6C.2 Evaluation of Upper Ocean Mixing Parameterizations for Use in Coupled Models

S. Daniel Jacob[1], D.M. Le Vine[2], L.K. Shay[3], G.R. Halliwell[3], C. Lozano[4] and A. Mehra[4]
[1]GEST, UMBC/ NASA GSFC, Greenbelt, MD 20771
[2]NASA GSFC, Greenbelt, MD 20771
[3]RSMAS, University of Miami, Miami, FL 33149
[4]NOAA NCEP, Camp Springs, MD 20746

1. Introduction:

Upper ocean heat potential is an important factor in the rapid intensification of tropical cyclones. During storm passage, a large fraction of upper ocean cooling and reduction in heat potential is due to entrainment of cooler less turbulent water from below the oceanic mixed layer (ML). 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 a NOAA 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.

2. Data Resources:

Upper ocean response to three storms namely Gilbert (1988), Isidore (2002) and Lili (2002) is investigated in this paper. In addition to data availability, all the three storms occurred in the same region, enabling the use of the similar model domain. Oceanic data available for these storms are briefly described below. Each of these storms, provide a unique set of conditions for evaluating the upper ocean mixing schemes and the resulting surface fluxes.

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 the Miami Isopycnic Coordinate Ocean Model (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.

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.

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.

Important storm parameters and data availability are summarized in Table 1. 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.

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.

3. 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-*kl* 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; KT). 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.

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.

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 65° to 98° W and 9° to 31° 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.

4. Pre-storm Conditions and Evaluation:

Gilbert Case:

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

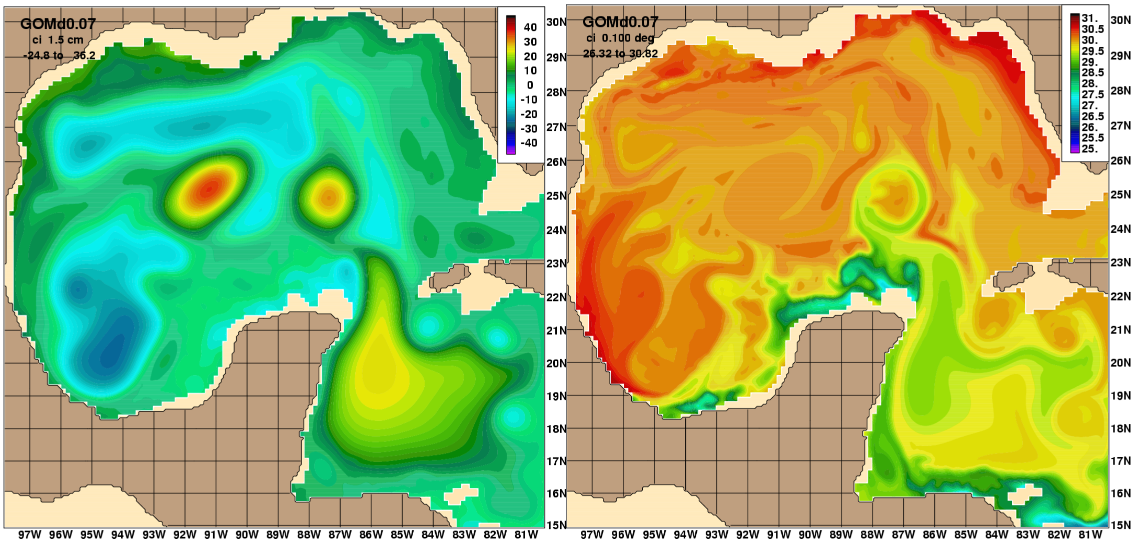

Figure 1: Pre-Gilbert realistic initial conditions. The sea surface height field is on the left and the sea surface temperature is on the right.

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 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 (Fig.1).

Isidore Case:

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. With the assimilation of MODAS sea surface temperatures, pre-Isidore SSTs agree well with the data over most of the domain, however significant differences still remain in the eastern Gulf of Mexico. Additionally, comparison of profiler data indicates that the model fields underestimate the upper ocean heat content. In particular, the temperature structure below the oceanic mixed layer differs from the observed structure significantly. These initial conditions are being updated and the results will be presented at the meeting.

In collaboration with the Environmental Modeling Center, sensitivity studies will be conducted for an independent set of ocean initial conditions prepared with and without data assimilation, atmospheric forcing and changes in the vertical mixing parameterizations. These conditions are obtained from the basin-scale NCEP Atlantic Real Time Ocean Forecast System and will be evaluated against observations.

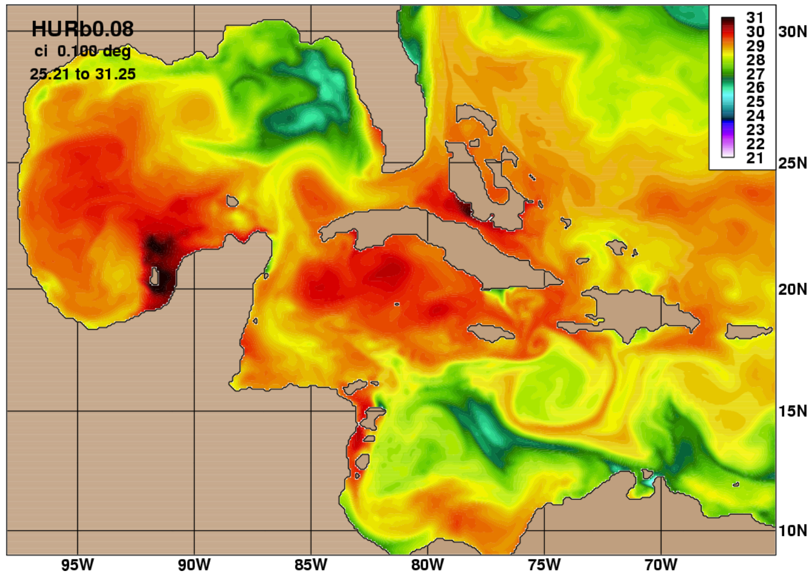

Figure 2: Pre-Isidore sea surface temperatures for realistic initialization from the 0.08° North Atlantic basin-scale data assimilative HYCOM.

5. 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 from the ECMWF data for the Gilbert case, whereas NCEP reanalysis fields are used in the case of Isidore and Lili. While the Gilbert forcing structure was generated every 3 hours, due to the size of the Isidore and Lili, hourly winds are generated to force the ocean model.

6. Simulations and Results:

Gilbert Case:

As mentioned earlier, 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. 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. 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. With 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 (Fig.3).

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

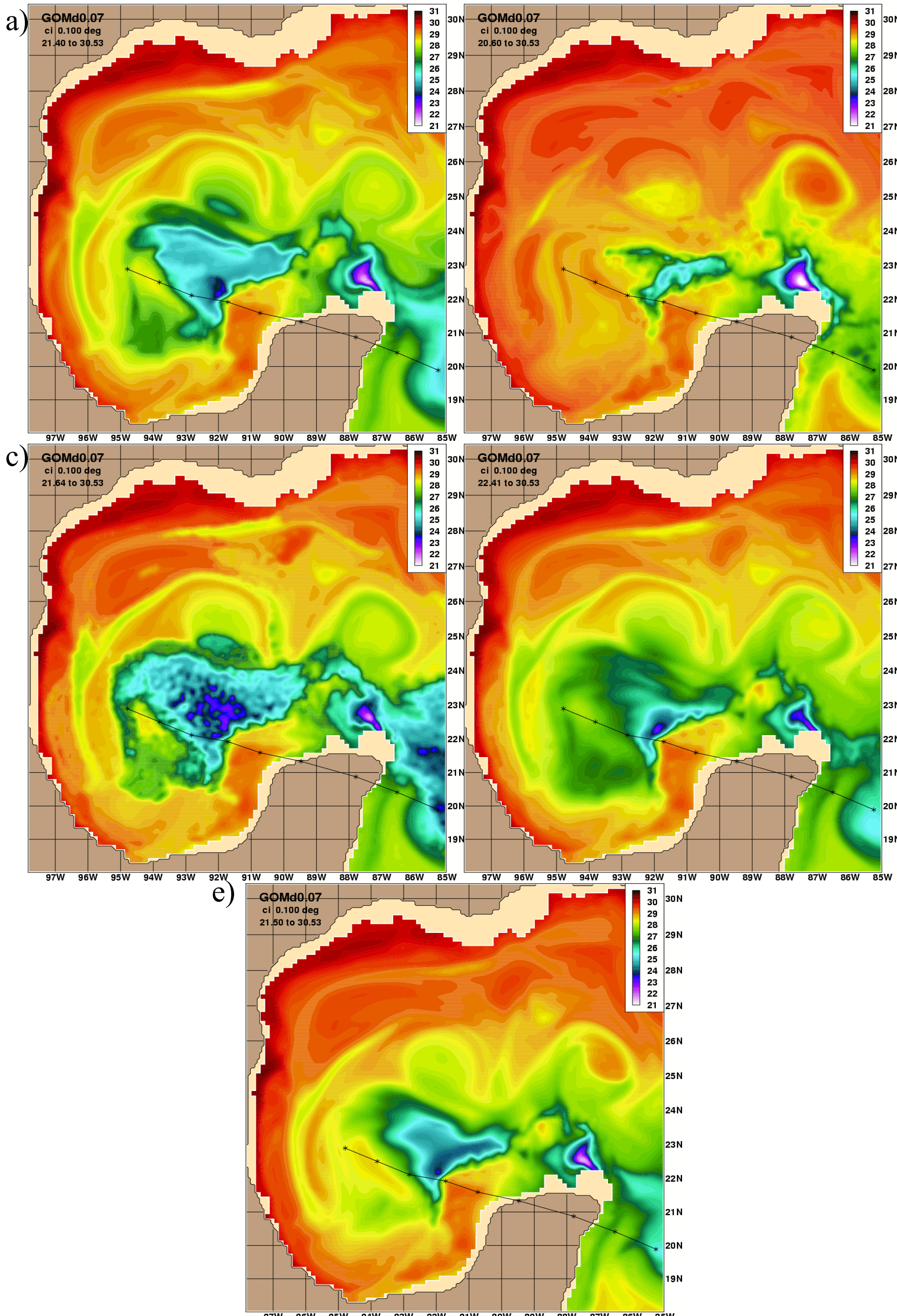

Figure 3: Simulated mixed layer temperatures during hurricane Gilbert for a) KPP, b) KT, c) PWP, d) MY, and e) GISS mixing schemes. Differences between the cases are clearly visible with PWP being the coolest and KT being the warmest. Black line indicates track of the Storm till 06 UTC 16 September 1988.

bulk KT and quasi-bulk PWP schemes are not as satisfactory as indicated by Fig.4 and Table 2. 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.

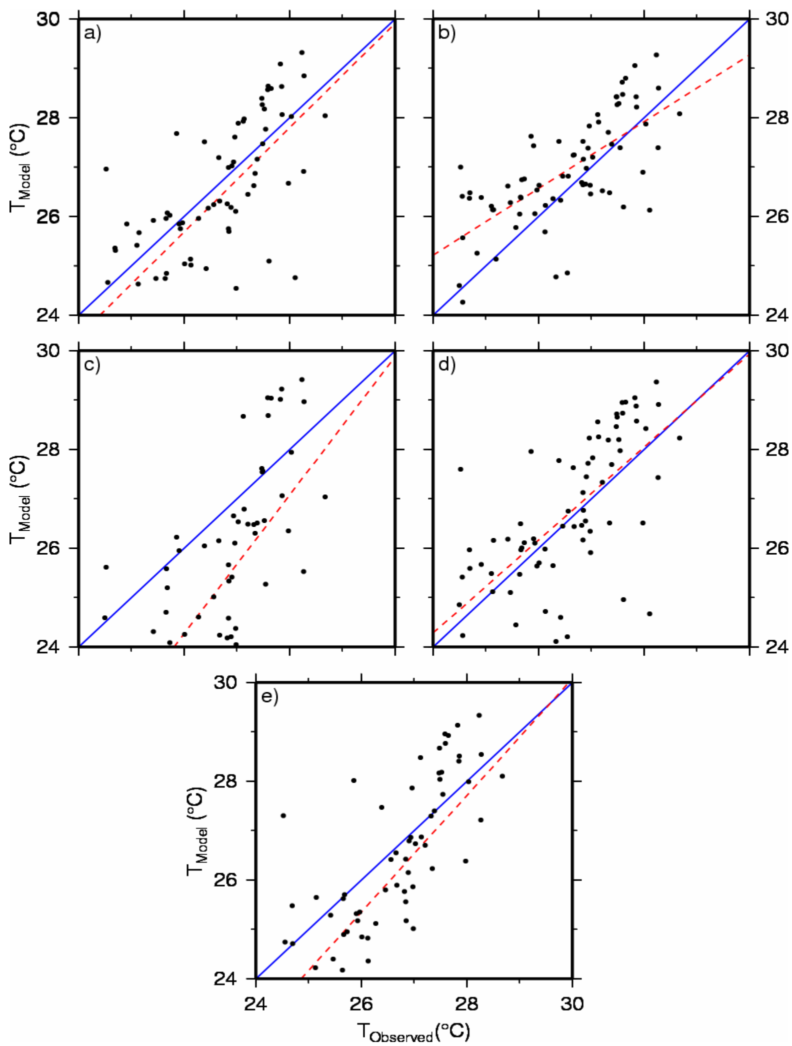

Figure 4: Comparison of observed and simulated mixed layer temperatures for a) KPP, b) KT, c) PWP, d) MY and e) GISS mixing schemes. The solid blue line represents perfect comparison with the dashed red line indicating the linear regression fit. KPP and MY schemes show a better comparison to data.

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 (not shown). However, as mentioned earlier, there are still problems with the initial conditions. Due to a combination of cool mixed layers in the eastern Gulf of Mexico and incorrect thermal structure below the mixed layer in the Caribbean, numerical simulations predict somewhat higher cooling in the model domain than observed. Additionally, there is a strong topographic interaction near the Yucatan that leads to higher cooling. Though comparisons are performed with the profiler data during Isidore and Lili, the statistics are to be considered preliminary due to uncertain initial conditions. These statistics shown in Table 3 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. The GISS scheme compares best to data in the Isidore 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. Positive mean differences also indicate that the simulated mixed layers are cooler than observed in both the Isidore and Lili cases.

	KPP	KT	PWP	MY	GISS
Slope	1.05	0.68	1.40	0.94	1.18
Bias	1.75	9.00	12.18	1.68	-5.40
Mean diff.	0.28	0.40	1.52	0.14	0.56
σ diff.	1.19	0.85	1.76	1.12	1.38
RMS diff.	1.21	0.94	2.30	1.12	1.48

Table 2: Linear regression statistics and parameters that quantify differences between simulated mixed layer temperatures from the model and the observed profiler data. Units are in degrees Celsius except the non-dimensional slope of the regression line.

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 3: 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.

Simulations and comparisons in the Isidore and Lili cases will be refined further when the updated initial conditions are available from NRL and EMC and will be presented at the meeting.

7. Summary and Conclusions:

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. Additionally, while the computational speeds for all the schemes are comparable, the GISS scheme is the fastest in our experiments.

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. 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. These conclusions are constrained by the inaccurate initial conditions during Isidore and Lili. 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.

Acknowledgments: This research was partially funded by the NOAA Joint Hurricane Testbed through grant NA03-OAR-431-0174. SDJ gratefully acknowledges support from NASA. Special thanks are due to Dr. Alan Wallcraft (NRL Stennis) for clarifying model related issues and Dr. Mark Powell (NOAA HRD) for making the forcing fields available for Isidore and Lili. The data assimilative initial conditions were provided by O.M. Smesteadt of Planning Systems Incorporated at NRL Stennis.

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