **114**, C10001, doi:10.1029/2008JC004918.

Hasselmann, K., T. P. Barnett, E. Bouws, H. Carlson, D. E. Cartwright, K. Enke, J. A. Ewing, H. Gienapp, D. E. Hasselmann, P. Kruseman, A. Meerburg, P. Miller, D. J. Olbers, K. Richter, W. Sell, H. Walden, 1973: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). *Ergnzungsheft zur Deutschen Hydrographischen Zeitschrift Reihe* **12**.

Moon I-J, I. Ginis, and T. Hara, 2004: Effect of surface waves on Charnock coefficient under tropical cyclones: *Geophy. Res. Letters*, vol 31, L20302, doi:10.1029/2004GL020988.

Kundu, P.K., (1976). Ekman veering observed near the ocean bottom, *J. Phys. Oceanogr*., **6**: 238-242.

Kuzmic, M., I. Janekovic, J. W. Book, P. J. Martin, and J. D. Doyle, (2006). Modeling the northern Adriatic double-gyre response to intense bora wind: A revisit, *J. Geophys. Res*., 111: C03S13.

Hwang, P. A. (2011): A note on the ocean surface roughness spectra. Submitted to J. Geophysical Research.

Rogers, W. E., A. V. Babanin, and D. W. Wang (2011). Observation-based input and whitecapping-dissipation in a model for wind-generated surface waves: Description and simple calculations. Accepted for publication in *J. Ocean Tech*.

Teague, W. J., E. Jarosz, D. W. Wang, D. A. Mitchell, (2007): Observed Oceanic Response over the Upper Continental Slope and Outer Shelf during Hurricane Ivan. *J. Phys. Oceanogr.*, **37**: 2181–2206.

PUBLICATIONS

Donelan, M. A., M. Curcic, S. S. Chen, and A. K. Magnusson, 2011: Modeling waves and wind stress, *J. Geophys. Res.*, submitted.

Chen, S., T. J. Campbell, H. Jin, S. Gaberšek, R. M. Hodur, and P. Martin, 2010: Effect of two-way air-sea coupling in high and low wind speed regimes, *MWR*, **138**, 3579–3602.

Judt, F., and S. S. Chen, 2010: Convectively Generated Potential Vorticity in Rainbands and Formation of Secondary Eyewall in Hurricane Rita of 2005, *J. Atmos. Sci.,* **67**, 3581–3599.