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 development of the unified air-sea interface module has been consistent with the proposed scientific and technical approaches over the last three years. 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 March 2012 at RSMAS/UM. The meeting summary has been posted on the NOPP website at http://www.nopp.org/2012/national-oceanographic-partnership-program-nopp-tropical-cyclone-principal-investigators-meeting-at-the-university-of-miami-1-2-march-2012/

The work completed during the third year is summarized in the following sections. The work plan for the remaining FY13 will be: 1) to improve the unified air-sea interface physics, 2) 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), 3) to complete the implementation of the unified air-sea interface based on the NUOPC interoperability software layer, and 4) summarize the results in publications and assisting transition the outcome to community research and operational models.

WORK COMPLETED

During the third year of this NOPP project (November 2011-October 2012), the PI team have completed the following tasks: 1) implementation of the unified air-sea interface using ESMF and a common exchange grid for all component models in the coupled model systems; 2) University of Miami Wave Model (UMWM) has been integrated into COAMPS-TC and UMCM, which demonstrate the interoperability of the coupling systems; 3) both coupled modeling systems have configured to test the air-sea interface with UMWM using Hurricane Isaac (2012), 4) integration of the 2011 atmospheric physics upgrade from the uncoupled COAMPS-TC into the coupled 2012 COAMPS-TC version; 5) assimilation of AXBT data in COAMPS-TC with NCODA in Tropical Storm Emily (2011) and Isaac (2012); 6) integrated ESMF interface layer for Wavewatch III into the latest development version; 7) updated Wavewatch III ESMF interface layer to use the NUOPC conventions; and 8) improved ITOP dropsonde data analysis and calculations of air-sea momentum, heat, and moisture fluxes for coupled model evaluation and verification.

RESULTS

1. Unified Air-Sea Interface

Prototype air-sea interface module approaches have been separately, and successfully, implemented in COAMPS and UMCM. Interoperability is demonstrated through the integration of UMWM into both systems. Significant progress has been made towards development of a single air-sea interface coupling infrastructure that is based on the National Unified Operational Prediction Capability (NUOPC) ESMF interoperability software layer. The interoperability software layer consists of a collection of generic code and a catalog of very specific technical rules. The technical rules form the underpinning of a common model architecture, while the generic code collection implements the rules and provides tangible pieces of software. NUOPC/ESMF software modules are now available for developing coupled application drivers, model components and the couplers that transform data between components. The NUOPC/ESMF based unified air-sea interface coupling software profits from the benefits of increased interoperability and compatibility checking.

The PIs from UM, NRL-SSC and NRL-MRY have conducted a number of fully coupled atmosphere-wave-ocean model forecasts of tropical cyclones from the West Pacific – Typhoon Fanapi (2010) observed in ITOP and recent Atlantic tropical storms and hurricanes.

2. Coupled Model Experiments with the Unified Air-Sea Interface

The University of Miami Wave Model (UMWM, Donelan et al. 2012) has been integrated into both COAMPS-TC and UMCM to facilitate the unified air-sea interface development and continued improvement. UMCM calculates the directional wind-wave (form) stress on the waves and adds the vector form stress to the sheltering-modified skin stress similar to that of Chen et al. (2012). 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. UMCM has been extensive tested in real-time forecast mode from July-September 2012. The model is evaluated and verified with in situ observations from the NDBC buoys and surface Met drifters deployed during the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) field campaign that covers a wide range of weather conditions from calm winds to extreme winds in hurricanes.

Examples of the UMCM forecasts of Tropical Storm Debby and Hurricane Isaac show that the coupled model can improve forecasts not only intensity but also storm tracks in these cases. Fig. 2.1 shows UMCM real-time 5-day forecasts initialized 0000 UTC daily from 23-28 June 2012. Forecasts are compared with the NHC best track data and the NOAA operational models including GFS, HWRF and GDFL.

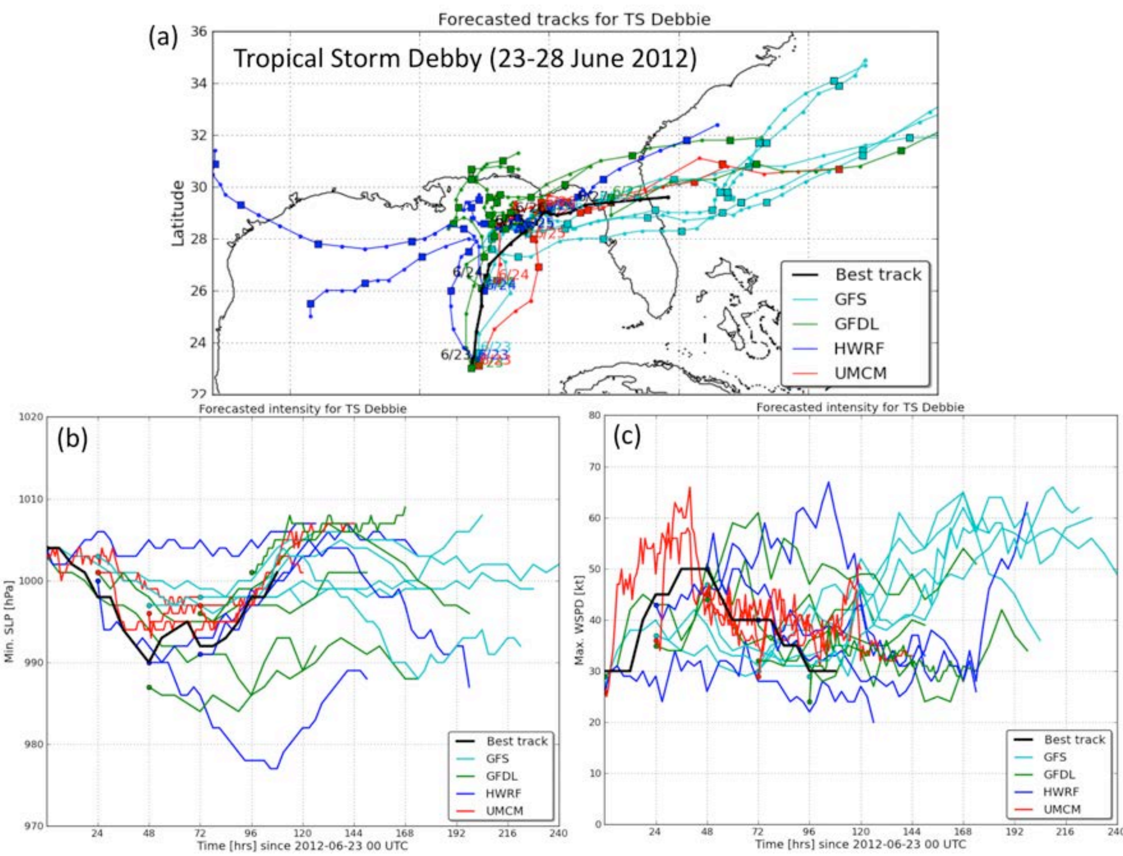


Fig. 2.1 UMCM forecasts (red) of TS Debby from 23-28 June 2012 compared with the NHC best track (black), GFS (cyan), GFDL (green), and HWRF (blue): (a) tracks, (b) MSLP, and (c) maximum wind speed. The models are initialized at 0000 UTC daily from 23-28 June 2012.

We have conduced a number of model experiments to better understand the coupled model physics compared with that of uncoupled model. Figs. 2.2 and 2.3 show the comparisons of uncoupled atmosphere (WRF), coupled atmosphere-ocean (WRF-HYCOM), and fully coupled atmosphere-wave-ocean (WRF-UMWM-HYCOM) models. The coupled models have a better track forecasts compared to the uncoupled model (Fig. 2.2), largely due to the fact that coupled model captured the asymmetric structure of Hurricane Isaac, whereas the uncoupled model over-predict storm intensity with a stronger and more symmetric storm (Fig. 2.3). UMCM is configured in multi-nested grids with 12-, 4-, and 1.3-km grid resolutions.

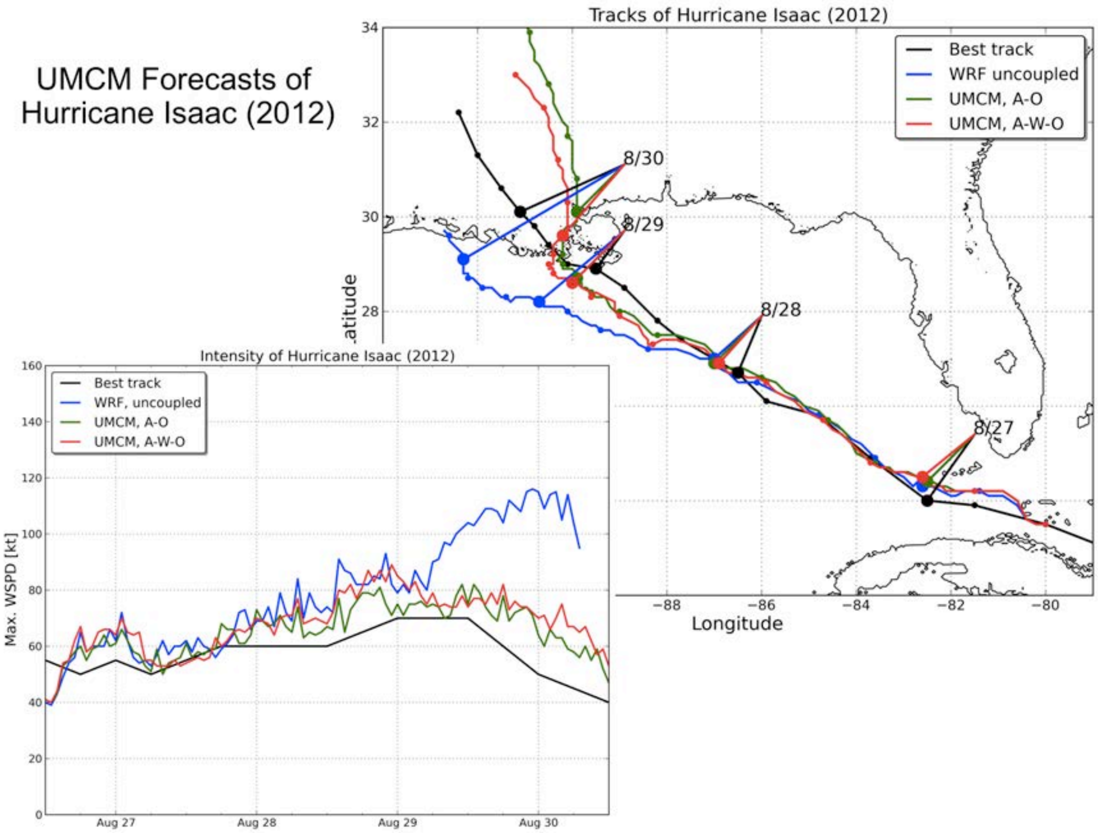


Fig. 2.2 Model forecasts (uncoupled UA-blue, coupled AO-green, and fully coupled AWO-red) of Hurricane Isaac (initialized at 1200 UTC 26 August 2012) compared with the NHC best track (black): storm tracks (top right) and maximum wind speed (bottom left).

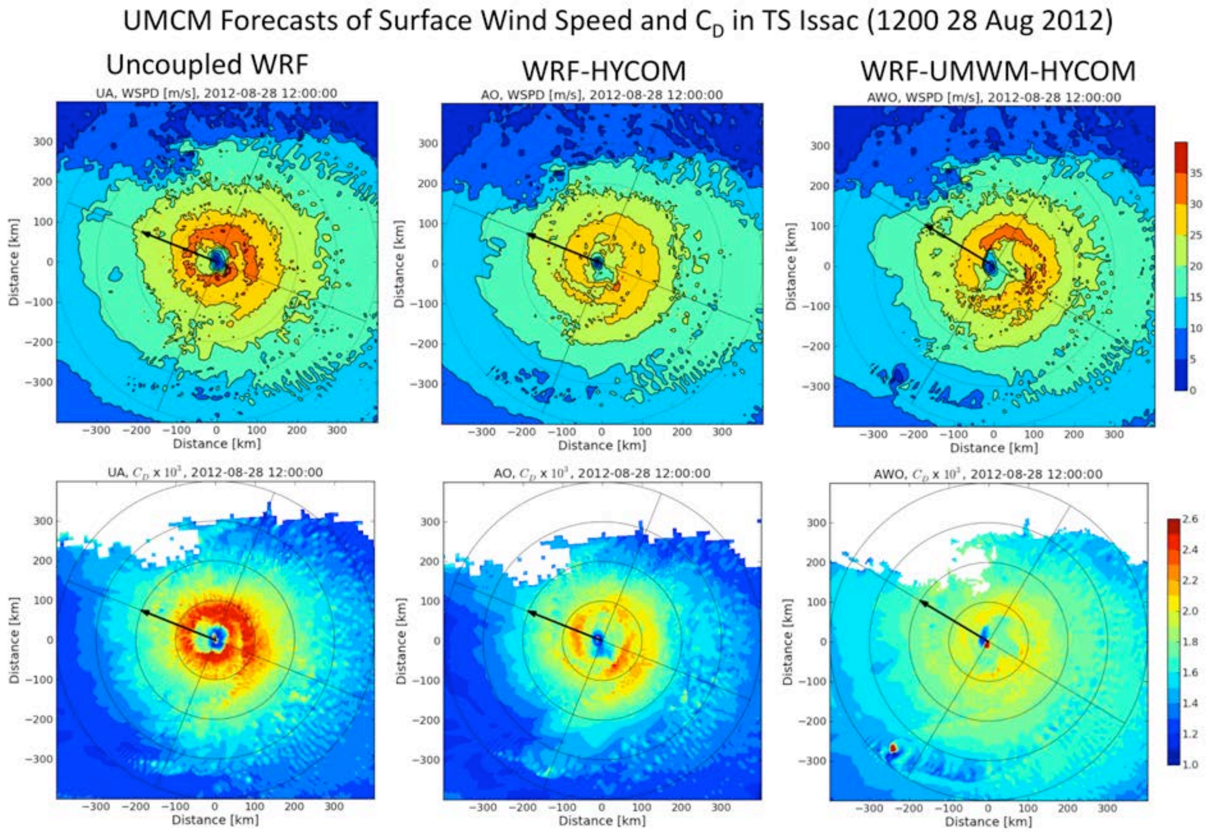


Fig. 2.3 Model forecasts of surface wind speed and drag coefficient from the uncoupled UA (WRF), coupled AO (WRF-HYCOM), and fully coupled AWO (WRF-UMWM-HYCOM) in Hurricane Isaac at 1200 UTC 28 August 2012.

3. Assimilation of AXBT data in COAMPS-TC

We integrated the 2011 atmospheric physics upgrade from the uncoupled COAMPS-TC into the coupled 2012 COAMPS-TC version. The most significant improvement seen in the uncoupled COAMPS-TC is the generalized microphysics (Schmidt, personal communication), which decreased the model tropospheric temperature bias and 3-5 days track errors. We use this new version to demonstrate the air-ocean coupled COAMPS-TC system in real-time during the 2011 Atlantic hurricane season in conjunction with the Airborne eXpendable BathyThermographs (AXBTs) demonstration project (Sanabia et al. 2012). The purpose of the AXBT project is to investigate the usefulness of AXBTs in an *operational* setting and their impact on the forecast hurricane track, intensity, and upper-ocean structure.

Two case studies were performed using the air-ocean coupled COAMPS-TC. A data denial experiment of the COAMPS-TC model revealed the impact of the AXBT data on the upper-ocean thermal structure. The first case samples the warm core ring (WCR) structure in the Gulf of Mexico. The AXBTs were deployed across the center of this WCR during the training flight. Inclusion of the AXBT data in the COAMPS-TC NCODA assimilation resulted in the reduction of the temperature in the center, northeast, and northwest edges of the WCR by up to 1.5°C and the warming of the fringes of the WCR by up to 0.5°C.

The second case study performed is for hurricane Emily. The intensity of hurricane Emily dropped from 45 to 30 kts between 3-5Aug due to unfavorable environmental shear. The 1200 UTC 03 August 2011 COAMPS-TC ocean model indicated that the upper ocean in the vicinity of Emily was characterized by several relatively warm and cool regions (Fig. 1). The SSTs varied between 27°C and 31°C, with the warmest waters generally located south and east of Emily as well as between Cuba and Jamaica and west of Haiti. Ocean heat content showed similar variability, with the maximum OHC above 100 kJ cm^{-2} and the remainder of the Caribbean Sea generally less than 80 kJ cm^{-2}. A data denial sensitivity run of COAMPS-TC without the AXBT data showed that the inclusion of AXBT data resulted in changes in SSTs between -0.15°C and +0.3°C. At 100-m depth, the AXBT observations resulted in a 0.2-0.8°C temperature increase south of Puerto Rico. A similar pattern was seen in OHC, where values were 5-15 kJ cm^{-2} greater ahead of Emily, and 5 kJ cm^{-2} less behind Emily. When denied the AXBTs in COAMPS-TC, the track and intensity were degraded slightly (Fig. 2) but these difference is not significant. Similar results were also seen in the AXBTs denied experiment with hurricane Irene (not shown). The track and intensity differences for hurricane Irene was smaller than Emily. The reason that coupled COAMPS-TC did not show a great sensitivity for Irene was probably due to the ocean condition underneath Irene were also sampled by the NDBC buoys located near the Carolina coast. Therefore the AXBTs did not provide added information compare to the routine moored buoys.

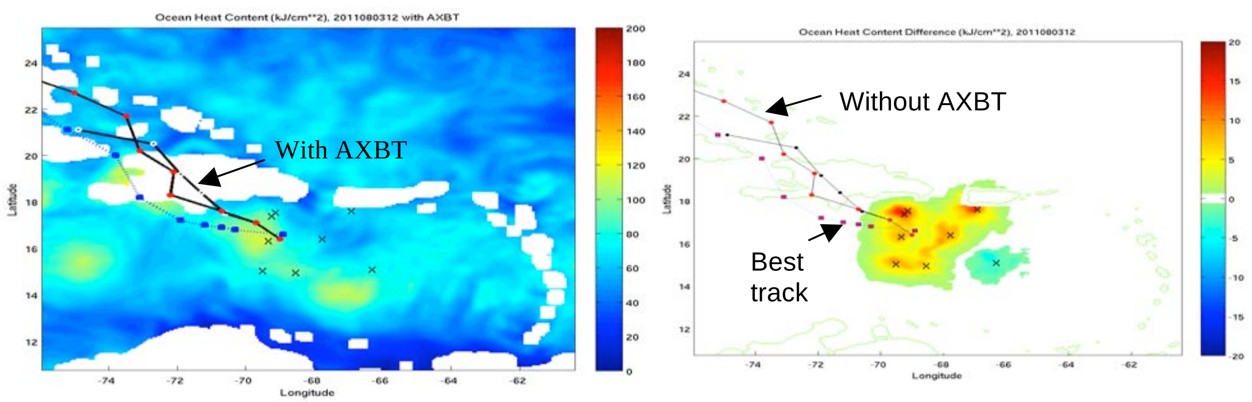


Figure 1. (a) Visible GOES-13 satellite imagery (in units of GOES VARiable Format (GVAR), scaled) of Tropical Storm Emily from 1245 UTC 03 August 2011. (b) Brightness temperatures (in K) from the F-17 SSMIS microwave imager at 1020 UTC 03 August 2011. Comparison of COAMPS-TC ocean heat content (OHC in kJ cm^{-2}) with and without AXBTs. =The numbered AXBT drop locations are denoted by black x's. The blue dashed line is the best track. COAMPS-TC track with AXBT is the black line with black dots and the track without the AXBT is the black line with red dots. The right panel shows the OHC with the AXBTs and the left panel is the OHC difference between with and without AXBTs.

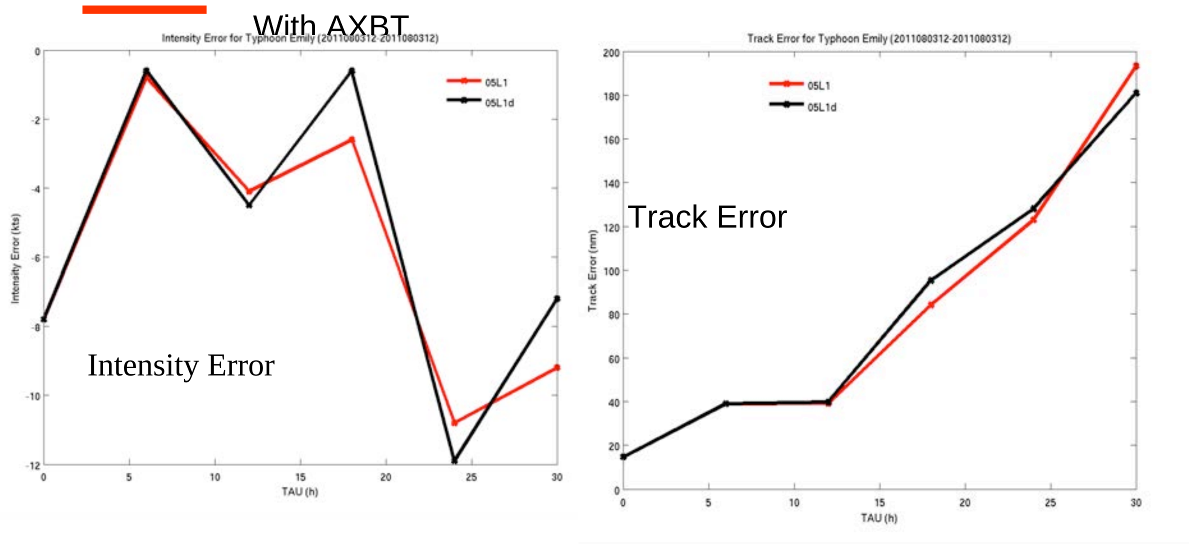


Fig. 2 Comparison of Coupled COAMPS-TC track and intensity errors for hurricane Emily. The red and black line are with and without AXBTs with respectively.

Overall during the 2011 Atlantic season, the homogeneous sample of real-time coupled COAMPS-TC from 5 storms (Irene, Katia, Maria, Ophelia, and Philippe) showed the track bias reached about 350 nautical miles by the end of five-day forecast. While the intensity was consistently lower throughout these five days. The trend of negative bias in coupled COAMPS-TC did not appear in uncoupled COAMPS-TC. The real-time uncoupled COAMPS-TC statistics showed a mean slightly over-intensification (Moskaitis, personal communication).

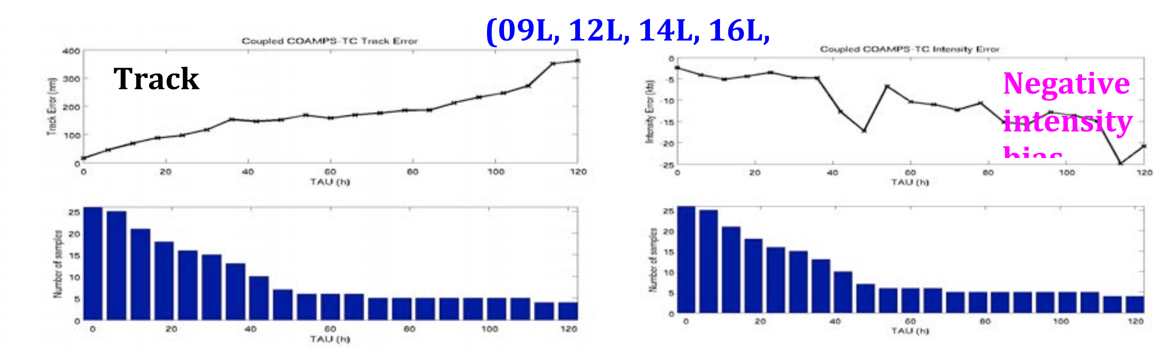


Fig. 3 Homogenous track (nautical miles, left panel) and intensity (knots, right panel) errors of air-ocean coupled COAMPS-TC for five hurricanes (Irene, Katia, Maria, Ophelia, and Philippe) during the 2011 Atlantic season. Number of sampling is shown in the bar chart at the lower panels.

To understand the source of low-intensity bias in coupled COAMPS-TC and to improve the intensity forecast, we implemented and tested a new sea spray parameterization (Fairall et al.

2009 ad Bao et al. 2011) from NOAA ESRL. The test case used for this study is Typhoon Fanapi observed during the ONR Impact of Typhoon on the Upper Ocean (ITOP). Compare to the Fairall old sea spray scheme, this new version considered the loading effect of spray particles and lower the momentum drag in higher wind speed (Bao *et al.* 2011). This effect is tested in air-ocean-wave coupled Fanapi simulation and the momentum dag was reduced from above 2.5e-3 to as low as 1.5e-3 for various sensitivity experiments. When caped the momentum drag to 2e-3 or 2.5e-3 in the AOW tests using the scalar wind-wave coupling scheme (Moon 2004 and new University of Rode Island scheme, Ginis personal communication) that returns a sea-state dependent Charnock based on an empirical relationship of wave age and wind speed. Sensitivity runs varying the momentum drag showed the coupled COAMPS-TC maximum wind speed intensity was improved by lower the momentum drag but little change has seen in the predicted minimum sea level pressure. Domain averaged sensible and latent heat fluxes in 150 km radius from the Fanapi eye indicated lowering the momentum drag did not seem to modify much of either fluxes. Further analysis is under way to investigate the cause of intensity change.

The effect of new spray parameterization is to increase the sensible heat flux slightly and little change in the latent heat flux (Fig. 5). The averaged total flux change in the 150 km radius from the eye due to sea spray is about 5%. Even with the help of sea spray, the total flux difference between the coupled and uncoupled runs is still about 32%. There is a large discrepancy in turns of total energy transferred from the ocean to the atmosphere between coupled and uncoupled COAMPS-TC which is closely tie to the amount of induced ocean wake cooling. Work is underway to use in-situ ocean measurements to evaluate the COAMPS-TC upper-ocean forecast and to evaluate the nonlinear ocean feedback from the wind and surface wave forcing.

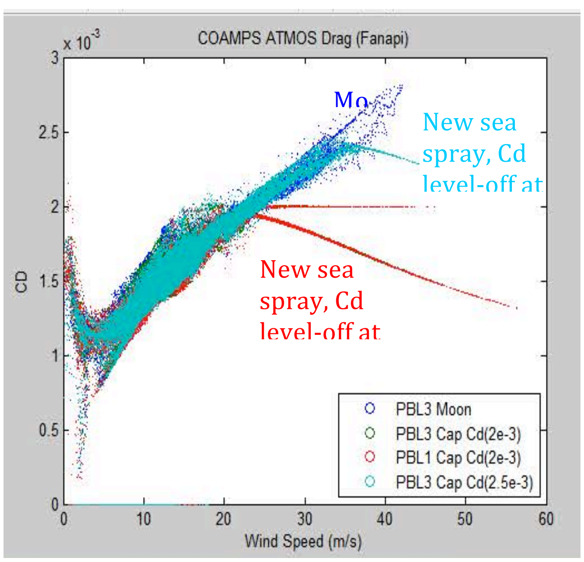


Fig. 4 Sensitivity of air-ocean-wave coupled COAMPS-TC momentum drag formulation. The blue dots are from wind-wave coupling (Moon, 2004). The green and cyan dots are Moon plus caped the momentum drag at 2e-3 and 2.5e-3 with respectively. The red dots are similar to green dots except the run used the original Mellor-Yamada turbulent mixing.

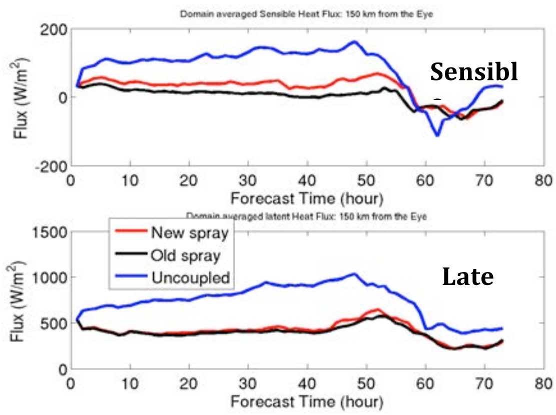


Fig. 5 Sensitivity of air-ocean-wave coupled COAMPS-TC sensible and latent heat fluxes due to sea spray.

In summary, we have seen some sensitivity of coupled COAMPS-TC with respect to the momentum drag. A new improved vector wind-wave parameterizations developed by University of Miami (UM, Donelan *et al.* 2012) is currently being implemented in coupled COAMPS-TC. We plan to test and compare this vector wind stress-wave coupling with the current scalar wind stress approach in COAMPS-TC and continue to use three test cases (Frances, Ivan, and Fanapi) to compare the 4D representation of air-ocean-wave coupled COAMPS-TC with in-situ observations.

4. Stokes' Drift Current and its Role in Wave-Ocean Coupling in TCs

The Stokes' Drift current profile generated from the SWAN wave frequency spectrum is utilized in NCOM in four ways following Kantha and Clayson (2004):

1) in the Coriolis terms of the NCOM momentum equations
2) in the continuity equation
3) for advection of the momentum and scalar field
4) for shear production terms in the turbulent kinetic energy (TKE) and turbulent length-scale equations.

Stokes' production of TKE is computed from the vertical shear of the Stokes' Drift Current and shear stress of the Eulerian current:

$$P_{ST} = -\rho\overline{uw}\frac{\partial u_s}{\partial z} - \rho\overline{vw}\frac{\partial v_s}{\partial z}\,. \qquad (1)$$

The shear stress is computed from the vertical shear of the current:

$$\overline{uw} = -K_m \frac{\partial U}{\partial z}; \ \overline{vw} = -K_m \frac{\partial V}{\partial z} \quad (2)$$

Substituting, the Stokes' production of TKE calculated in NCOM is the following:

$$P_{ST} = K_m \left(\frac{\partial U}{\partial z} \frac{\partial U_s}{\partial z} + \frac{\partial V}{\partial z} \frac{\partial V_s}{\partial z} \right) \quad (3)$$

where K_m is the eddy viscosity determined from the turbulence closure model (Kantha and Clayson (2004)). In the TKE equation, the Kantha and Clayson (2004) parameterization scales K_m to a value of 7.2 for the Stokes' Drift shear production term versus the normal scaling factor of 1.8 for the normal shear production term. When SDC is present, a significant increase in the turbulent length scale will occur and significantly increase mixing in the upper ocean.

Early studies of the SDC assumed that the SDC vectors are mostly aligned with the surface wind stress vectors; however, extreme situations such as a tropical cyclone (TC), tend to produce a large misalignment angle between these vectors. The misalignment of both wind and waves is important to understanding the dynamics of Langmuir turbulence (LT) on the mixed layer, especially in the context of TCs. The wind/wave field is extremely complex in tropical cyclones, especially since the TC produces a wave field that contains both large swell and wind waves. Propagating swell waves in particular are susceptible to misalignment with the wind direction as well as quick changes in wind direction associated with TCs. Recent studies show that greater misalignment decreases the generation of LT and it has been hypothesized that in extreme cases when the SDC directly opposes the wind stress, there is minimal generation of LT (Van Roekel et al. 2012). There are no modeling studies currently published discussing these concepts in the context of a tropical cyclone.

Example: Hurricane Ivan (2004)

Hurricane Ivan, generated in a fully-coupled air-ocean-wave COAMPS-TC simulation, is translating to the north at about 10 kts in Fig. 1. The eyewall, denoted as a circle in Fig. 1, shows that the misalignment angle between the SDC and wind stress within the core of the hurricane approaches 180 degrees on the left flank relative to the spatial translation. This misalignment angle, as shown in the idealized study of Van Roekel et al. (2012) (not in terms of a tropical cyclone) works to inhibit upwelling/downwelling. The large misalignment angle in Hurricane Ivan (Point A) occurs where surface wind speeds within the eyewall are greater than 50 m s^{-1} and wave heights are in excess of 10 m. In terms of upper-ocean shear production of TKE and mixing in the same misalignment angle region, calculations of the shear term in Eq. 3 yield interesting results. A simple grid point calculation of the vertical shear terms (surface to 10 m depth) in Eq. 3 at each forecast hour at points A and B is shown in Table 1. At Point A, the Stokes' shear production term becomes very small at forecast hour 42 and even changes sign at forecast hour 43 at the time of greatest misalignment angle. A negative contribution to the total shear production of TKE implies that the inclusion of the SDC at this particular time may actually *decrease* mixing in the left flank relative to the spatial translation. Nevertheless, the small Stokes' shear production TKE terms at point A compared to point B in the right flank of the eyewall implies that there is less mixing occurring at point A than at point B, given that the magnitude of the wind stress is similar at both locations within the nearly axisymmetric eyewall.

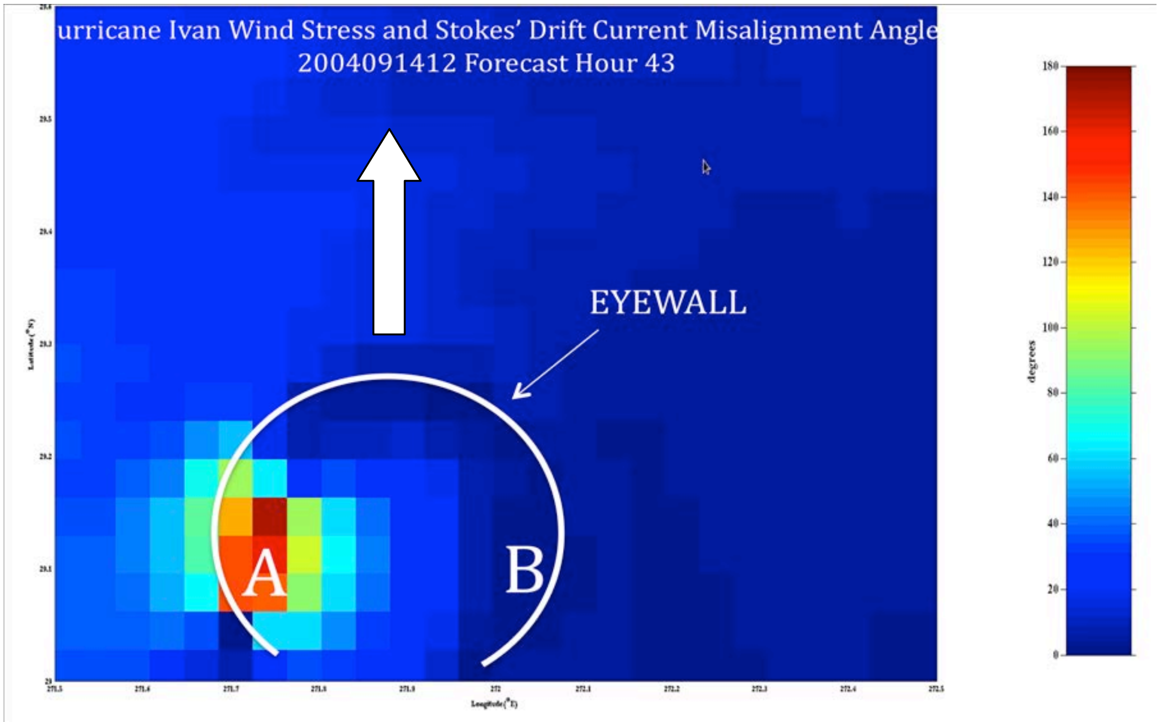


Fig. 1: Misalignment angle (degrees) between the surface wind stress vectors and surface Stokes' drift current vectors. The eyewall of Hurricane Ivan is denoted by the circle. The translation direction and speed is north at 10 kts.

Hurricane Ivan (Stokes' drift shear production term in TKE equation)			
Forecast Hour	left eyewall (x 10^{-4}) (point A)	right eyewall (x 10^{-4}) (point B)	Point A θ_m
38	7.4	7.4	14.5
39	8.5	8.2	12.1
40	9.0	7.9	10.8
41	9.0	7.6	13.4
42	1.9	7.6	1.2
43	-0.5	8.9	142.0
44	6.4	7.5	15.3
45	6.3	7.3	4.9
46	5.8	6.1	4.2
47	5.2	4.9	1.1
48	4.6	4.6	0.3
49	4.2	2.7	0.5
50	3.0	2.3	2.3

Table 1: Magnitude of the Stokes' drift shear production term in the TKE equation (Eq. 3) at points A and B in Fig. 1 for each forecast hour 38-50. The TKE shear production term at point A is negative at hour 43 at the time of greatest misalignment angle.

5. Improving Dropsonde analysis for Coupled Model Evaluations

Dropsonde data are frequently the only measurements in the near-surface hurricane boundary layer. Consequently, they are used to make estimates of the surface fluxes for evaluating numerical model output. However, the data provided by dropsondes are not ideal for the purpose. We are attempting to develop means to make the estimates more rigorous.

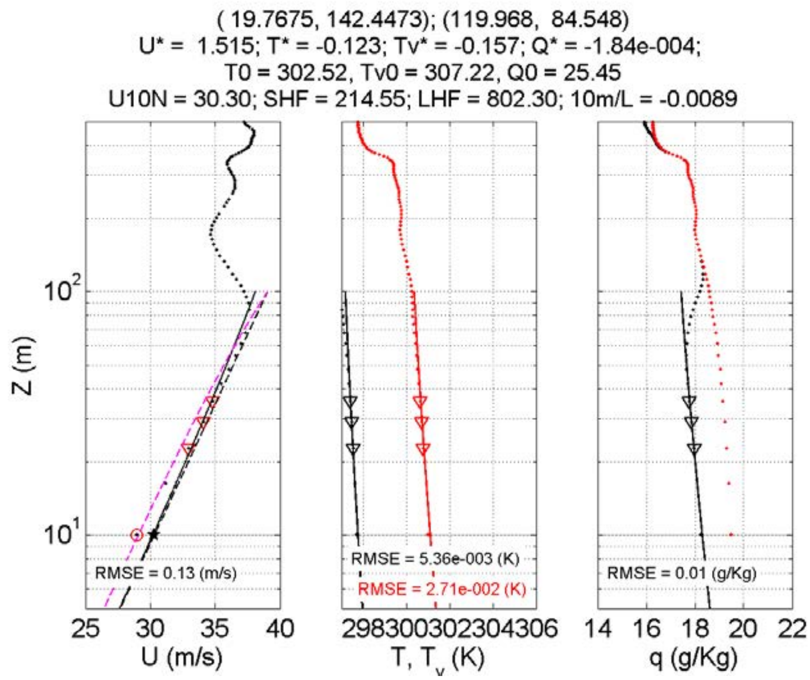
Surface fluxes are usually estimated from drop sondes by applying standard bulk flux algorithms to sonde data interpolated to 10 m. Bulk flux models are based on Monin-Obukhov similarity (MOS), so the implicit assumption that goes into such flux estimates is that there is a layer within the sonde profile over which MOS is valid. However, MOS relates fluxes to *mean* profiles of wind, temperature and humidity. Sonde profiles must be considered to be approximately snapshot measurements of the highly turbulent boundary layer flow. That is, a single sonde profile is not necessarily representative of the mean flow and a given profile might, at first glance, appear to be quite inconsistent with MOS. It is not possible to state confidently whether or such poor agreement is due to MOS being invalid. Ideally ten or more drop sondes would be deployed simultaneously and the results averaged to produce an approximate mean flow for evaluating whether or not MOS is valid in the given case and to calculate surface fluxes. Currently, this is not possible.

An additional complication is that the estimate of the surface wind speed, which is a key parameter in bulk flux models, from drop sonde profiles is based on very precise knowledge of the sonde's location over very short time intervals. In high shear regions, such as the near-surface region of the hurricane boundary layer, the sampling rate of the GPS in the sonde is insufficient to measure velocities accurately, even though the data are frequently recorded as low as six or seven meters above the surface. The net result is that interpolated 10 m winds are not trustworthy.

Hence, we are left with two issues: the sonde winds are highly suspect in the highly-sheared near-surface region of particular interest and we have only single realizations of the flow in a very turbulent environment. From these data we must attempt to estimate the mean flow profile and the surface fluxes in order to estimate U10 and the surface fluxes.

Two methods commonly for estimating U10 use the mean of the lowest 150 m of the sonde profile (U150; Franklin et al., 2003; and Uhlhorn et al. 2007). Franklin et al. (2003) analyzed eyewall profiles and fit a reduction factor that relates U150 to the surface wind as a function of the mean height of the 150 m layer used in the averaging (Z150). Sonde profiles ending as high as 180 m above the surface are used. Uhlhorn et al. (2007) made a linear fit of U10 (interpolated from the sonde profiles) to U150. They found that this was, within measurement error, equivalent to the Franklin method when Z150 ~ 85 m, which corresponds to profiles that extend to approximately 10 m above the surface. Because the parameterization is based on data from all available flights, the inherent averaging used in the curve fit is assumed to address single-realization aspect of sonde profiles.

However, examination of profiles from ITOP calls the U150 surface wind parameterizations into some question. Quite commonly there is clear change in the slope of the wind speed profile well below 150 m that strongly suggests that the upper and lower parts profile contributing to U150 sample parts of the near surface flow that are in different dynamical regimes.



We addressed this problem from a slightly different perspective. We assume that we cannot trust sonde wind speeds at or below about 10 to 15 m above the surface. Furthermore, we assume that the dynamical regime strongly affected by the sea surface extends to approximately 50 m or so above the surface. This is a fairly conservative estimate in some cases, but inspection suggested that it does well in separating surface layer data from data that is subjected to more complex boundary layer dynamics. We further made the strong assumption that, even though the particular sonde profile represents a single realization through the turbulent flow, we can treat the measurements at different levels as being independent from each other. Instead of applying a bulk flux model to the interpolated 10 m values, we fit the implicit MOS similarity model profiles consistent with the COARE 3.0 bulk flux model (incorporating the CBLAST cap on CDN) to the wind, temperature and humidity measurements within this layer. Small corrections to the temperature to account for the radial displacement of the sonde during the drop were made. Similarly, we used the SFMR wind speeds to make small adjustments for the radial change in wind speed during the sonde descent. Neither of these corrections made significant differences in the results. When possible we used sea surface temperatures (SSTs) from co-located AXBTs. In other cases we used time- and space-interpolated SSTs from Remote Sensing Systems (RSS). This product combines microwave and IR SSTs and is produced on a 9 km grid. The RSS SSTs were generally with a few tenths of a degree with the AXBT SSTs. The model produces estimates of the MOS scaling variables U*, T* and q* from which estimates of the surface fluxes can be calculated.

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.

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