2003-05 Joint Hurricane Testbed Final Report Submitted 1 August 2005
Project: Evaluation of Upper Ocean Mixing Parameterizations

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Introduction:

The primary energy source driving tropical cyclones is the latent heat release due to the condensation of water vapor, the primary source of which is evaporation at the ocean surface. As a storm intensifies, increasing wind speed tends to increase evaporation and supply the storm with the additional thermal energy required for further intensification. However, increasing wind speed also increases oceanic vertical mixing and the entrainment of colder fluid from below, which then act to reduce sea surface temperature and the thermal energy available to the storm. Based on previous studies (Elsberry et al. 1976; Chang and Anthes 1978; Price 1981; Black 1983; Shay et al. 1992; Jacob et al. 2000), up to 80-90% of mixed layer (ML) cooling is caused by entrainment during a tropical cyclone passage. Thus, accurate estimates of the rate at which the turbulent ML entrains colder fluid from below are essential to predicting surface mixed layer deepening and cooling. The high frequency and small-scale turbulent processes responsible for ocean mixing must be parameterized in ocean models as functions of the resolved fields. Turbulent processes that govern the exchanges of momentum, heat, and mass across the ocean surface must also be parameterized. The evolution of tropical cyclones in coupled ocean-atmosphere predictive models, in particular the change in intensity, depends critically on these parameterizations. As part of this Joint Hurricane Testbed (JHT) funded project, using a primitive equation ocean model configured with different entrainment mixing schemes, this issue is investigated in detail. 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. Temperature data acquired during these storms are directly compared to simulated results to identify the best mixing schemes for different forcing characteristics and background oceanographic conditions for use in the coupled intensity prediction models.

Objectives:

This project focused on addressing Environmental Modeling Center (EMC) Objectives 1 and 2 namely to advance the general intensity forecasts and use of data to improve boundary layer representation in the coupled track-intensity prediction system. Our specific objectives to identify the better performing turbulent mixing schemes in the ocean component of the coupled system are:

- Configuration of the numerical model based on suitability of geographic coverage and vertical structure representation for hurricanes Gilbert (1988), Isidore (2002) and Lili (2002);

- 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;

- Simulation of ocean response for all the three storms and comparison with the observed profiler data; and

- Identification and recommendation of better oceanic vertical mixing parameterizations for use in coupled intensity prediction models.

These objectives have been achieved through the JHT funding for this project. During the past six months simulations have been completed for the Isidore and Lili cases and the simulated profiles were compared to observations. While not part of the original objectives, dependence of ocean model vertical resolution on the comparison statistics also was investigated as part of this work. In the following sections, work performed during the past two years is summarized. More detailed analyses of the numerical results are being performed and will be communicated to professional journals and to the JHT.

Data Resources:

As mentioned earlier, upper ocean response to three storms namely Gilbert (1988), Isidore (2002) and Lili (2002) is investigated in this project. Important storm parameters and data availability are summarized in Table 1. In addition to data availability, all the three storms occurred in the same region, enabling the use of the same model domain. Oceanic data available for these storms are briefly described below. The simulated upper ocean thermal structure is compared with data from airborne expendable bathythermographs (AXBTs), conductivity, temperature and depths probes (AXCTDs) and current profilers (AXCPs) and identify the mixing scheme that compares well with the data. Each of these storms, provide a unique set of conditions for evaluating the upper ocean mixing schemes and the resulting surface fluxes.

Gilbert (1988):

Hurricane Gilbert is one of the major storms in the Atlantic in recent history with a minimum central pressure of 888 *mb*. As part of a ONR-NOAA joint experiment, extensive upper ocean measurements were acquired and the data set is described in detail in Shay et al. (1992). Jacob and Shay (2003) used this data set to evaluate four bulk mixed layer entrainment parameterizations in MICOM. Data from 76 AXCPs at 3 *m* intervals in the vertical during, one and three days after the storm provide a good overall constraint to compare simulations.

Isidore (2002):

Multiple snapshots of ocean data were acquired prior to, during and after the passage of hurricane Isidore in the Caribbean Sea and Gulf of Mexico as part of a NSF sponsored USWRP-NOAA Experiment. The storm intensified rapidly over the high oceanic heat content Caribbean Sea and Loop Current region before its landfall in the Yucatan peninsula. In addition to the in situ measurements of temperature, conductivity and currents, precipitation rates from the Tropical Rainfall Measuring Mission (TRMM) satellite overpasses are also available. While the temperature and conductivity data available from AXCTDs can be used to quantify precipitation effects on the upper ocean mixing, we focus mainly on the thermal response. Analysis of sea surface temperatures indicated a cooling of 2.5°C in the directly forced region and a corresponding heat content reduction of 30 $KJ\ cm^{-2}$.

Storm	Category	Min. R_{max} (km)	Max Winds (ms^{-1})	Translation Speed (ms^{-1})	Data Availability AXBT, AXCP, AXCTD
Gilbert	3	60	47	5.6	51, 76, 0
Isidore	3	23	55	2.0	149,49,62
Lili	1 to 3	18	55	7.7	139,53,72

Table 1: Details of storms proposed for numerical simulations. Category, minimum R_{max} and maximum winds are during periods where data are available.

Lili (2002):

Strongest storm of 2002, fast moving Lili rapidly intensified in the eastern Gulf of Mexico. The ocean response data consists of AXBTs, AXCTDs and AXCPs acquired during the storm on 30 Sept 2002 and 2 Oct 2002 and a post storm survey on 4 Oct 2002. Pre-storm surveys on 19 and 29 Sept 2002 provide the ocean state over this high heat content region. This data set provides a very interesting case for evaluating entrainment parameterizations due to the higher storm translation speed. This reduces the time available for oceanic vertical mixing and the magnitude of upper ocean thermal response in the directly forced region. Vertical structure in the ocean as observed by AXCPs during the post-storm mission showed strong currents and deep mixed layers in the domain.

A total of 339 AXBTs, 134 AXCTDs and 178 AXCPs provide a broad data set to evaluate the entrainment mixing schemes during these three storms. While all of the profile data are used to evaluate the initial conditions and simulated ocean response, comparisons during the in-storm and post-storm snapshots are presented in this report due to their relevance in coupled intensity prediction models.

Numerical Model:

The HYbrid Coordinate Ocean Model (Bleck 2002, Halliwell 2004) is used in this study. This is a primitive equation, ocean general circulation model that is an extension of MICOM. HYCOM uses a hybrid vertical grid that is designed to correct known shortcomings of the MICOM isopycnic vertical grid. In MICOM, the isopycnic model layers are capped by a single non-isopycnic slab mixed layer. In HYCOM, however, the model isopycnic layers transition smoothly to fixed level coordinates just beneath the ocean surface. Details of the hybrid vertical coordinate algorithm are presented in Bleck (2002). Such a coordinate system also enables the use of more complex mixing schemes. In particular, there are five state of-the-art mixing schemes that are evaluated in this study: the K-Profile Parameterization model of Large et al. (1994) (KPP), the Goddard Institute for Space Studies level 2 turbulence closure of Canuto et al. (2001; 2002) (GISS), the level 2.5 K-ε turbulence closure of Mellor and Yamada (1982) (MY), the quasi-slab dynamical instability model of Price et al. (1986) (PWP) and the turbulent kinetic energy balance model of Kraus and Turner (1967) modified by Gaspar (1988). The first three of these models are vertically continuous that provide vertical mixing from surface to bottom (higher order schemes). Among these models, the MY scheme is presently used in the operational coupled model for hurricane track and intensity prediction. Details of the implementation of the five vertical mixing algorithms are presented in Halliwell (2004).

Surface forcing fields in the model include vector wind stress, wind speed, air temperature, air specific humidity, net shortwave radiation, net longwave radiation, and precipitation. Evaporation and surface turbulent heat flux components are computed during model run time using bulk formula.

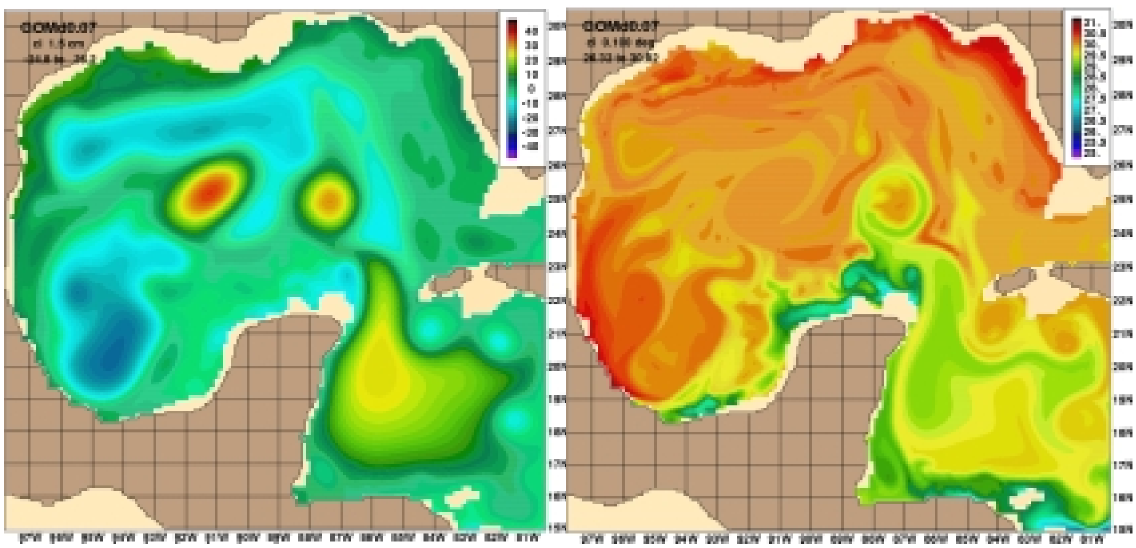

Figure 1: Pre-Gilbert realistic initial conditions from the simulation with a 50 levels/ layers in the vertical. The sea surface height field is on the left and the sea surface temperature is on the right.

Configurations:

Two configurations of HYCOM are set up to perform the 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. Ocean response simulations are performed for many cases with the number of vertical layers ranging from 22 to 50. 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. We also performed many numerical simulations using open boundary conditions and found that the model results are not sensitive to these boundary conditions here.

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 21 days. The model domain extends from 65º to 98º W and 9º to 31º N with a resolution of 0.08°. 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 3 *m* resolution near surface until it transitions into the isopycnic domain. Additional simulations are also performed with different vertical resolution as in the Gilbert case.

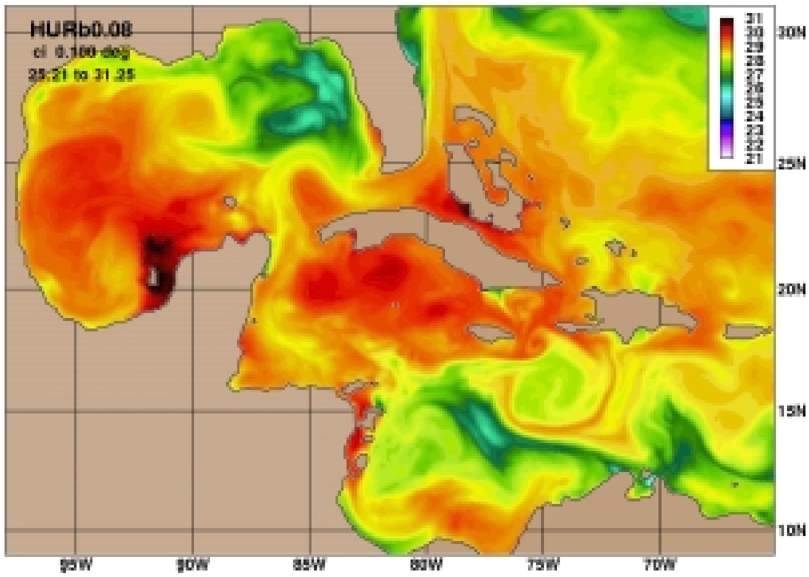

Figure 2: Pre-Isidore sea surface temperatures for realistic initialization from the 0.08° North Atlantic basin-scale data assimilative HYCOM.

Initial Conditions:

<u>*Gilbert*</u>

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 realistic conditions prior to the passage of Gilbert. At the end of the integration, the model eddy has a maximum sea surface height of 34 to 38 *cm* depending on the number of vertical coordinate layers. 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* (Fig.1). While a similar approach was used in our earlier Miami Isopycnic Coordinate Ocean Model (MICOM) simulation, considerable effort had to be expended to derive the initial conditions for use in these simulations. In particular, higher vertical resolution resulted in a weaker eddy in HYCOM initially, that was resolved by a different initialization approach.

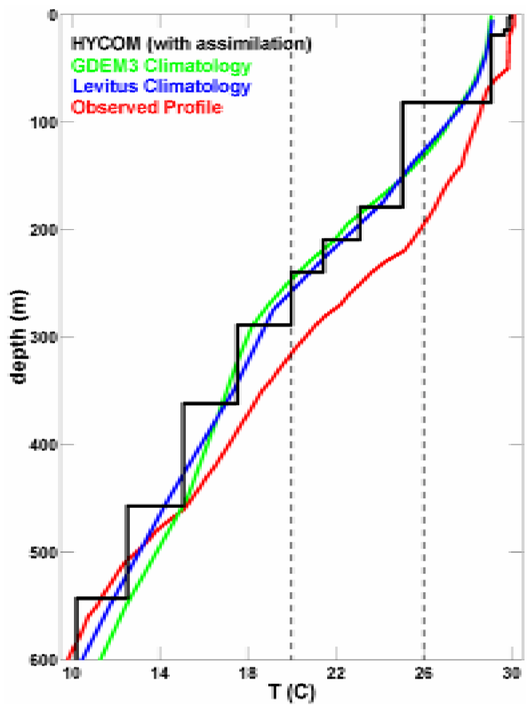

Figure 3: Observed and model simulated pre-Isidore temperature structure in the Western Caribbean sea. While the sea surface temperature is comparable to observations, the depth of 26°C and 20°C isotherms, climatology and model vertical structure underestimate the oceanic heat content and the temperature gradient below the oceanic mixed layer.

Isidore

In the case of Hurricane Isidore, the initial pre-storm fields are derived from the standard 0.08° Atlantic HYCOM simulations performed by the HYCOM group at the Naval Research Laboratory. 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 are generated as part of the ocean response simulations. The initial conditions were updated three times due to unrealistic temperatures and salinity in comparison with observed profiles. After the assimilation of MODAS sea surface temperatures, pre-Isidore SSTs agree well with the data over most of the domain, although comparison of profiler data indicates that the model fields underestimate the upper ocean heat content (Fig.3). In particular, the temperature structure below the oceanic mixed layer differs from the observed structure significantly. While the NRL group has a fix in progress, simulations for this report were performed using these conditions with a lower heat content than observed.

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.

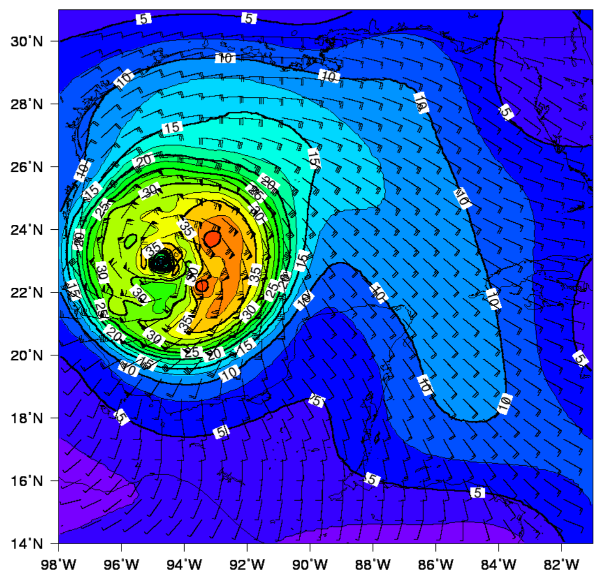

Figure 4: Surface winds derived from flight-level reduced, ECMWF surface and buoy winds for 06 UTC, 16 September 1988 during hurricane Gilbert in the Gulf of Mexico.

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. 4. The analyzed wind field is broad with wind speeds up to 30 *m/s* 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. This broad wind structure with dual maxima has an impact on the simulated upper ocean response (Jacob et al. 2000).

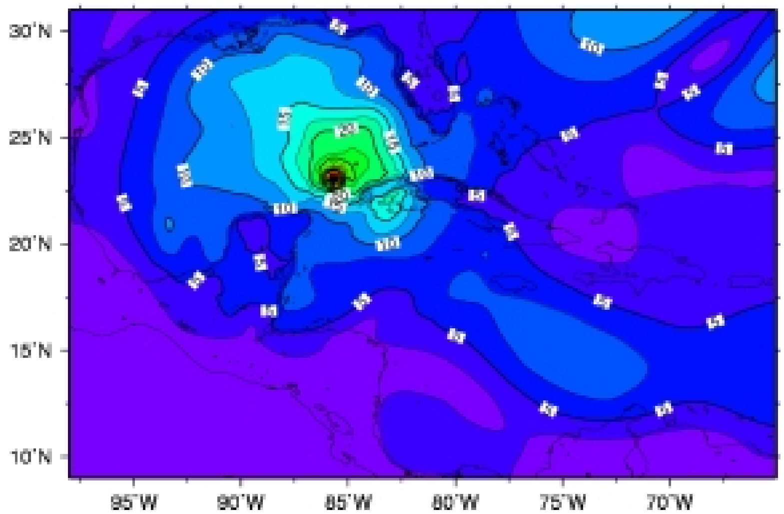

Figure 5: Boundary layer wind field during hurricane Lili on 2 October 2002 0 UTC derived as a blend of HWIND analysis and large scale numerical model winds. In contrast to Gilbert, both Isidore Lili were smaller in size.

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 from NCEP using a cubic B-spline analysis. Here, we first removed the large scale model flow field where analyzed data were available and therefore 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.5. As the model is integrated beginning 00 UTC on 14 September 2002 to 00 UTC on 5 October 2002, the NCEP surface wind forcing is smoothly transitioned to the analyzed hurricane forcing. Additionally, due to the size of Isidore and Lili, the three hourly winds are sub-sampled to every hour to avoid smearing of the hurricane core winds.

Simulations and Results:

Gilbert Case: As initially proposed, 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 34 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 to 50 levels/ layers in the vertical with a minimum resolution of 3 *m* in the upper ocean. As shown in the previous progress reports, although the simulated temperature fields have similar patterns of surface temperature reduction, the magnitude remains very different. In particular, the KT mixing scheme (Kraus and Turner 1967; Gaspar 1988) simulates warmer temperature and the PWP scheme (Price, Weller and Pinkel 1986) simulates much colder temperatures that are almost 1.5° C cooler than the three higher order schemes. Quantitative analysis of results from quiescent conditions also suggested that the PWP scheme is more sensitive to precipitation that had a minor mitigating effect to reduce the large cooling simulated. In the absence of realistic ocean features in the domain, the three higher order schemes (KPP, MY and GISS) are grouped together with the KT and PWP schemes simulating the least and most cooling respectively.

Case	**Initial Conditions**	**Vertical Levels**	**Mixing Scheme**
GQL	Quiescent	20,22,50	KPP
GQP	Quiescent	20,22,50	PWP
GQG	Quiescent	20,22,50	KT
GQM	Quiescent	20,22,50	MY
GQN	Quiescent	20,22,50	GISS
GRL	Realistic	22,25,30,40,50	KPP
GRP	Realistic	22	PWP
GRG	Realistic	22,30,50	KT
GRM	Realistic	22,25,30,40,50	MY
GRN	Realistic	22,25,30,40,50	GISS
IRL	Realistic	22,30	KPP
IRP	Realistic	22,30	PWP
IRG	Realistic	22,30	KT
IRM	Realistic	22,30	MY
IRN	Realistic	22,30	GISS

Table 2: Details of the numerical experiments for different mixing schemes, different initial conditions and vertical levels. Prefix “G” is for Gilbert simulations whereas prefix “I” represents the combined Isidore and Lili experiments.

Simulated profiles are extracted corresponding to the drop time with respect to the storm center for comparison to the actual profiles and a full comparison is performed using linear regression analyses. This comparison is first conducted for simulations with 22 levels in the vertical. Results based on the regression statistics indicate that the KPP (Large et al. 1994) and MY (Mellor and Yamada 1972) schemes compare best to observations followed closely by the GISS scheme (Canuto et al. 2001). Comparison of results from bulk KT and quasi-bulk PWP schemes are not as satisfactory as indicated by Fig.6. This conclusion is mainly based on the slope of the regression line in addition to the root mean square error because an inaccurate slope here indicates inaccurate spatial variability in the simulated sea surface temperature. This is also confirmed by the spatial pattern of the simulated sea surface temperatures. As with the quiescent initial conditions, the differences between the three higher order schemes are smaller than the differences between KT and PWP schemes. However, the model mixed layer is not well resolved due to resolution limitations of a 22 layer vertical structure. This issue is investigated by progressively increasing the vertical resolution and comparing the simulated temperatures to the observed values.

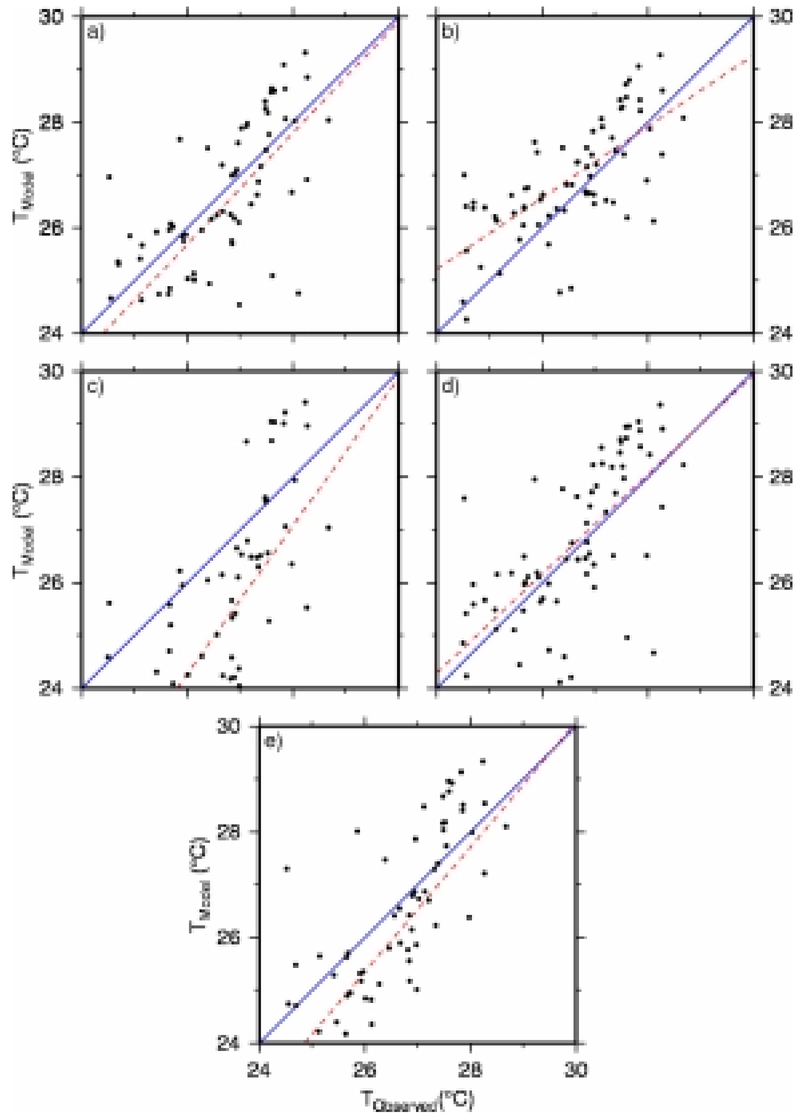

Figure 6: Comparison of observed and simulated mixed layer temperatures for a) KPP, b) KT, c) PWP, d) MY and e) GISS mixing schemes for the Gilbert case. The solid blue line represents perfect comparison with the dashed red line indicating the linear regression fit. KPP and MY schemes show a better comparison to data.

Due to the initial unsatisfactory comparison statistics, additional simulations are not performed for the PWP scheme with realistic initial conditions. In addition, the KT scheme is examined for simulations only with a subset of vertical resolutions that are investigated using the higher order schemes. While the sea surface temperatures simulated with a quiescent initial condition showed very little difference between various vertical resolutions, the differences are higher (0.2 to 0.5° C) when realistic initial conditions are used. More analysis is needed to understand this variability. Additionally, simulated temperatures get progressively warmer with increasing vertical resolution in the domain when the higher order schemes are used (Fig.7) in contrast to marginally reducing surface temperatures in the KT case. The comparison statistics are shown in Table 3 for the different vertical resolutions. While in the KT case the comparison improves with higher vertical resolution, it is progressively degrading in the MY case. Such a clear progression is not seen in the other two cases. However since it is not an operational feasibility to use a configuration with 50 vertical coordinates, one of the high resolution schemes will be more appropriate for use in the ocean component of the coupled system. While simulations with 40 and 50 levels do not differ significantly, the KPP scheme appears to perform better with 40 vertical levels/ layers. Although the slope of the regression line is closer to one for the GISS scheme simulations, ideal comparison with observations may be achieved with vertical levels between 30 and 40. Therefore, the MY scheme appears more suitable for the ocean component with less than 30 vertical levels.

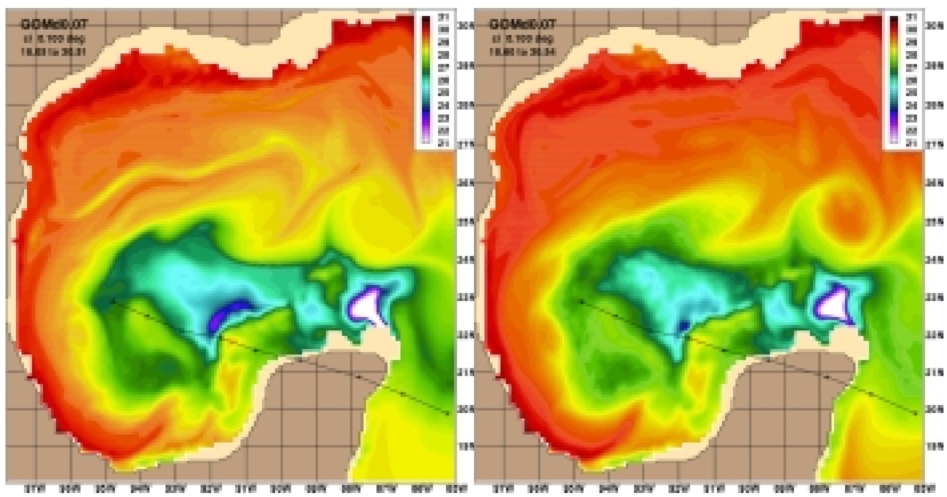

Figure 7: Simulated mixed layer temperature response using 22 (left panel) and 50 vertical levels/ layers for the MY scheme. The mixed layer temperature from the 22 level simulation is slightly colder than the 50 level simulation. Storm track is shown as a black line with asterisks indicating storm center fixes.

Isidore and Lili Cases: In contrast to the Gilbert case of 6 day integration, Isidore and Lili cases are combined in to a single simulation spanning 21 days. Starting form 0 UTC 14 Sept 2002, integrations are performed up to 0 UTC 5 Oct 2002 to compare profiler observations to simulated results. As with the Gilbert case, results from the KT and PWP indicate least and most cooling respectively due to the storm passage. Mixed layer response using the KPP scheme during Isidore is shown in Fig.8. However, as mentioned earlier, there are still problems with the initial conditions. Because of the incorrect thermal structure below the mixed layer, numerical simulations predict somewhat higher cooling in the Loop Current region than observed. Additionally, there is a strong topographic interaction near the Yucatan that leads to higher cooling. While a methodology to improve these initial conditions was identified by the data assimilative HYCOM group, due to implementation problems, the fields are not yet available for improving the simulations. Though comparisons are performed with the profiler data during Isidore and Lili for the sake of completeness of this report, the statistics are to be considered very preliminary due to uncertain initial conditions. These statistics shown in Table 4 for the Isidore case indicate a better comparison for the KT scheme and a worse comparison for the KPP scheme with respect to the Gilbert case. While the statistics in the Lili case indicate a poor performance of all the schemes except PWP compared to earlier cases, results from the GISS scheme are comparable to that of MY in Isidore. Based on these results weighted higher by the Gilbert simulations and taking into account the vertical resolution issues, our recommendation is to use the MY scheme in the ocean component of the coupled prediction model. The GISS scheme is seen as the next best based on the statistics of comparisons. Since HYCOM will be implemented as the ocean component of H-WRF track and intensity prediction system, further sensitivity analysis needs to be done in the coupled system.

Experiment	Mixing Scheme	Slope	Bias	Mean diff.	σ diff.	RMS diff.
GRL 22	KPP	1.05	-1.75	0.28	1.19	1.21
GRG 22	KT	0.68	9.00	-0.40	0.85	0.94
GRP 22	PWP	1.40	-12.18	1.52	1.76	2.30
GRM 22	MY	0.94	1.68	-0.14	1.12	1.12
GRN 22	GISS	1.18	-5.40	0.56	1.38	1.48
GRL 25	KPP	0.88	2.36	0.89	0.86	1.23
GRM 25	MY	0.89	2.20	0.65	0.89	1.10
GRN 25	GISS	0.87	2.38	1.02	0.91	1.36
GRL 30	KPP	1.13	-4.50	0.97	1.07	1.44
GRG 30	KT	0.72	7.25	0.30	0.84	0.89
GRM 30	MY	0.86	3.22	0.53	0.88	1.02
GRN 30	GISS	1.04	-1.83	0.64	1.04	1.33
GRL 40	KPP	0.99	-0.26	0.60	0.91	1.09
GRM 40	MY	0.76	6.00	0.30	0.82	0.88
GRN 40	GISS	0.87	3.23	0.32	0.87	0.92
GRL 50	KPP	0.95	0.76	0.53	0.88	1.02
GRG 50	KT	0.78	5.76	0.18	0.82	0.83
GRM 50	MY	0.74	6.62	0.35	0.83	0.89
GRN 50	GISS	0.83	4.06	0.27	0.81	0.85

Table 3: Linear regression statistics and parameters that quantify differences between simulated mixed layer temperatures from the model and the observed profiler data for the Gilbert Case. Units are in degrees Celsius except the non-dimensional slope of the regression line. The numbers in the experiment indicates the number of vertical coordinates.

Simulations and comparisons in the Isidore and Lili cases will be refined further when the revised initial conditions are available from the Naval Research Laboratory. Additionally, we are collaborating with EMC to use the conditions derived from the Operational North Atlantic HYCOM in these simulations prior to the fiscal completion date of September 30, 2005 of the project. Updated results and recommendations will be made available to JHT and EMC based on the new findings.

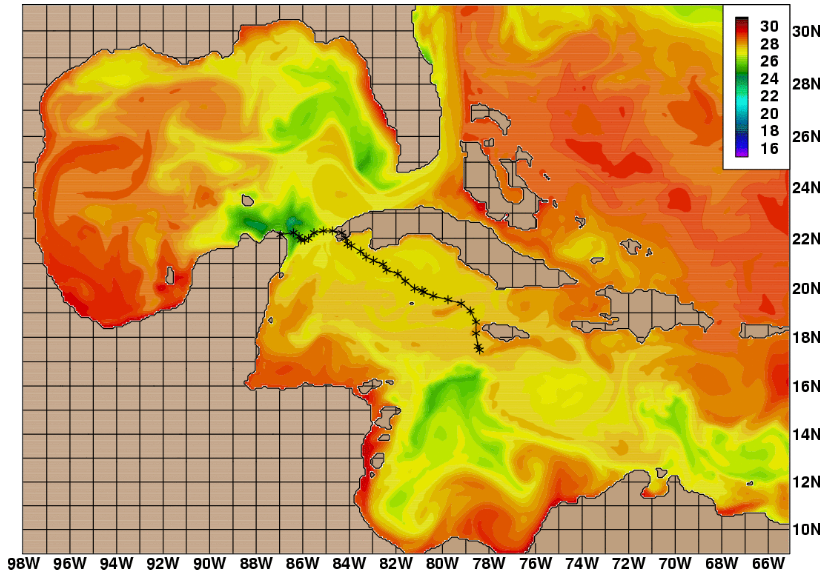

Figure 8: Mixed layer temperature response during Isidore for KPP scheme in the combined cases of Isidore and Lili. Cooling of about 4°C is seen to the right of the storm center. While the cooling is reduced over the loop current and in the Caribbean, it is up to 0.5°C more than what is observed.

Isidore	Slope	Bias	Mean diff.	σ diff.	RMS diff.
IRL 22 KPP	1.05	-3.09	1.63	1.30	2.07
IRG 22 KT	0.94	0.17	1.52	0.84	1.73
IRP 22 PWP	1.08	-4.15	1.83	1.03	2.09
IRM 22 MY	1.05	-2.87	1.39	0.94	1.67
IRN 22 GISS	0.98	-1.01	1.46	0.82	1.67
Lili					
IRL 22 KPP	0.75	5.15	1.84	0.95	2.06
IRG 22 KT	0.70	6.22	2.04	0.93	2.23
IRP 22 PWP	0.83	2.34	2.16	1.01	2.38
IRM 22 MY	0.75	5.19	1.75	0.95	1.98
IRN 22 GISS	0.75	5.29	1.76	0.98	2.02

Table 4: Linear regression statistics and parameters that quantify differences between simulated mixed layer temperatures from the model and the observed profiler data for Isidore and Lili cases. Units are in degrees Celsius except the non-dimensional slope of the regression line.

Summary and Recommendations:

As originally proposed, simulations of upper ocean response to hurricanes Gilbert, Isidore and Lili are performed for the different upper ocean mixing schemes as more than 80% of the observed upper ocean cooling is due to entrainment mixing parameterized by the models. While comparisons of the simulated results to observations in the Gilbert case indicate a better fit for higher order KPP and MY schemes, MY and to a lesser extent GISS schemes are seen to be more consistent for all the three storms. In general, all the higher order schemes seem to perform better than the KT and PWP schemes. Due to the inaccurate initial conditions, the statistics are only preliminary in the Isidore and Lili cases. These comparison statistics are affected by the vertical resolution as seen in the Gilbert case. A higher vertical resolution degrades the performance of MY scheme whereas the performance of the KT scheme improves. Additionally, while the computational speeds for all the schemes are comparable, the GISS scheme is the fastest in our experiments. We recommend the following based on this research:

- Based on the comparison statistics the MY scheme would be the more appropriate scheme for use in the ocean component of the coupled system followed by the GISS scheme. With less than 30 vertical coordinates, results using the MY scheme compare better with data although the GISS scheme is marginally faster than the MY scheme.
- Ocean model initial conditions need to be validated on a regular basis for a better representation of the ocean in the coupled intensity prediction models as the oceanic thermal structure also significantly affects the observed cooling.
- HYCOM configured with terrain following σ coordinates is almost 30% slower than the level/ isopycnic hybrid coordinate system. Therefore the cost benefit analysis of using this configuration must be considered.

These recommendations are constrained by the inaccurate initial conditions during Isidore and Lili. With better initial conditions we will revisit this issue and update JHT and EMC on our findings. Even with satisfactory initial conditions for Isidore and Lili we have only considered three storms and the sample size is still small. Evaluation of these schemes also requires ocean only simulations due to the other uncertainties that are introduced because of inaccurate forcing from the atmospheric component. Past observations may be used with realistic forcing and initial conditions to further improve the statistical base of comparisons along with routine future observations to evaluate the ocean component on a post-hurricane season basis.

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