

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: This applied effort has proceeded along two closely related tracks: the preparation and analysis of the *in-situ* ocean observations required to evaluate ocean model performance, and the thorough evaluation of ocean model performance using these and other available ocean observations. The observational effort includes processing in situ Acoustic Doppler Current Profiler (ADCP) data from Ivan (provided by the U.S. Naval Research Laboratory), moored observations during Katrina and Rita (data courtesy of Minerals Management Service-MMS), and NOAA Hurricane Research Division (HRD) Intensity Fluctuation Experiments (IFEX) observations for pre and post Rita in 2005 (Rogers *et al.*, 2006; Jaimes and Shay, 2009, 2010). In addition, oceanic and atmospheric profiler measurements were acquired during hurricanes Gustav and Ike in 2008 in and over the Gulf of Mexico. In all these cases, satellite observations (altimetry and SST) have been obtained and Ocean Heat Content (OHC) maps have been produced following the Shay and Brewster (2010) approach.

The centerpiece of the modeling effort to date has been a thorough evaluation of ocean model performance during Hurricane Ivan (2004) designed to address the specific objectives listed above. A paper describing these results including detailed comparisons to oceanic observations (Halliwell *et al.*, 2010) is in submission to *Monthly Weather Review*. Reference experiments have also been performed for Hurricanes Katrina and Rita (05), and are beginning for Gustav and Ike (08) where fairly comprehensive data sets exist. These experiments have demonstrated that accurate ocean model initialization with respect to upper-ocean temperature and salinity (density) profiles along with the correct location of ocean currents and eddies is the most important factor influencing the accuracy of SST cooling forecast by an ocean model. Efforts are now underway to evaluate existing ocean model initialization products prior to a large number of storms to quantify errors and biases and to design observational strategies to improve the initial ocean fields.

Modeling: The Hybrid Coordinate Ocean Model (HYCOM) is the chosen ocean model because it is being evaluated as the ocean model component of the next-generation coupled hurricane forecast model under development at NOAA/NCEP/EMC. It also contains multiple choices of numerical schemes and subgrid-scale parameterizations, making it possible to isolate model sensitivity to individual processes and devise strategies to improve model representation of these processes. In this context, fifteen free-running HYCOM simulations were conducted to assess model sensitivity to vertical resolution in the surface mixed layer, horizontal resolution, vertical mixing scheme, wind stress drag coefficient, surface turbulent flux drag coefficient, resolution of surface forcing, accuracy of ocean model initialization, and ocean dynamics (one dimensional versus three dimensional) for hurricane Ivan (numerical 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 control 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 wind fields, and then wind stress is calculated using bulk formula with the Donelan *et al.* (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. Attributes of the control experiment are summarized in Table 1.

The remaining experiments all differ from GOM1 by altering one single model attribute (Table 1). GOM2 isolates sensitivity to horizontal resolution, GOM3 and GOM4 to vertical resolution, GOM5 and GOM6 to vertical mixing scheme, GOM7-GOM11 to wind stress drag coefficient parameterization, GOM12 to turbulent heat flux drag coefficient representation, GOM13 to surface forcing resolution (COAMPS without HWIND patching), GOM14 to ocean model initialization (nesting within a non-assimilative ocean model), and GOM15 to one-dimensional ocean dynamics.

SST Response Evaluation: Halliwell *et al.* (2010) evaluate the simulated SST cooling patterns forced by Ivan against daily SST fields generated by the objective analysis of *in-situ* observations along with AVHRR and microwave satellite observations onto a 0.25° global grid (Reynolds *et*

al., 2007), hereinafter referred to as “blended” SST. Model sensitivities are initially evaluated by calculating the changes in SST that occurred between 11 and 17 September 2004 (before and after Ivan). The mean differences listed in Table 2 demonstrate that in the eastern GOM subdomain over which these analyses were performed, the ocean model did not cool as much as indicated by the blended SST fields. Although the model overcooled within a cold-core cyclone centered near 25°N, 87°W by >4°C (Halliwell *et al.*, 2010), this overcooling was more than compensated for by undercooling over the remainder of the domain. Mean differences display the largest sensitivity to ocean model initialization, surface forcing resolution, and wind stress drag coefficient, with more (less) cooling occurring for larger (smaller) values of C_D . Smaller sensitivity is evident for vertical mixing choice, with the MY and GISS schemes producing slightly more cooling than KPP. Little sensitivity is evident to vertical and horizontal resolution. RMS differences between the simulations and blended SST are substantially affected by the large simulated overcooling in the cold-core cyclone centered near 25°N, 87°W.

Table 1. Summary of the 15 numerical experiments simulating the ocean response to hurricane Ivan conducted in the GOM domain. Key model attributes that are varied are broken into major categories and listed in column 1. Characteristics of the control experiment are listed in column 2 while the single model attributes varied in each of the remaining experiments are listed in column 3.

| Model Attribute | Control Experiment (GOM1) | Alternate Experiments |
|-----------------------|---------------------------|--|
| Horizontal resolution | 0.04° Mercator | GOM2: 0.08° Mercator |
| Vertical resolution | 26 layers, 4-8m in OML | GOM3: 21 layers, 7.5-15m in OML GOM4: 31 layers, 3-5m in OML |
| Vertical mixing | KPP | GOM5: MY GOM6: GISS |
| C_D | Donelan | GOM7: Powell GOM8: Large and Pond GOM9: Large and Pond (capped) GOM10: Shay and Jacob GOM11: Jarosz <i>et al.</i> |
| C_{EL} , C_{ES} | COARE3.0 algorithm | GOM12: Kara <i>et al.</i> |
| Atmospheric forcing | 27-km COAMPS+H*WIND | GOM13: 27-km COAMPS only |
| Outer model | NCODA GOM hindcast | GOM14: Free GOM simulation |
| Ocean dynamics | Three-dimensional | GOM15: One-dimensional |

Halliwell *et al.* (2010) further evaluate the fidelity of simulated SST cooling patterns using advanced analysis techniques, specifically Taylor (2001) diagrams and the Murphy (1988) skill scores (not shown). Summarizing the overall conclusions, the control experiment produced one of the most realistic SST response patterns as expected. Three experiments stood out as much inferior to the control experiment, specifically GOM13 (low-resolution atmospheric forcing, GOM14 (alternate initialization) and GOM15 (one-dimensional ocean dynamics). All other experiments produced SST cooling patterns that were equally correlated with cooling in the blended analysis (≈ 0.7), but some of the wind stress drag coefficient choices degraded the realism of the cooling response. Drag coefficient values substantially smaller than the Donelan choice used in the control experiment tended to underestimate the magnitude of the cooling

pattern (GOM7) while values substantially larger than Donelan substantially overestimated the magnitude of the cooling pattern (GOM8, GOM10). The quality of the eight other experiments was almost identical to the quality of the control experiment. However, this does not mean that all of the model attributes evaluated in these eight experiments will have an insignificant influence on storm intensity. For example, although the SST cooling pattern was only slightly different among the three vertical mixing choices (GOM1, GOM5, GOM6), they produced potentially significant differences in the turbulent heat flux from ocean to atmosphere (up to 200 W m^{-2}) beneath the inner core of the storm. Although changing the surface turbulent heat flux parameterization (GOM12) had little influence on the SST cooling pattern, it also had a potentially significant influence on the surface heat flux (differences up to 300 W m^{-2}). Further details on model evaluation are contained in Halliwell *et al.* (2010).

Table 2. Comparison of ΔT (forced by Ivan) images (17 Sept. minus 10 Sept.) between the 15 experiments and blended SST: mean difference (column 2) and RMS difference (column 3)

| Experiment | ΔT Mean Difference (°C) | ΔT RMS Difference (°C) |
|------------|---------------------------------|--------------------------------|
| GOM1 | 0.24 | 1.33 |
| GOM2 | 0.25 | 1.29 |
| GOM3 | 0.30 | 1.40 |
| GOM4 | 0.22 | 1.40 |
| GOM5 | 0.30 | 1.26 |
| GOM6 | 0.47 | 1.33 |
| GOM7 | 0.38 | 1.33 |
| GOM8 | 0.04 | 1.57 |
| GOM9 | 0.14 | 1.47 |
| GOM10 | -0.19 | 1.71 |
| GOM11 | 0.06 | 1.37 |
| GOM12 | 0.11 | 1.34 |
| GOM13 | 0.51 | 1.24 |
| GOM14 | 0.84 | 1.51 |
| GOM15 | 0.06 | 1.55 |

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.* 2007) (Figure 1). 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.

Table 3: 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 °N | Long °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 |

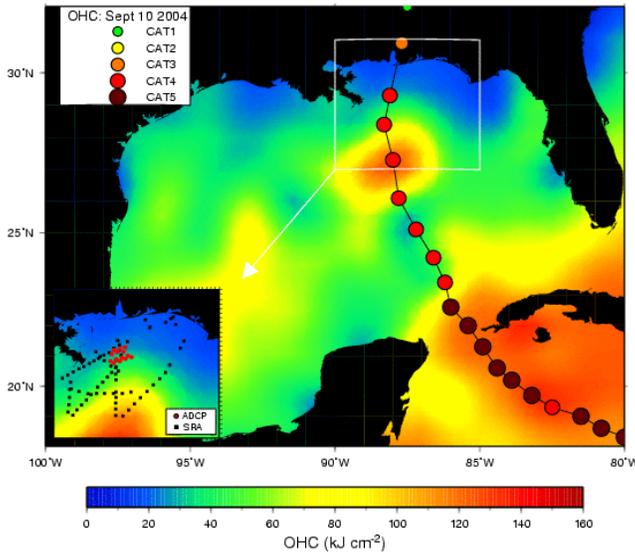


Figure 1: OHC map and inset showing NRL mooring locations (red) and SRA wave measurements (black) relative to Ivan’s storm track and intensity. The OHC pattern shows the WCR encountered by Ivan prior to landfall. The cooler shelf water ($OHC < 20 \text{ kJ cm}^{-2}$) resulted from the passage of Frances two weeks earlier.

Current Profiler Analyses: As shown in Table 3, 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.* (2007). 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 2 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 ($2R_{max} \sim 64 \text{ km}$ 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.* 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.

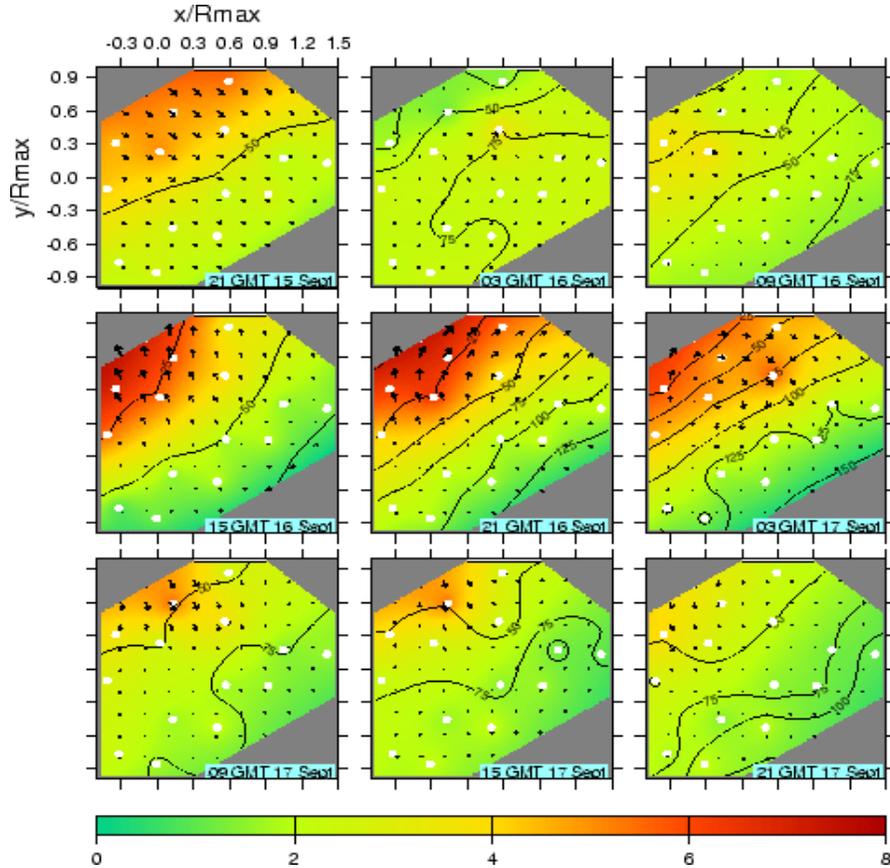


Figure 2: Spatial evolution of the rotated current shear magnitude normalized by observed shears from the ADCP measurements (white dots) normalized by observed shears in the Loop Current of $1.5 \times 10^{-2} \text{ s}^{-1}$ (color) during Lili starting at 2100 GMT 15 Sept every 6 hours. Black contours (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 Rmax of 32 km.

Observed current shear profiles that were estimated over 4-m vertical scales for each time sample following hurricane passage at arrays 8 and 9 are shown in Figure 3. 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 (Nowlin and Hubertz, 1972) and similar to those documented during hurricane Gilbert's passage where up to 3.5°C cooling was observed. In the near-inertial wave wake (Shay *et al.*, 1998), the key issue is how much of the current shear is associated with near-inertial wave processes. Compared to the Gulf Common Water, the presence warm and cold eddies significantly impact these levels of near-inertial wave (and shear) activity (Jaimes and Shay, 2010). This is now being explored prior to comparing these values to those from the HYCOM model for each of the experiments discussed above.

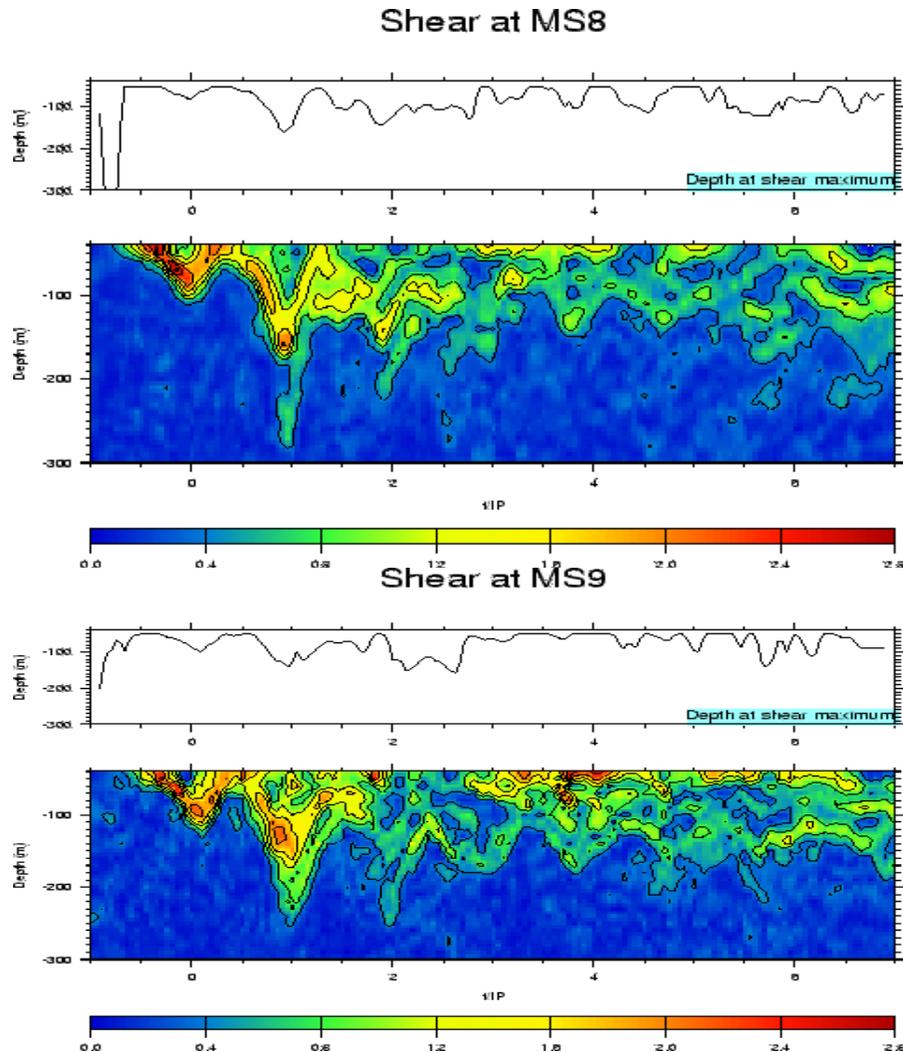


Figure 3: Time series (normalized by inertial period) of observed current shear magnitudes (colored contours) and the respective depths (m) of maximum current shears observed at Moorings 8 (upper: along Ivan's track) and 9 (lower: 1.5 R_{max} to the right of the Ivan) relative to the time of the closest approach. Shears are normalized by a value of $1.5 \times 10^{-2} \text{ s}^{-1}$ that have been observed in the Loop Current (Shay and Uhlhorn, 2008).

Model versus Observed Current Comparisons: At mooring 9 (Figure 4), velocity component profiles from the control experiment GOM1 are compared to the observed profiles over the upper 150 m. Good agreement exists between observed and simulated currents over the first two inertial periods. These observations and simulations suggest vertical energy propagation out of the surface mixed layer and into the thermocline consistent with theory. Velocity comparisons reveal differences among the three vertical mixing schemes evaluated in GOM1, GOM5, and GOM6. Given the same initialization, wind forcing and drag coefficient formulation as well as the same number of layers, the KPP scheme used in GOM1 duplicates the observed profiles better than the other two schemes. The simulations and observations are regressed and fit to a line in a least squares sense (not shown). 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} . By contrast, the MY (GOM5) and GISS (GOM6) 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.

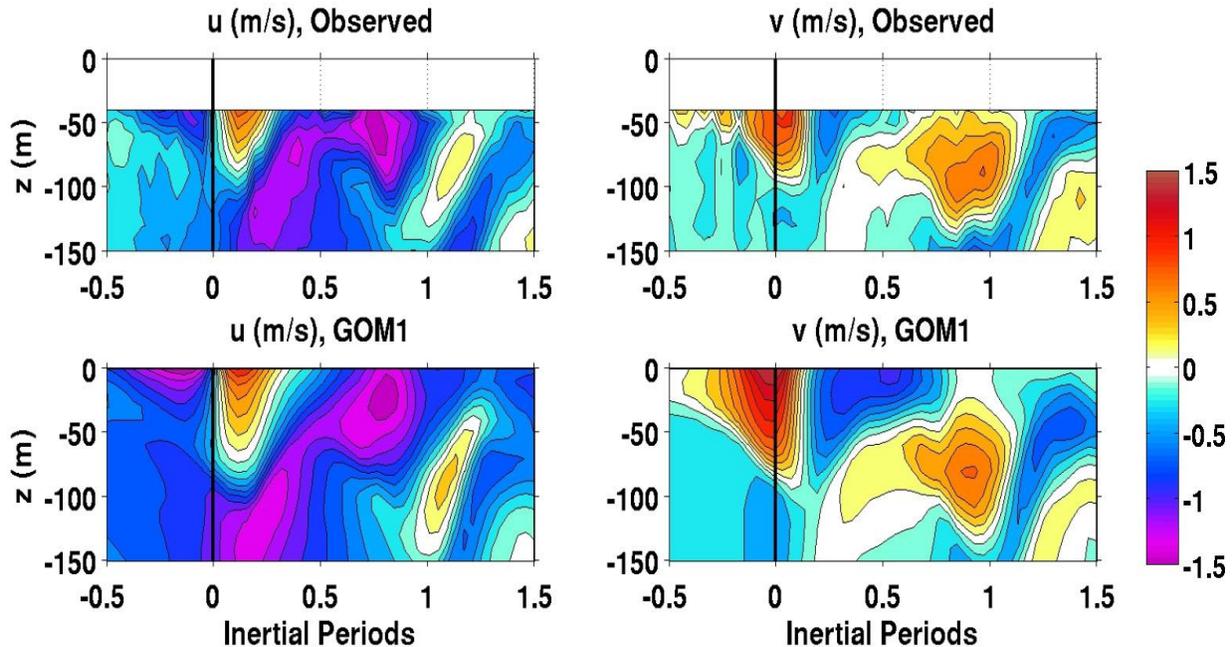


Figure 4: Time series (normalized by inertial period) of observed current components (top panels) and simulated current components from the control Ivan experiment GOM1 in m s^{-1} at SEED Mooring 9 from Halliwell et al. (2010).

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 5). 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 proper ocean model initialization. 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. During January 2010, G. Halliwell has been in contact with Carlos

Lozano of EMC to devise strategies to decrease model run time for the planned HWRF tests during the 2010 season.

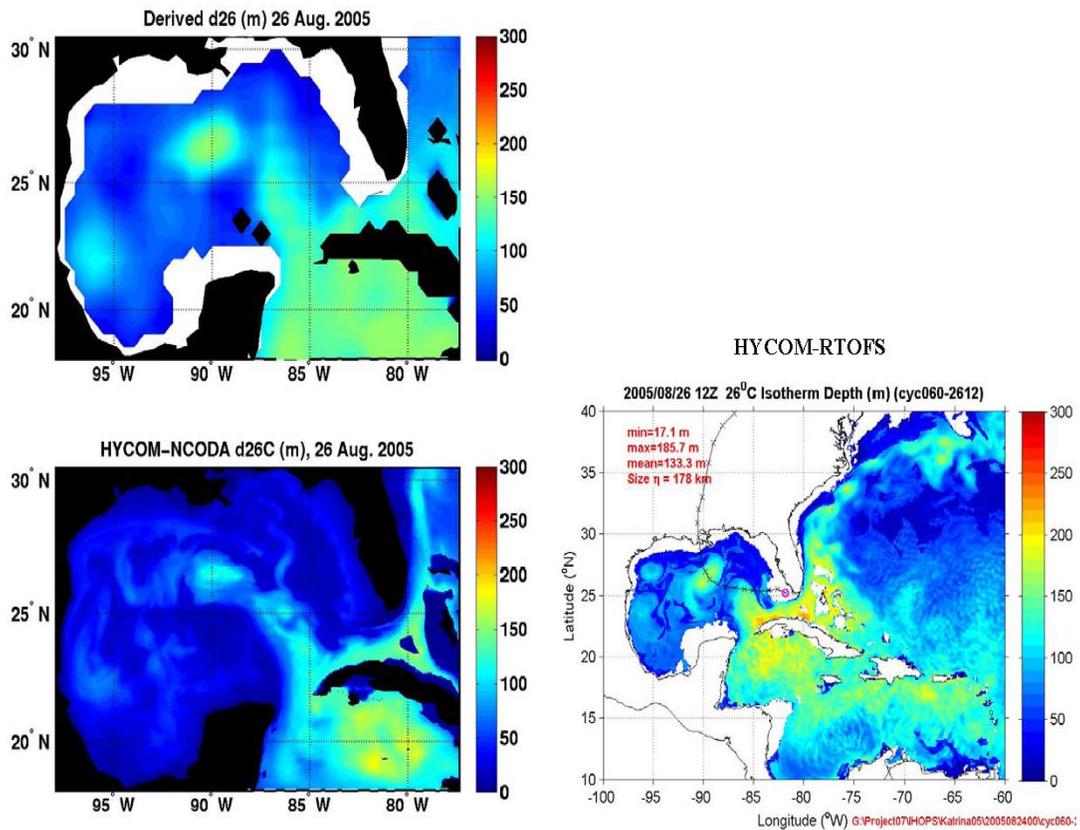


Figure 5. Maps of the depth of the 26°C isotherm derived from satellite altimetry and SST (upper left), obtained from the HYCOM-NCODA ocean hindcast produced by NRL (lower left), and obtained from the HYCOM-RTOFS ocean hindcast produced by NOAA/NCEP/EMC.

Katrina and Rita: The 3-D upper ocean thermal and salinity structure in the LC system was surveyed with Airborne eXpendable BathyThermographs (AXBT), Current Profilers (AXCP), and Conductivity-Temperature-Depth sensors (AXCTD) deployed from four aircraft flights during September 2005, as part of a joint NOAA and National Science Foundation experiment (Rogers *et al.*, 2006; Shay, 2009). Flight patterns were designed to sample the mesoscale features in the LC system: the LC bulge (amplifying WCE), the WCE that separated from the LC about two days before the passage of Rita, and two CCEs that moved along the LC periphery during the WCR shedding event (Fig. 6). The first aircraft flight was conducted on 15 Sept (two weeks after Katrina or one week before Rita, i.e. pre-Rita), the second and third flights were conducted during Rita's passage (22 and 23 Sept, respectively), and the final flight was conducted on 26 Sept, a few days after Rita's passage. Pre-Rita and post-Rita (not shown) flights followed the same pattern, while these other Rita flights focused on different regions along Rita's track. Data acquired during pre-Rita includes temperature profilers from AXBTs, temperature and salinity profilers from AXCTDs, and current and temperature profilers from two AXCPs deployed in the western and eastern sides of the WCE (Jaimes and Shay 2009). A salient characteristic of the

WCE is the salinity maximum of ~36.4 to 36.7 practical salinity units. This behavior must be incorporated into numerical models, as a climatological salinity profile is insufficient to accurately initialize an model ocean with a WCE. Realistic salinity profiles to match the temperature profiles would then resolve horizontal density gradients and the corresponding geostrophic flows associated with oceanic features (Shay *et al.*, 1998).

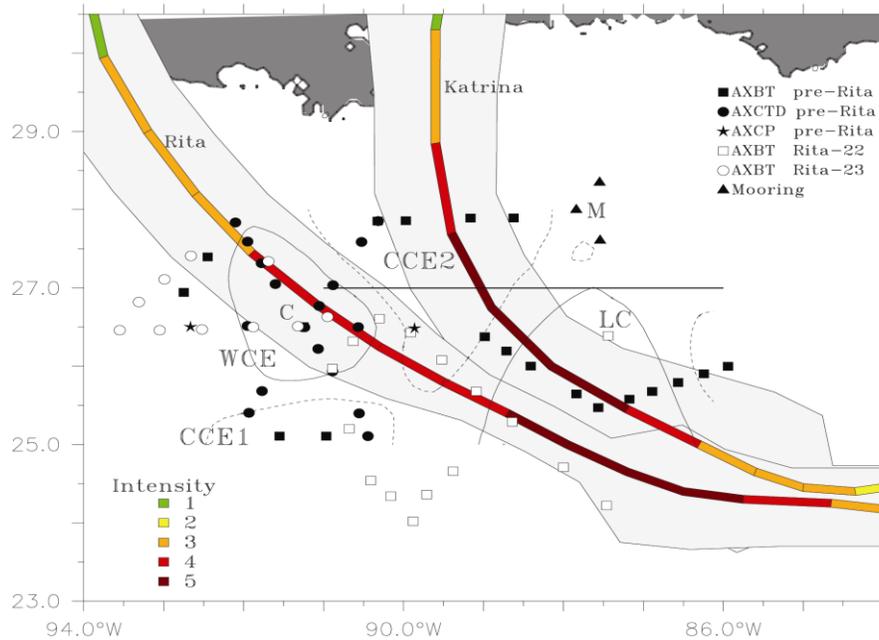


Figure. 6: Airborne profilers deployed in Sept 2005 relative the track and intensity of Katrina and Rita (colored lines, with color indicating intensity as per the legend) over the LC System. The light-gray shades on the sides of the storm tracks represent twice the radius of maximum winds (R_{max}). The contours are envelopes of anticyclonic (solid: WCE and LC) and cyclonic (dashed: CCE1 and CCE2) circulations. A set of AXBTs (not shown) was deployed after hurricane Rita (26 Sept), following a sampling pattern similar to pre-Rita (or post Katrina) (15 September). Point M indicates the position of several MMS moorings used during this study, and Point C represents the drop site for profiler comparison (AXBT versus AXCTD). The transect along 27°N indicates the extent of vertical sections discussed in the text (Jaimes and Shay 2009).

The combination of these airborne profiles of temperature and salinity measurements with the MMS-sponsored ADCP and CTD moorings were fairly consistent. These continuous measurements of ocean temperatures, salinities (via conductivities), and currents were acquired from the mooring sensors at intervals of 0.5 and 1 hr for CTDs and ADCPs, respectively. Although the moorings were located outside the radius of maximum winds R_{max} of hurricanes Katrina (~4.5 R_{max} where $R_{max} = 47$ km) and Rita (~17.5 R_{max} where $R_{max} = 19$ km) (Fig.6), CCE2 that was affected by Katrina (category 5 status) propagated over the mooring site ≈ 2 days after interacting with the storm. The circulation of the LC bulge that interacted with Rita (category 5 status) extended over the mooring ≈ 3 days after having been affected by the storm. The cluster averages of the thermal structure revealed that the LC cooled by 1°C, the WCE temperature cooled by 0.5°C, and the eddy shedding region and the CCE cooled by more than 4.5°C (Jaimes and Shay 2009). These profiles will represent a challenge for the model especially placing the

oceanic features in the correct position as suggested by the Ivan model analyses (Halliwell *et al.*, 2010).

More recently, Jaimes and Shay (2010) analyzed the contrasting thermal responses during and subsequent to Katrina and Rita by estimating the energetic geostrophic currents in these oceanic features. Increased and reduced oceanic mixed layer (OML) cooling was measured following the passage of both storms over cyclonic (CCE) and anticyclonic (WCE) geostrophic relative vorticity ζ_g , respectively. Within the context of the storms' near-inertial wave wake in geostrophic eddies, ray-tracing techniques in realistic geostrophic flow indicate that hurricane forced OML near-inertial waves are trapped in regions of negative ζ_g , where they rapidly propagate into the thermocline. These anticyclonic-rotating regimes coincided with distribution of reduced OML cooling, as rapid downward dispersion of near-inertial energy reduced the amount of kinetic energy available to increase vertical shears at the OML base. By contrast, forced OML near-inertial waves were stalled in upper layers of cyclonic circulations, which strengthened vertical shears and entrainment cooling. Upgoing near-inertial energy propagation dominated inside a geostrophic cyclone that interacted with Katrina; the salient characteristics of these upward propagating waves were: (i) radiated from the ocean interior due to geostrophic adjustment following the upwelling and downwelling processes; (ii) rather than with the buoyancy frequency, they amplified horizontally as they encountered increasing values of during upward propagation; (iii) produced episodic vertical mixing through shear-instability at a critical layer underneath the OML. To improve the prediction of TC-induced OML cooling, models must capture geostrophic features; and turbulence closures must represent near-inertial wave processes such dispersion and breaking between the OML base and the thermocline. Models must capture this variability to get the correct entrainment in cold and warm oceanic features.

Gustav and Ike: More recently, hurricane Gustav and Ike moved over the Gulf of Mexico and interacted with the LC and the eddy field in August and September 2008 (Fig. 7). As part of the NCEP tail Doppler Radar Missions, oceanic and atmospheric measurements were acquired on sixteen NOAA WP-3D research flights for pre, during and post-storm flights. In total, over 400 AXBTs and 200 GPS sondes were deployed to document the evolving atmospheric and oceanic structure over warm and cooler ocean features in these two hurricanes (Table 4). In addition, forty-five GPS sondes were deployed on 1 Sept over the float and drifter array deployed by the United States Air Force WC-130J north and west of the Loop Current. Similar to CBLAST observations, the float array also included the EM/APEX floats that measure the horizontal velocities as well as temperature and salinity structure (Sanford *et al.*, 2007). However, this effort significantly improved upon the CBLAST effort in that the forcing is better documented with the combination of GPS sondes and the Stepped Frequency Microwave Radiometer (Uhlhorn *et al.*, 2007) directly over the float and drifter array. In addition, each research flight carried AXBTs to document the evolving upper ocean thermal structure across the entire Gulf of Mexico for the first time. Note that the AXBTs were deployed to document pre- and post-storm oceanic variability in the Loop Current and its periphery where float and drifter measurements would be advected away from the storm track by the energetic ocean current. This is precisely why we need current profilers to deploy from the research aircraft on a routine basis.

Summary: We made significant progress on this grant as the numerical simulations with ocean conditions observed during hurricane Ivan's passage by Walker *et al.* (2005). Warm and cold eddies suggest regimes of less and more negative feedback to the atmosphere. We have completed 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.*, 2007). In addition, we have analyzed pre- Katrina and Rita

observations including detailed ray-tracing techniques to demonstrate the markedly different character of the forced near-inertial motions (Jaimes 2009; Jaimes and Shay 2010). We will conduct a similar analysis on the model simulations to assess the impact on the mixing schemes via shear-instability. Such combined numerical and observational efforts here have benefitted from a PhD student (B. Jaimes) to examine model sensitivities and comparing these simulations to the NRL and MMS profiler measurements.

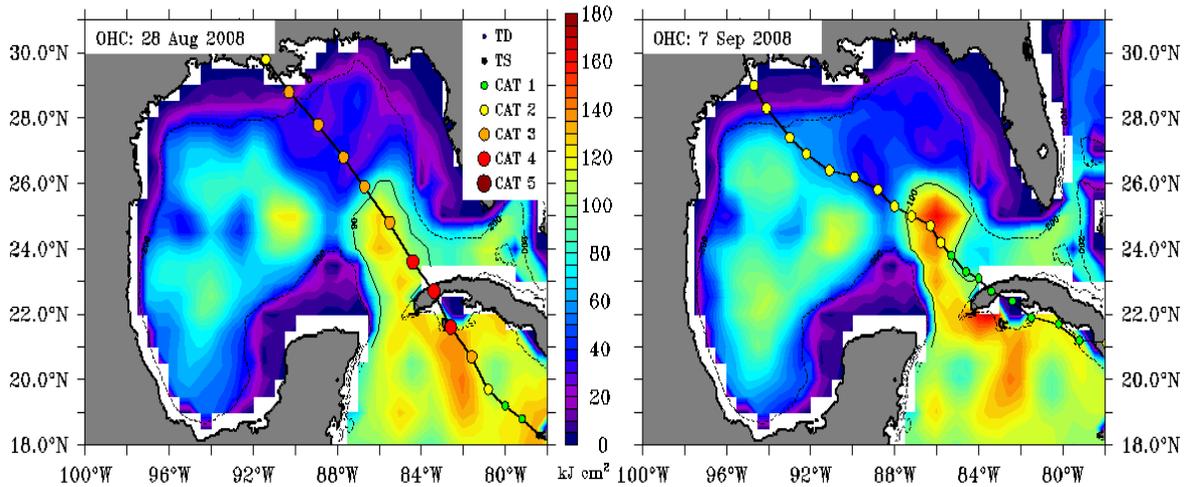


Figure 7: Track (black line) and intensity (circles:legend) of hurricanes a) Gustav and b) Ike relative to the pre-storm OHC (kJ cm^{-2}) distributions in the Gulf of Mexico prior to their passages on 28 Aug and 7 Sep 2008.

Given the 5-year program of the recently funded MMS Dynamics of the Loop Current Study (\$7M), this project will benefit significantly from in-situ mooring data as well as the detailed aircraft measurements that will be acquired during the NOAA IFEX, NASA GRIP, and NSF PREDICT experiments during the summer of 2010. Our focus will be on the Gulf of Mexico's Loop Current and eddy shedding regime where hurricanes can rapidly weaken or deepen as they interact with both warm and cold ocean features. Even under quiescent conditions, these data will represent a challenge to the model to get the 3-D temperature, salinity and current structure accurately through vertical projection of the altimetry data. Finally processed profiler data from Gustav and Ike flights are being synthesized with drifter and float data to provide a clearer description of the cold wake northeast of the Loop Current where cooling exceeded 3°C compared to the Loop Current of about 1°C .

With this observational preparation effort well underway, HYCOM simulations of the ocean response to Katrina, Rita, Gustav, and Ike will be performed soon to extend the evaluation effort beyond Ivan. The effort to generate the atmospheric forcing datasets with HWIND patched in over the storm regions has been completed. These future model evaluation efforts will benefit from collaboration with the Hurricane Forecast Improvement Project (HFIP). Under HFIP, G. Halliwell will evaluate HYCOM performance within the HWRFx experimental coupled forecast model. This effort will also involve close collaboration with NOAA/EMC.

Acknowledgments: This study has benefited from the interactions with Mr. William Teague in the Oceanography Department at the US Naval Research Laboratory at Stennis Space Center, Dr. Alexis Lugo-Fernandez at Minerals Management Service sponsored ADCP moorings. This project has also benefited from continuing support from the National Science Foundation (Dr. Stephen Nelson) in the acquisition and analysis of measurements acquired during hurricanes in collaboration with NOAA’s Hurricane Research Division (Drs. Frank Marks, Rob Rogers, Eric Uhlhorn) and Aircraft Operations Center (Dr. James McFadden). Dr. Benjamin Jaimes also contributed to this effort.

Table 4: Summary of atmospheric (GPS) and oceanic (AXBT) profiler measurements from sixteen flights acquired in hurricanes Gustav and Ike in 2008. Numbers in parentheses represent profiler failures.

| Hurricane Gustav | | | | Hurricane Ike | | | |
|------------------|--------|--------|---------|---------------|--------|--------|---------|
| Date | Flight | GPS | AXBT | Date | Flight | GPS | AXBT |
| (2008) | | | | (2008) | | | |
| 28 Aug | RF43 | 0 | 49(2) | 08 Sep | RF43 | 0 | 47(2) |
| 29 Aug | RF42 | 12(4) | 16(0) | 09 Sep | RF42 | 19 | 6(0) |
| 30 Aug | RF43 | 9 | 19(2) | 10 Sep | RF42 | 17(1) | 10(2) |
| 31 Aug | RF42 | 24 | 16(1) | 10 Sep | RF43 | 11 | 20(7) |
| 31 Aug | RF43 | 17(2) | 19(1) | 11 Sep | RF42 | 16 | 10(1) |
| 01 Sep | RF43 | 44 | 19 | 11 Sep | RF43 | 10 | 22(3) |
| 03 Sep | RF43 | 4 | 54(4) | 12 Sep | RF42 | 21(2) | 10(4) |
| | | | | 12 Sep | RF43 | 8 | 20(4) |
| | | | | 15 Sep | RF43 | 0 | 61(5) |
| Total | 7 | 111(6) | 191(10) | | 9 | 111(3) | 216(28) |

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