# Mid-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 evaluates and improves 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 analysis and model initialization. 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; and,
iv) generating the realistic high-resolution atmospheric forcing fields necessary to achieve the previous objectives.

**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). An initial set of seven model experiments has been performed to document sensitivity to the factors addressed by the specific objectives listed above.

**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 (HWRF) presently under development at NOAA/NCEP/EMC. Another key reason for this model choice is that it 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 evaluation is first being performed for Hurricane Ivan in the GOM, where high-quality *in-situ* moored current measurements have been acquired, focusing on the impact of the Loop Current and associated warm and cold rings, along with the complex bathymetry of the continental shelf/slope region.

Table 1. Characteristics of the seven model experiments where entries highlighted in red signify differences from the base experiment Exp1.

| Experiment | Vertical Layers | Nearsurface Layer Thickness Range (m) | Vertical Mixing | Surface Forcing | Outer Nesting Model |
|---|---|---|---|---|---|
| Exp1 (base) | 26 | 4-8 | KPP | 1° NOGAPS plus HWIND | GoM NCODA |
| Exp2 | 21 | 3-5 | KPP | 1° NOGAPS plus HWIND | GoM NCODA |
| Exp3 | 31 | 7.5-15 | KPP | 1° NOGAPS plus HWIND | GoM NCODA |
| Exp4 | 26 | 4-8 | MY | 1° NOGAPS plus HWIND | GoM-NCODA |
| Exp5 | 26 | 4-8 | GISS | 1° NOGAPS plus HWIND | GoM-NCODA |
| Exp6 | 26 | 4-8 | KPP | 1° NOGAPS only | GoM-NCODA |
| Exp7 | 26 | 4-8 | KPP | 1° NOGAPS plus HWIND | GoM - No Assimilation |

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. Seven free-running HYCOM simulations were run to assess model sensitivity to (1) vertical resolution in the surface mixed layer, (2) the choice of vertical mixing scheme, (3) the quality of the surface forcing, and (4) the accuracy of ocean feature initialization as provided by the outer model within which the simulations are nested. Characteristics of the experiments are listed in Table 1. All experiments were run within a Gulf of Mexico (GoM) domain where the coastline follows the actual land/sea boundary with a minimum water depth of 2 m. They are all forced by surface fields of vector wind stress, wind speed, surface atmospheric temperature and humidity, longwave and shortwave radiation, and precipitation. Turbulent heat and mass fluxes are determined using bulk formula during model runs. Freshwater input from 12 rivers is included. A base experiment (Exp1) is defined that is forced by atmospheric fields from the 1.0-degree NOGAPS model, but with high-resolution wind stress and wind speed fields obtained from the HRD HWIND Ivan analysis patched in for the storm region. It is nested within a GoM data-assimilative hindcast that uses the Navy Coupled Ocean Data Assimilation (NCODA) system. It is run with 26 vertical layers and KPP vertical mixing is used. To test sensitivity to vertical resolution, Exp2 and Exp3 are run with 21 and 31 vertical layers, respectively. Exp4 and Exp5 are run with the same settings as Exp1 except for using the MY and GISS mixing schemes, respectively. Exp6 is forced with the $1^{o}$ NOGAPS fields only (no HWIND), while Exp7 is nested within a non-assimilative model that is not expected to accurately represent the initial location of the Loop Current and its associated rings and eddies.

Model sensitivities are initially evaluated by first calculating ΔSST and ΔOHC, which represent the changes in these variables that occurred between 11 and 17 September 2004 (before and after Ivan). RMS differences between the base experiment and the six other experiments (Table 2) quantify the sensitivity to the individual factor that was altered from Exp1. Also included in Table 2 is the difference between Exp4 and Exp5 to illustrate RMS differences between the MY and GISS vertical mixing experiments, which can be compared to the differences between Exp4 and Exp1 (MY and KPP) and the differences between Exp5 and Exp1 (GISS and KPP). The impact of these differences, listed in order from greatest to least model sensitivity are: (1) accurate initialization of ocean features; (2) accurate representation of the storm structure in the surface forcing; (3) choice of vertical mixing scheme; and, (4) vertical resolution. For vertical resolution, substantially 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 Vertical Mixing JHT grant (04-05), 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. Work is commencing on evaluating model-generated currents against the observations described below.

Table 2. RMS differences in ΔSST (ºC) and ΔOHC (kJ $cm^{-2}$) between the base experiment Exp1 and the other six experiments. The RMS difference between Exp4 and Exp5 is also listed.

| Experiments | Difference Factor from Base Experiment | ΔSST (ºC) | ΔOHC (kJ $cm^{-2}$) |
|---|---|---|---|
| Exp2 –Exp1 | Lower vert. res. | 0.20 | 2.85 |
| Exp3 – Exp1 | Higher vert. res. | 0.10 | 1.63 |
| Exp4 –Exp1 | MY mixing | 0.38 | 5.87 |
| Exp5 –Exp1 | GISS mixing | 0.34 | 4.52 |
| Exp6 – Exp1 | No HWIND | 0.41 | 9.99 |
| Exp7 – Exp1 | No assimilation | **1.04** | **24.40** |
| Exp5 – Exp4 | | 0.28 | 3.45 |

These model experiments are just the initial set that will be analyzed. Experiments with coarser horizontal resolution are now being prepared to determine the coarsest feasible resolution that should be used in the coupled forecast model. <u>We are planning another suite of experiments to carefully evaluate model sensitivity to drag coefficient parameterizations and vertical mixing representation to identify optimal choices for the coupled forecast model.</u>

**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). 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.

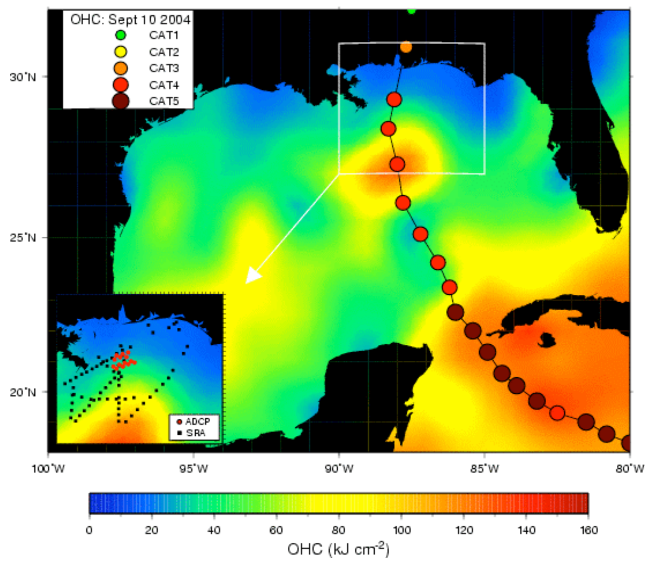


Figure 1: OHC map and inset showing NRL mooring locations (red) and SRA wave measurements (black) relative to Ivan's storm track and intensity. The OHC pattern shows the WCR encountered by Ivan prior to landfall. The cooler shelf water (OHC < 20 KJ $cm^{-2}$) resulted from the passage of Frances two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

**Preliminary 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. (CSR, 2005).

| 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 |

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.

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 ($2R_{max}$~64 km in Ivan during time 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. 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.

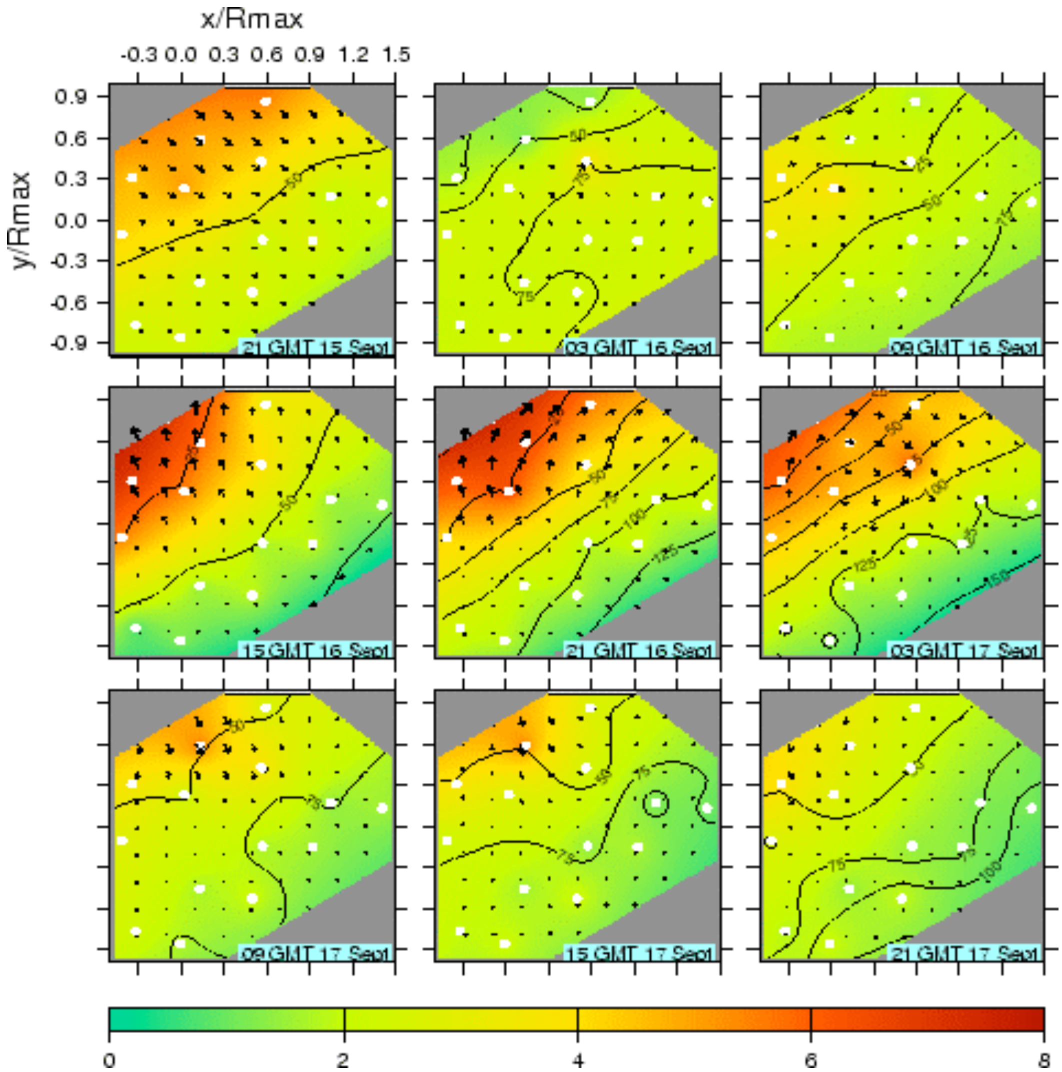


Figure 2: Spatial evolution of the rotated current shear magnitude normalized by observed shears from the ADCP measurements (white dots) normalized by observed shears in the LC of 1.5 x $10^{-2}$ $s^{-1}$ (color) during Lili starting at 2100 GMT 15 Sept every 6 hours. Black contours (25-m intervals) 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.

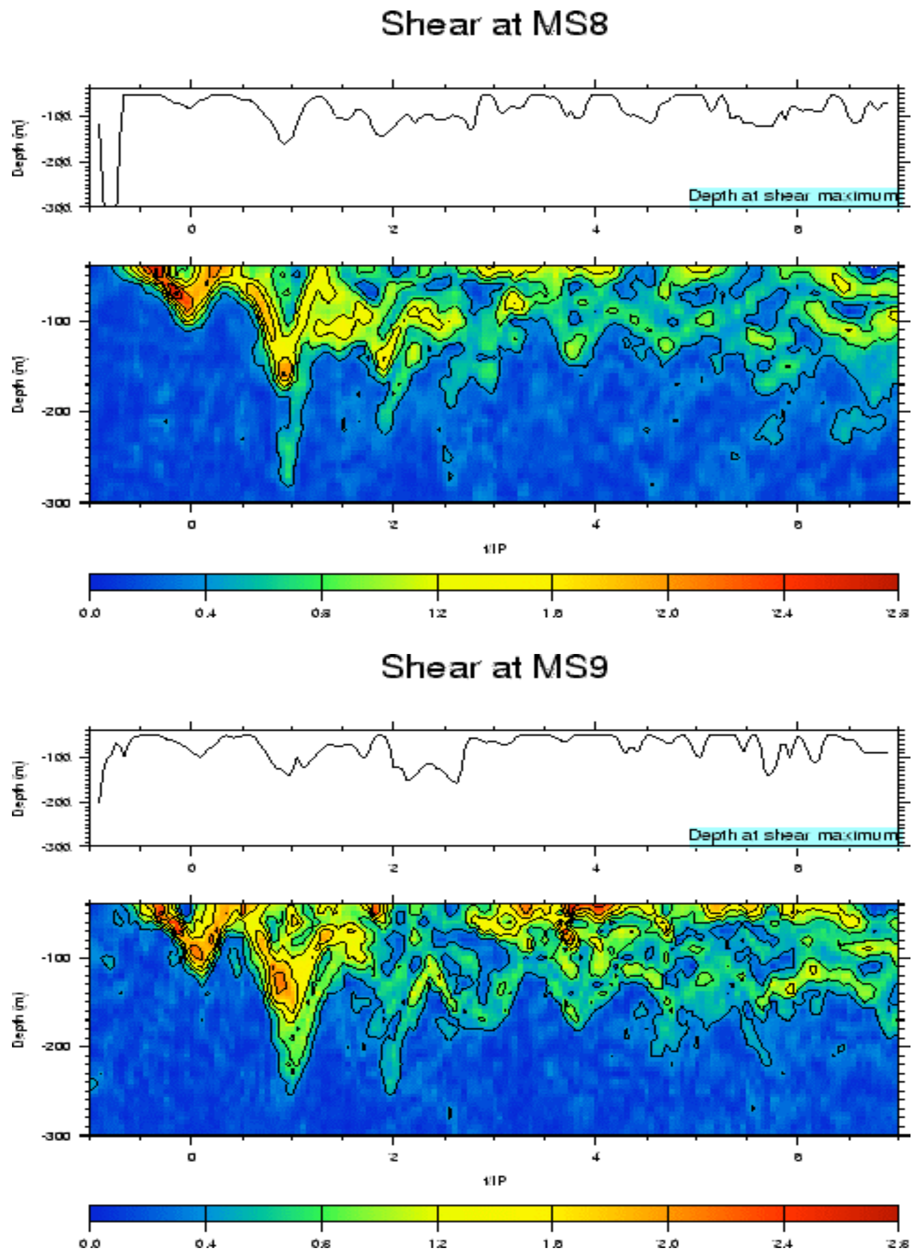


Figure 3: Time series (normalized by inertial period) of observed current shear magnitudes (colored contours) and the respective depths (m) of maximum current shears observed at Moorings 8 (upper: along Ivan' s track) and 9 (lower: 1.5 $R_{max}$ to the right of the Ivan) relative to the time of the closest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

The 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 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 and similar to those documented during hurricane Gilbert's passage where up to 3.5ºC

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 three vertical mixing schemes discussed above.

**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 few months we will look at the details of the mixing and upwelling/downwelling processes and compare the model simulations of the currents and shears to *in situ* measurements from the SEED moorings (Teague et al., JPO, 2007). This effort represents an excellent opportunity for a PhD student to examine the model sensitivities and comparing these simulations to the NRL profiler measurements.

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