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Evaluation of Updated MPIPOM-TC Ocean Model Initializing and Sea-State Dependent Mixing Scheme

Austen Blair

University of Rhode Island, austen.blair@gmail.com

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EVALUATION OF UPDATED MPIPOM-TC OCEAN MODEL INITIALIZATION AND
SEA-STATE DEPENDENT MIXING SCHEME

BY
AUSTEN BLAIR

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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OF

AUSTEN BLAIR

APPROVED:

Thesis Committee:

Major Professor Isaac Ginis

Major Professor Tetsu Hara

Jamie Palter

Jason Dahl

Nasser H. Zawia

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND

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ABSTRACT

Tropical cyclone (TC) forecast models have numerous components that must be properly implemented to achieve accurate forecast of TC track and intensity. The simulation of upper ocean response underneath a TC is of particular importance to TC intensity forecasts. This is because a TC relies on the upper ocean as a source of latent heat energy for its formation and maintenance of its intensity. When a large wind stress applies at the ocean surface underneath a TC, it enhances upper ocean vertical turbulent mixing, promotes deepening of the mixed layer and entrainment of colder water from below the thermocline, and reduces the sea surface temperature (SST). Even a slight SST decrease can significantly reduce the latent heat flux to the atmosphere and weaken the storm. For this reason, coupling of an ocean model to the atmospheric model used for TC forecasting is essential.

Accuracy of upper ocean modeling strongly depends on the quality of the ocean model initialization, the wind forcing (air-sea momentum flux) specification, and the upper ocean mixing scheme. Recent studies suggest that the latter two can be significantly modified by different sea states (surface wave fields) and that accurate upper ocean modeling requires coupling of a wave prediction model to the TC-ocean model, as well as implementation of the sea-state dependent upper ocean mixing scheme (Langmuir Turbulence, or LT parameterization).

In this thesis we investigate both ocean initialization methods and ocean mixing schemes in the Message Passing Interface Princeton Ocean Model (MPIPOM) underneath ideal and realistic TC wind fields and evaluate their performance against available observations.

The second chapter evaluates the Feature-Based (FB), HYbrid Coordinate Ocean Model (HYCOM) and the Navy Coupled Ocean Data Assimilation (NCODA) ocean model initializations in a standalone version of MPIPOM. The model ocean is compared to satellite sea surface temperature (SST) and Airborne eXpendable BathyThermograph (AXBT) data before, during, and after Hurricane Edouard has passed the region. Both statistical and visual comparisons are used to evaluate the methods. All three initialization methods are shown to produce reasonable

initial ocean temperature fields as well as reasonable SST cooling responses, with some notable biases.

The third chapter investigates the effects of implicit (sea-state independent) and explicit (sea-state dependent) Langmuir turbulence parameterizations, based on the modified K Profile Parameterization scheme, on the upper ocean underneath TCs. The MPIPOM is coupled with the WaveWatch III (WW3) surface wave model to simulate the complex surface wave fields generated by TCs. Both idealized and Hurricane Edouard wind fields are utilized. The air-sea momentum flux budget is also implemented, accounting for the change in momentum flux to ocean currents due to growing or decaying wave fields. These experiments are performed on an idealized horizontally uniform ocean to clarify the impacts of different mixing schemes. In agreement with previous studies, the sea-state dependent mixing schemes are shown to significantly modify the spatial distribution of SST cooling underneath TCs.

The final chapter utilizes the same model setup as the third chapter with two realistic ocean initializations (FB and Real-Time Ocean Forecasting System, RTOFS), a realistic bathymetry, and the Hurricane Edouard wind forcing. The Feature-Based initialization method is found to be more accurate than the RTOFS method. The SST cooling patterns agree well with those in the idealized cases of the previous chapter, as expected. Visual and statistical comparisons with satellite SST and AXBT observations suggest that the sea-state dependent Langmuir turbulence mixing scheme is more skillful than the implicit scheme in predicting the cold wake generated by the storm. The results therefore suggest that the coupling of both wave and ocean models to a TC model, with an explicit sea-state dependent mixing scheme, is needed for accurate predictions of SST and upper ocean structure underneath TCs.

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Chapter 1

Introduction

A tropical cyclone (TC) relies on the upper ocean as a source of latent heat energy for its formation and maintenance of its intensity. Therefore, the air-sea heat flux is a primary constraint on the energy budget of a TC (Emanuel, 1991). When a large wind stress applies at the ocean surface underneath a TC, it enhances upper ocean vertical turbulent mixing, promotes deepening of the mixed layer and entrainment of colder water from below the thermocline, and reduces the sea surface temperature (SST). Even a slight SST decrease, on the order of tenths of a degree, can significantly impact storm intensity because the latent heat flux is very sensitive to the temperature difference between the ocean surface and the air immediately above it (Bender and Ginis, 2000; Ginis, 2002). For this reason, coupling of an ocean model to the atmospheric model used for TC forecasting is essential, as an accurate SST forecast is critical for storm intensity prediction. Furthermore, a one-dimensional (1D) ocean model may not properly simulate the intensity and spatial variability of this upper ocean cooling (Yablonsky and Ginis, 2009) as strong horizontal currents can cause upwelling and horizontal heat advection and modify the SST. The coupling of a three-dimensional (3D) ocean model to a TC model, accounting for both 1D and 3D upper ocean feedback mechanisms, can greatly improve TC intensity predictions (Ginis, 2002; Schade and Emanuel, 1999).

It is critically important to initialize the ocean model realistically both at the surface and at depth in order to accurately predict the SST cooling under TCs. Existing methods of ocean initialization typically involve assimilation of data from ocean climatologies, satellite observations, and available *in situ* observations. The initialization products vary significantly, depending on the method of assimilation, number and resolution of data sources, and numerical tuning or smoothing. It is therefore necessary to assess different initialization approaches and their impacts on ocean model performance. The second chapter of this thesis investigates the performance of three initialization methods. The ocean model initial conditions as well as the post storm model

results under Hurricane Edouard are generated with the three initialization products, and the results are compared with available satellite and *in situ* observations.

Accurate predictions of upper ocean responses to TCs naturally depend on accurate wind forcing (wind stress) fields and proper parameterizations of turbulent mixing. There is increasing recognition that both upper ocean forcing and mixing can be significantly modified depending on different sea-states (surface wave conditions), and that the TC-ocean model needs to be coupled with a wave prediction model in order to account for such sea-state dependent processes. It is expected that the sea-state impacts are particularly significant under TCs where the surface wave fields are highly complex, transient and spatially varying.

Growing or decaying wave fields absorb or release momentum and modify the momentum flux into upper ocean relative to the wind stress (Smith, 2006; Fan et al., 2010). This effect is often called the “air-sea momentum flux budget”. Ocean surface gravity waves also enhance vertical turbulent mixing via the interaction of Stokes drift and ocean currents (Langmuir turbulence or LT). Since the Stokes drift is responsible for LT energy production, the LT is highly sea-state dependent. The LT significantly alters the spatial distribution and intensity of vertical mixing in the upper ocean underneath a TC, and can affect the mixing of both momentum and scalar properties like temperature. Various mixing scheme modifications have been developed to account for these sea-state dependent LT effects. In particular, Reichl et al. (2016a) have developed a modified K Profile Parameterization mixing scheme based on a comprehensive large eddy simulation (LES) survey of upper ocean turbulence under TCs. This mixing scheme has been incorporated in a coupled ocean-wave model to investigate the impact of the sea-state dependent LT on upper ocean processes under idealized TCs (Reichl et al., 2016b). Their results show that the sea-state dependent LT significantly modifies the spatial pattern of SST cooling by affecting both 1D processes (vertical mixing, mixed layer deepening), and 3D processes (advection, upwelling). The third and fourth chapters of this thesis extend the study of Reichl et al. (2016b) by applying the same LT mixing scheme, together with the air-sea momentum flux budget, in a real historical TC condition (Hurricane Edouard in 2014). While an idealized ocean initial condition is used to clarify the impact of different mixing parameterizations in Chapter 3, two different

(more realistic) ocean initialization techniques are introduced in Chapter 4. The model results are then validated against both satellite and *in situ* observations.

For the reader's convenience, a list of the abbreviations commonly used in this document can be found in table 1.1.

Table 1.1. Commonly used abbreviations throughout the thesis.

Abbreviation	Description and Chapter of Appearance
--------------	---------------------------------------

General

TC	Tropical Cyclone (Ch. 1)
SST	Sea Surface Temperature (Ch. 1)
LT	Langmuir Turbulence (Ch. 1)
OHC	Ocean Heat Content (Ch. 2)

Physical Sensors

AXBT	Airborne eXpendable BathyThermograph (Ch. 2)
------	--

Model Components

MPIPOM-TC	Message Passing Interface Princeton Ocean Model for Tropical Cyclones (Ch. 2)
POM	Princeton Ocean Model, sometimes used as shorthand for MPIPOM-TC (Ch. 2)
WW3	WaveWatch III wave model (Ch. 3)
KPP	K-Profile Parameterization (Ch. 3)

Model Initialization Methods

FB	Feature-Based (Ch. 2)
NCODA	Navy Coupled Ocean Data Assimilation Model (Ch. 2)
HYCOM	HYbrid Coordinate Ocean Model (Ch. 2)
RTOFS	Real-Time Ocean Forecasting System (Ch. 4)

Calculations

RMSE	Root Mean Square Error (Ch. 2)
------	--------------------------------

Papers

RGHTKW	Reichl et al. 2016, Impact of sea-state dependent Langmuir turbulence on the ocean response to a tropical cyclone. Journal of Physical Oceanography (Ch. 3)
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KPP Mixing Schemes

KPP-iLT	KPP implicit Langmuir Turbulence (Not sea-state dependent) (Ch. 3)
KPP-LT	KPP explicit Langmuir Turbulence (Ch. 3)
KPP-ST	KPP Shear Turbulence only (Ch. 3)

Chapter 2

Evaluation of Ocean Model Initializations with Available Observations

2.1 Introduction

As described in chapter 1, the temperature of the upper ocean plays a crucial role in tropical cyclone formation and intensification. The initialization of ocean temperature fields in ocean model simulations is therefore critical to obtaining accurate and realistic forecasts. In this chapter we examine three initialization products implemented in the ocean model. These initializations mainly differ in their technique of assimilating available observations into initial ocean fields. Their performance is evaluated by comparing the model temperature fields against in situ measurements taken via Airborne eXpendable BathyThermograph (AXBT) during tropical cyclone Edouard in 2014.

2.2 Methods

2.2.1 Ocean Model

The tests in this chapter were conducted using MPIPOM-TC (Yablonsky et al., 2015), a version of the Princeton Ocean Model (POM, Blumberg and Mellor, 1987; Mellor, 2004), modified to use a message passing interface (MPI) for parallel processing. MPIPOM-TC is a three-dimensional primitive equation numerical model implemented here with a classic Mellor-Yamada vertical mixing scheme (Mellor and Yamada, 1982). Horizontal differencing scheme calculations are carried out on an Arakawa C-grid with curvilinear orthogonal coordinates. The horizontal grid spacing is $1/12^\circ$ while the vertical coordinates are comprised of 23 depth scaled sigma levels. The model domain covers -98.5° E to -15.3° E longitudinally, and 10° N to 47.5° N latitudinally, with realistic topography.

2.2.2 Hurricane Edouard Observation Campaign

A tropical depression traveling westward across the Atlantic ocean strengthened sufficiently early on September 12th, 2014 to be classified as Tropical Storm Edouard. By September 14th, the storm had reached hurricane intensity. As part of a National Oceanic and Atmospheric Administration Hurricane Research Division (NOAA-HRD) model evaluation study, AXBTs were dropped in the projected path of Edouard from Hurricane Hunter aircraft on September 12th (fig. 2.1). Further AXBT deployments were carried out in the same region as the hurricane passed over on September 14th, 15th and 16th. A final survey was conducted on September 17th after Edouard had left the area. The AXBTs usually provide data to at least 350m depth, making the data useful for both sea surface temperature (SST) and upper ocean heat content (OHC) assessments.

2.2.3 Initialization Techniques

This study compares three methods of model initialization: Feature-Based, HYCOM, and NCODA. All three methods are modularly integrated into MIPOM-TC (Yablonsky et al., 2015). The Feature-Based (FB) method begins by generating an initial ocean from the Generalized Digital Environmental Model (GDEM, Falkovich et al., 2005; Yablonsky and Ginis, 2008). This monthly temperature and salinity climatology has $1/2^\circ$ horizontal grid spacing and 33 fixed vertical levels, ranging from 0 to 5500m depth. Data from this climatology is interpolated temporally and spatially onto the MIPOM grid for the initialization date, and undergoes a cross-frontal sharpening process to improve the realism of the fields. Since the climatology does not represent mesoscale features well, available observations can be assimilated, and specific features, such as eddies or Gulf Stream meanders can be manually added. Placement of these features is frequently determined by using satellite sea surface height observations. After these changes are assimilated, the upper ocean temperature is further updated using daily SST fields obtained from the NCEP Global Forecast System (NCEP GFS, Reynolds and Smith, 1994). Finally, the ocean model is spun up for two days to allow ocean currents to form before the hurricane simulation begins.

The Navy Coupled Ocean Data Assimilation (NCODA) system produces operational products at the Fleet Numerical Meteorology and Oceanography Center (FNMOC) and Naval Oceanographic Office (NAVOCEANO). Developed as an initialization method for the HYbrid Coordinate Ocean Model (HYCOM), a short numerical model forecast based on previous conditions is made as a first guess at current conditions. Available observations are then assimilated using an updated multivariate optimum interpolation (MVOI) method known as 3DVAR (Cummings, 2005; Cummings et al., 2013; Yablonsky et al., 2015). Daily temperature and salinity fields are produced for public use.

The HYCOM is an operational global ocean forecast system that is nudged daily towards the NCODA product (Chassignet and Verron, 2006; Chassignet et al., 2007, 2009). Wind and thermal forcing are then provided by the Navy Operational Global Atmospheric Forcing System (NOGAPS) (Chassignet and Verron, 2006). HYCOM utilizes a $1/12^\circ$ horizontal grid with 32 vertical levels. Vertical scaling switches between fixed depth level, terrain following sigma level, and density following isopycnal level systems, depending on location and ocean stratification. Each technique is preferred in the unstratified deep ocean, shallow coastal ocean, and deep stratified ocean, respectively.

2.3 Results

2.3.1 Pre-Storm Model Assessment

Initial model SST fields in the AXBT drop area based on the three initialization methods show characteristic differences in the degree of horizontal variability produced (fig. 2.2). The Feature-Based SST field has less spatial variation than the other methods, as the GFS SST it is based on has a coarse resolution and therefore smooths horizontal SST anomalies. All three methods show the same general horizontal distribution of temperature with a large warm pool near the center of the region. The HYCOM and NCODA initial fields both tend towards cooler surface temperatures than FB, with NCODA being slightly warmer than HYCOM. This can be seen more clearly in the difference fields of fig. 2.3.

All three initializations agree reasonably well with satellite observations of SST, with dif-

ferences mostly less than $\pm 1^\circ \text{ C}$. Here, the Microwave OI SST data are produced by Remote Sensing Systems and sponsored by National Oceanographic Partnership Program (NOPP) and the NASA Earth Science Physical Oceanography Program. These are optimally interpolated SST data from the TMI, AMSR-E, AMSR2, and WindSat satellites. Data are available at www.remss.com/measurements/sea-surface-temperature. The FB initialization shows a slight positive bias from the satellite data (fig. 2.4). The HYCOM method is somewhat negatively biased, with most areas appearing cooler than the satellite SST (fig. 2.5). The NCODA method produces a field that appears to have the least bias (fig. 2.6).

A total of 24 AXBTs were successfully deployed in a zigzag pattern across Edouards predicted path on September 12th between 1500 and 2000 UTC. Model outputs were generated every 1.5 hours, so all comparisons are made using the model output temporally closest to the AXBT drop time. Comparisons of AXBT measured SSTs to model SSTs, spatially interpolated to the AXBT location, show generally good agreement throughout the water column. In many locations, the HYCOM method produces a temperature profile closest to the AXBT profile (e.g. fig. 2.7), however in some locations other models more closely match the AXBT profile (e.g. fig. 2.8). Using these profiles, the root mean square error (RMSE) and the bias are calculated using eqs. (2.1) and (2.2) to statistically examine the agreement

$$RMSE = \sqrt{(\overline{SST_{Model} - SST_{AXBT}})^2} \quad (2.1)$$

$$Bias = \overline{SST_{Model} - SST_{AXBT}} \quad (2.2)$$

where the bar indicates the mean. The results are summarized in tables 2.1 and 2.2. The magnitude of bias is smallest in the HYCOM initialization at 0.09° C , followed by the NCODA method at 0.10° C , and finally the FB method with 0.29° C . The HYCOM bias is the only negative bias, meaning the method is biased towards producing slightly cooler temperatures on average than observed by the AXBTs. The FB and NCODA biases are both positive, indicating they produce warmer SSTs on average than the observations. These biases support the trend in fig. 2.3 that the NCODA method produces cooler SSTs than the FB method, and the HYCOM cooler than NCODA. The SST RMSE value is also smallest with HYCOM at 0.35° C , followed by NCODA with 0.38° C and FB with 0.54° C .

As both the AXBTs and MPIPOM provide temperature over depth, another diagnostic value known as Ocean Heat Content (OHC) can be calculated and compared. The OHC is a measure of the heat available in the upper ocean to fuel tropical cyclones and is calculated as

$$OHC = \int_0^{d_{26}} \rho c_p [T(^{\circ}C) - 26] dz \quad (2.3)$$

where d_{26} is the depth of the $26^{\circ}C$ isotherm, ρ is the density of the seawater, and c_p is specific heat at a constant pressure. We assume a constant density of $1025 kg/m^3$ for these calculations. For the model OHC, virtual temperature profiles were first constructed by horizontally interpolating model temperatures at every model depth level onto the AXBT location point. Both the AXBT and model profiles were then vertically interpolated onto 0.5m intervals, and OHC was calculated using the trapezoidal numerical integration method available in the commercial software package MATLAB 2014a.

The FB initialization is the only method to produce a positive OHC bias, with a magnitude of 14.02 kJ/cm^2 and an RMSE of 19.13 kJ/cm^2 (tables 2.3 and 2.4). The HYCOM method produces the smallest magnitude bias and the lowest RMSE, -8.13 kJ/cm^2 and 13.98 kJ/cm^2 , respectively. The NCODA fields show the strongest bias with -17.19 kJ/cm^2 and the largest RMSE of 20.76 kJ/cm^2 . It is interesting that the NCODA overestimates the SST but underestimates the OHC. It suggests that the NCODA underestimates the depth of the warm water layer, that is, the mixed layer depth.

2.3.2 Mid-Storm Model Assessment

A total of 26 AXBTs were successfully deployed inside Hurricane Edouard from September 14th through September 16th. We calculate the RMSE and bias of SST and OHC for these three days as a group representing the model performance during the storm. Note that the OHC calculation requires the presence of a $26^{\circ}C$ isotherm, meaning profiles where all temperatures are below $26.0^{\circ}C$ yield an OHC of 0. As some AXBT locations lacked this isotherm in either observation or model profiles, these locations were not used in the OHC analysis. As such, the OHC calculations were performed on 24 profiles for FB, 22 profiles for HYCOM, and 20 profiles for NCODA.

The SST bias trends differ somewhat from the pre-storm results, with the HYCOM method now biased positively by 0.05°C above the AXBT observations, but the NCODA biased negatively by -0.25°C . The FB bias remains positive and its magnitude greatest at 0.69°C . The SST RMSE has increased for all methods: FB 1.01°C , HYCOM 0.66°C and NCODA 0.68°C . The significant decrease of the NCODA SST bias (from positive to negative) means that the model integration has overestimated the SST cooling during the storm. This is qualitatively consistent with the earlier observation that the NCODA initialization underestimates the mixed layer depth.

The OHC biases have decreased in magnitude for all three methods, with FB biased 12.64 kJ/cm^2 , HYCOM -3.90 kJ/cm^2 and NCODA -11.81 kJ/cm^2 . The OHC RMSE has decreased from the pre-storm results to 10.66 kJ/cm^2 for HYCOM and 13.86 kJ/cm^2 for NCODA, and has increased slightly for FB to 19.48 kJ/cm^2 .

2.3.3 Post-Storm Model Assessment

All three simulations show cold wakes of similar magnitude (fig. 2.9), with the minimum surface temperature of about 22°C . The FB model yields an area of maximum cooling slightly smaller and less intense than the HYCOM or NCODA models. The FB simulation slightly overestimates the SST (under predicts the SST cooling) compared with satellite observations (fig. 2.10) along part of the track. The HYCOM and NCODA simulations both underestimate the SST (overpredicts cooling) by up to 2°C along part of the track (figs. 2.11 and 2.12).

A final Hurricane Hunter flight was made on September 17th that deployed 34 AXBTs. The SST statistics were calculated using all 34 profiles. For the OHC calculation the number of usable profiles was 33 for the FB initialization, 31 for the HYCOM method and 32 for the NCODA method.

The SST biases remain similar to the mid-storm values for each method: FB= 0.63°C , HYCOM= 0.02°C and NCODA= -0.26°C . The SST RMSE for HYCOM and NCODA has increased to 0.81°C and 0.74°C respectively, while the FB error has been reduced to 0.87°C . The OHC bias has slightly increased in magnitude for all methods over the mid-storm period: FB = 13.60 kJ/cm^2 , HYCOM = -5.15 kJ/cm^2 , NCODA = -13.35 kJ/cm^2 . The OHC RMSE also

has increased to 24.34 kJ/cm^2 for the FB method, 18.80 kJ/cm^2 for HYCOM and 23.56 kJ/cm^2 for NCODA. An example of the better performance of the HYCOM method can be seen in the profile of fig. 2.13, and a location where HYCOM did not perform as well is shown in fig. 2.14.

2.4 Conclusion

In comparison to the AXBT measurements via the SST and OHC metrics described above, the HYCOM initialized model consistently outperformed the other two methods (figs. 2.15 and 2.16). The HYCOM SST biases were very close to zero in all three (pre storm, during storm, post storm) periods and much lower than the FB and NCODA biases, although HYCOM SST RMSE was comparable to the NCODA method. The HYCOM OHC was always negatively biased, but to a smaller degree than the negative NCODA or positive FB biases. The OHC RMSE was also consistently lower for the HYCOM method. These results indicate that the application of thermal and wind forcing during the HYCOM modeling process that leads to the HYCOM initialization product yields a better representation of the upper ocean thermal structure than the other methods.

Table 2.1. Model vs. AXBT SST RMSE during Hurricane Edouard in degrees C.

	Feature Based	HYCOM	NCODA
Pre-Storm	0.54	0.35	0.38
Mid-Storm	1.01	0.66	0.68
Post-Storm	0.87	0.81	0.74

Table 2.2. Model vs. AXBT SST Bias during Hurricane Edouard in degrees C.

	Feature Based	HYCOM	NCODA
Pre-Storm	0.29	-0.09	0.10
Mid-Storm	0.69	0.05	-0.25
Post-Storm	0.63	0.02	-0.26

Table 2.3. Model vs. AXBT OHC RMSE during Hurricane Edouard in kJ/cm^2 .

	Feature Based	HYCOM	NCODA
Pre-Storm	19.13	13.98	20.76
Mid-Storm	19.48	10.66	13.86
Post-Storm	24.43	18.80	23.56

Table 2.4. Model vs. AXBT OHC Bias during Hurricane Edouard in kJ/cm^2 .

	Feature Based	HYCOM	NCODA
Pre-Storm	14.02	-8.13	-17.19
Mid-Storm	12.64	-3.90	-11.81
Post-Storm	13.60	-5.15	-13.35

Figure 2.1. AXBT deployments during Hurricane Edouard NOAA-HRD field program. Red line is the hurricane track. AXBTs were deployed before the storm (squares), during the storm (circles), and after the storm (diamonds).

Figure 2.2. Comparison of SST fields produced by each initialization method at the start of the hurricane simulation. Dotted line shows the future track of Hurricane Edouard

Figure 2.3. The HYCOM and NCODA fields of fig. 2.2 are differenced with the FB field.

Figure 2.4. Comparison of initial SST fields produced by the FB method to microwave satellite SST measurements (Model minus observations).

Figure 2.5. Same as fig. 2.4 for the HYCOM initialization method.

Figure 2.6. Same as fig. 2.4 for the NCODA initialization method.

Figure 2.7. At this drop location, the HYCOM method has better agreement with observations above 50 meters. The NCODA method agrees better with the observation below 50 meters, while all methods converge near 250 meters.

Figure 2.8. Same as fig. 2.7 for a location where the HYCOM method temperature profile does not agree well with the AXBT in the upper 50 meter, but has a better agreement below.

Figure 2.9. Comparison of SST fields produced by each initialization method on September 17th, 1200Z of the simulations. Solid grey line is hurricane track, dashed grey line is future track. Black dots are locaion in 24 hour intervals beginning with September 13th, 0000Z. Black star is hurricane location on September 17th at 1200Z.

Figure 2.10. Comparison of SST fields produced by FB initialization method on September 17th, 1200Z of the simulation. Solid grey line is hurricane track, dashed grey line is future track. Black dots are location in 24 hour intervals beginning with September 13th, 0000Z. Black star is hurricane location on September 17th at 1200Z. Satellite SST field is shown in the left panel, model in the middle, and difference (model - satellite) on the right.

Figure 2.11. Same as fig. 2.10 for the HYCOM initialized model.

Figure 2.12. Same as fig. 2.10 for the NCODA initialized model.

Figure 2.13. An AXBT drop location demonstrating good HYCOM method temperature profile agreement to the AXBT throughout the water column and poor agreement from the other methods.

Figure 2.14. Same as fig. 2.7 for a location where HYCOM did not have the best temperature agreement with AXBT observation.

Figure 2.15. Comparisons of model and AXBT SST for each AXBT location. Black line is AXBT observed SST, color lines represent model SSTs. Vertical grey dashed lines demark date of AXBT drop: Sept. 12th (left), Sept. 14-16 (middle), Sept. 17th (right).

Figure 2.16. Comparisons of model and AXBT OHC for each AXBT location. Black line is AXBT observed OHC, color lines represent model OHC. Vertical grey dashed lines demark date of AXBT drop: Sept. 12th (left), Sept. 14-16 (middle), Sept. 17th (right).

Chapter 3

Impact of Sea-State Dependent Langmuir Turbulence and Air-Sea Momentum Flux Budget on Upper Ocean Response to a Tropical Cyclone

3.1 Introduction

As discussed in chapter 1, the upper ocean mixing and the entrainment of cold water to the surface underneath tropical cyclones can have a large impact on the air-sea heat flux that fuels the storm. The upper ocean turbulence and mixing is significantly enhanced by the Stokes drift of the surface waves (Langmuir turbulence) created by the TC wind stress. It is expected that the Langmuir turbulence under TC wind forcing is strongly sea-state dependent because the surface wave fields are particularly complex and varied. Recently, Reichl et al. (2016b, in press) developed a coupled wave-ocean model with the K Profile Parameterization (KPP, Large et al. (1994)) mixing scheme to explicitly model the sea-state dependent Langmuir turbulence and investigate its impact on the upper ocean response to a TC. The explicit modeling of wave fields and Langmuir turbulence under idealized TC wind fields produced significantly different results from those with the traditional (sea-state independent) turbulence parameterization (Reichl et al., 2016a,b). This indicates that accurate TC intensity prediction requires coupling of a wave model to the ocean model used in hurricane prediction systems.

Here, we continue the development and evaluation of this coupled wave-ocean model, with a particular focus on applying realistic TC winds. Ideally, all three components in an atmosphere-wave-ocean modeling system would communicate with each other. However, in this study we substitute prescribed winds for an atmospheric model to clarify the impact of different sea states on the upper ocean responses.

3.2 Methods

3.2.1 Model Description

The experiments described in this chapter are performed using a two-way coupled ocean and wave model (fig. 3.1). The ocean component is an updated version of the Message Passing Interface Princeton Ocean Model (MPIPOM) described in chapter 2. Several changes to the MPIPOM have been made. The Mellor-Yamada mixing scheme has been replaced by the K Profile Parameterization scheme (KPP, Large et al. (1994)). Several modifications to the original KPP were made, including use of Lagrangian current shear and an enhanced (sea-state dependent) eddy viscosity in calculating the turbulent momentum flux. These changes are described fully in Reichl et al. (2016a, hereafter RGHTKW). In addition, in this study we have replaced the Eulerian currents with the Lagrangian currents in the momentum equations solved in the MPIPOM. Specifically, the momentum equations solved in the original MPIPOM are

$$\partial_t u_h + (\mathbf{u} \cdot \nabla) u_h + \varepsilon_{h3j} f u_j - D_h + \partial_h p = 0 \quad (3.1)$$

$$-b + \partial_z p = 0 \quad (3.2)$$

where $h = 1, 2$; $j = 1, 2, 3$. Here, (x, y) are the horizontal coordinates, z is the vertical coordinate, t is the time, ∇ denotes 3D gradient, b is the buoyancy, p is the pressure divided by the reference density, f is the Coriolis parameter, D_h is the turbulent diffusion, $\mathbf{u} = (u, v, w)$ is the (3D) Eulerian velocity. In the presence of surface waves (Stokes drift), Fox-Kemper and Suzuki (2016) show that this equation should be modified to

$$\partial_t u_h + (\mathbf{u}^L \cdot \nabla) u_h + \varepsilon_{h3j} f u_j^L - D_h + \partial_h p = -u_i^L \partial_h u_i^S \quad (3.3)$$

$$-b + \partial_z p = -u_i^L \partial_z u_i^S \quad (3.4)$$

where all flow variables are now averaged over a short time to filter out the rapid oscillation of surface waves, $\mathbf{u}^S$ is the Stokes drift of surface waves, and $\mathbf{u}^L = \mathbf{u} + \mathbf{u}^S$ is the Lagrangian velocity. When the Stokes drift is horizontally divergent, the vertical component of the Stokes drift is added to satisfy the continuity. The right hand terms in (3.3) and (3.4) are called the

Stokes shear force. Note that the Stokes shear force is responsible for enhancing the turbulent mixing (Langmuir turbulence) in unresolved (subgrid) scales. This horizontal equation (3.3) can be rewritten as

$$\partial_t u_h^L + (\mathbf{u}^L \cdot \nabla) u_h^L + \varepsilon_{h3j} f u_j^L - D_h + \partial_h p = \partial_t u_h^S + (\mathbf{u}^L \cdot \nabla) u_h^S - u_i^L \partial_h u_i^S. \quad (3.5)$$

Here, the left hand terms are identical to the left hand terms of the original MPIPOM equation (3.1) if the Eulerian current is replaced by the Lagrangian current. Furthermore, under typical TC conditions the last two terms on the right of (3.5) is negligibly small. Therefore, if we add the term $\partial_t u_h^S$ to the MPIPOM equation, the model properly solves for the Lagrangian current without further modifying the code. This approach is particularly convenient because (1) the turbulent diffusion D_h is parameterized in terms of the Lagrangian current shear, instead of the Eulerian current shear, in the presence of surface waves, and (2) the scalar equation and the continuity equation are also written in terms of the Lagrangian current instead of the Eulerian current in the presence of surface waves.

The momentum equation (3.5) is forced by the wind stress τ_h applied at the surface. Therefore, if we integrate (3.5) in z from $-\infty$ to 0, the diffusion term D_h disappears but the right hand side should include the surface forcing term τ_h . However, Smith (2006) and Fan et al. (2010) show that the momentum flux into upper ocean is different from the wind stress when surface waves are growing or decaying, and the difference is approximately

$$\nabla \tau_h = -\nabla_t M_h - \nabla_i S_{hi}, \quad (3.6)$$

where $M_h = \int_{-\infty}^0 u_h^S(z) dz$ is the vertically integrated Stoke drift and S_{hi} is the vertically integrated radiation stress. We call this growing/decaying wave effect “air-sea momentum flux budget”. Therefore, the forcing on the ocean model must be $\tau_h + \nabla \tau_h$ instead of τ_h . Notice that the vertical integral of the first term on the right of (3.5) is identical to the negative of the first term on the right of (3.6). Therefore, these two terms exactly cancel if we ignore the fact that the former applies in the water column and the latter applies at the surface.

In summary,

(1) In the air-sea momentum flux budget calculation, we remove the time dependence term $\nabla_t M_h$.

(2) The MPIPOM equation is not modified, but the current output of the model is interpreted as the Lagrangian current instead of the Eulerian current.

Note that our approach ignores the right hand term of (3.4), the vertical Stokes shear force term, which is not necessarily small under TC conditions. Investigation of possible impacts of this force is left for future studies.

Finally, the 23 vertical levels of the original MPIPOM are increased to 60 levels to allow for a finer resolution of the mixing layer in KPP (fig. 3.2). The initial ocean conditions are horizontally homogeneous, with a temperature profile (fig. 3.3) similar to the Gulf of Mexico Common Water profile used in (Yablonsky and Ginis, 2009). Salinity is a uniform 35 psu everywhere.

The KPP mixing scheme is used in three different configurations, similar to those used in Reichl et al. (2016a). In the first, KPP-ST, no explicit Langmuir turbulence is applied and the critical Richardson number is tuned to 0.27, appropriate for shear turbulence only conditions. This experiment setting has no sea-state dependent effects. The second configuration for implicit Langmuir turbulence (KPP-iLT) also has no explicit sea-state dependent effects and uses a critical Richardson number of 0.35 to simulate typical Langmuir turbulence in the open ocean. The last configuration (KPP-LT) uses explicit sea-state dependent Langmuir turbulence calculations, where the critical Richardson number is set back to 0.27 and additional sea-state dependent enhancement is added to the turbulence parameterization. As the Langmuir turbulence in KPP-LT is sea-state dependent, this configuration also includes the momentum flux budget effect as explained above.

The wave component of the coupled model system is Wave Watch III (WW3). We use WW3 version 3.14, a 3rd generation model that solves the spectral action density balance equation for wavenumber-direction spectra (Tolman, 2009). The wave spectrum is calculated at 40 frequencies spaced logarithmically starting at a minimum frequency of 0.0285 Hz. Wave directions range from 0 to 2π in $\pi/12$ increments (24 directions).

3.2.2 Experimental Design

To begin our experiments, we repeat some of the simulations performed in RGHTKW and investigate the impact of our modifications to the momentum calculations and the addition of the momentum flux budget (section 3.2.1), which is expected to be small based on scaling estimates. We select the simulation of an ideal tropical cyclone with winds following a Holland profile (Holland, 1980) translating east to west at approximately 2.85 ms^{-1} . The maximum wind speed is 50 ms^{-1} at a radius of 50 km. This simulation is performed with MPIPOM in both 1D and 3D modes and with all three of the mixing regimes described in section 3.2.1. A drag coefficient parameterization identical to that used in Reichl et al. (2016a) and based on Sullivan et al. (2012) is utilized (fig. 3.4). The storm was allowed to run for 72 hours to reach a quasi-steady state. In summary, this set consists of a total of 6 simulations: one for each of three mixing schemes, KPP-ST, KPP-iLT, and KPP-LT, with each performed in 1D and 3D.

The next series of tests is identical to those described above but utilizes the track and wind profile of hurricane Edouard, a storm from 2014 (figs. 3.5 and 3.6). The ocean initializations, mixing schemes, and drag coefficient for these 6 simulations are the same as those of the idealized storm. The track and wind fields for Edouard are input directly from the NOAA-NCEP TCVitals history product for the storm. A final set of experiments is performed using the same Edouard wind field but using the GFDL Bulk drag parameterization (fig. 3.4), bringing the overall total to 18 simulations.

3.3 Results

3.3.1 Idealized Hurricane Simulations

We first examine the overall results of the SST and near surface currents from the first set of experiments, with a straight, ideal track, and with the KPP-iLT mixing scheme (the results with the other two schemes are similar and are not shown). In the 1D case, the cold wake of the storm is around 4° C cooler than the initial 29° C SST (fig. 3.7). The cold wake is centered about half a degree to the right of the storm track. In the 3D case, the cooling is much stronger, up to 8°

C (fig. 3.8). The spatial coverage of the cooling has also increased, though it is still strongest to the right of the track, as expected. Near surface currents up to 1.5 m/s, evaluated at the 11.36 m depth, are produced. These results are very similar to those obtained in RGHTKW with the identical wind forcing.

We next focus on the differences in SST and near surface currents due to differing mixing schemes. The 1D KPP-LT produces stronger cooling on the left hand side of the storm than the shear turbulence only KPP-ST (fig. 3.9), to a similar degree (0.7° C cooler) as observed by RGHTKW. This enhanced cooling is due to Langmuir turbulence and affects the entire area under the storm. As this is a 1D simulation, no horizontal advection of heat and momentum is present, meaning all cooling is due to vertical upwelling of cooler waters from depth. As described in RGHTKW, the stronger cooling on the left side is due to relatively weak shear-driven mixing (compared to the right side), thereby making it more sensitive to Langmuir turbulence.

The 3D version of the KPP-LT minus KPP-ST shows a similar enhancement of cooling on the left side of the storm (fig. 3.10). On the right hand side, cooling is slightly reduced over a large area. This is also observed in RGHTKW and is likely due to the modified horizontal advection of heat as discussed in RGHTKW.

The 1D KPP-iLT minus KPP-ST also show similar results to RGHTKW. Cooling is strongly enhanced on the right hand side of the storm track and relatively weakly everywhere else. The rightmost panel of fig. 3.9 displays the difference between the KPP-LT and KPP-iLT. The explicit Langmuir turbulence results in warmer temperatures to the right of the track and cooler temperatures to the left.

The 3D KPP-iLT shows less cooling enhancement over KPP-ST than the 1D case, and the enhancement is more centered near the storm track (fig. 3.10). Currents are very similar between the two simulations. Both SST and currents agree well with RGHTKW. The KPP-LT to KPP-iLT difference shows a similar degree of enhanced cooling as the RGHTKW result, approximately 0.21° C, on the left hand side. On the right hand side, however, our simulations show greater reduction of cooling in KPP-LT than the RGHTKW result. This may be due to the addition of our momentum flux budget.

Overall, the coupled model system described here closely replicates the experiments performed in RGHTKW with the identical wind forcing, suggesting that the impacts of the air-sea momentum flux budget and other changes (replacing the Eulerian current by the Lagrangian current in the model calculation) are much smaller than the impact of the different mixing parameterizations.

3.3.2 Hurricane Edouard Simulations

All figures of simulations performed using the TCVitals track and wind information for hurricane Edouard are for September 17th, 1200Z, when the simulation had run for 132 hours. This time point is just after Edouard had completed an eastward turn and shortly before it was downgraded to a tropical storm by the National Hurricane Center.

We first examine the cold wake produced by the Edouard wind and Sullivan drag parameterization with the KPP-iLT (results with the other two schemes are very similar and are not shown). The results are qualitatively similar to the ideal track simulations. In the 1D case, cooling is around 4°C (fig. 3.11). Maximum cooling occurs in the center of the bend in Edouard's track when the storm was strongest. In the 3D case, cooling is more intense, reaching a maximum of around 6°C , due to the additional effect of the storm induced upwelling (fig. 3.12).

Next, we examine the differences between the KPP-ST, KPP-iLT, and KPP-LT simulations performed with the Edouard wind and Sullivan drag parameterization. Overall, the effects of different mixing schemes are qualitatively similar to the idealized track cases, though somewhat different quantitatively. In the 1D model, KPP-LT generally enhances cooling over KPP-ST everywhere, particularly on the left side of the track. KPP-iLT enhances cooling over KPP-ST on the right of the track (fig. 3.13). Both decrease SST by about 0.35 to 0.4 degrees more than KPP-ST. When KPP-LT and KPP-iLT are compared, KPP-LT produces stronger cooling on the left side and weaker cooling on the right. The trends between mixing schemes remain much the same in the 3D versions of these simulations (fig. 3.14), although the reduction in cooling for KPP-LT over KPP-iLT on the right is slightly more pronounced in 3D than in 1D.

One notable difference between the idealized and real storm cases is seen in 3D KPP-

iLT minus 3D KPP-ST. While cooling enhancement is similar on the right side and left side in the idealized case, cooling enhancement remains stronger on the right side of the storm in the Edouard case. This may be due to the curve of the storm track, causing enhanced upwelling and horizontal advection that does not occur with the straight idealized track.

Finally, our last set of experiments utilizes the GFDL bulk drag parameterization. The cooling enhancement/reduction patterns are the same as those described above with the Sullivan drag parameterization, but with slightly larger amplitudes in both enhancement and reduction (figs. 3.15 and 3.16). The GFDL drag parameterization provides a considerably larger drag than the Sullivan parameterization at high wind speeds, which can explain this result.

3.4 Conclusion

We have investigated the impact of the sea-state dependent Langmuir turbulence and the air-sea momentum flux budget on upper ocean responses to a tropical cyclone. We have extended the work of RGHTKW by (1) modifying the momentum equation, i.e., replacing the Eulerian current by the Lagrangian current, (2) adding the air-sea momentum flux budget, and (3) applying the real hurricane wind forcing.

As expected, the impacts of the modified momentum equations and the air-sea momentum flux budget are much smaller than the impacts of the different mixing schemes. Our results with the idealized storm are very similar to those of RGHTKW. When the wind field of hurricane Edouard is applied, the results are qualitatively similar to the idealized storm case but some quantitative differences appear, possibly due to the complexity of the storm track and the translation speed.

Our study with the real hurricane wind further confirms the following conclusions of RGHTKW:

(1) The upper ocean response (SST cooling) is strongly modified when the sea-state dependent LT parameterization is introduced. Although the simulation with the implicit (sea-state independent) LT parametrization also shows enhanced SST cooling compared to the simulation with the shear only parameterization, the spatial pattern of SST cooling is significantly different between the sea-state dependent and implicit LT parameterizations.

(2) Therefore, accurate predictions of upper ocean response (SST cooling) require a fully coupled wave-ocean model with a sea-state dependent Langmuir turbulence parameterization.

Figure 3.1. A schematic describing the physical interactions of the model components in the sea-state dependent KPP-LT system. Note that in the other mixing schemes, the wave model does not influence the ocean model in any way.

Figure 3.2. A comparison of sigma level distribution in the upper 200m in the 23 level (left, black) and 60 level (right, red) regimes. Total depth is 2500m.

Figure 3.3. The initial temperature profile used throughout the idealized ocean, similar to Gulf of Mexico Common Water.

Figure 3.4. Drag under Sullivan parameterization (solid line) for the idealized model cases. Dashed line is the GFDL Bulk drag parametrization.

Figure 3.5. Tropical Cyclone Edouard wind field at sample dates.

Figure 3.6. Tropical Cyclone Edouard wave field (significant wave height) at sample dates.

Figure 3.7. SST at 72 hours (left panel) and cooling from initial temperature field (right) for the 1D idealized track storm simulation. Black line is storm track with circles every 6 hours.

Figure 3.8. Same as fig. 3.7 for the 3D version of the idealized track simulation. Black arrows are currents at 11.36 m depth.

Figure 3.9. SST differences for 1-dimensional ideal track simulations.

Figure 3.10. SST (color) and 11.36m current (arrows) differences for 3-dimensional ideal track simulations.

Figure 3.11. SST on Sept. 17th, 1200Z (left panel) and cooling from initial temperature field (right) for the 1D Edouard storm simulation using KPP-iLT mixing and Sullivan drag parameterization. Black line is storm track with circles every 24 hours.

Figure 3.12. Same as fig. 3.11 for the 3D version of the simulation.

Figure 3.13. SST differences for 1-dimensional Edouard track simulations with Sullivan drag.

Figure 3.14. SST differences for 3-dimensional Edouard track simulations with Sullivan drag.

Figure 3.15. SST differences for 1-dimensional Edouard track simulations with GFDL Bulk drag.

Figure 3.16. SST differences for 3-dimensional Edouard track simulations with GFDL Bulk drag.

Chapter 4

Impact of Sea State Dependent Processes on Upper Ocean Response to a Tropical Cyclone - Comparison with Observations

4.1 Introduction and Methods

In chapter 2 we have shown that our ocean initialization methods are reasonably skillful in creating accurate initial conditions for hurricane simulations. In chapter 3 we have confirmed that the upper ocean response (SST cooling in particular) to a tropical cyclone is significantly modified if the sea-state dependent Langmuir turbulence parameterization is introduced in the ocean model. In chapter 3 the model simulations with Hurricane Edouard wind forcing have been conducted with an idealized ocean initialization with a spatially uniform density profile. In this chapter we extend the Edouard simulations with more realistic ocean initial conditions generated using two different initialization methods. We then analyze the skill of the different mixing schemes by comparing the model results against the SST and AXBT observations. All model parameters and settings are the same as described in chapter 3 with the GFDL Bulk drag coefficient.

The first model initialization method is the Feature Based method described in chapter 2. The only modification to the method is the use of 60 vertical sigma levels instead of 23. The second method is similar to the HYCOM method described in chapter 2 and is called Global Real-Time Ocean Forecast System (RTOFS). This operational NOAA-NCEP product is based on the HYCOM but forced with 3-hourly momentum, radiation and precipitation fluxes from the operational Global Forecast System (GFS) fields. the Global Forecast System. It also utilizes the latest HYCOM based initialization system for operational use. The NCODA initialization is not used here, as results are generally very similar to those produced by the HYCOM or RTOFS methods.

4.2 Results

4.2.1 Pre-Storm Model Assessment

Comparison with Satellite SST

The initial SST fields produced by both initialization methods show a warm pool of water with maximum temperatures at or above 29°C extending from west to east in the area Hurricane Edouard passed over. The RTOFS method has much more small scale spatial variability than the FB method. As expected, they compare reasonably well with the same satellite SST described in section 2.3.1. The difference between the FB product and the satellite observation is mostly less than $\pm 1^{\circ}\text{C}$ (fig. 2.4). The RTOFS initialization is slightly cooler than the satellite observations over much of the domain (fig. 4.1).

Comparison with AXBT SST and OHC

The pre-storm assessments are based on AXBT drops performed on September 12th, 2014, with model data interpolated onto the AXBT drop location and matched as closely as possible to the drop time. The bias and the RMSE of the SST and OHC are calculated as explained in chapter 2. Note that the pre-storm FB SST is based on the NCEP GFS SST analysis (ref) and RTOFS SST is based on the HYCOM SST analysis (ref). In comparisons with the available AXBT measurements, the initial FB SST field is biased positively by 0.29°C , while the RTOFS field is biased negatively by -0.41°C (table 4.1). Similar biases were observed in chapter 2 for the FB method. The SST RMSE is smaller for FB at 0.54°C than for RTOFS at 0.73°C (table 4.2). The OHC is also positively biased by 14.82 kJ/cm^2 for the FB method and is negatively biased by -16.98 kJ/cm^2 for the RTOFS method (table 4.3). The RMSE for the FB method is slightly smaller at 19.72 kJ/cm^2 compared to the RTOFS error of 21.95 kJ/cm^2 (table 4.4).

Comparison with AXBT Profiles

Two of the most important characteristics of temperature profiles affecting the ocean response to a hurricane are SST and the mixed layer depth. For both the FB and RTOFS initializations,

model to AXBT profile comparisons show that in some cases, the mixed layer depth is in good agreement, but the surface temperature is off, shifting the entire near-surface profile (figs. 4.2 and 4.3). In other cases, SST is in good agreement but the mixed layer depth is not, usually being too shallow (figs. 4.4 and 4.5). At other profile locations, the FB method does a good job of simulating the near-surface temperature (fig. 4.6). The RTOFS initialization method profiles are generally negatively biased (cooler temperatures throughout) as the OHC and SST biases suggest.

4.2.2 Mid-Storm Model Assessment

Comparison with AXBT SST and OHC

The mid-storm assessments include AXBT data from September 14th, 15th and 16th. As the storm is now passing over the sample locations, differences in the model mixing schemes can be seen in the temperature profiles and summary statistics.

For the FB method, the KPP-iLT and KPP-LT schemes significantly reduce the SST and OHC biases, but the shear turbulence only KPP-ST scheme yields a minor reduction of the biases (tables 4.1 and 4.3). This is consistent with the fact that the Langmuir turbulence enhances the upper ocean mixing and cooling. The RMSE values somewhat increase for the SST but remain similar for the OHC (tables 4.2 and 4.4). These results suggest that the ocean model is overall reasonably skillful in predicting the upper ocean cooling under the storm. It is difficult to assess the skills of the different mixing schemes from these statistical values.

The RTOFS bias magnitude and RMSE values are consistently larger than those of the FB results. SST bias and RMSE increase from the pre-storm values, indicating that the model is overcooling the SST. This may be due to the RTOFS method initially having a shallower mixed layer depth, allowing cool water to be upwelled more easily. The RTOFS OHC bias and RMSE actually improve in the mid-storm measurements, indicating that the RTOFS vertical temperature profiles better match the AXBT profiles.

4.2.3 Post-Storm Model Assessment

Comparison with Satellite SST

The analysis of the post storm model SST fields and their comparison with the satellite SST are made at September 17th, 1200Z, after approximately 132 hours of model integration. First, we present the model predicted SST and SST cooling with the two initialization methods with the iLT mixing scheme (figs. 4.7 and 4.8). Both initialization methods result in similar cooling patterns, with a maximum cooling of about 8° C compared to the initial surface temperature (figs. 4.7 and 4.8).

Comparisons with satellite data indicate that all three mixing schemes over-predict the cooling in the cold wake with both initial products. This overcooling can be partially explained by the experimental design in which we ignored SST warming induced by solar radiation after the storm. The FB results agree better than the RTOFS results, which are more negatively biased compared to the satellite SST over the whole domain. Between mixing schemes, the KPP-iLT scheme clearly over-predicts the cooling, particularly on the right of the storm track (figs. 4.13 and 4.14). The sea state dependent KPP-LT parameterization significantly reduces the cooling on the right of the track and makes the overall results more consistent with the observation (figs. 4.9 and 4.10). The reduction of cooling in the cold wake with the KPP-LT is likely because of the reduced horizontal advection of heat as discussed by RGHTKW. These results suggest that the KPP-LT, coupled with the wave model, is more skillful in predicting the SST cooling than the KPP-iLT without the wave coupling. Note that the results with the shear only KPP-ST appear to agree with the observations almost as well as those with the KPP-LT (figs. 4.11 and 4.12). However, this agreement does not mean that the KPP-ST is as skillful as the KPP-LT, because the SST cooling has been reduced in the cold wake due to underestimated upper ocean mixing, which is obviously a wrong reason.

The SST differences between different mixing schemes show similar spatial patterns to those observed in chapter 3 with both initialization methods (figs. 4.15 and 4.16). Compared to KPP-ST, KPP-LT produces stronger cooling on the left side of the track, but the KPP-iLT increases cooling on the right side of the track. The comparison between the KPP-LT and the

KPP-iLT shows significant reduction of the SST cooling on the right of the track with the KPP-LT, which is the main reason why the KPP-LT improves the overall SST agreement with the satellite observation.

Comparison with AXBT

This assessment is conducted against AXBTs deployed on September 17th, 2014. The overall trends of the SST and OHC biases and RMSEs remain similar to those of the mid-storm results. Some increase in the bias or RMSE is explained by the lack of solar insolation in the ocean model. The cold wake of Edouard began to recover, or return to the initial SST, relatively quickly after the storm due to solar heating, and this is not properly reflected in the models. The KPP-LT results now show less cooling of the SST and less reduction of the OHC compared to the KPP-iLT in the post storm results (they were similar in the mid storm results). This suggests that the difference between the KPP-LT and the KPP-iLT becomes more significant after the storm has passed. This trend is also seen in fig. 4.17 to fig. 4.20.

The better performance of the KPP-LT relative to the KPP-iLT can also clearly be seen when the model results are compared to the AXBT profiles within the cold wake. We present two such examples (with the FB initialization) where the pre-storm profiles are also available (figs. 4.21 and 4.22). At both locations, the initial model profiles are reasonably close to the observations. After the storm, the reduced cooling produced by the KPP-LT scheme results in the upper ocean temperature profile that agrees better with the AXBT observation. The KPP-iLT scheme clearly over predicts cooling. Interestingly, the KPP-ST scheme performs similarly to KPP-iLT in one profile and similarly to KPP-LT in the other. Again, the apparent good performance of the KPP-ST in one case is likely due to an incorrect reason.

4.3 Conclusion

In this chapter we have continued our investigation of the three different mixing schemes (KPP-ST, KPP-iLT, and KPP-LT) on the upper ocean under Hurricane Edouard with two different ocean initialization schemes (FB and RTOFS). As expected, the impacts of the different mix-

ing schemes are very similar to the results with an idealized ocean initialization presented in chapter 3. The pre-storm analysis suggests that the FB initialization is more consistent with the satellite and AXBT observations than the RTOFS initialization, which underestimates the SST and OHC. The post-storm SST comparison between the FB model and the satellite observation shows that the KPP-LT is more skillful than the KPP-iLT, mainly because the KPP-iLT over predicts SST cooling significantly more than the KPP-LT does in the cold wake. The comparison with the AXBT observations during and after the storm suggests that the difference between the KPP-LT and KPP-iLT becomes more significant after the storm has passed.

In summary, our results suggest that the introduction of the sea-state dependent LT parameterization, coupled with the wave model, does improve the prediction of SST cooling under TC wind forcing. Of course, more model validation studies with different storms are needed to substantiate this conclusion.

Table 4.1. Model vs. AXBT SST Bias during Hurricane Edouard in degrees C.

	Feature-Based			RTOFS		
	KPP-iLT	KPP-LT	KPP-ST	KPP-iLT	KPP-LT	KPP-ST
Pre-Storm	0.29	0.29	0.29	-0.41	-0.41	-0.41
Mid-Storm	0.05	0.07	0.22	-0.99	-0.98	-0.81
Post-Storm	0.18	0.30	0.31	-0.88	-0.77	-0.74

Table 4.2. Model vs. AXBT SST RMSE during Hurricane Edouard in degrees C.

	Feature-Based			RTOFS		
	KPP-iLT	KPP-LT	KPP-ST	KPP-iLT	KPP-LT	KPP-ST
Pre-Storm	0.54	0.54	0.54	0.73	0.73	0.73
Mid-Storm	1.05	1.00	0.99	1.49	1.45	1.32
Post-Storm	0.79	0.74	0.77	1.20	1.08	1.09

Table 4.3. Model vs. AXBT OHC Bias during Hurricane Edouard in kJ/cm^2 .

	Feature-Based			RTOFS		
	KPP-iLT	KPP-LT	KPP-ST	KPP-iLT	KPP-LT	KPP-ST
Pre-Storm	14.82	14.82	14.82	-16.98	-16.98	-16.98
Mid-Storm	10.93	12.16	13.28	-11.78	-11.54	-10.52
Post-Storm	9.53	11.34	11.12	-18.40	-17.69	-17.22

Table 4.4. Model vs. AXBT OHC RMSE during Hurricane Edouard in kJ/cm^2 .

	Feature-Based			RTOFS		
	KPP-iLT	KPP-LT	KPP-ST	KPP-iLT	KPP-LT	KPP-ST
Pre-Storm	19.72	19.72	19.72	21.95	21.95	21.95
Mid-Storm	18.10	18.26	19.10	15.25	14.84	13.49
Post-Storm	23.77	24.02	24.06	26.90	26.09	26.05

Figure 4.1. Same as fig. 2.4 for RTOFS initialization.

Figure 4.2. Pre-Storm virtual profile from the FB initialization method demonstrating a location where the model temperature (colored line) does not match the AXBT observation (black line) near the surface, but does have an accurate mixed layer depth (about 25m). Note that results from all three model mixing schemes are shown, but have identical profiles as the storm has not entered the area yet.

Figure 4.3. Same as fig. 4.2 for the RTOFS initialization method. Note that results from all three model mixing schemes are shown, but have identical profiles as the storm has not entered the area yet.

Figure 4.4. Pre-Storm virtual profile from the FB initialization method demonstrating a location where the model temperature (colored line) matches well with the AXBT observation at the surface (black line), but does not have an accurate mixed layer depth. Note that results from all three model mixing schemes are shown, but have identical profiles as the storm has not entered the area yet.

Figure 4.5. Same as fig. 4.4 for the RTOFS initialization method. Note that results from all three model mixing schemes are shown, but have identical profiles as the storm has not entered the area yet.

Figure 4.6. Pre-Storm virtual profile from the FB initialization method demonstrating a location where both model SST and mixed layer depth (colored line) match well with the AXBT observation (black line). Note that results from all three model mixing schemes are shown, but have identical profiles as the storm has not entered the area yet.

Figure 4.7. Initial temperature field created via the FB method (left), SST on September 17th, 1200Z of the simulation, showing Hurricane Edouard's cold wake (middle), and the difference between the fields, showing the degree of cooling (right). Note that these images are from the iLT mixing scheme simulation; other mixing schemes produced similar results.

Figure 4.8. Same as fig. 4.7 for the RTOFS initialization method, again using the iLT mixing simulation as an example.

Figure 4.9. Comparison of satellite observed SST (left panel), FB initialized model SST (middle panel) with KPP-LT mixing scheme, and the difference between the two (model - satellite, right panel). Model data is from September 17th, 1200Z, SST is a daily product. Grey line in all panels is hurricane track, with dashed representing future path. Black dots indicate hurricane location in 24 intervals, beginning on Sept. 13th. Black star is hurricane location on September 17th, 1200Z.

Figure 4.10. Same as fig. 4.9 for RTOFS initialized model with KPP-LT mixing scheme.

Figure 4.11. Same as fig. 4.9 for FB initialized model with KPP-ST mixing scheme.

Figure 4.12. Same as fig. 4.9 for RTOFS initialized model with KPP-ST mixing scheme.

Figure 4.13. Same as fig. 4.9 for FB initialized model with KPP-iLT mixing scheme.

Figure 4.14. Same as fig. 4.9 for RTOFS initialized model with KPP-iLT mixing scheme.

Figure 4.15. SST differences for FB initialized Edouard simulations with varying mixing schemes. Note that white bars on right of each panel are simply excluding some data points outside the area of interest that were skewing the colorbar in such a way as to decrease clarity of the visualization; the domain is kept constant for referencing other similar figures.

Figure 4.16. Same as fig. 4.15 for the RTOFS initialized simulations.

Figure 4.17. Comparisons of model and AXBT SST for each AXBT location. Black line is AXBT observed SST, color lines represent FB initialized model SSTs. Vertical grey dashed lines demark date of AXBT drop: Sept. 12th (left), Sept. 14-16 (middle), Sept. 17th (right).

Figure 4.18. Comparisons of model and AXBT OHC for each AXBT location. Black line is AXBT OHC, color lines represent FB initialized model OHCs. Vertical grey dashed lines demark date of AXBT drop: Sept. 12th (left), Sept. 14-16 (middle), Sept. 17th (right).

Figure 4.19. Same as fig. 4.17 for the RTOFS initialized simulations.

Figure 4.20. Same as fig. 4.18 for the RTOFS initialized simulations.

Figure 4.21. AXBTs # 10 and 60 were dropped less than 12 km from each other, before (10, left) and after (60, right) Hurricane Edouard passed over their location. Model results are from the FB initialized simulations at the time step closest to the AXBT drop and spatially interpolated to the AXBT location.

Figure 4.22. AXBTs # 16 and 74 were dropped less than 12 km from each other, before (16, left) and after (74, right) Hurricane Edouard passed over their location. Model results are from the FB initialized simulations at the time step closest to the AXBT drop and spatially interpolated to the AXBT location.

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