Year 1 Report: Evaluation and Improvement of Ocean Model Parameterizations for NCEP Operations

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Goal: The long term goal of this NOAA Joint Hurricane Testbed (JHT) grant is to evaluate and improve ocean model parameterizations in NOAA National Centers for Environmental Prediction (NCEP) coupled hurricane forecast models in collaboration with the NOAA Tropical Prediction Center (TPC) and NOAA/NCEP Environmental Modeling Center (EMC). This effort targets the Joint Hurricane Testbed programmatic priorities **EMC-1** and **EMC-2** along with hurricane forecaster priorities **TPC-1** and **TPC-2** that focus on improving intensity forecasts through evaluating and improving oceanic boundary layer performance in the coupled model and improving observations required for model initialization, evaluation, and analysis. This project will be conducted under the auspices of the Cooperative Institute of Marine and Atmospheric Science program, and addresses **CIMAS Theme 5: Air-Sea Interactions and Exchanges** and **NOAA Strategic Goal 3: Weather and Water (local forecasts and warnings)**.

Specific objectives of this grant are:

i) optimizing spatial resolution that will permit the ocean model to run efficiently as possible without degrading the simulated response;
ii) improving the initial background state provided to the ocean model;
iii) improving the representation of vertical and horizontal friction and mixing;
iv) generating the realistic high-resolution atmospheric forcing fields necessary to achieve the previous objectives; and
v) interacting with NOAA/NCEP/EMC in implementing ocean model code and evaluating the ocean model response in coupled hurricane forecast tests

Progress: Over the initial five months of the grant, this applied effort has focused on testing model initialization schemes, primarily in the Gulf of Mexico, and processing in situ Acoustic Doppler Current Profiler (ADCP) data from Ivan (data courtesy of US Naval Research Laboratory (NRL)) during Katrina and Rita (data courtesy of Minerals Management Service) as well as NOAA Hurricane Research Division Intensity Fluctuation Experiments (IFEX) in pre and post Rita in 2005 (Rogers *et al.*, BAMS, 2006; Jaimes and Shay, MWR, 2008). An initial set of 13 model experiments of the ocean response to hurricane Ivan has been performed to document sensitivity to the factors addressed by the specific objectives listed above. Interactions with NOAA/NCEP/EMC concerning this year's tests of HYCOM-HWRF are ongoing.

Modeling: The Hybrid Coordinate Ocean Model (HYCOM) is evaluated because it has been selected as the ocean model component of the next-generation coupled hurricane forecast model (HYCOM-HWRF) under development at NOAA/NCEP/EMC. It also contains multiple parameterizations of horizontal and vertical mixing and friction, making it possible to isolate model sensitivity to parameterizations of individual processes and devise strategies to improve them. The initial evaluation was performed for Hurricane Ivan in the GOM, where high-quality *in-situ* moored current measurements have been acquired. It focuses on the impact of the Loop Current and associated warm and cold rings, along with the complex bathymetry of the continental shelf/slope region.

The modeling effort builds upon a previous NOAA JHT grant of Jacob, Halliwell and Shay that eliminated two mixing schemes from contention leaving Mellor Yamada (MY), K- Profile Parameterization (KPP) and Goddard Institute of Space Sciences (GISS) schemes. Thirteen free-running HYCOM simulations were conducted to assess model sensitivity to vertical resolution in the surface mixed layer, horizontal resolution, the vertical mixing scheme, the wind stress drag coefficient, the surface turbulent flux drag coefficients, the quality of the surface forcing, and the accuracy of ocean feature initialization. Characteristics of the experiments are listed in Table 1. All experiments were conducted within a GOM domain where the coastline follows the actual land/sea boundary with a minimum water depth of 2 m. They are all nested within an outer model and are forced by surface fields of vector wind stress, wind speed, surface atmospheric temperature and humidity, longwave and shortwave radiation, and precipitation. Surface turbulent heat fluxes and evaporation are calculated during model runs using bulk formula. Freshwater input from 12 rivers is included. A baseline experiment (GOM1) is performed that is forced by atmospheric fields from the 27 km resolution COAMPS model, but with high-resolution wind speed and stress fields obtained from the NOAA/HRD HWIND analysis patched in for the storm region. HWIND vector wind fields are first patched into COAMPS fields, and then wind stress is calculated using bulk formula with the Donelan et al. (GRL, 2003) drag coefficient prior to model runs. The model is nested within a GOM data-assimilative hindcast that uses the U. S. Navy NCODA system. It is run with 26 vertical layers and KPP vertical mixing is used. Surface turbulent fluxes are calculated during the model run using the COARE 2.6 algorithm bulk formula.

The remaining experiments (GOM2-GOM13) all differ from GOM1 in a single aspect. GOM2 isolates sensitivity to horizontal resolution, GOM3 and GOM4 to vertical resolution, GOM5 and GOM6 to vertical mixing scheme, GOM7-GOM10 to wind stress drag coefficient parameterization, GOM11 to turbulent heat flux drag coefficient representation, GOM12 to surface forcing fidelity (COAMPS without HWIND), and GOM13 to the ocean model initialization. Model sensitivities are initially evaluated by calculating the changes in SST that occurred between 11 and 17 September 2004 (before and after Ivan). RMS differences between temperature changes produced by the baseline experiment and each of the 13 other experiments (Figure 1) quantify the sensitivity to the individual model property that was altered from the baseline experiment. It is immediately evident in Figure 1 that accurate initialization of ocean features (GOM13) is the most important single factor for improving the accuracy of the ocean response. Four factors are of intermediate importance: (1) parameterization of surface momentum flux through the drag coefficient (GOM7-GOM10); (2) choice of vertical mixing scheme (GOM5, GOM6); (3) horizontal resolution (GOM2); and (4) accurate representation of the storm structure in the surface forcing (GOM12). The least important factors are vertical resolution (GOM3, GOM4) and the parameterization of surface heat flux through the sensible and latent heat drag coefficients (GOM11). For vertical resolution, larger RMS differences are observed going from 21 to 26 layers than from 26 to 31 layers. Consistent with Jacob *et al.* results from a previous Vertical Mixing JHT grant, these diminishing returns with increasing resolution suggest that the intermediate vertical resolution (26 layers, 4-8 m resolution in the mixed layer) is a reasonable choice.

Table 1. Summary of the 13 experiments simulating the ocean response to hurricane Ivan conducted in the GOM domain. Characteristics of the reference baseline experiment are highlighted in blue. For the remaining experiments, characteristics in red highlight the individual differences between each experiment and the base experiment GOM1.

Experiment Number [HYCOM Name]	Horizontal Resolution [Region Name]	Vert. Layers	OML Layer Thickness Range (m)	Vert. Mixing	Wind Stress Drag Coefficient	Turbulent Flux Drag Coefficients	Surface Forcing	Outer Nesting Model
GOM1 [expt_02.0]	0.04° [GOMh0.04]	26	4-8	KPP	Donelan	COARE 2.6	27 km COAMPS plus HWIND	GOM-NCODA
GOM2 [expt_02.0]	0.08° [GOMd0.08]	26	4-8	KPP	Donelan	COARE 2.6	27 km COAMPS plus HWIND	GOM-NCODA
GOM3 [expt_01.1]	0.04° [GOMh0.04]	21	3-5	KPP	Donelan	COARE 2.6	27 km COAMPS plus HWIND	GOM--NCODA
GOM4 [expt_01.2]	0.04° [GOMh0.04]	31	7.5-15	KPP	Donelan	COARE 2.6	27 km COAMPS plus HWIND	GOM-NCODA
GOM5 [expt_02.1]	0.04° [GOMh0.04]	26	4-8	MY	Donelan	COARE 2.6	27 km COAMPS plus HWIND	GOM-NCODA
GOM6 [expt_02.2]	0.04° [GOMh0.04]	26	4-8	GISS	Donelan	COARE 2.6	27 km COAMPS Plus HWIND	GOM-NCODA
GOM7 [expt_03.0]	0.04° [GOMh0.04]	26	4-8	KPP	Powell	COARE 2.6	27 km COAMPS plus HWIND	GOM-NCODA
GOM8 [expt_03.1]	0.04° [GOMh0.04]	26	4-8	KPP	Large & Pond	COARE 2.6	27 km COAMPS plus HWIND	GOM-NCODA
GOM9 [expt_03.2]	0.04° [GOMh0.04]	26	4-8	KPP	L & P (capped)	COARE 2.6	27 km COAMPS plus HWIND	GOM-NCODA
GOM10 [expt_03.3]	0.04° [GOMh0.04]	26	4-8	KPP	Shay & Jacob	COARE 2.6	27 km COAMPS plus HWIND	GOM-NCODA
GOM11 [expt_03.4]	0.04° [GOMh0.04]	26	4-8	KPP	Donelan	Kara *et al.* (2002)	27 km COAMPS plus HWIND	GOM-NCODA
GOM12 [expt_02.5]	0.04° [GOMh0.04]	26	4-8	KPP	Donelan	COARE 2.6	27 km COAMPS only	GOM-NCODA
GOM13 [expt_04.1]	0.04° [GOMh0.04]	26	4-8	KPP	Donelan	COARE 2.6	27 km COAMPS plus HWIND	GOM Free.

Measurements: Hurricane Ivan passed directly over 14 ADCP moorings that were deployed as part of the NRL *Slope to Shelf Energetics and Exchange Dynamics (SEED)* project from May through Nov 2004 (Teague *et al.*, JPO, 2007) (Figure 2). These observations enable the simulated ocean current (and shear) response to a hurricane over a continental shelf/slope region to be evaluated. This evaluation also involves detailed comparisons between *in-situ* and satellite–derived OHC estimates based on Surface Height Anomaly (SHA) fields from available radar altimeters (NASA TOPEX, Jason-1, ERS-2, NOAA GEOSAT Follow-On-Missions), and infrared and microwave SSTs from TRMM and AMSR-E.

$$\Delta T = \left(T_2 - T_1\right)_{Exp2} - \left(T_2 - T_1\right)_{Exp1}$$

Experiments	Difference from Baseline Expt.	RMS ΔT (C)
GOM2 - GOM1	Low horiz. res.	0.45
GOM3 – GOM1	Low vert. res.	0.23
GOM4 - GOM1	High vert. res.	0.12
GOM5 – GOM1	MY mixing	0.49
GOM6 - GOM1	GISS mixing	0.37
GOM7 - GOM1	Powell C_D	0.33
GOM8 - GOM1	Large&Pond	0.48
GOM9 - GOM1	Large&Pond (capped)	0.19
GOM10 - GOM1	Shay&Jacob	0.75
GOM11 - GOM1	Kara et al. C_L, C_S	0.18
GOM12 – GOM1	No HWIND Forcing	0.41
GOM13 - GOM1	Outer Model	1.57

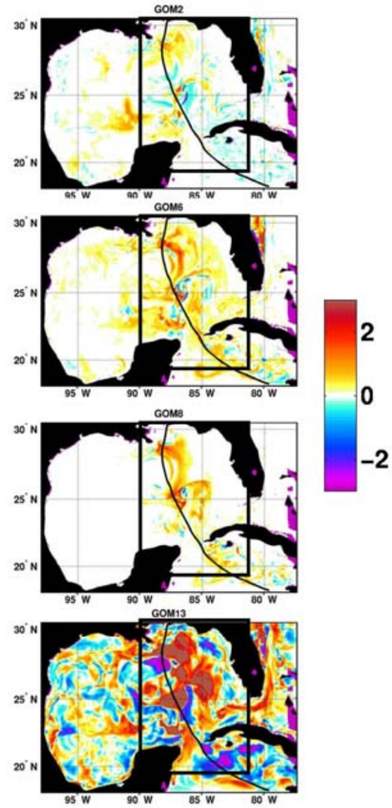

Figure 1. Sensitivity analysis of SST change forced by hurricane Ivan, as summarized by differences in the SST change (Sept. 17 minus Sept. 11) between experiments GOM2-GOM13 and the baseline experiment GOM1 calculated using the formula for Δ*T* shown at top left. The RMS amplitude of Δ*T*, which represents the RMS difference between the SST changes forced by the two experiments, tabulated in the third column. Four Δ*T* maps are shown as examples. RMS Δ*T* (^{o}C) values are calculated within the black boxes in the maps.

Table 2: Summary of measurements from four of the fourteen NRL SEED ADCP arrays (LR- Long Ranger, TRBM- Trawl Resistant Bottom Mount) spanning the coastal ocean (60 m) to the continental slope (1029 m). For the purposes of this brief report we will focus on Array 8 and 9 as they were located along Ivan's track (8) and at 1.5 R_{max} (9) to the right of the track.

Array #	Lat ^{o}N	Long ^{o}W	Start Date 2004	End Date 2004	Δt (hr)	Depth Range (m)	Δz (m)	Bottom Depth (m)	Instrument Type
2	29.43	88.01	05/01	10/31	**0.25**	4-54	**2**	**60**	TRBM
8	29.14	88.11	05/03	11/07	**1.0**	42-492	**10**	518	LR
9	29.19	87.94	05/03	11/07	**1.0**	40-500	**10**	518	LR
14	29.20	87.65	05/05	11/07	**1.0**	42-502	**10**	**1029**	LR

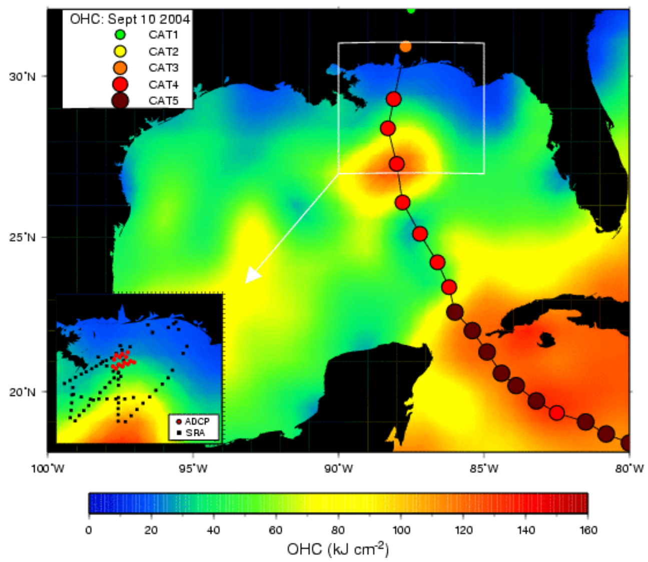

Figure 2: OHC map and inset showing NRL mooring locations (red) and SRA wave measurements (black) relative to Ivan's storm track and intensity. The OHC pattern shows the WCR encountered by Ivan prior to landfall. The cooler shelf water (OHC < 20 KJ cm^{-2}) resulted from the passage of Frances two weeks earlier.

Current Profiler Analyses: As shown in Table 2, a synopsis of four of the fourteen ADCP arrays are summarized with respect to position, range of measurements temporal vertical sampling intervals as discussed by Teague *et al*. (CSR, 2005). These profiler measurements provided the evolution of the current (and shear) structure from the deep ocean across the shelf break and over the continental shelf. The current shear response, estimated over 4-m vertical scales, is shown in Figure 3 based on objectively analyzed data from these moorings. Over the shelf, the current shears increased due to hurricane Ivan strong winds. The normalized shear magnitude is a factor of four times larger over the shelf (depths of 100 m) compared to normalized values over the deeper part of the mooring array (500 to 1000 m). Notice that the current shear rotates anticyclonically (clockwise) in time over 6-h intervals consistent with the forced near-inertial response (periods slightly shorter than the local inertial period). In this measurement domain, the local inertial period is close to 24 h which is close to the diurnal tide. By removing the weaker tidal currents and filtering the records, the analysis revealed that the predominant response was due to forced near-inertial motions. These motions have a characteristic time scale for the phase of each mode to separate from the wind-forced OML current response when the wind stress scale ($2R_{max}$~64 km in Ivan during time of closest approach) exceeds the deformation radius associated with the first baroclinic mode (≈ 30 to 40 km). This time scale increases with the number of baroclinic modes due to decreasing phase speeds (Shay *et al.*, JPO, 1998). The resultant vertical energy propagation from the OML response is associated with the predominance of the anticyclonic (clockwise) rotating energy with depth and time that is about four times larger than the cyclonic (counterclockwise) rotating component.

Observed current shear profiles were estimated over 4 m vertical scales for each time sample following hurricane passage at arrays 8 and 9 are shown in Figure 4. Notice that the shear magnitudes are typically two to three times larger than observed in the Loop Current during Lili's passage. This is not surprising since these measurements were acquired in the Gulf Common Water and similar to those documented during hurricane Gilbert's passage where up to 3.5^{o}C cooling was observed. In the near-inertial wave wake (Shay *et al*., JGR, 1992), the key issue is how much of the current shear is associated with near-inertial wave processes. This is now being explored prior to comparing these values to those from the HYCOM model for each of the experiments discussed above.

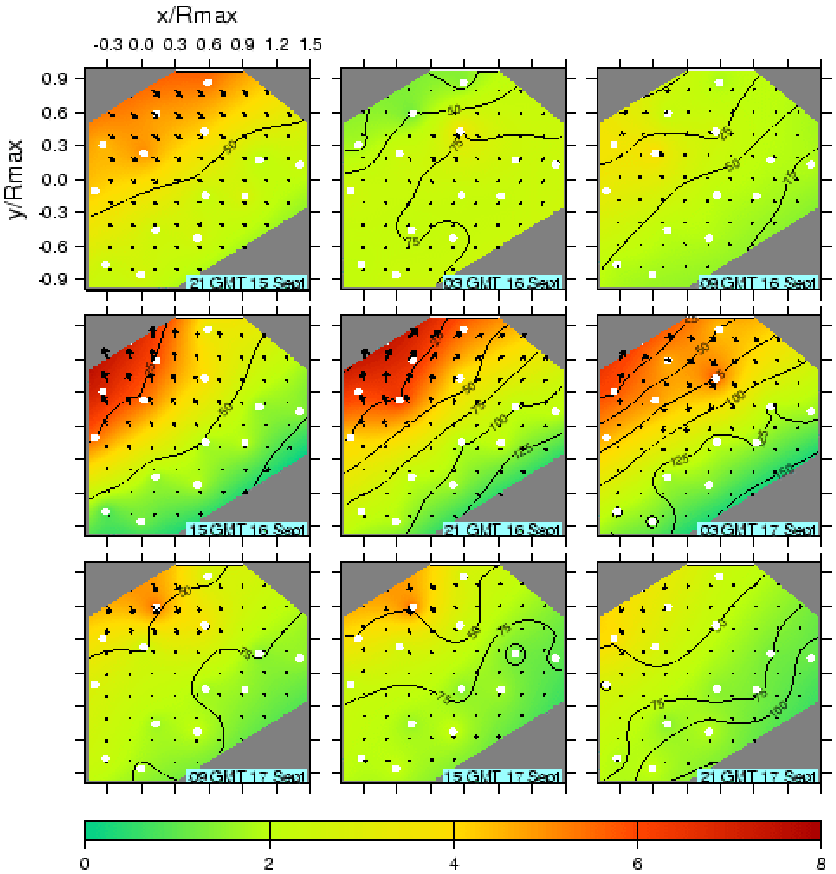

Figure 3: Spatial evolution of the rotated current shear magnitude normalized by observed shears from the ADCP measurements (white dots) normalized by observed shears in the LC of 1.5 x 10^{-2} s^{-1} (color) during Lili starting at 2100 GMT 15 Sept every 6 hours. Black contours (25-m intervals) represent the depth of the maximum shears based on the current profiles from the moored ADCP. Cross-track (x) and along-track (y) are normalized by the observed R_{max} of 32 km.

Model versus Observed Current Comparisons: At mooring 9 (Figure 5), the experiments for KPP (GOM1), MY (GOM5) and GISS (GOM6) mixing models are compared to the observed cross and along-track profiles over the upper 150 m. The momentum drag coefficient of Donelan *et al.* (GRL, 2003) is used in all of these simulations. Notice the marked agreement between the observed and the KPP scheme profiles over the first two IPs. These observations and simulations suggest vertical energy propagation out of the surface mixed layer and into the thermocline consistent with theory. Compared to GISS and MY, the KPP scheme captures the fairly large northward (essentially along-track) current of more than 1 m s^{-1} within an IP following passage. Given the same initialization, wind forcing and drag coefficient formulation as well as the same number of layers, the KPP scheme duplicates the observed profiles better than these other two schemes. As shown in Figure 6, the simulations and observations are regressed and fit to a line in a least squares sense. For the comparison with KPP mixing model, the slope between observed and simulated cross-track current is 0.9 with no bias, suggestive of good correlation with RMS difference of 0.14 m s^{-1}. This is reflected in the histogram of the differences. By contrast, the MY and GISS comparisons suggest larger RMS differences and slopes of 0.5 and 0.7, respectively. The distribution of the differences reflects the lower correlation and the increased scatter. Thus these results point to the KPP scheme being superior to both the MY and GISS schemes, at least for this storm at this location. We are now working on comparing the simulations to observed currents and shears from the other 13 ADCPs.

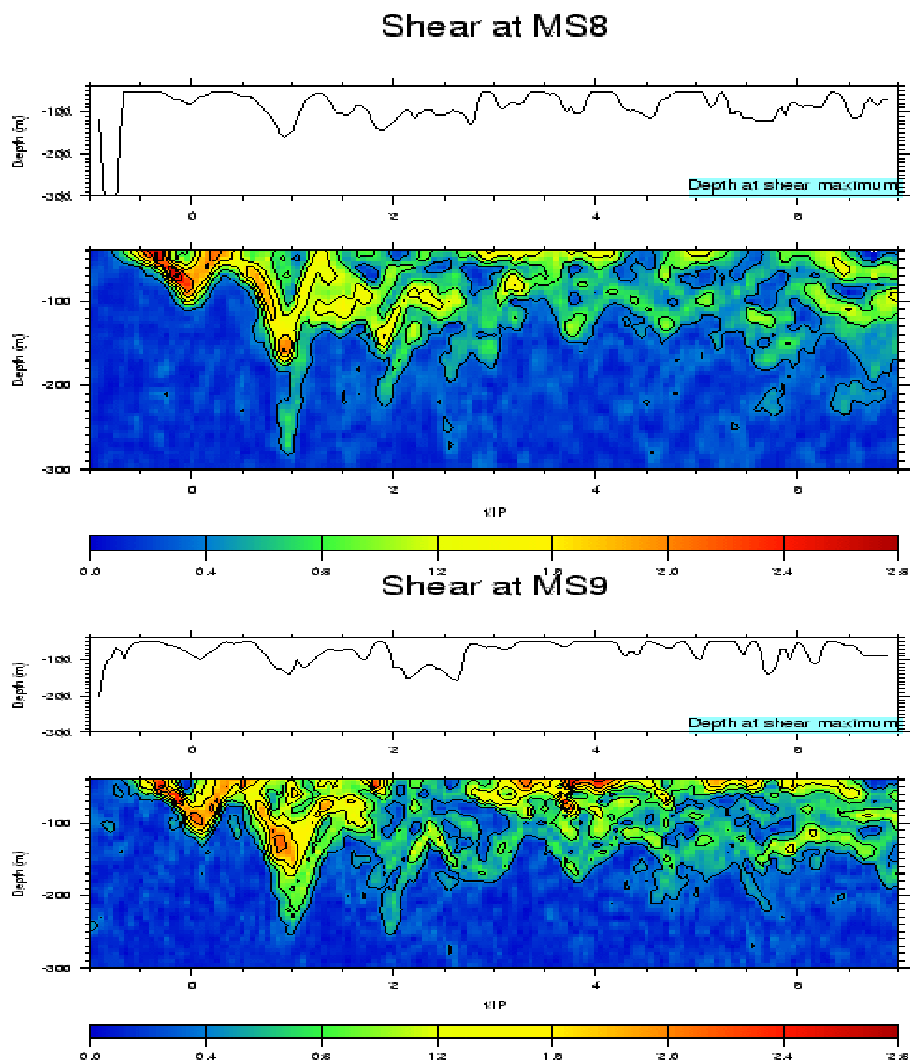

Figure 4: Time series (normalized by inertial period) of observed current shear magnitudes (colored contours) and the respective depths (m) of maximum current shears observed at Moorings 8 (upper: along Ivan' s track) and 9 (lower: 1.5 R_{max} to the right of the Ivan) relative to the time of the closest approach. Shears are normalized by a value of 1.5 x 10^{-2} s^{-1} that have been observed in the Loop Current (Shay and Uhlhorn, MWR, 2008).

Interactions with NOAA/NCEP/EMC: A major goal of this project is to interact with the HWRF developers at EMC to evaluate the performance of HYCOM in the next-generation HWRF model and to improve the performance of the ocean model. As part of this effort, G. Halliwell visited EMC during June 2008, presented a seminar highlighting results of the hurricane Ivan evaluation, and interacted with model developers to optimize the ocean model code for the planned 2008 tests of the next-generation HWRF. Evaluation of these tests are now commencing for an HWRF forecast of hurricane Katrina. The first significant result involves evaluating the pre-Katrina initialization of the ocean model. The EMC tests initialize the model with ocean fields produced by their in-house Atlantic Ocean hindcasts using the Real-Time Ocean Forecast System (RTOFS). Comparisons of the depth of the 26°C isotherm between values derived from satellite altimetry and the RTOFS analysis demonstrate that the RTOFS realistically reproduces the magnitude and pattern of this field (Figure 7). The RTOFS field is more realistic than the field produced by the NRL-NCODA data-assimilative hindcast, even though both assimilation systems use HYCOM. This is encouraging given the paramount importance of ocean model initialization (Figure 1). Although the RTOFS initialization for Katrina is realistic, additional storms must be considered to produce a thorough evaluation of this product for ocean model initialization.

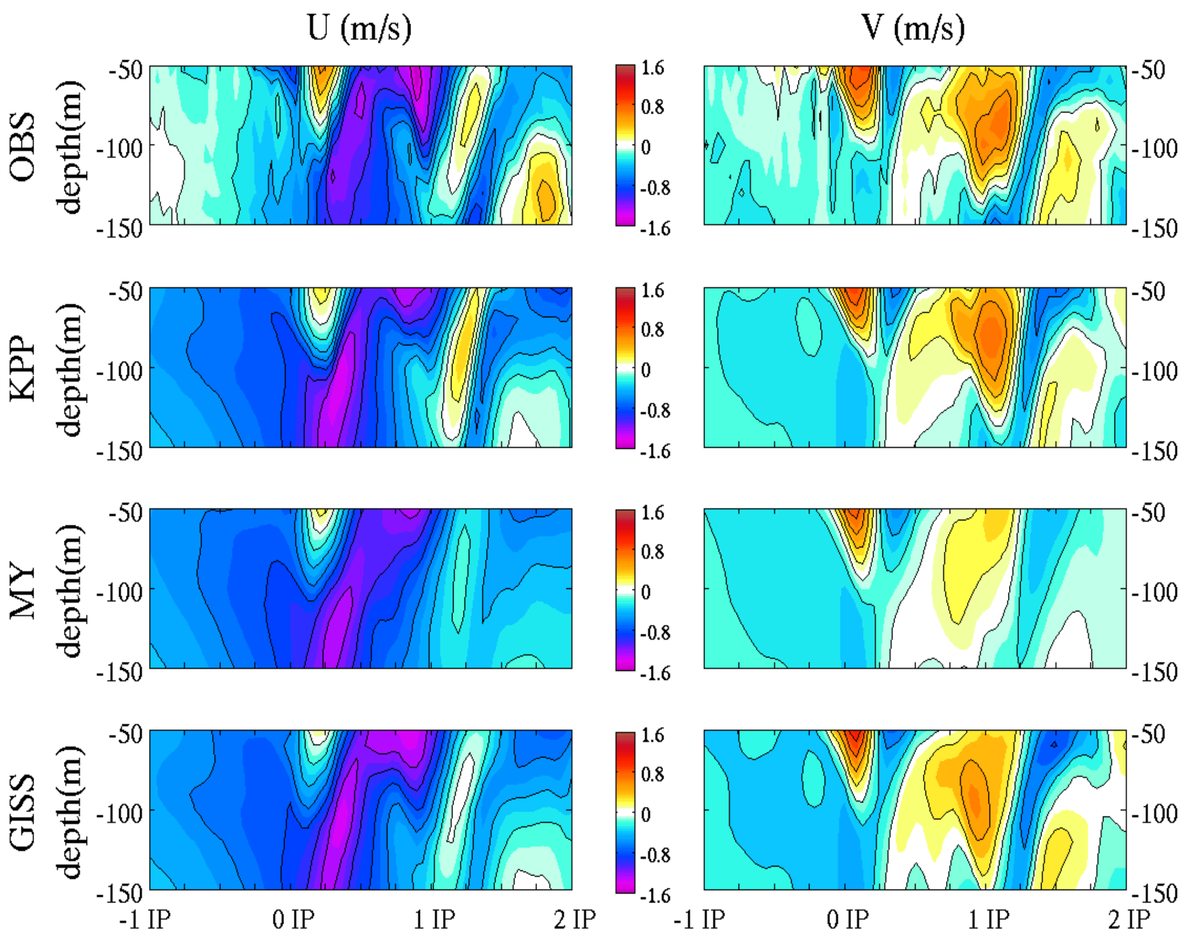

Figure 5: Time series (normalized by inertial period) of observed, KPP, MY and GISS simulated currents (cross-track (U): left panels; along-track (V): right panel) in m s^{-1} as per the color bar in the upper 150 m at Mooring 9.

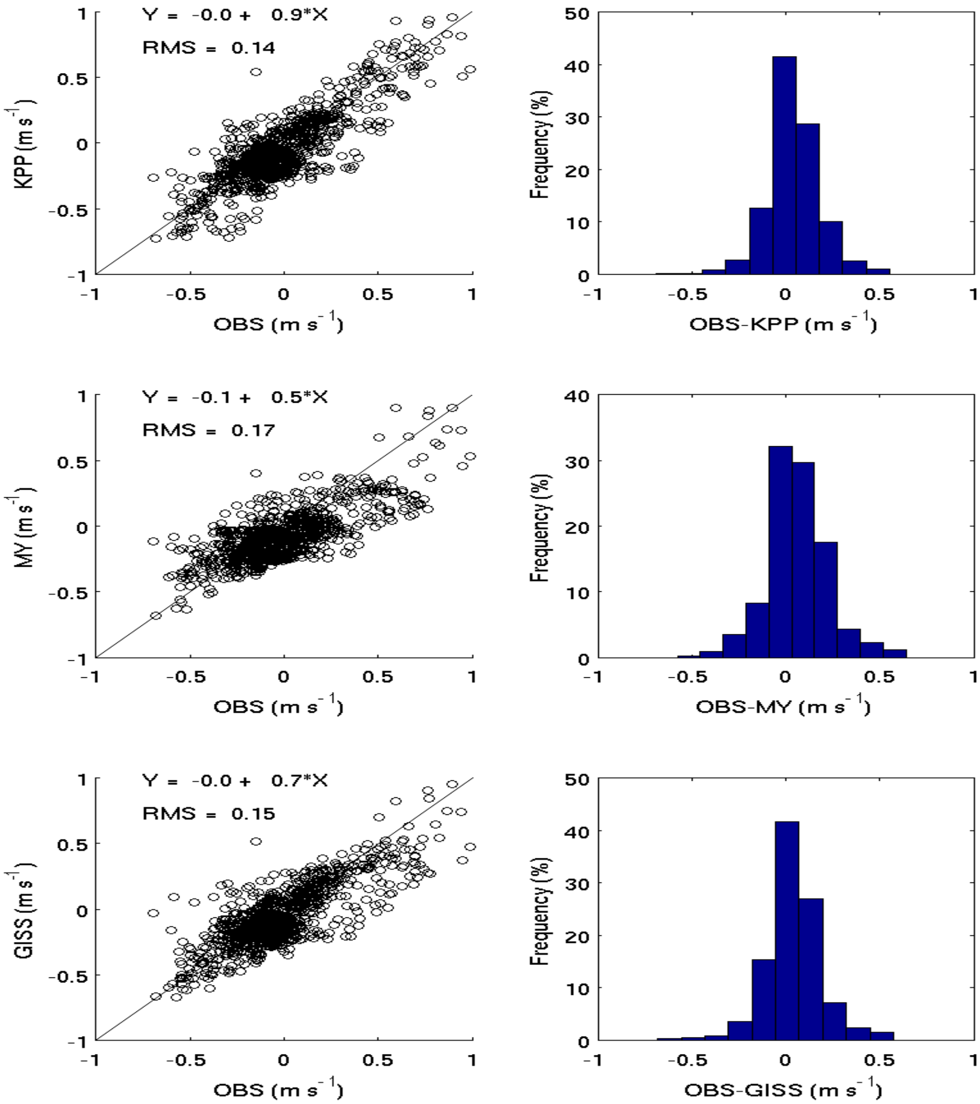

Figure 6: Scatter plot of observed (abscissa) and simulated (ordinate) v-component of the current (left panels) and the histograms of the observed and simulated differences (right panels) in m s^{-1} using KPP, MY and GISS mixing models. Scatter plots have the equation of the regression line as well as the RMS differences at mooring

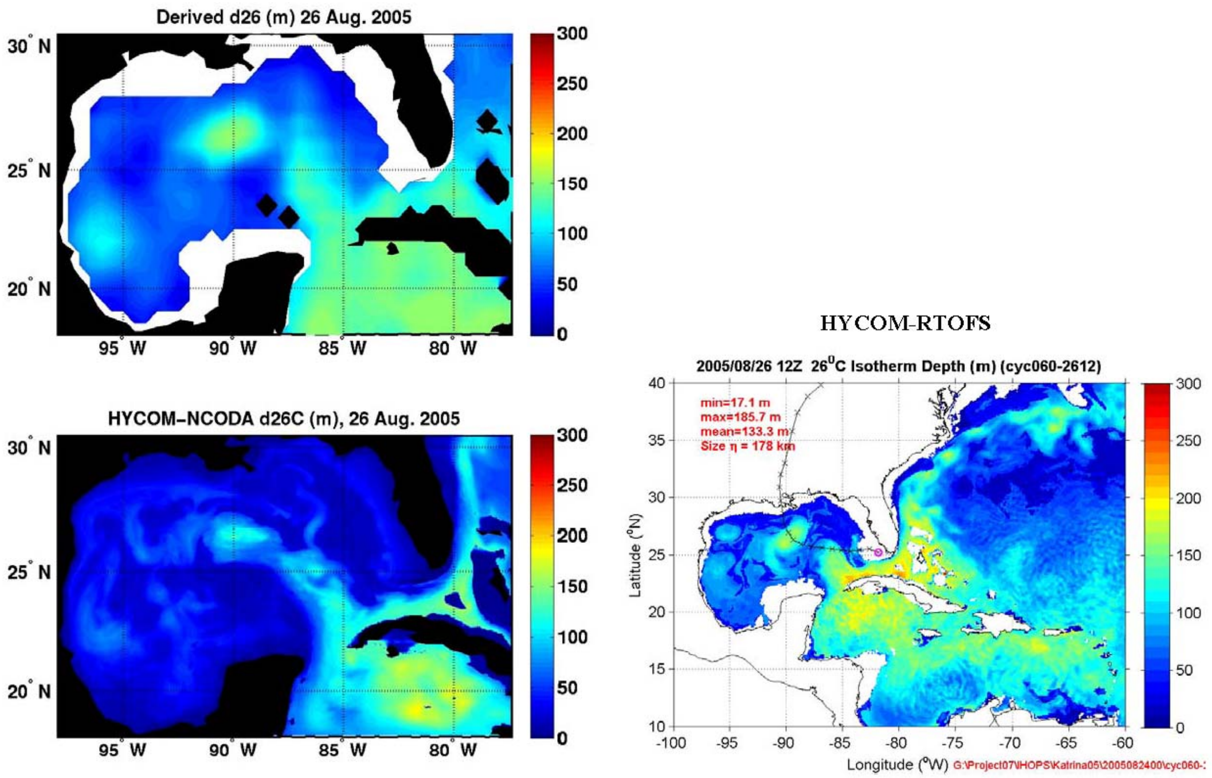

Figure 7. Maps of the depth of the 26°C isotherm derived from satellite altimetry and SST (upper left), obtained from the HYCOM-NCODA ocean hindcast produced by NRL (lower left), and obtained from the HYCOM-RTOFS ocean hindcast produced by NOAA/NCEP/EMC.

Summary: We are making progress on this grant as the numerical simulations with ocean conditions observed during hurricane Ivan's passage by Walker *et al*. (GRL, 2005). Warm and cold rings suggest regimes of less and more negative feedback to the atmosphere. Over the next year we will complete the analysis of Ivan within the context of mixing and upwelling and downwelling processes by comparing simulations of the currents and shears to *in situ* measurements from the SEED moorings (Teague *et al*., JPO, 2007). In addition, we envision that the Katrina and Rita cases will be evaluated with model simulations and observations. These combined numerical and observational efforts represent an excellent opportunity for a PhD student to examine the model sensitivities and comparing these simulations to the NRL and MMS profiler measurements.

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Recent Publications:

Halliwell, G., L. K. Shay, S. D. Jacob, O. Smedstad, and E. Uhlhorn, 2008: Improving ocean model initialization for coupled tropical cyclone forecast models using GODAE nowcasts. *Mon. Wea Rev***., 136 (7)***,* 2576–2591.

Jaimes B., and L. K. Shay, 2008: Mixed layer cooling in Gulf of Mexico mesoscale eddies during Hurricanes Katrina and Rita. *Mon. Wea Rev***., (Submitted).**

Mainelli, M., M. DeMaria, L. K. Shay and G. Goni. 2008: Application of oceanic heat content estimation to operational forecasting of recent category 5 hurricanes, *Wea and Forecast.*, **23,** 3-16.

Rogers, R., S. Aberson, M. Black, P. Black, J. Cione, P. Dodge, J. Dunion, J. Gamache, J. Kaplan, M. Powell, L. K.Shay, N. Surgi, E. Uhlhorn, 2006: The intensity forecasting experiment (IFEX), a NOAA multiple year field program for improving intensity forecasts. *BAMS***, 87(11),** 1523-1537.

Shay, L. K. and E. Uhlhorn, 2008: Loop Current Response to hurricanes Isidore and Lili, *Mon. Wea. Rev*., **137,** 3248-3274.

Shay, L.K., 2008: Upper Ocean Structure: a Revisit of the Response to Strong Forcing Events. In*: Encyclopedia of Ocean Sciences*, ed. John Steele, S.A. Thorpe, Karl Turekian and R. A. Weller, Elsevier Press International, Oxford, UK ***(In Press),*** *19 pp.*

Shay, L. K., 2008: Air-sea interactions in tropical cyclones (Chapter 4). *In Global Perspectives of Tropical Cyclones:* 2nd Edition, Edited by J. C. Chan and C. P. Chang (Submitted), 38 pp.