**Joint Hurricane Testbed First Year Progress Report**
**Project: Evaluation of Upper Ocean Mixing Parameterizations**

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## Introduction:

Past observational, theoretical and numerical studies have substantiated the fact that tropical cyclone intensity is sensitive to the upper ocean heat potential in the directly forced region of the storm. Observational and numerical investigation of ocean response during hurricane Gilbert in the western Gulf of Mexico suggested that the upper ocean heat and mass budgets have a strong dependence on the entrainment mixing scheme. Thus, one of the major uncertainties in a coupled hurricane ocean forecasting model is the choice of mixing scheme as significant oceanic mixed layer cooling and deepening during a storm passage is due to mixing. As part of this Joint Hurricane Testbed (JHT) funded project, using the Hybrid Coordinate Ocean Model (HYCOM) configured with different entrainment mixing schemes, this issue is being investigated in detail. Our focus here is to identify and recommend a more accurate entrainment parameterization scheme for use in the ocean component of operational coupled models based on detailed simulations of the ocean response to tropical cyclones and comparison to observations. This effort addresses EMC high priority areas of work associated with general model improvements to advance track and intensity forecasts (EMC 1) and improved boundary layer representation in coupled models (EMC 2). Available high-resolution oceanic observations during the passage of three tropical cyclones (Gilbert 1988, Isidore 2002 and Lili 2002) in the Atlantic provide the data set to evaluate model results. Overall, 702 temperature, 102 salinity and 210 current profiles acquired during these storms will be directly compared to simulated results to identify the best mixing schemes for different forcing characteristics and background oceanographic conditions that can be used in the coupled intensity prediction models. While the identified parameterizations can be implemented in the operational coupled model, HYCOM is being implemented as part of the EMC ocean prediction system that will make the transition to operations much simpler. In this report, progress so far on the project in achieving the final objectives is presented.

## Objectives for the Period ending May 2004:

Our principal objectives during the past year were:

- Configuration of two numerical model domains based on suitability of geographic coverage and vertical structure representation;

- Derivation of realistic initial conditions for hurricanes Gilbert and Isidore using a combination of in situ and remotely sensed data;

- Derivation of realistic boundary layer forcing by blending in situ and aircraft derived quantities with the large scale model fields; and

- Simulation of ocean response to forcing associated with hurricane Gilbert for different state of the art mixing parameterizations and compare results to profiler observations.

Much of these objectives have been achieved on schedule. Simulated upper ocean temperatures and currents during hurricane Gilbert are presently being compared to profiler observations. This is scheduled to be completed by the end of the month and will be followed by detailed simulations of ocean response for hurricanes Isidore and Lili in the next six months.

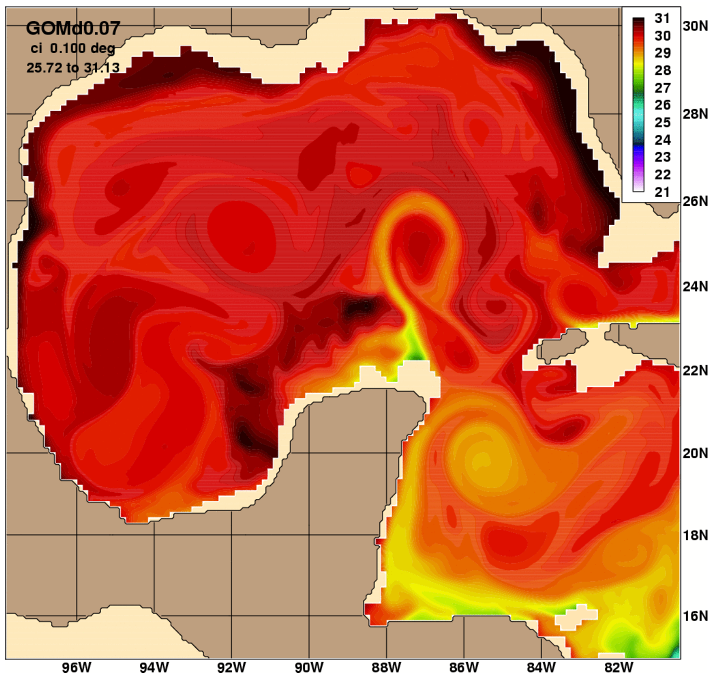


Figure 1: Geographic extent of the model domain for the Gilbert case with the pre-storm mixed layer temperatures. Pre-storm oceanic variability is represented well by the derived initial conditions.

## Model Configuration:

Two configurations of HYCOM are set up to perform numerical simulations for the different mixing schemes. As most of the observations are in the western Gulf of Mexico during hurricane Gilbert, the model domain extends from 80 to 98° W longitude and from 14 to 31° N latitude. With a horizontal grid resolution of 0.07°, the model has 250×242 horizontal points and 22 layers in the vertical. The bathymetry used in the model is derived from ETOPO 5 topography and the boundaries along Florida Straits and the Caribbean sea are closed by vertical sidewalls as the area of interest is in the Western Gulf of Mexico (Fig.1).

With the occurrence of hurricanes Isidore and Lili in the same general geographic region, ocean response simulations are combined into a single continuous case spanning 20 days. The model domain extends from 65º to 98º W and 9º to 31º N with a resolution of 0.08° (Fig.2). The model has 22 vertical layers on a 413×296 horizontal grid and the boundary conditions are provided from basin-scale Atlantic Ocean HYCOM simulations driven by realistic atmospheric forcing. While the profiler acquired data are at very high resolution in the vertical (~ 1 *m*), the model is configured with a 5 *m* resolution at the surface and increasing it with depth until it transitions into the isopycnic domain. This will be reduced to 3 *m* if necessary during the simulation phase.

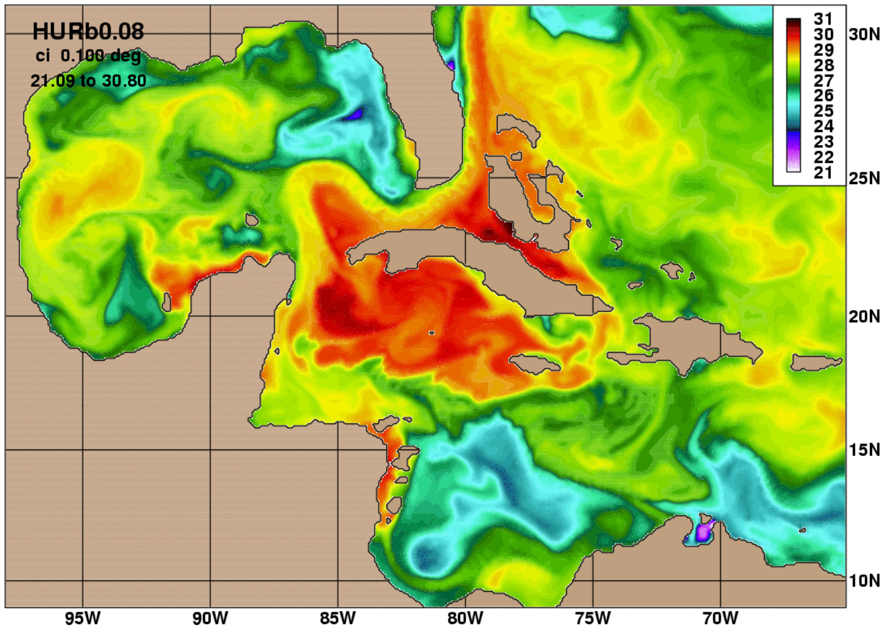


Figure 2: Model domain for hurricanes Isidore and Lili. Oceanic variability prior to hurricane Isidore is indicated by the sea surface temperature field. The mesoscale oceanic features are positioned accurately corresponding to altimetric height observations.

## Initial Conditions:

### *Gilbert*

During the passage of hurricane Gilbert in the Gulf of Mexico, the predominant oceanic circulation was due to a Loop Current Warm Core Eddy. As there is a distinct signature in both the mass and momentum fields due to this pre-storm variability, a combination of climatology and in situ measurements are used to provide the oceanic initial conditions for Gilbert. Prior to the passage of Gilbert, extensive data were acquired by the Minerals Management Service. The data from yeardays 187 to 217 are designated as the yearday 200 data and are objectively analyzed at every 10 *m* depth (Shay et al. 1998). The Temperature-Salinity (T-S) relationship of this data set compares well with the historic T-S curves for the different water masses in the Gulf of Mexico. These data are combined with the Levitus (1982) climatology data set to derive model layers/ levels. Using the Coupled Ocean Atmospheric Data Set (COADS) climatological forcing, the ocean model is integrated for about 60 days to provide a realistic conditions prior to the passage of Gilbert. At the end of the integration, the model eddy has a maximum sea surface height of 35 *cm*. The velocities associated with the eddy in the model are about 0.8 to 0.9 $ms^{-1}$ compared to 1 $ms^{-1}$ from the observations. The major and minor axes of the eddy ellipse are about 225 *km* and 110 *km*, respectively compared to the observed maximum of 250 *km*.

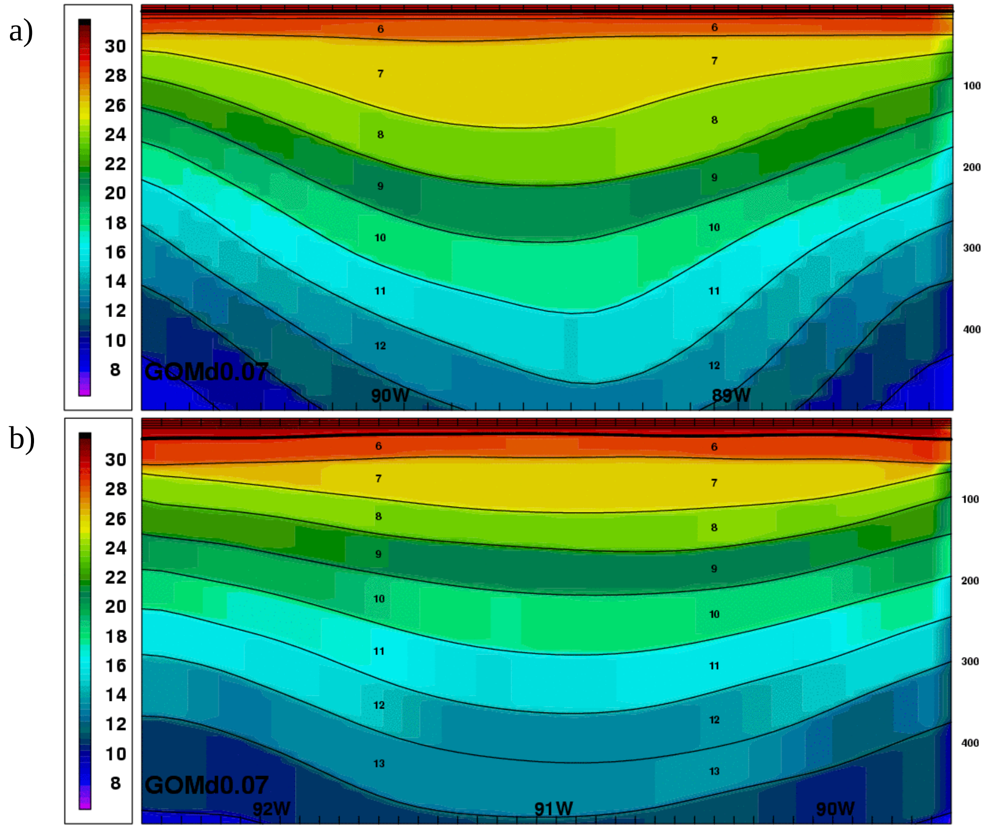


Figure 3: Zonal cross-sections across the eddy in the model to evaluate derived initial conditions where a) day 200 initialization of the model and, b) pre-Gilbert vertical structure. Depth of the 26° C isotherm is marginally shallower compared to observations.

## *Isidore*

In the case of Hurricane Isidore, the initial pre-storm fields are derived from the standard 0.08° Atlantic HYCOM simulations. Satellite altimetric sea surface height anomalies from the Modular Ocean Data Assimilation System (MODAS) operational implementation at the Naval Oceanographic Office combined with the mean sea surface height fields from the 0.08° Miami Isopycnic Coordinate Ocean Model have been assimilated into these runs using a vertical projection technique (Cooper and Haines 1996), so ocean eddies and boundary currents are reproduced quite accurately. Fig.2 shows the pre-Isidore sea surface temperature patterns in the eastern Gulf of Mexico and Caribbean Sea. Since both Isidore and Lili cases are combined in to a single case, Lili pre-storm conditions will be generated as part of the ocean response simulations.

## *Evaluation of Initial Conditions*

Since the simulated ocean response is compared to profiler data, the derived realistic initial conditions are evaluated with respect to observations to identify pre-existing biases in these fields. In the Gilbert case, day 200 observations indicated that the 18° *C* water extended up to a depth of 325 *m* in the eddy and 150 *m* in the Gulf. The depth of the 26° *C* isotherm is at 130 *m* and 75 *m* outside indicating a much higher heat content in the eddy. The derived model layers capture this vertical structure very well (Fig.3a). While the geographic location of the eddy center is in excellent agreement with observations after the 60 day integration, the model eddy is marginally weaker with the depth of the 26° $C$ isotherm shallower by about 10 $m$ compared to observations (Fig. 3b). Simulated sea surface or mixed layer temperatures (Fig.1) compare well with objectively analyzed pre-storm fields of Shay et al. (1992). Therefore, initial conditions provided by this approach are appropriate for use in the Gilbert case.

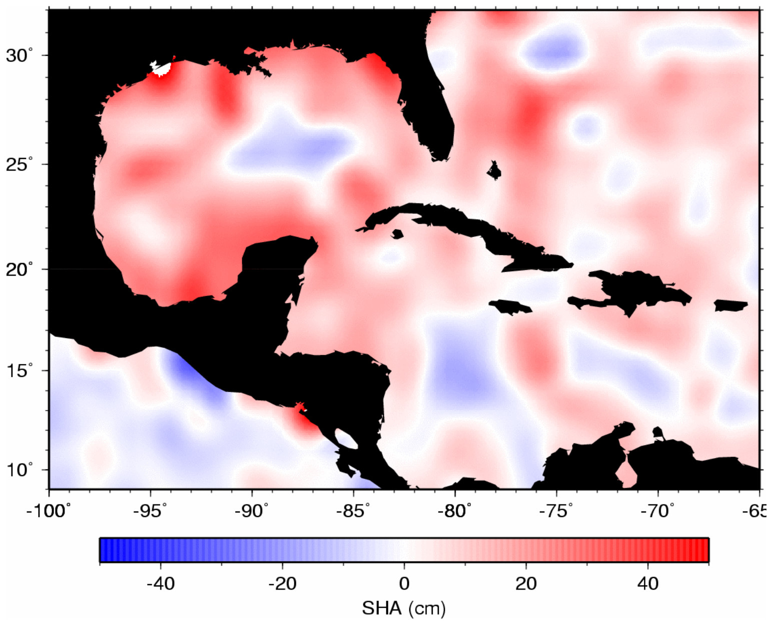


Figure 4: Altimeter measured sea surface height anomalies prior to the passage of Isidore. Positive anomalies correspond to warm mesoscale features.

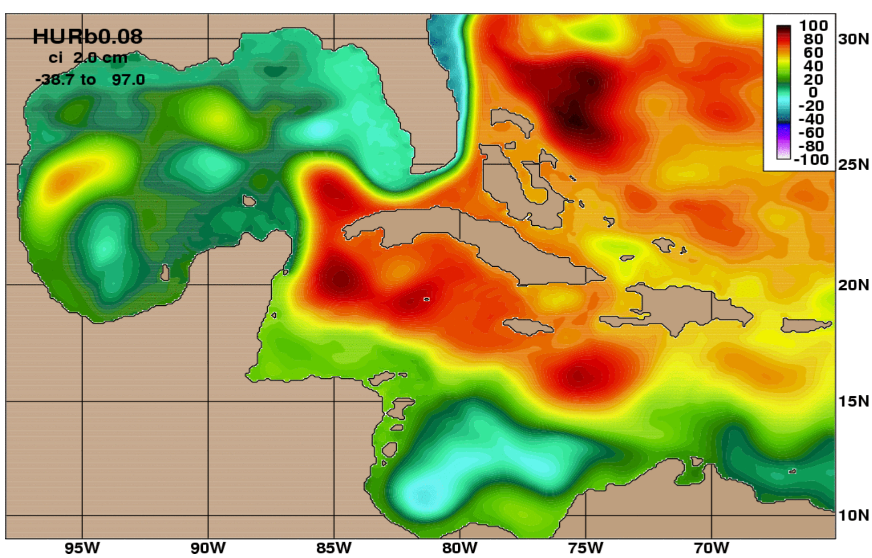


Figure 5: Total sea surface height prior to the passage of Isidore from the high resolution North Atlantic HYCOM. Warm core ring structures in the domain compare well with positive height anomalies from the altimeter data.

The Isidore pre-storm conditions are first evaluated in comparison with the sea surface height anomalies from the altimeter data (Fig.4). While the model sea surface heights include mean (Fig.5), a good comparison with the observed anomalies are seen in the region of interest. However, the simulated sea surface temperatures in the model are biased lower throughout the model domain (Fig.2). In comparison to profiler data, the biases are estimated to be 0.5° *C* in the Caribbean Sea to more than 1° *C* in the central Gulf of Mexico. The lower surface temperatures also lead to very shallow depths of the 26° *C* isotherm in the initial fields. To correct this bias, efforts are currently underway by the HYCOM group where the MODAS sea surface temperature will also be assimilated in the North Atlantic model. These fields will be made available to us for the Isidore and Lili simulations before the end of the month.

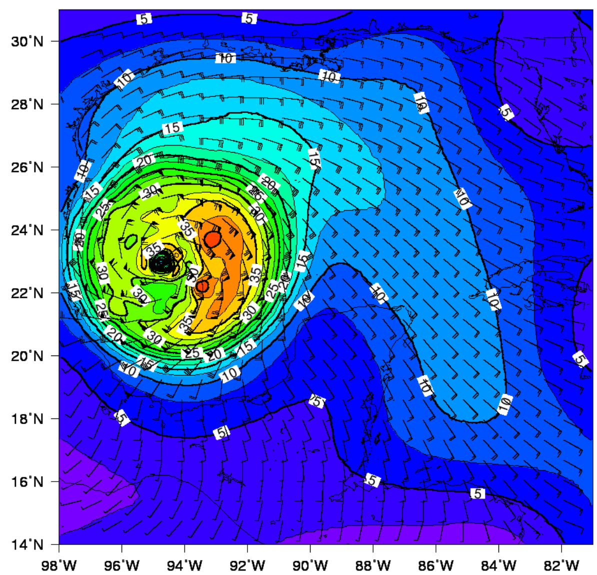


Figure 6: Surface winds derived from flight-level reduced, ECMWF surface and buoy winds for 06 UTC, 16 September 1988 during hurricane Gilbert in the Gulf of Mexico.

## Surface Forcing:

Realistic forcing of the ocean model is crucial when comparing the simulated ocean response to data because for storms undergoing an eye wall replacement cycle, wind stress curl and divergence will not be otherwise represented correctly. Therefore, the NOAA Hurricane Research Division HWIND methodology is used to combine flight-level reduced and in situ winds to provide the boundary layer forcing for the ocean model. While similar approaches are used to derive boundary layer winds in the strongly forced region during the three storms, large scale wind field is based on different sources as described below.

### *Gilbert*

During Gilbert's passage in the Gulf of Mexico, flight level data were acquired by two NOAA aircraft at least twice a day in the inner-core area of the storm. The large scale environmental flow in the boundary layer from the European Center for Medium-Range Weather Forecasts (ECMWF) model is then objectively analyzed using the HWIND package to generate surface winds every three hours. Boundary layer wind field thus estimated at 0600 UTC, 16 September 1988 is shown in Fig. 6. The analyzed wind field is broad with wind speeds up to 30 $ms^{1}$ extending out to 160 *km* from the eye, and the maximum sustained 10-min wind is about 40 $ms^{-1}$. Winds at the secondary radius of maximum wind exceeded the primary wind maximum (Fig.6). This broad wind structure with dual maxima has an impact on the simulated upper ocean response (Jacob et al. 2000).

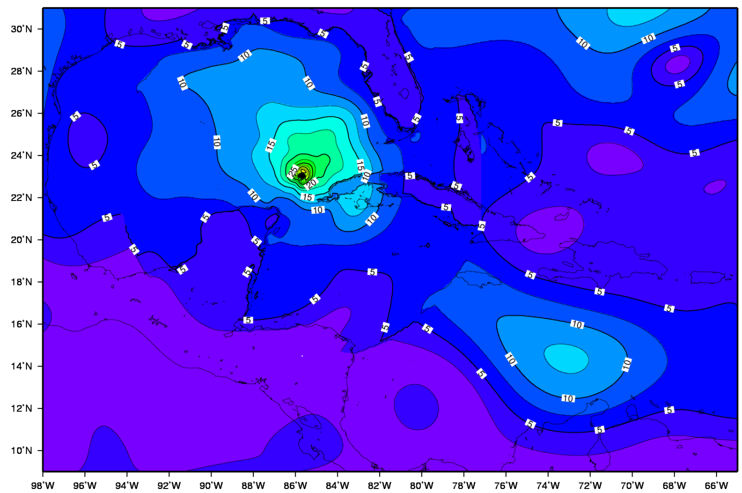


Figure 7: Boundary layer wind field during hurricane Lili on 2 October 2002 0 UTC derived as a blend of HWIND analysis and large scale numerical model winds.

## *Isidore and Lili*

A slightly different approach is followed to estimate boundary layer winds during hurricanes Isidore and Lili. A three hourly HWIND analysis of surface winds from 0900 UTC on 18 September 2002 to 1200 UTC on 04 October 2002 was made available to this project by Dr. Mark Powell of NOAA Hurricane Research Division. While the data from these high resolution analyses covered a 17° square around the storm center, the winds are blended with the large scale forcing field consistent with the North Atlantic data assimilative HYCOM using the parameter matrix objective analysis technique of Mariano and Brown (1992). This technique makes use of cubic splines to optimally interpolate data on different spatial scales and also provides interpolation uncertainties. Here, we first removed the large scale model flow field where analyzed data were available and therefore the inner-core forcing structure from the HWIND analysis is preserved. Merged boundary layer field during Lili on 02 October 2002, 00 UTC is shown in Fig.7. As the model will be integrated beginning 00 UTC on 14 September 2002, consistent large scale forcing from the NOGAPS boundary layer fields will be smoothly transitioned to the analyzed forcing.

## *Precipitation Forcing*

Available rain rates from TRMM satellite and Special Sensor Microwave/ Imager during Isidore and Lili will be used to investigate the salinity budgets and ensure that the vertical mixing parameterizations properly account for these effects. Due to the lack of data, a simpler wind speed dependent precipitation structure is used with the Gilbert simulations.

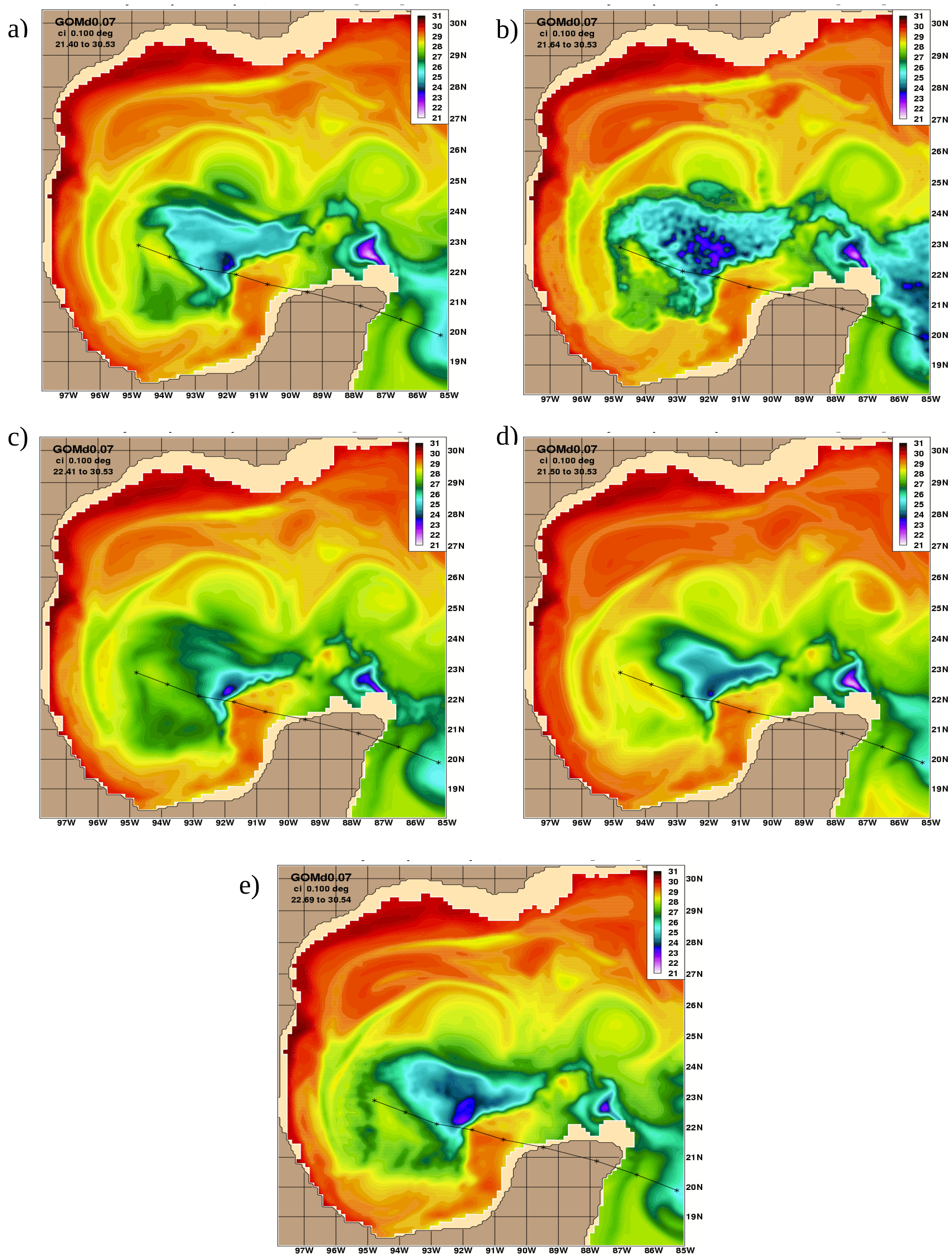


Figure 8: Simulated mixed layer temperatures during hurricane Gilbert in cases a) RL, b) RP, c) RG, d) RM, and e) RN for the five mixing schemes. Differences between the cases are clearly visible with PWP being the coolest and KT being the warmest. Black line indicates track of the Storm till 06 UTC 16 September 1988.

## Gilbert Simulations:

Hycom configured with the derived realistic initial conditions and quiescent (no pre-storm mass or momentum structure) conditions is used to simulate the upper ocean response for five mixing schemes. Overall 10 numerical simulations were conducted to quantify the upper ocean response for realistic forcing associated with hurricane Gilbert (Table 1). The model is integrated for six days from 0 UTC 14 September 1988 to 0 UTC 20 September 1988 such that the simulated currents and temperatures are directly comparable to observed profiler data. Investigating the ocean response for the same mixing scheme for the two initial conditions will help to quantify their effect on the mixing scheme. These simulations use 22 levels/ layers in the vertical with a minimum resolution of 3 *m* in the upper ocean. A higher resolution simulation with 50 vertical levels did not significantly affect the results in our initial tests, however this issue will be further revisited as there are more vertical data points to compare to profiler data if higher resolution is used. Detailed comparison of simulations with observed profiles is in progress and qualitative discussion of results from the numerical experiment is presented in this section.

| Case | Initial Conditions | Mixing Scheme |
|---|---|---|
| QL | Quiescent | KPP |
| QP | Quiescent | PWP |
| QG | Quiescent | KT |
| QM | Quiescent | MY |
| QN | Quiescent | GISS |
| RL | Realistic | KPP |
| RP | Realistic | PWP |
| RG | Realistic | KT |
| RM | Realistic | MY |
| RN | Realistic | GISS |

Table 1: Details of Numerical Experiments.

*Mixing Parameterizations*

Overall, five mixing parameterizations are evaluated based on the simulated upper ocean response during hurricane Gilbert as originally proposed. These five schemes are: 1. the K-Profile Parameterization (KPP) scheme of Large et al. (1994), 2. the Price et al. (1986; PWP) quasi-slab scheme, 3. the Gaspar (1988) slab scheme based on the original scheme of Kraus and Turner (1967; KT), 4. the level 2.5 turbulence closure scheme of Mellor and Yamada (1982; MY) that is presently being used in the operational coupled model, and 5. the level 2 closure scheme of Canuto et al. (2001; 2002; GISS). Details of these schemes are discussed in Halliwell (2004).

*Initial Results*

Since our main focus is to evaluate the upper ocean heat content and surface fluxes simulated for each of the five mixing schemes, a snapshot of mixed layer temperature is shown in Fig.8 in the directly forced region for 06 UTC 16 September 1988. Although all the simulations used the same initial conditions, differences are apparent in the domain. While maximum cooling of the mixed layer occurs in the right rear-quadrant of the storm, magnitude of the cooling significantly differs between the five cases. In particular, in case RP, the oceanic mixed layer cools significantly compared to the other four cases (Fig. 8b). By contrast, minimal cooling is found in case RG. This finding is consistent with our earlier Miami Isopycnic Coordinate Ocean Model study (Jacob and Shay 2003). While there are differences between the simulated mixed layer temperatures in the other three cases, magnitude of this variability is between the two extremes of those simulated in cases RP and RG. Available data from 74 airborne expendable current profilers (AXCPs) are being used to evaluate these simulated temperature and current structure which will be completed in the near future to identify the parameterization that more accurately simulates the ocean response.

## Summary:

During the first phase of the project, our focus has been on deriving realistic initial conditions and boundary layer forcing that are crucial to simulating the upper ocean response accurately during hurricanes Gilbert, Isidore and Lili. Realistic conditions for the Gilbert case are evaluated with respect to observations and found appropriate for use in this work. However, initial conditions evaluated against profiler data for hurricane Isidore revealed a systematic bias in the temperature structure. Therefore, these conditions are being revised for actual ocean response simulations.

Appropriate high resolution boundary forcing fields have also been successfully derived for all the three storms. Using the realistic initial conditions, simulations for five mixing parameterizations have been conducted on schedule. These results are being compared to profiler data to identify the most appropriate mixing parameterization. This phase of the work will be completed by the month end, followed by Isidore and Lili simulations.

**References:**


Canuto, V.M., A. Howard, Y. Cheng and M.S. Dubovikov, 2001: Ocean turbulence. Part I: One-point closure model – Momentum and heat vertical diffusivities. J. Phys. Oceanogr., 31, 1413-1426.

Canuto, V.M., A. Howard, Y. Cheng and M.S. Dubovikov, 2002: Ocean turbulence. Part II: Vertical diffusivities of momentum, heat, salt, mass and passive scalars. J. Phys. Oceanogr., 32, 240-264.

Gaspar, Ph., 1988: Modeling the seasonal cycle of the upper ocean. J. Phys. Oceanogr., 18, 161-180.

Halliwell, Jr., G.R., 2004: Evaluation of vertical coordinate and vertical mixing algorithms in the HYbrid-Coordinate Ocean Model (HYCOM). Ocean Modelling, In Press.

Jacob, S.D., L.K. Shay, P.G. Black and S.H. Houston, 2000: Upper ocean response to hurricane wind asymmetries. Extended Abstracts: *Proceedings of the 10th Conference on Interaction of the Sea and Atmosphere*, 29 May - 2 June 2000, Ft. Lauderdale, FL, American Meteorological Society, J66-J67.

Jacob, S.D. and L.K. Shay, 2003: The role of oceanic mesoscale features on the tropical cyclone induced mixed layer response *J. Phys. Oceanogr.*, **33,** 2003, 649-676.

Kraus, E.B. and J.S. Turner, 1967: A one-dimensional model of the seasonal thermocline. II: The general theory and its consequences. Tellus, 1, 98-105.

Large, W., G. Danabasoglu, S.C. Doney and J.C. McWilliams, 1997: Sensitivity to surface forcing and boundary layer mixing in a global ocean model: Annual mean climatology. J. Phys. Oceanogr., 27, 2418-2447.

Levitus, S., 1982: Climatological Atlas of the World Ocean. NOAA Prof. Paper 13, U.S. Govt. Printing Office, Washington D.C. 20401, 173pp.

Mariano, A.J., and O.B. Brown, 1992: Efficient objective analysis of heterogeneous and nonstationary files via parameter matrix. Deep. Sea. Res., Part A, 39(7), 197-207.

Mellor, G. L. and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys., 20, 851-875.

Price, J. F., R. A. Weller, and R. Pinkel, 1986: Diurnal cycling: Observations and models of the upper ocean response to diurnal heating, cooling, and wind mixing. J. Geophys. Res., 91, 8411-8427.

Shay, L.K., P.G. Black, A.J. Mariano, J.D. Hawkins and R.L. Elsberry, 1992: Upper ocean response to hurricane Gilbert. J. Geophys. Res., C12, 20,277-20,248.

Shay, L.K., A.J. Mariano, S.D. Jacob and E.H. Ryan, 1998: Mean and Near-Inertial Ocean Current Response to Hurricane Gilbert. J. Phys. Oceanogr., 28, 858-889.