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

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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 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

The approach in the proposed research 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. The current model components are COAMPS, WRF, NCOM, HYCOM, SWAN and WAVEWATCH III. One of the most critical components in the air-sea interface module is the energy balance. To address issues related to computational efficiency, a new wave model is developed. In addition, transitions of the air-sea coupling parameterizations to the operational coupled models will take advantage of the recent advancement in the applications of the Earth System Modeling Framework (ESMF) in the multi-model system.

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. R. Foster of UW, C. Fairall and J.W. Bao of NOAA/ESRL provide the expertise in PBL and air-sea physics including sea-spray parameterization. This PI team and the team at URI (I. Ginis, T. Hara, et al.) will work together on the overall model development and simulations in tropical cyclones.

The entire PI team of the NOPP project has met in January 2010 at RSMAS/UM. A detailed model development and implementation plan was the main outcome of the meeting. The work completed during the first year is summarized in the following sections. The work plan for the coming year (FY11-12) will be: 1) to implement the new UMWM in the interface module, 2) to complete the development of the wave-current coupling parameterization in collaboration with researchers working with the UM air-sea wave tank, 3) continue the investigation on the impact of sea-spray on the sea-state dependent air-sea heat and momentum fluxes and refinement of the sea spray parameterizations based on available observations, 4) 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), 5) implementation of the improved UM and URI sea-spray and wind-wave-current coupled parameterizations in the unified air-sea interface module, 6) initial implementation of the unified air-sea interface coupler will be completed and tested, and 7) full testing of the multi-model coupled modeling system with coupled model TC simulations.

## WORK COMPLETED

During the first year of this NOPP project (FY10-11), the PI team have completed the following tasks: 1) development and testing of the new University of Miami Wave Model (UMWM) that is physically-based and computationally efficient for fully coupled modeling system, 2) comparisons of UMWM, WAVEWATCH III model results with in situ buoy observations in Hurricane Ike (2008), 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 Hurricanes Frances (2004) and Ivan (2004), 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, 9) extended the COAMPS coupler to support regridding for general curvilinear grids, and 10) wind-wave tank experiments of spray and bubble with both fresh and salt water in high-wind conditions.

The work completed by the URI PI team will be described in a separate report.

## RESULTS

The new wave model developed at RSMAS/UM (UMWM) is a full physics wave model that solves wave action density equation similar to that of SWAN and WAVEWATCH III:

$$\frac{\partial N}{\partial t}+\frac{\partial(\dot{x}N)}{\partial x}+\frac{\partial(\dot{k}N)}{\partial k}+\frac{\partial(\dot{\theta}N)}{\partial \theta}=S_{in}+S_{ds}+S_{nl}+S_{bf}$$

where $N(k,\theta,x,t)$ is the wave action density spectrum, and $k$, $\theta$, $x$ and t are the wavenumber, wave direction, vector in geographical space, and time, respectively. The wind input source term $S_{in}$ is based on laboratory results by Donelan (1999):

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$$S_{in}=s\frac{\rho_a}{\rho_w}\left|\frac{U(\frac{\lambda}{2})}{c}-1\right|\left(\frac{U(\frac{\lambda}{2})}{c}-1\right)\omega N$$

where $\rho_a$ and $\rho_w$ are densities of air and water, respectively, $U(\frac{\lambda}{2})$ the wind speed at the height of half wave length, $c$ the phase speed of the wave, $\omega$ the corresponding wave frequency, and $s$ the sheltering coefficient. The wave dissipation (wave breaking) term $S_{ds}$ is based on Donelan (2001):

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$$S_{ds}=-C_{ds}\omega N\left[\left(1+400\overline{\chi^2}\right)^2k^4N\right]^{\frac{5}{2}}$$

where $\overline{\chi^2}$ is the mean square slope of the surface, $k$ the wave number, and $C_{ds}$ the dissipation coefficient. The non-linear wave-wave interaction term is simplified for computationally efficient. It assumes that a portion of wave energy dissipated through wave breaking is transferred to adjacent lower frequencies. Based on wave tank experiments of Pierson et al. (1992) and Donelan (2010), the source term is defined as:

$$S_{nl} = C_{nl} S_{ds}$$

where $C_{nl}$ is the fraction of dissipated energy transferred to lower frequencies and currently set to be 0.65. The bottom friction term $S_{bf}$ is from Hasselmann et al. (1973):

$$S_{bf} = -2\Gamma \frac{n - 1/2}{gd} N$$

where $n$ is the ratio of group velocity and phase speed, $g$ the gravitational acceleration, $d$ the water depth, and $\Gamma$ a tunable parameter with values of the current value of $0.067\ m^2 s^{-3}$.

The software implementation of UMWM is written in standard Fortran. It uses MPICH2 for parallel execution on multi-processors in a distributed-memory paradigm. It can be set up for idealized or real case simulations with both regional and global configurations. It is computationally efficient and about 10 times faster than the current WAVEWATCH III.

UMWM has been fully tested in number hurricane simulations. The results are compared with both WAVEWATCH III and in situ NDBC buoy observations in Hurricane Ike (2008). The wave models are forced with the wind forecast (at 1.3 km resolution) from the UM coupled model (UMCM) in realtime. The model was initialized at 1200 UTC on 9 September 2008. Figure 1 shows the UMWM simulated significant wave height (SWH) over a 5-day period. The SWH is asymmetric to the storm center, similar to previous results in Chen et al. (2007) as expected.

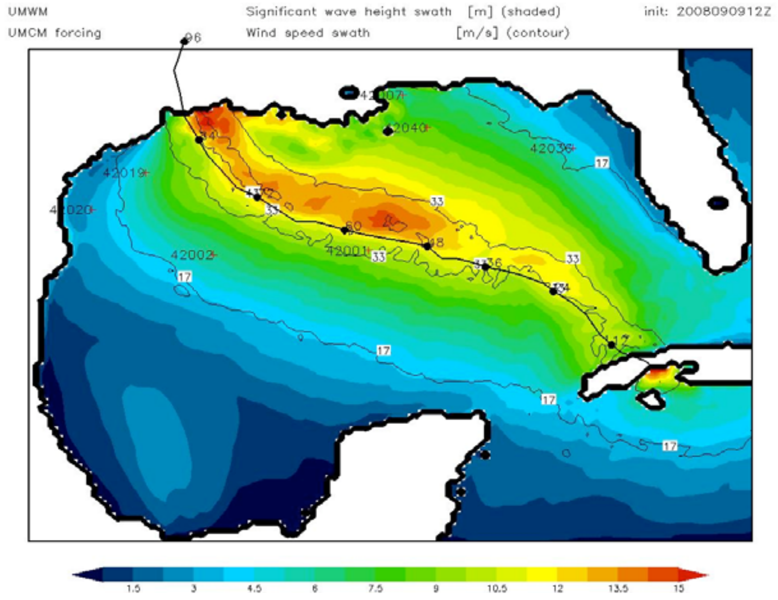

Fig. 1 UMWM simulated SWH (m, color) in Hurricane Ike using the winds (m/s, contour) from the 5-day UMCM realtime forecast initialized at 1200 UTC September 9, 2008. The locations of NDBC buoys are marked.

The UMCM wind forecasts are similar to that observed at most buoy locations (Fig. 2), which make it easier to evaluate wave model performance in this case. The model simulated SWH and mean wave periods from UMWM are generally similar to the results of WAVEWATCH III, with the exception near the coast where WAVEWATCH III underestimated SWH significantly (Fig. 2d). Both wave models have a slightly low bias in SWH at three buoy locations away from the storm center in Ike (Fig. 3). The low bias is mostly from the longwaves (swells). The wind-sea waves are well captured by the models, which are particularly important in the coupled models for TC forecasting. Because of the computational efficiency and flexibility in coupling, UMWM will be an excellent wave model to be used in the air-sea interface module.

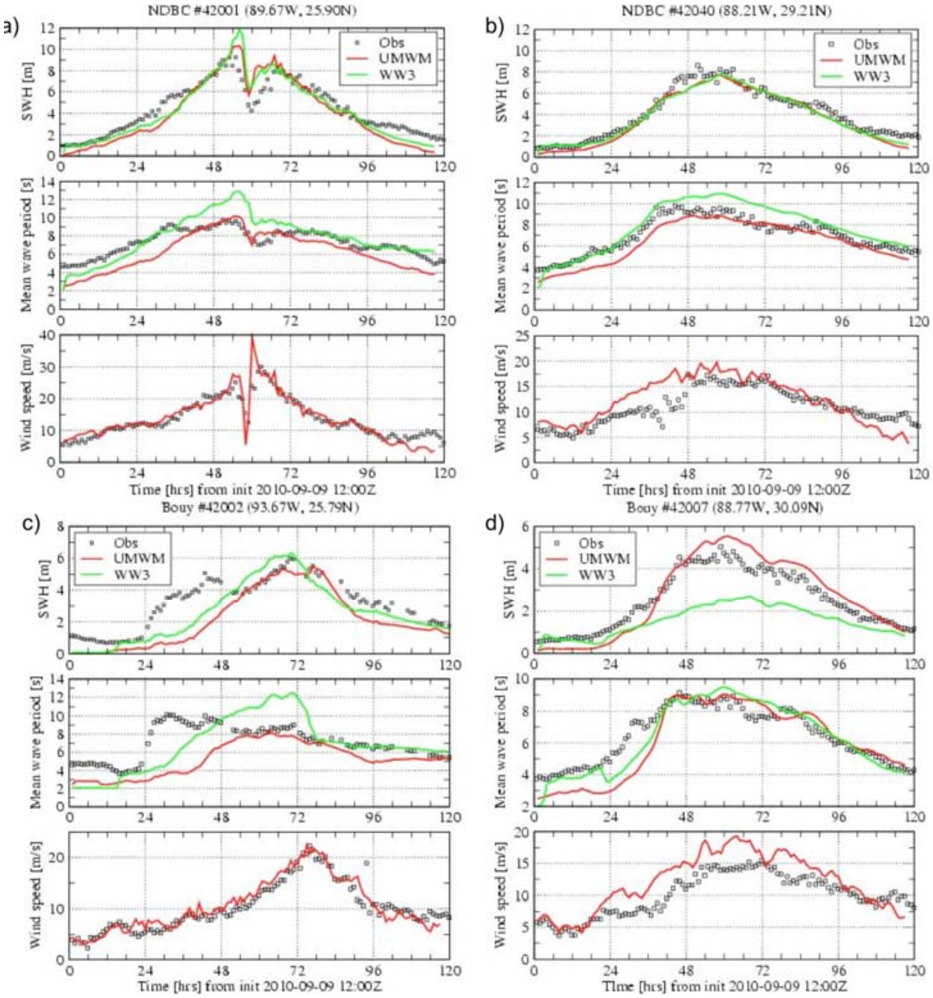

Fig. 2 Examples of UMWM and WAVEWATCH III (WW3) simulated SWH compared with observations from four NDBC buoys indicated in Fig. 1: a) 42001 near the storm center, b) 42040 at right side of the storm passage, c) 42002 at left side of the storm passage, and d) 42007 near the coast.

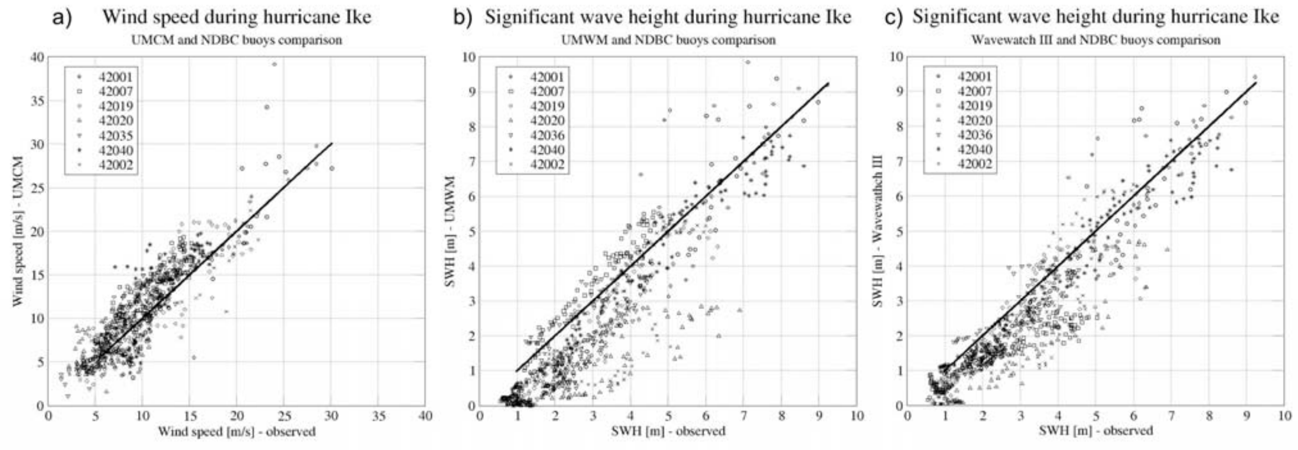

Fig. 3 Model simulations are compared with all 7 NDBC buoy observations during Hurricane Ike: a) surface wind speed (m/s), b) UMWM SWH (m), and c) WAVEWATCH III SWH (m).

Fully coupled COAMPS-TC (COAMPS-SWAN-NCOM) has between evaluated using floater data from CBLAST for Hurricane Frances (2004) (courtesy of Tom Sanford of University of Washington) and ADCP data for Hurricane Ivan (2004) (from Bill Teague's group at NRL-SSC) containing both shallow and deep water current and temperature measurements. Comparison of the ADCP data to the coupled simulation in Ivan (excluding feedback from waves to winds) indicated an excellent ocean response in terms of near surface current speed and direction (Fig. 4), although the coupled model intensity for Ivan was approximately 5-10 m/s lower than observed. Complex correlation coefficients (CCC) and mean directional errors (MDE) were calculated at each of the ADCPs bins (up to 500 m). At some of the ADCPs, CCC values of near 0.8 were measured while MDE values were less than 10 degrees, indicating the good ocean response.

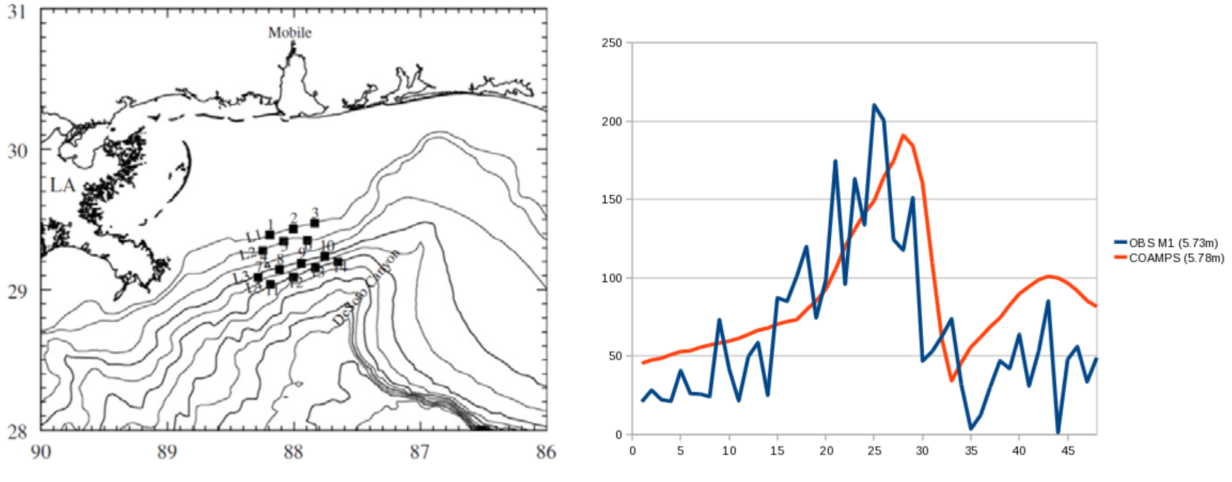

Fig. 4 Model simulated (red) and observed (blue) current speed (cm/s, right panel) at ADCP location M1 (top left location in the left panel) at ~6 m water depth over a 48-h period from September 16, 2004.

Three COAMPS-TC simulations in Hurricane Frances (2004) were conducted to exam the impact of wave-state-dependent momentum drag and the sea spray effect on the TC track and intensity forecasts. The control simulation is a fully coupled simulation with NCOM and SWAN. The interaction between the air-ocean, air-wave, and ocean-wave are all two-way. Sensitivity Exp1 excludes the wave effect and only allows for the interaction between the air-ocean. This run uses the COAMPS bulk formulation of drag coefficient that level-off for wind speed > 30 m/s. Sensitivity Exp2 is the control simulation plus the sea spray effect. The current version of COAMPS sea spray parameterization does not dependent on the wave state. The comparisons of the momentum drag between the control and Exp1 show the fully coupled wave-state-dependent drag has more special variation and higher values near the eyewall region than the drag from the bulk scheme (Fig. 5). The drag versus wind speed relationship (Fig. 6) show the wave-state-dependent drag coefficient is slightly lower for wind speed between 15-35 m/s and higher for wind speed >35 m/s compare to the bulk scheme. In the lower wind speed regime (<15 m/s), the wave-state-dependent drag coefficient is similar to the bulk scheme but has less scattering for wind speed less than 2 m/s. The maximum drag value from the control simulation is about 3.0e-3, compared to the bulk formulations that level-off around 2.5e-3. The drag value from Moon et al. (2004) using WAVEWATCH III for wind speed >50 m/s is around 2.2e-3. We plan to conduct additional tests using SWAN with caped frictional velocity to 6% of the wind speed in SWAN and implemented the same algorithm in WAVEWATCH III as in Moon et al. (2004) to further understand the discrepancies in the forecast drag values.

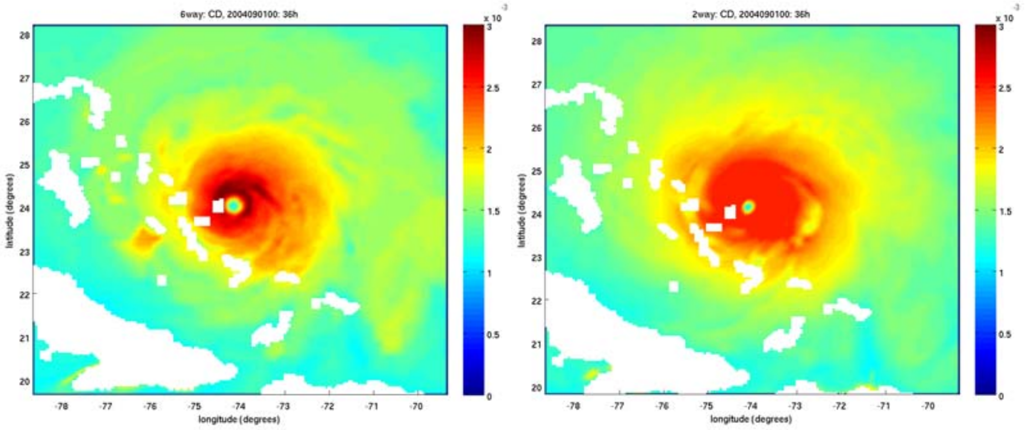

Fig. 5 Model simulated 36-h momentum drag for the fully coupled air-ocean-wave control simulation (right panel) and the two-way air-ocean sensitivity Exp1 (left panel).

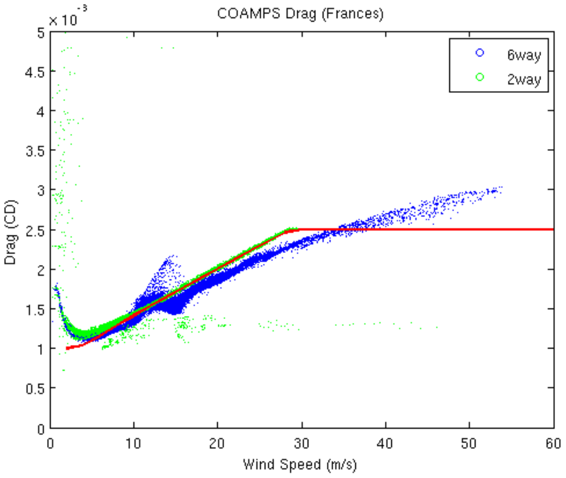

Fig. 6 Scatter plot of momentum drag versus wind speed at 36-h model forecast time from the fully coupled air-ocean-wave control simulation (blue) and the two-way air-ocean coupled sensitivity Exp1 (green). The red line represents the standard COAMPS drag formulation under a neutral condition.

## 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

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.

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.

## PUBLICATIONS

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.