2013

Evaluating Ocean Model Resolution and Initialization Under Hurricane Conditions

Melissa R. S. Kaufman
University of Rhode Island, mkaufman@gso.uri.edu

Follow this and additional works at: <https://digitalcommons.uri.edu/theses>

Recommended Citation

Kaufman, Melissa R. S., "Evaluating Ocean Model Resolution and Initialization Under Hurricane Conditions" (2013). *Open Access Master's Theses*. Paper 85.
<https://digitalcommons.uri.edu/theses/85>

This Thesis is brought to you for free and open access by DigitalCommons@URI. It has been accepted for inclusion in Open Access Master's Theses by an authorized administrator of DigitalCommons@URI. For more information, please contact digitalcommons-group@uri.edu.

EVALUATING OCEAN MODEL RESOLUTION AND
INITIALIZATION UNDER HURRICANE CONDITIONS

BY

MELISSA R.S. KAUFMAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
OCEANOGRAPHY

UNIVERSITY OF RHODE ISLAND

2013

MASTER OF SCIENCE THESIS
OF
MELISSA R.S. KAUFMAN

APPROVED:

Thesis Committee:

Major Professor	Isaac Ginis
	Tetsu Hara
	Alexander Meyerovich

Nasser H. Zawia
DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2013

ABSTRACT

Although hurricane models can now more accurately forecast storm track, they have not made significant improvement in forecasting hurricane intensity. Sea surface temperature and ocean heat content play an important role in regulating tropical cyclone intensity. The focus of this study is on two important ocean model parameters: the resolution and initialization scheme. The Princeton Ocean Model (POM) is used to calculate the temperature fields under a specified hurricane wind stress, utilizing either an idealized storm structure for the resolution experiments or wind data from National Hurricane Center message files for the initialization simulations.

This study examines ocean model response under idealized hurricane conditions for a range of horizontal resolutions spanning from $\frac{1}{2}^\circ$ to $1/18^\circ$. Resolution sensitivity was examined for different storm speeds, different storm sizes, different model physics (3D or 1D), and different initial ocean conditions. The higher resolution experiments better represent the structure of the hurricane eye and the eyewall. It is found that the magnitude of sea surface temperature (SST) in the cold wake is less at coarser resolutions than at finer resolutions. Horizontal resolution is more important in experiments with 3D physics than 1D physics. Horizontal resolution has a larger impact in resolving slower moving storms than faster moving storms. Latent heat flux is also generally larger at higher resolutions than coarser resolutions. The values of SST, latent heat flux, and turbulent kinetic energy (TKE) converge in experiments with $1/12^\circ$ and $1/18^\circ$ grid spacing. Ocean heat uptake (OHU) increases as resolution increases. Vertical resolution also plays an important role in ocean heat loss and

uptake estimations. Vertical grid spacing of at least 5 m in the mixed layer and at least 10 m in the upper thermocline are necessary for accurate calculations of ocean heat loss and uptake.

Different model initializations, primarily differing in the method of data assimilation, were tested and model output was compared to in-situ data from buoys and Airborne eXpendable BathyThermographs (AXBTs) and satellite observations from a survey mission on 16 July 2009 and during Hurricane Isaac in 2012. The initializations tested were Global HYCOM and Feature-Based. For the survey, the feature-based initialization was run three times, once using only CCAR altimetry input, a second time using CCAR as well as AXBTs to determine the warm core ring structure and location, and a third time using CCAR altimetry input and AXBTs to determine the location only. The survey model comparisons show that the feature-based simulation with AXBT assimilation had the best agreement with the data. The results are less conclusive when assessing the model response to hurricane conditions during Hurricane Isaac. Both simulations have locations where they good skill, but no initialization out-performs the other overall. Both of the simulations overestimate the sea surface temperature cooling; the feature-based simulation typically underestimates the mixed layer depth whereas the HYCOM simulation overestimates it.

ACKNOWLEDGMENTS

First I would like to thank my advisor, Isaac Ginis, for all his advice and support. I would also like to thank my committee members, Professors Tetsu Hara and Alexander Meyerovich. I would like to thank the other members of the URI/GSO Numerical Modeling Lab, especially Dr. Biju Thomas and Michael Bueti for their technical assistance, and an extra thank you to Dr. Richard Yablonsky for his advice, guidance, and optimism. Finally I would like to thank my friends and family for their unwavering support and encouragement. I would especially like to thank my mother for reading many drafts of this document. I would also like to thank Ardith Welwood for helping me reach my goals.

PREFACE

This thesis is being written in manuscript format and consists of two scientific journal articles. Both chapters are still in preparation and will be submitted for publication in the near future.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENTS	iv
PREFACE	v
TABLE OF CONTENTS	vi
LIST OF TABLES	viii
LIST OF FIGURES.....	ix
I. Evaluating Ocean Model Resolution Under Hurricane	
Conditions.....	1
Abstract.....	2
1. Introduction	3
2. Description of Model and Experimental Set-up.....	8
3. Sea Surface Temperature and Latent Heat Flux.....	10
4. Ocean Heat Uptake	15
4.1 Effect of horizontal resolution.....	16
4.2 Effect of vertical resolution	17
5. Conclusion.....	20
References	21
II. Evaluating Ocean Model Initializations for Hurricane Prediction	
Abstract	54
1. Introduction	55
2. Model Initialization Methods	56

3. Evaluation of HYCOM/Feature-Based Initial fields using AXBT data	
.....	59
4. Evaluation of Simulated Ocean Response Under Hurricane Conditions	
.....	67
5. Summary	75
References	76
BIBLIOGRAPHY	115

LIST OF TABLES

TABLE	PAGE
Table I.1. Experiment Parameters for Sea Surface Temperature Tests	24
Table I.2. Vertical Resolution Experiments	25
Table I.3. Impact of Vertical Resolution on Heat Uptake and Heat Loss Rates for G1D-R3-U5 1/18°	26
Table I.4. Impact of Vertical Resolution on Heat Uptake and Heat Loss Rates for G3D-R3-U5 1/18°	27
Table II.1. Data Sources used for assimilation into NCODA (Cummings 2005)	81
Table II.2. Root mean square error and bias of OHC values for simulations compared to AXBT calculated value for 16 July 2009 Survey	82
Table II.3 Extended track file for Hurricane Isaac. The first column is the reporting agency (National Hurricane Center). The second column is the storm ID; the third column is the storm name. The fourth column is the date (year, month, day). The fifth column is the hour and minutes. The sixth column is the latitude measured in tenths of a degree. The seventh column is the longitude west in tenths of a degree. The eighth column is the direction of the storm motion in degrees from North; the ninth column is the storm speed in tenths of a m/s. The tenth column is the storm central pressure in mb; the eleventh column is the environmental pressure in mb. The twelfth column is the estimated radius of the outermost closed isobar in km. The thirteenth column is the estimated maximum wind speed in m/s and the fourteenth column it the estimated radius of maximum wind in km. Columns 15 through 18 are the estimated radius of 34 knot winds in NE/SE/NW/SW quadrants; columns 19 through 22 are the same for the 50 knot winds. -999 indicates that there is no estimate or the data are missing. (http://www.emc.ncep.noaa.gov/mmb/data_processing/tcvitals_description.htm)	83
Table II.4 Root mean square error and bias for OHC values of simulations compared to AXBT calculated value for Hurricane Isaac.	84

LIST OF FIGURES

FIGURE	PAGE
Figure I.1. The figure on the left shows the initial temperature profile (dashed line) and the profile at the same location 72 hours after storm passage (solid line). The temperature anomaly is shown on the figure in the right; the filled blue area is the region of cooling and the red area is the region of sub-surface warming	28
Figure I.2 Initial temperature profiles in the upper 150 meters for Gulf Common Water (GCW) or Caribbean Sea (CRB) profiles. For these idealized experiments, the initial temperature field is horizontally homogeneous.	29
Figure I.3. Radial cross-section of the wind speed based on the Holland profile. Here, the maximum wind is 55 m/s and the radius of maximum wind is either 30 or 55 km.	30
Figure I.4. Wind Swath (top) and Wind Swath Anomalies (middle and bottom) in m s^{-1} for the experiments with a 30 km radius of maximum wind.	31
Figure I.5. Wind field anomalies in m s^{-1} in different horizontal resolution experiments relative to the $1/18^\circ$ resolution for the experiments with 30 km radius of maximum wind. The dashed line is the radius of maximum wind and the solid line is the 60 km radius from the storm center.....	32
Figure I.6. Sea surface temperature anomaly at 72 hours from initial state for experiment G3D-R3-U5. Temperature contours are every 0.5° . The solid black line is the storm track. The dashed lines are the locations of the cross-track cross-sections shown in Figure I.7. The dashed ellipse represents the radius of maximum wind (30 km). Because the figure axes are not equal, the radius of maximum wind does not appear axisymmetric.	33
Figure I.7. Cross-track cross-sections of SST anomaly for G3D-R3-U5. The cross-section to the left is taken through the storm center. The cross section to the right is taken 100 km in the wake of the storm. The x-axis is the horizontal distance north/south to the storm track normalized by the radius of maximum wind	34
Figure I.8. Sea surface temperature anomaly differences for G3D-R3-U5. The dashed white circle shows the radius of maximum wind; the solid white circle shows the 60 km radius from the storm center. Contours are every $1/2^\circ$	35

Figure I.9. Average sea surface temperature anomaly within 60 km of storm center. Each cluster shows the results for the five resolutions tested for one parameter set. The clusters shown are (left to right): G3D-R3-U5, G1D-R3-U5, G3D-R3-U2, and G1D-R3-U2.....	36
Figure I.10. Difference between G3D-R5-U5 and G1D-R5-U5 for the experiments with horizontal grid spacing of $1/18^\circ$ (top) and $1/3^\circ$ (bottom). The solid line is the storm track; the dashed “circle” is the radius of maximum wind.....	37
Figure I.11. Average latent heat flux within 60 km of storm center. Each cluster shows the results for the five resolutions tested for one parameter set. The clusters shown are (left to right): G3D-R3-U5, G1D-R3-U5, G3D-R3-U2, G1D-R3-U2	38
Figure I.12. Top: latent heat flux (W m^{-2}) for $1/18^\circ$ G3D-R3-U5 experiment. The black circle is the 60 km radius. Bottom: Latent heat flux differences (W m^{-2}) for G3D-R3-U5. The white dashed circle is the radius of maximum winds. The white solid circle is 60 km from the storm center. Solid black contours are positive differences; dashed black contours are negative differences. The contour spacing is every 100 W m^{-2}	39
Figure I.13. Same as the bottom of Figure I.12 but for G3D-R3 U2	40
Figure I.14. Vertical cross-section of turbulent kinetic energy taken 100 km parallel to the right of the track. The dashed white line shows the longitude of the storm center.	41
Figure I.15. Vertical cross-section of the turbulent kinetic energy. The cross-section is taken one degree behind the storm center. The dashed white line shows the latitude of the storm center.	42
Figure I.16. Domain-averaged vertical temperature anomaly. The area in blue is the cold anomaly and the area in red is the warm anomaly. Z1 is at the depth where the curve first shifts from positive to negative, between the blue and red areas (top black line). Z2 is the depth at the bottom of the warm anomaly where the anomaly is approximately zero from there to the ocean floor, at the bottom of the red area, bottom black line.	43
Figure I.17. Ocean heat uptake (W m^{-2}) for G1D-R3-U5 for the experiments with horizontal grid spacing of $1/18^\circ$ (top) and $1/3^\circ$ (bottom). The solid line is the storm track; the dashed “circle” is the radius of maximum wind..	44
Figure I.18. G1D-R3-U5 domain-averaged vertical temperature profile for different resolutions.....	45

Figure I.19. Domain integrated OHU in G1D-R3-U5 experiments. The ocean heat uptake rate (J) is found by taking the slope of the linear fit to the ocean heat uptake between hours 24 and 72.	46
Figure I.20. Average vertical temperature anomaly profiles in G3D-R3-U5 experiments	47
Figure I.21. Ocean heat uptake rates (J) for G3D-R3-U5.	48
Figure I.22 Domain averaged vertical temperature anomaly profile in G1D-R3-U5 for different vertical resolutions	49
Figure I.23. : Same as Figure I.18 but for G3D-R3-U5 1/18° experiments.	50
Figure I.24. Same as Figure I.14 but comparing vertical resolutions for the experiment with 1D physics (left), 3D physics (right). Within each panel, the upper left is for ML5-UT>5; the upper right is ML10-UT10; the lower left is ML5-UT10, and the lower right is ML5-UT5.	51
Figure I.25. Same as Figure I.15 but comparing vertical resolutions for the experiment with 1D physics (left), 3D physics (right). Within each panel, the upper left is for ML5-UT>5; the upper right is ML10-UT10; the lower left is ML5-UT10, and the lower right is ML5-UT5.	52
Figure II.1: Transatlantic and United Domains.	85
Figure II.2 AXBT instrument (left). Schematic diagram of AXBT deployment (right). (hurricanescience.org).....	86
Figure II.3 AXBT locations for July 16, 2009 survey..	87
Figure II.4 GDEM Climatology for July SST (left) and temperature at 75 m (right).	88
Figure II.5 CCAR SSH for 16 July 2009. The Loop Current is in the lower right. There is a large warm core ring and a smaller cold core ring (CCR). The block dots are the positions of the northern extent of the Loop Current and the ends of the major axes of the rings used in the FB method. The black lines are the radii of the minor axes of the rings. Contours are every 10 cm. The marked locations are based on the 17 cm contours.	89
Figure II.6 Sea surface temperature (left) and 75 m temperature (right) after Loop Current, WCR, and CCR have been assimilated using the FB method.	90

Figure II.7. : AXBT # 33, 32, 31 (left to right).	91
Figure II.8 Temperature profile at center of WCR.	92
Figure II.9 Sea surface temperature (left) and 75 m temperature (right) after GFS SST and AXBTs have been assimilated.	93
Figure II.10. Sea surface height (cm) from CCAR (top), Global HYCOM (middle left), FB-CCAR (middle right), FB-AXBT (bottom left), and FB-AXBT-POSONLY (bottom right). Contours are every 10 cm.....	94
Figure II.11. Sea surface temperature on 16 July 2009 from observed TMI (top left), blended from 57 AXBT observations (top right), HYCOM (bottom left), FB-CCAR (bottom right).	95
Figure II.12 Sea surface temperature on 16 July 2009 blended from 57 AXBT observations (top), HYCOM (middle left), FB-CCAR (middle right), FB-AXBT (bottom left), and FB-AXBT-POSONLY (bottom right). Contour lines are every 1°	96
Figure II.13. Observed temperature at 75-m depth using a blend of 57 AXBTs on 16 July 2009 (upper left); temperature profiles at the locations of AXBT #28 (upper right), AXBT #31 (lower left), and AXBT #33 (lower right).	97
Figure II.14 Vertical cross-section of temperature through center of ring from AXBT # 33-24 (top), HYCOM (middle left), FB-CCAR (middle right), FB-AXBT (bottom left), and FB-AXBT-POSONLY (bottom right). Contour lines are every 1°.	98
Figure II.15 Temperature profiles at the locations of AXBT #16 (upper left), AXBT #52 (upper right), AXBT #40 (lower left), and AXBT #48 (lower right).	99
Figure II.16 Ocean heat content calculated from 57 AXBT observations (top), HYCOM (middle left), FB-CCAR (middle right), FB-AXBT (bottom left), and FB-AXBT-POSONLY (bottom right). Contour lines are every 10 kJ/cm ²	100
Figure II.17 Ocean heat content for the model output at the AXBT location versus the AXBT location for the simulations initialized with HYCOM (upper left), FB-CCAR (upper right) . FB-AXBT (lower left), and FB-AXBT-POSONLY (lower right). The dashed line is the 1:1 line.	101

Figure II.18 AXBT drop position for August 28 (red) and August 29 (blue) during Hurricane Isaac (2012). Buoy 42003 is marked by a black circle. The thick black line is the storm track, with the storm position marked every 6 hours. The top figure covers the entire Gulf of Mexico; the bottom figure is zoomed in on the AXBT drop locations.	102
Figure II.19 Sea surface height on August 26 th 2012 from CCAR altimetry (top), simulation run with feature-based initialization (lower left) and Global HYCOM initialization (lower right).	103
Figure II.20 Wind stress (N m^{-2}) on 26 August 2012 (left) and 28 August 2012 (right)	104
Figure II.21 Sea surface temperature and currents on August 29, 2012 for TRMM-TMI (top), FB (lower left), HYCOM (lower right). The black line is the track of Hurricane Isaac. The black line is the track of Hurricane Isaac.	105
Figure II.22 Temperature and currents at 75 m on August 29, 2012 for FB (left), HYCOM (right). The black line is the track of Hurricane Isaac.....	106
Figure II.23 Time series of sea surface temperature as measured by buoy 42003 compared to model output at (-85.612, 26.044). The time is measured as hours after 00Z on 26 August 2012.....	107
Figure II.24 Temperature profile on 28 August 2012 for AXBT #2 and model output.	108
Figure II.25 Temperature profile on 28 August 2012 for AXBT #4 and model output.	109
Figure II.26 Temperature profile for AXBT #10 (left) and AXBT #23 (right) and model output along the storm track.	110
Figure II.27 Temperature profile for AXBT #7 (top left), AXBT #15 (top right), AXBT #24 (bottom left), AXBT #27 (bottom right) and model output on the right of the storm track.	111
Figure II.28 Temperature profile for AXBT #19 (top left), AXBT #26 (top right), AXBT #20 (bottom left), AXBT #29 (bottom right) and model output – on the left of the storm track.	112
Figure II.29 Temperature profiles at AXBT #16 (left) and AXBT #17 (right) – near the edge of the WCR.	113

Figure II.30 Ocean heat content for each AXBT (top). Comparisons of OHC for the Feature-based initialized simulation to AXBTs (lower) and OHC HYCOM-AXBT (lower right). The dashed line is 1:1 line. 114

Chapter 1

"Evaluating Ocean Model Resolution Under Hurricane Conditions"

by

Melissa Kaufman¹, Isaac Ginis², Richard Yablonsky³

is being prepared for publication in Weather and Forecasting.

¹ MS Candidate, Graduate School of Oceanography, The University of Rhode Island, Narragansett, RI 02882. Email: mkaufman@gso.uri.edu

² Professor, Graduate School of Oceanography, The University of Rhode Island, Narragansett, RI, 02882. Email: iginis@gso.uri.edu

³ Marine Research Associate, Graduate School of Oceanography, The University of Rhode Island, Narragansett, RI, 02882. Email: ryablonsky@gso.uri.edu

ABSTRACT

Although hurricane models can now more accurately forecast storm track, they have not made significant improvement in forecasting hurricane intensity. Sea surface temperature and ocean heat content play an important role in regulating tropical cyclone intensity. The focus of this chapter is on ocean model resolution. The Princeton Ocean Model (POM) is used to calculate the temperature fields under a specified hurricane wind stress, utilizing an idealized storm structure.

This study examines ocean model response under idealized hurricane conditions for a range of horizontal resolutions spanning from $\frac{1}{2}^\circ$ to $1/18^\circ$. Resolution sensitivity was examined for different storm speeds, different storm sizes, different model physics (3D or 1D) and different initial ocean conditions. The higher resolution experiments better represent the structure of the hurricane eye and the eyewall. It is found that the magnitude of sea surface temperature (SST) in the cold wake is less at coarser resolutions than at finer resolutions. Horizontal resolution is more important in experiments with 3D physics than 1D physics. Horizontal resolution has a larger impact in resolving slower moving storms than faster moving storms. Latent heat flux is also generally larger at higher resolutions than coarser resolutions. The values of SST, latent heat flux, and turbulent kinetic energy (TKE) converge in experiments with $1/12^\circ$ and $1/18^\circ$ grid spacing. Ocean heat uptake (OHU) increases as resolution increases. Vertical resolution also plays an important role in ocean heat loss and uptake estimations. Vertical grid spacing of at least 5 m in the mixed layer and at

least 10 m in the upper thermocline are necessary for accurate calculations of ocean heat loss and uptake.

1. Introduction

Designing skillful ocean models is a difficult task because there are many sub-grid scale processes not explicitly resolved. For example, surface fluxes must be parameterized, accurate initialization and open-ocean boundary conditions must be selected, and the horizontal and vertical resolutions must be set. Accurately reproducing ocean conditions is of importance in hurricane modeling because the ocean is a driving force behind hurricane genesis and evolution (e.g. Price 1981, Ginis 2002). Current research and operational ocean models use a range of horizontal resolutions. For example, the Princeton Ocean Model (POM), which is a component of the operational GFDL coupled hurricane model, uses $1/6^\circ$ grid spacing. Global HYCOM uses $1/12^\circ$ spacing, and up to $1/24^\circ$ resolution is frequently used in regional models, such as the Intra Americas Sea Nowcast Forecast System for the Gulf of Mexico and Caribbean Waters (Northern Gulf Institute 2012). $1/2^\circ$ or coarser resolutions are frequently used in global studies (e.g. Vincent et al. 2012).

Previous sensitivity studies on horizontal and vertical resolution in ocean models under hurricane conditions have found mixed results and have not tested a wide range of possible values. Halliwell et al. (2008) found horizontal resolution had a noticeable effect on sea surface temperature (SST) cooling, but a small effect on the heat flux from the ocean to the atmosphere when modeling Hurricane Ivan (2004). The higher grid spacing allows sharper resolution of the temperature change across

fronts, which results in only a small impact on the area-integrated heat flux. They found that a horizontal resolution of less than 10 km was sufficient, which is much finer than those used in many climate models. They also found a low impact of vertical resolution, with the ideal vertical resolution being 10 m in the ocean mixed layer. Mao et al. (2000) found that as they increased model resolution, the storms had greater intensity and the track moved farther northward. However, the resolutions they tested were 30, 40, and 50 km, which are too coarse to resolve mesoscale dynamics.

Ocean models designed for use under hurricane conditions must accurately predict sea surface temperature and upper ocean structure, as these are significant factors in forecasting storm intensity. Idealized and real case studies of coupled tropical cyclone models have shown that the storm intensity is sensitive to ocean coupling, especially for slow moving storms or those over shallow mixed layers (Bender and Ginis 2000, Ginis 2002). The interaction between the ocean and a hurricane involves both positive and negative feedback; as the storm strengthens (wind speed increases), the evaporation rate at the sea surface increases, resulting in an increase in the latent heat which enables the storm to strengthen. On the other hand, as the wind stress increases, the turbulent mixing increases, which leads to a deeper mixed layer and a decrease in sea surface temperature. This change causes a decrease in the total air-sea heat flux which results in a decrease in storm intensity. Studies examining the effect of tropical cyclones (TCs) on climate and global circulation must also accurately predict the subsurface warming, or ocean heat uptake, caused by storm-induced turbulent mixing. The wind mechanically stirs the

water in the upper ocean layer. Cold water is entrained into the mixed layer from the thermocline below causing the mixed layer to deepen. As a result, the water in the mixed layer cools and water in the upper part of the thermocline warms, as shown in Figure I.1.

Solar radiation and weaker winds restore the surface to pre-storm conditions after the passage of the storm; however, the warm anomaly will remain for a period of weeks to months and can contribute to the global ocean circulation (Emanuel 2001, Pasquero and Emanuel 2008). The mixed layer is the well-mixed, nearly homogenous temperature layer near the ocean surface. The mixed layer temperature is determined by surface heat flux, horizontal advection, and the turbulent heat flux at the mixed layer base. The spatial variations in ocean mixed layer depth (OMLD) have a significant role in SST response, the amount of cooling and the rate of intensification. Shallower mixed layer depths allow for greater SST cooling and more weakening of storms (Mao et al. 2000). Upwelling may increase the entrainment rate by reducing the mixed layer thickness (Ginis 2002). Wind-induced turbulent mixing entrains cooler water from the thermocline into the mixed layer, resulting in a deeper ocean mixed layer depth and a decreased SST.

Tropic cyclone-induced subsurface warm anomalies generated locally by turbulent mixing could play a role in driving the thermohaline circulation of the global oceans (Emanuel 2001, Pasquero and Emanuel 2008, Dare and McBride 2011). These warm anomalies monotonically decrease as lateral advection and diffusion carry heat away from the water column. The evolution of heat content is a balance between the anomalous surface heating and the heat flux away from the

column warming the surrounding waters. For the first few months post-storm, the air-sea heat flux dominates and there is a net positive heat flux; however, four to six months later, the lateral heat loss from the deeper layers of the water column results in a net negative heat flux (Pasquero and Emanuel 2008). They further concluded that approximately half of the maximum heat anomaly in the water column is lost into the atmosphere without being horizontally advected. The ocean gains heat over the perturbed region and loses heat over the equatorial band and near the coasts. The warm subsurface water is advected toward lower latitudes, driven by winds which cause equatorial upwelling. SST anomaly is reduced in about a month by air-sea heat flux and lateral displacement while the warming at the base of the mixed layer remains in the tropical regions for periods of months (Pasquero and Emanuel 2008).

Emanuel (2001) speculated that it is conceivable that much of the observed lateral heat flux carried by the ocean is induced by tropical cyclones. While tropical cyclones are relatively infrequent (there are ~90/year globally), they are very efficient mixers of the upper ocean. After the storm, the return of SST to pre-storm conditions is balanced by the lateral oceanic heat transported out of the region. By averaging the cold anomaly over the volume, he estimated the global effect of tropical cyclones on lateral heat transport to be 1.4 ± 0.7 PW. Sriver and Huber (2007) found similar values; approximately half of the global heat budget that drives the thermohaline circulation could be accounted for by mechanical stirring by cyclones. However, Jansen et al. (2010) argued that one must be careful in distinguishing between seasonal and permanent thermocline warming. They concluded that previous studies overestimate the lateral heat transport since they do not account for heat returned to

the atmosphere during the winter; they found that only 0-0.3 PW eventually make its way into the permanent thermocline and contribute to ocean heat transport. Another reason that the estimates might be too large is through the parameterization of tropical cyclones as a source of permanent mixing (Manucharyan et al. 2011) instead of as discrete events. They ran a series of simulations with a constant annual mean diffusivity but with different temporal dependences of the mixing, i.e. in one case the mixing is applied for all twelve months at a lower maximum value, and in other cases the mixing is more intermittent but has a higher maximum value. Their results showed a reduction of the local SST anomaly and anomalous heat transport from the mixing region when they decreased the fraction of the year experiencing mixing. Therefore climate studies that try to apply a constant vertical diffusivity throughout the year might overestimate the total heat transport.

This paper aims to answer the following questions: What are the effects of horizontal ocean resolution on sea surface temperature under hurricane conditions? What is the optimal horizontal ocean resolution for SST prediction? What is the impact of horizontal ocean resolution and vertical ocean resolution on the upper ocean heat uptake under hurricanes? What is the difference in impact of horizontal resolution if the model has 1D or 3D physics?

Section 2 will describe the ocean model used for these experiments. Section 3 will discuss the impact of ocean model horizontal resolution on sea surface temperature and heat fluxes. Section 4 will discuss the impact of ocean model horizontal and vertical resolution on ocean heat uptake. Section 5 will summarize the results.

2. Description of Model and Experimental Set-up

The experiments for this study were performed using a version of the Princeton Ocean Model (POM; Mellor 2004) used in the operational Geophysical Fluid Dynamics Laboratory-University of Rhode Island (GFDL-URI) coupled hurricane-ocean prediction system for the Atlantic basin (Bender et al. 2007). The idealized set-up used for this study is similar to the set-up used in Yablonsky and Ginis (2009). The horizontal POM grid is on curvilinear orthogonal coordinates, with horizontal differencing done on a staggered Arakawa C-grid. The vertical coordinates are terrain-following sigma coordinates (Gopalakrishnan et al. 2011). POM is a primitive equation model. For the 1D experiments, the advection, horizontal diffusion, and pressure gradient terms are removed so that at each grid point, there is no interaction among surrounding grid points in the horizontal.

The ocean grid is a rectangle spanning 17.773°N to 27.0227°N and 90°W to 65°W . Unlike the operational model, the ocean grid is set on an f-plane centered on 22.4°N . The domain is assumed to have a constant depth of 2500-m (no land or bathymetry).

In all experiments, the ocean is initialized with a horizontally homogeneous temperature and salinity profile and with no background currents. The temperature profile is based on the 0-2500 m portion of the Generalized Digital Environmental Model (GDEM) climatological profile in the Gulf of Mexico Common Water (GCW) or Caribbean (CRB) during the month of September (Teague et al. 1990), as shown in Figure I.2.

The axisymmetric wind field distribution is based on the wind field derived from an analytic Holland profile (Holland 1980), in this case with a central pressure of 950 hPa, environmental pressure of 1013 hPa, maximum wind speed of 55 m s^{-1} , radius of maximum wind of 55 km or 30 km, and air density of 1.28 kg m^{-3} . The wind field is then projected onto the ocean model grid. In all experiments, the wind stress field translates westward at either 2.4 or 4.8 m s^{-1} for 72 hours. The wind field remains perfectly axisymmetric; no adjustment is made for the translation speed. Figure I.3 shows the calculated Holland profiles used in these experiments.

The five horizontal resolutions tested in these experiments are: $1/2^\circ$ (51 by 21 grid points in the x and y directions), $1/3^\circ$ (76 by 31), $1/6^\circ$ (151 by 61), $1/12^\circ$ (301 by 121), and $1/18^\circ$ (451 by 181) to cover the range of grid spacings used in global studies, operationally, and in regional models. Figures I.4 and I.5 show the projection of the Holland wind profile onto the ocean model grid. Figure I.4 is a section of the wind swath for each of the resolutions, and Figure I.5 shows the wind field differences between the experiments with coarser resolutions compared to the experiment with $1/18^\circ$ grid spacing.

There are differences in the swath and instantaneous wind fields when projected onto the ocean grids of various resolutions. The maximum wind is underestimated and the radius of maximum wind is overestimated at lower resolutions. Farther from the storm center, the wind is stronger at coarser resolutions. The swath shows weaker winds over a wider swath at lower resolutions. These

differences in swath and wind speed are reflected in the differences in sea surface temperature cooling and latent heat fluxes, as discussed in Section 3.

Five sets of vertical levels were also tested: 23, 27, 32, 42, and 55 levels. All of them had the lowest sigma level located at 2500 m. The experiments with 23 vertical levels have full sigma levels at 0, 5, 10, 15, 20, 25, 30, 35, 45, 60, 75, 100, 150, 225, 325, 450, 650, 900, 1200, 1600, 2000, and 2500 m. The 23 levels are identical to those used in the operation HWRF POM model (Gopalakrishnan et al. 2011). Section 3 examining the impact of horizontal resolution on sea surface temperature and heat flux will only use the models with 23 vertical levels. The other sets of vertical levels will be discussed more thoroughly in Section 4.

3. Sea Surface Temperature and Latent Heat Flux

The high winds found in a tropical cyclone mix the ocean water causing sea surface temperatures to decrease. Hurricanes are fueled by heat from the ocean, so sea surface temperature is an important parameter in forecasting storm intensity and track. The effect of varying horizontal resolution on SST was examined for two different ocean conditions (Gulf Common Water (GCW) and Caribbean Water (CRB) initial temperature profiles (Figure I.2), and three sets of storm conditions (storm size, storm speed, and 1D or 3D physics). Table I.1 lists the sets of parameter combinations and abbreviations used for these tests.

Sea surface temperature anomalies were calculated by subtracting the initial sea surface temperature (28.86°C) from the sea surface temperature after 72 hours.

Figure I.6 shows the sea surface temperature anomaly for GCW-R3-U5 for the different resolutions tested. As depicted in the figure, there is greater SST cooling at higher resolutions. This difference can be seen more clearly in Figure I.7 by looking at cross-track cross-sections taken through the storm center and 100 km behind the storm center.

The magnitude of the cooling is greater and the asymmetry is more pronounced at higher resolutions. The rightward bias in SST cooling is due to the wind stress on the right enhancing the inertial motions. Directly under the storm, the difference in cooling between $1/2^\circ$ and $1/18^\circ$ experiments is about half a degree. The location of the maximum cooling shifts further to the right of the track; the minimum temperature for the experiments with $1/2^\circ$ and $1/3^\circ$ grid spacings is more than one times the radius of maximum winds to the left of the track whereas the minimum temperature for the experiment with $1/18^\circ$ grid spacing is about half a radius of maximum wind to the right of the storm center. There is more than a 2.5° difference in the maximum cooling at 100 km behind the storm center between the experiments with $1/2^\circ$ and $1/18^\circ$ grid spacing. The asymmetry of the storm response is more evident at higher resolutions, with a greater area of cooling to the right of the track at higher resolutions and an area more centered on the storm track at coarser resolutions. This is likely due to the stronger winds and stronger currents resonating. The coarser resolutions show larger cooling on the left hand of the storm on the periphery. These changes are also evident in looking at a zoomed-in section of the sea surface temperature anomaly differences (Figure I.8).

Figure I.9 shows the average sea surface temperature anomaly within the inner core (60 km), measured from the storm center. For G3D-R3-U5 and G1D-R3-U5, the differences in average cooling are not substantial and there is almost no difference between $1/6^\circ$, $1/12^\circ$, and $1/18^\circ$ experiments. The differences in the projection of the wind and the wind swath were not great among these resolutions and this is reflected in small differences in cooling. The experiment with $1/2^\circ$ horizontal resolution shows less cooling. The cooling is greater for the slower storm (G3D-R3-U2 and G1D-R3-U2) and the differences within the parameter cluster between resolutions are also greater. However, the ratio between the cooling for the experiments with low resolution and high resolution are similar for the two translation speeds; i.e. the ratio of cooling between $1/2^\circ$ and $1/18^\circ$ for the faster and slower experiment was similar.

There is not an appreciable impact in the effect of resolution with 1D or 3D physics for the faster storm when the temperature anomalies are averaged. However, there are significant differences in the spatial fields. Figure I.10 shows the sea surface temperature anomaly difference between the experiment with 3D physics (G3D-R3-U5) and 1D physics (G1D-R3-U5) for the same resolution. This difference is greater at higher resolution; therefore, the difference in physics is less important for experiments with coarser resolutions and more important for experiments with higher resolution. This is likely due to the higher resolution better resolving upwelling and downwelling, which are only represented by 3D physics.

Resolution sensitivity was compared for storms of two sizes, a smaller storm with a radius of maximum wind of 30 km and a larger storm with a radius of maximum wind of 55 km. For the experiment with larger storm, the experiment with $1/2^\circ$ grid

spacing has the most cooling and the experiment with $1/3^\circ$ spacing has the least.

Since 55 km is approximately half a degree, the $1/2^\circ$ experiment captures the maximum wind but does not capture the decrease in wind speed as accurately as the experiments with higher resolution. The experiment with $1/3^\circ$ grid spacing does not capture the maximum wind speed and therefore has less mixing and less cooling.

The most drastic differences in average sea surface temperature anomaly are in the experiment with the slower storm. However, while it has the largest differences and largest cooling overall, the proportion of cooling in the $1/2^\circ$ experiment to the cooling in the $1/18^\circ$ is only slightly more than in the faster moving storm.

Another important measure of the effect of sea surface temperature on hurricane intensity is the latent heat flux. The flux was calculated assuming a fixed horizontally homogenous atmosphere with 10-m air temperature of 25°C , 95% relative humidity, and a fixed atmospheric pressure of 980 mb. These values are similar to those used in Cione and Ulhorn (2003). The latent heat flux, H_L is computed by

$$H_L = \rho L_v C_e U (q_{SST} - q_A) \quad (1)$$

where ρ is the air density, U is the 10-m wind speed, C_e is the dimensionless coefficient of moisture exchange at 10 m, L_v is the latent heat of vaporization, and q_{SST} and q_A are the saturation mixing ratios at the SST and the air temperature respectively. H_L is calculated for each point in the domain, interpolated onto a $1/18^\circ$ mesh, and then averaged within a 60 km radius from the storm center. Any values that were calculated to be less than zero, which is unphysical, were set to zero before averaging. Generally an increase in resolution results in an increase in latent heat flux due the reduced maximum winds in the coarser resolution experiments. For the

faster moving storm, the differences between $1/6^\circ$, $1/12^\circ$, and $1/18^\circ$ average latent heat flux are small. It is not necessary to increase the horizontal resolution beyond this range. For the slower moving storms, the maximum wind speed is the same as for the faster moving storm experiment, but the sea surface temperature cooling is greater, especially in the 3D experiments, so the flux is smaller. For the slower storm, the different trend in average heat flux with increasing grid spacing from $1/2^\circ$ to $1/6^\circ$ resolutions might be explained by the fact while the maximum wind is stronger for higher resolutions, the SST cooling is larger. Latent heat flux may decrease if the rate of SST cooling is larger than the rate of the wind increase (see Equation 1). The role of resolution is masked when comparing averages, as there are spatial differences that emerge when looking at the latent heat flux fields, as shown in Figures I.12 and I.13.

At lower resolutions, the wind is stronger near the eye, and weaker toward the periphery and SST cooling is less. These patterns are reflected in the latent heat flux differences in the inner core as shown in Equation 1. The averages appear similar in Figure I.11 because the negative and positive differences are off-setting each other. The largest spatial differences in the latent heat flux between resolutions are in the case of the slower moving storm, shown in Figure I.13.

It has been shown that horizontal resolution has a greater impact on sea surface temperature anomaly and fluxes for smaller and slower moving storms than larger or faster ones. The differences in sea surface temperature can be traced back to differences in turbulent kinetic energy (TKE), as shown in Figures I.14 and I.15. The wind stirs the water and generates currents. The turbulent kinetic energy is related to

the vertical shear of the currents and is a measure of the amount of mixing. The degree of mixing is correlated with the sea surface temperature decrease under the storm. The model experiments with higher resolution also have higher TKE. Higher resolution allows for better representation of the wind profile. The higher wind field thus results in stronger currents with stronger vertical shear, which is reflected in the higher TKE values.

This study also examined the sensitivity to horizontal resolution under different ocean conditions. The main difference between the Gulf of Mexico and Caribbean Sea initial temperature profiles is the depth of the mixed layer; they both have the same sea surface temperature (Figure I.2). For the Caribbean Sea (CRB) experiments (see Table I.1), the same SST anomaly trends hold as they do for the Gulf of Mexico Common Water experiments, but the magnitudes of the hurricane-induced temperature cooling are smaller, as expected. The ratio of maximum sea surface temperature anomalies and latent heat fluxes between $1/2^\circ$ to $1/18^\circ$ are similar for the experiments with the two different initial temperature profiles (not shown).

4. Ocean Heat Uptake

Ocean heat uptake (OHU) is an important measurement of the impact of hurricanes on global ocean circulation. It is calculated by:

$$OHU = \rho c_p \int_{z_1}^{z_2} (T_{t=72} - T_{t=0}) \cdot dz \quad (2)$$

where ρ is the density, c_p is the heat capacity, T is the temperature, z_1 is the depth of the top of the warm anomaly and z_2 is the depth of the bottom of the warm anomaly, as marked in Figure I.16 below. This section will examine the impact of horizontal resolution and vertical resolution on ocean heat uptake.

4.1 Effect of horizontal resolution:

Figure I.17 shows the spatial distribution of ocean heat uptake for the $1/18^\circ$ and $1/3^\circ$ experiments. The OHU field is much greater at higher resolutions than lower resolutions. The maximum ocean heat uptake is about 60 W/m^2 for the experiment with $1/18^\circ$ grid spacing and only 40 W/m^2 for the experiment with $1/3^\circ$ grid spacing.

Figure I.18 shows the domain-averaged vertical temperature anomaly profile for G1D-R3-U5.

The cold sea surface temperature anomaly magnitudes are greater at higher resolutions, but horizontal resolution has little impact on the location of z_1 . The depth of z_2 is deeper for higher horizontal resolution, resulting in larger ocean heat uptake. As the hurricane moves across the ocean, the domain-integrated ocean heat uptake increases. Figure I.19 shows the domain-integrated OHU for G1D-R3-U5 between hours 24 and 72. The figure shows that the OHU rate is higher at higher resolutions. The rates are 0.14, 0.15, 0.17, 0.18, 0.19 PW for the $1/2^\circ$, $1/3^\circ$, $1/6^\circ$, $1/12^\circ$, and $1/18^\circ$ experiments, respectively. Global models using coarser resolution could substantially underestimate the impact of hurricanes on the OHU.

The ocean heat uptake is harder to calculate for the experiments with 3D physics than 1D physics since the 3D effects of upwelling and downwelling can shift the vertical temperature profile, making it difficult to locate z_1 and z_2 . When averaged over the whole domain, the 3D vertical advection effects are cancelled out. Figure I.20 shows the average vertical temperature anomaly profile for G3D-R3-U5. The experiment with $1/2^\circ$ grid spacing was neglected from this figure due to suspect results that require further investigation. The location of z_1 is similar for the different horizontal resolutions, although the sea surface temperature cold anomalies are greater at higher resolutions as in G1D-R3-U5 experiments. The maximum warm anomaly is greater at higher resolutions, and the location of z_2 is deeper, so the ocean heat uptake will be larger at finer resolutions. Figure I.21 shows the domain averaged ocean heat uptake rates for these experiments between hours 24 and 72. The trends seen for the 3D model are similar to the trends seen in the 1D results. The rate increases as grid spacing increases, and there is very little difference between the experiments with $1/12^\circ$ and $1/18^\circ$ grid spacing. The OHU rates are 0.16, 0.20, 0.21, and 0.21 PW for $1/3$, $1/6$, $1/12$, and $1/18^\circ$ grid spacing respectively.

4.2 Effect of vertical resolution:

The impact of vertical resolution on ocean heat uptake was also investigated. The higher vertical resolution allow for more accurate calculations of z_1 and z_2 . The experiments were repeated with 23, 27, 32 and 42 vertical levels. The 23-level experiment was identical to the one used in Section 3. The experiments with 27 vertical levels have z levels every 10 meters starting at 0 m down to 160 meters; thereafter the levels are located at 180, 220, 300, 450, 650, 900, 1200, 1600, 2000,

and 2500 m. The experiments with 32 levels have levels located every 5 meters from 0 meters to 50 meters, thereafter every 10 meters down to 160 meters, thereafter they have match the levels found in the 27-level experiment. The experiments with 42 levels have 5 meter spacing from 0 m to 150 m, thereafter they followed the progression from 160 m, matching the 27 and 32 level experiments. These set-ups are summarized in Table I.2. For these experiments, the horizontal resolution was fixed at $1/18^\circ$. Here the “mixed layer vertical resolution” is defined as the vertical resolution from the surface down to 50 m; the “upper thermocline vertical resolution” is defined as the vertical spacing between 50 m and 150 m. These cut-offs are based roughly on the expected locations of z_1 and z_2 .

Differences in the calculation of OHU can arise due to different temperature values and different values of z_1 and z_2 . Figure I.22 shows the domain-averaged vertical temperature anomaly profiles for different vertical resolutions. The ML10-UT10 experiment differs from the others, as it has the coarsest mixed layer resolution. It has the smallest warm and cold anomalies. However, it does have a similar z_2 to ML5-UT10. ML5-UT >10 has the coarsest resolution in the upper thermocline and the deepest z_2 , which leads to a larger warm anomaly. Table I.3 shows the ocean heat uptake rate and heat loss rate for G1D-R3-U5 $1/18^\circ$ for the different vertical resolutions tested.

Theoretically the heat loss and heat uptake must be equal during 1D vertical mixing. However, in a numerical model there are errors due to finite difference approximation of the differential equations in the vertical. The heat loss and heat uptake rates are similar for all the experiments with mixed layer vertical resolution of

5 m; the heat loss rate is associated with the cold anomaly and therefore is dependent on z_1 and not z_2 . Mixed layer spacing of 10 m results in a much smaller heat loss rate. Therefore the 10 m vertical resolution in the mixed layer is inadequate. The heat uptake rate is dependent on both z_1 and z_2 , so both mixed layer resolution and upper thermocline resolution are important in this calculation. The small differences between ML5-UT10 and ML5-UT5 indicate that 10 m resolution is sufficient in the upper thermocline.

The impact of vertical resolution is more pronounced in the experiment with 3D physics, G3D-R3-U5 $1/18^\circ$. Figure I.23 shows the domain averaged vertical temperature anomaly profiles. Again, the mixed layer spacing of 10 m does not capture the full extent of the warm anomaly and the upper thermocline spacing of greater than 10 m has a deeper z_2 than the experiments with finer vertical resolution in the upper thermocline. These differences are also evident when comparing the heat uptake and heat loss rates (Table I.4). Note that in a 3D model the heat loss is greater than heat uptake because turbulent mixing is affected by hurricane-induced vertical upwelling.

The heat uptake rate is greater with higher resolution as z_2 is calculated more accurately; there is little difference in the heat loss rate. Again, it appears that vertical spacing of at least 5 m in the mixed layer and at least 10 m in the upper thermocline are necessary for accurate measurement of ocean heat uptake.

The differences in OHU rates for different vertical resolutions can be explained by comparing vertical cross-sections of turbulent kinetic energy. Figure I.24 shows a cross-section taken 100 km parallel to the track; Figure I.25 shows a

cross-section taken through the track, at the same locations as in Figures I.14 and I.15. In ML10-UT10 experiments, the turbulent kinetic energy has the smallest magnitude. As a result, the entrainment of colder water from the thermocline is reduced. This explains why the upper ocean heat loss is the smallest in these experiments. The differences in magnitude between vertical spacings are greater in the experiments with 3D physics than those with 1D physics.

5. Conclusions

The results of this study can be summarized as follows:

- Hurricane-induced sea surface temperature cooling in a numerical ocean model is sensitive to the grid spatial resolution. The cooling is less at coarser spatial resolutions than finer resolutions. This is primary because the hurricane wind structure is not well resolved for larger grid spacing, especially within the eyewall.
- The effect of horizontal resolution is larger in the model with 3D physics than 1D physics. This is primarily due to the higher resolution better resolving hurricane-induced upwelling and downwelling, which are only represented by 3D physics.
- Horizontal resolution has a greater impact in resolving the ocean response for smaller and slower moving storms than larger and faster moving storms.
- Generally, an increase in horizontal resolution tends to increase the latent heat flux due to more accurate representation of the hurricane winds.
- The differences in sea surface temperature cooling for different resolutions can be traced back to the spatial distribution of hurricane-induced turbulent kinetic energy in the upper ocean. TKE is typically stronger in a higher resolution model.

- The values of SST, latent heat flux, and TKE converge in experiments with 1/12° and 1/18° grid spacing. These resolutions may be considered optimal for coupled hurricane-ocean models.
- Ocean heat loss and uptake increase as both horizontal and vertical resolutions increase.
- Vertical grid spacing of at least 5 m in the mixed layer and at least 10 m in the upper thermocline are necessary for accurate calculations of ocean heat loss and uptake.

REFERENCES

- Bender, M. A., and I. Ginis, 2000: Real case simulation of hurricane-ocean interaction using a high-resolution coupled model: Effects on hurricane intensity. *Monthly Weather Review*, **128**, 917-946.
- Bender, M. A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The operational GFDL Coupled Hurricane-Ocean Prediction System and a summary of its performance. *Monthly Weather Review*, **135**, 3965-3989.
- Dare, R.A. and J.L. McBride, 2011: Sea surface temperature response to tropical cyclones. *Monthly Weather Review*, **139**, 3798-3808.
- Emanuel, K., 2001: Contribution of tropical cyclones to meridional heat transport by the oceans. *Journal of Geophysical Research*, **106**, 14771-154781.
- Ginis, I., 2002: Tropical cyclone-ocean interactions. *Atmosphere-Ocean Interactions, Advances in Fluid Mechanics Series*, No. 33, WIT Press, 83-114.
- Gopalakrishnan, S., Q. Liu, T. Marchok, D. Sheinin, N. Surgi, M. Tong, V. Tallapragada, R. Tuleya, R. Yablonsky, and X. Zhang, 2011: Hurricane Weather Research and Forecasting (HWRF) Model: 2011 Scientific Documentation. L. Bernardet, Ed., 81 pp. Available from DTCenter.org.
- Halliwell, G.R., Jr., L.K. Shay, S.D. Jacob, O.M. Smedstad, and E.W. Uhlhorn, 2008: Improving ocean model initialization for coupled tropical cyclone forecast models using GODAE nowcasts, *Monthly Weather Review*, **136**, 2576-2591.

- Holland, G. J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Monthly Weather Review*, **108**, 1212–1218.
- HYCOM, cited 2012: HYCOM + NCODA Global 1/12° Analysis (GLBa0.08/expt_90.0). [Available online at http://hycom.org/dataserver/glbanalysis/expt_90pt9]
- Jansen, M.F., R. Ferrari, and T.A. Mooring, 2010: Seasonal versus permanent thermocline warming by tropical cyclones. *Geophysical Research Letters*, **37**, L03602.
- Manucharyan, G.E., C.M. Brierley, and A.V. Fedorov, 2011: Climate impacts of intermittent upper ocean mixing induced by tropical cyclones. *Journal of Geophysical Research*, **116**, C11038.
- Mao, Q., S.W. Chang, and R.L. Pfeffer, 2000: Influence of large-scale initial oceanic mixed layer depth on tropical cyclones. *Monthly Weather Review*, **128**, 4058–4070.
- Mellor, G.L., 2004: Users guide for a three-dimensional, primitive equation, numerical ocean model (June 2004 version). Program in Atmospheric and Oceanic Science, Princeton University, 56 pp.
- Northern Gulf Institute/NOAA Developmental Ecosystem Data Assembly Center, cited 2012: Intra Americas Sea Nowcast Forecast System. [Available online at www.northerngulfinstitutue.org/edac/IASNFS.php]
- Pasquero, C. and K. Emanuel, 2008: Tropical cyclones and transient upper-ocean warming. *Journal of Climate*, **21**, 149–162.
- Price, J., 1981: Upper ocean response to a hurricane. *Journal of Physical Oceanography*, **11**, 153–175.
- Sriver, R.L. and M. Huber, 2007: Observational evidence for an ocean heat pump induced by tropical cyclones. *Nature*, **447**, 577–580.
- Teague, W.J., M. Carron, and P. Hogan, 1990: A comparison between the Generalized Digital Environment Model and Levitus climatologies. *Journal of Geophysical Research*, **95**, 7167–7183.
- Vincent, E., M., M. Lengaigne, G. Madec, J. Vialard, G. Samson, N. Jourdain, C. E. Menkes and S. Jullien, 2012: Processes setting the characteristics of sea surface cooling induced by Tropical Cyclones, *Journal of Geophysics Research*, **117**, C02020, doi:10.1029/2011JC007396.

Yablonsky, R. and I. Ginis, 2009: Limitations of one-dimensional ocean models for coupled hurricane-ocean model forecasts, *Monthly Weather Review*. **137**, 4410-4419.

Table I.1: Experiment Parameters for Sea Surface Temperature Tests

Initial T	1D/3D	Storm Size (km)	Storm Speed (m/s)	
GCW	3D	30	4.8	G3D-R3-U5
GCW	1D	30	4.8	G1D-R3-U5
GCW	3D	55	4.8	G3D-R5-U5
GCW	3D	30	2.4	G3D-R3-U2
CRB	3D	30	4.8	C3D-R3-U5
CRB	1D	30	4.8	C1D-R3-U5
CRB	3D	55	4.8	C3D-R5-U5
CRB	3D	30	2.4	C3D-R3-U2

Table I.2: Vertical Resolution Experiments

No. Vert. Levels	Mixed Layer Vertical Resolution (m)	Upper Thermocline Vertical Resolution (m)	
23	~5	>10	M5-U>10
27	10	10	M10-U10
32	5	10	M5-U10
42	5	5	M5-U5

Table I.3: Impact of Vertical Resolution on Heat Uptake and Heat Loss Rates for G1D-R3-U5 1/18°

	Heat Uptake Rate (PW)	Heat Loss Rate (PW)
ML5-UT>10	0.19	0.21
ML10-UT10	0.18	0.16
ML5-UT10	0.21	0.22
ML5-UT5	0.22	0.21

Table I.4: Impact of Vertical Resolution on Heat Uptake and Heat Loss Rates for G3D-R3-U5 1/18°

	Heat Uptake Rate (PW)	Heat Loss Rate (PW)
ML5-UT>10	0.21	0.31
ML10-UT10	0.15	0.32
ML5-UT10	0.28	0.32
ML5-UT5	0.28	0.32

Figure I.1: The figure on the left shows the initial temperature profile (dashed line) and the profile at the same location 72 hours after storm passage (solid line). The temperature anomaly is shown on the figure in the right; the filled blue area is the region of cooling and the red area is the region of sub-surface warming.

Figure I.2: Initial temperature profiles in the upper 150 meters for Gulf Common Water (GCW) or Caribbean Sea (CRB) profiles. For these idealized experiments, the initial temperature field is horizontally homogeneous.

Figure I.3: Radial cross-section of the wind speed based on the Holland profile. Here, the maximum wind is 55 m/s and the radius of maximum wind is either 30 or 55 km.

Figure I.4: Wind Swath (top) and Wind Swath Anomalies (middle and bottom) in m s^{-1} for the experiments with a 30 km radius of maximum wind.

Figure I.5: Wind field anomalies in m s^{-1} in different horizontal resolution experiments relative to the $1/18^\circ$ resolution for the experiments with 30 km radius of maximum wind. The dashed line is the radius of maximum wind and the solid line is the 60 km radius from the storm center.

Figure I.6: Sea surface temperature anomaly at 72 hours from initial state for experiment G3D-R3-U5. Temperature contours are every 0.5° . The solid black line is the storm track. The dashed lines are the locations of the cross-track cross-sections shown in Figure I.7. The dashed ellipse represents the radius of maximum wind (30 km). Because the figure axes are not equal, the radius of maximum wind does not appear axisymmetric.

Figure I.7: Cross-track cross-sections of SST anomaly for G3D-R3-U5. The cross-section to the left is taken through the storm center. The cross section to the right is taken 100 km in the wake of the storm. The x-axis is the horizontal distance north/south to the storm track normalized by the radius of maximum wind.

Figure I.8: Sea surface temperature anomaly differences for G3D-R3-U5. The dashed white circle shows the radius of maximum wind; the solid white circle shows the 60 km radius from the storm center. Contours are every $1/2^\circ$.

Figure I.9: Average sea surface temperature anomaly within 60 km of storm center. Each cluster shows the results for the five resolutions tested for one parameter set. The clusters shown are (left to right): G3D-R3-U5, G1D-R3-U5, G3D-R3-U2, and G1D-R3-U2.

Figure I.10: Difference between G3D-R5-U5 and G1D-R5-U5 for the experiments with horizontal grid spacing of $1/18^\circ$ (top) and $1/3^\circ$ (bottom). The solid line is the storm track; the dashed “circle” is the radius of maximum wind.

Figure I.11: Average latent heat flux within 60 km of storm center. Each cluster shows the results for the five resolutions tested for one parameter set. The clusters shown are (left to right): G3D-R3-U5, G1D-R3-U5, G3D-R3-U2, G1D-R3-U2.

Figure I.12: Top: latent heat flux (W m^{-2}) for $1/18^\circ$ G3D-R3-U5 experiment. The black circle is the 60 km radius. Bottom: Latent heat flux differences (W m^{-2}) for G3D-R3-U5. The white dashed circle is the radius of maximum winds. The white solid circle is 60 km from the storm center. Solid black contours are positive differences; dashed black contours are negative differences. The contour spacing is every 100 W m^{-2} .

Figure I.13: Same as bottom of Figure I.12 but for G3D-R3-U2.

Figure I.14: Vertical cross-section of turbulent kinetic energy taken 100 km parallel to the right of the track. The dashed white line shows the longitude of the storm center.

Figure I.15: Vertical cross-section of the turbulent kinetic energy. The cross-section is taken one degree behind the storm center. The dashed white line shows the latitude of the storm center.

Figure I.16: Domain-averaged vertical temperature anomaly. The area in blue is the cold anomaly and the area in red is the warm anomaly. $Z1$ is at the depth where the curve first shifts from positive to negative, between the blue and red areas (top black line). $Z2$ is the depth at the bottom of the warm anomaly where the anomaly is approximately zero from there to the ocean floor, at the bottom of the red area, bottom black line.

Figure I.17: Ocean heat uptake (W m^{-2}) for G1D-R3-U5 for the experiments with horizontal grid spacing of $1/18^\circ$ (top) and $1/3^\circ$ (bottom). The solid line is the storm track; the dashed “circle” is the radius of maximum wind.

Figure I.18: G1D-R3-U5 domain-averaged vertical temperature profile for different resolutions.

Figure I.19: Domain integrated OHU in G1D-R3-U5 experiments. The ocean heat uptake rate (J) is found by taking the slope of the linear fit to the ocean heat uptake between hours 24 and 72.

Figure I.20: Average vertical temperature anomaly profiles in G3D-R3-U5 experiments.

Figure I.21: Ocean heat uptake rates (J) for G3D-R3-U5.

Figure I.22: Domain averaged vertical temperature anomaly profile in G1D-R3-U5 for different vertical resolutions.

Figure I.23: Same as Figure I.18 but for G3D-R3-U5 $1/18^\circ$ experiments.

Figure I.24: Same as Figure I.14 but comparing vertical resolutions for the experiment with 1D physics (left), 3D physics (right). Within each panel, the upper left is for ML5-UT>5; the upper right is ML10-UT10; the lower left is ML5-UT10, and the lower right is ML5-UT5.

Figure I.25: Same as Figure I.15 but comparing vertical resolutions for the experiment with 1D physics (left), 3D physics (right). Within each panel, the upper left is for ML5-UT>5; the upper right is ML10-UT10; the lower left is ML5-UT10, and the lower right is ML5-UT5.

Chapter 2

"Evaluating Ocean Model Initializations for Hurricane Prediction"

by

Melissa Kaufman¹, Isaac Ginis², Richard Yablonsky³

is being prepared for publication in Weather and Forecasting.

¹ MS Candidate, Graduate School of Oceanography, The University of Rhode Island, Narragansett, RI 02882. Email: mkaufman@gso.uri.edu

² Professor, Graduate School of Oceanography, The University of Rhode Island, Narragansett, RI, 02882. Email: iginis@gso.uri.edu

³ Marine Research Associate, Graduate School of Oceanography, The University of Rhode Island, Narragansett, RI, 02882. Email: ryablonsky@gso.uri.edu

ABSTRACT

Although hurricane models can now more accurately forecast storm track, they have not made significant improvement in forecasting hurricane intensity. Sea surface temperature and ocean heat content play an important role in regulating tropical cyclone intensity. The focus of this study is on initialization scheme. The Princeton Ocean Model (POM) is used to calculate the temperature fields under a specified hurricane wind stress, utilizing wind data from National Hurricane Center message files for the initialization simulations.

Different model initializations, primarily differing in the method of data assimilation, were tested and model output was compared to in-situ data from buoys and Airborne eXpendable BathyThermographs (AXBTs) and satellite observations from a survey mission on 16 July 2009 and during Hurricane Isaac in 2012. The initializations tested were Global HYCOM and Feature-Based. For the survey, the feature-based initialization was run three times, once using only CCAR altimetry input, a second time using CCAR as well as AXBTs to determine the warm core ring structure and location, and a third time using CCAR altimetry input and AXBTs to determine the location only. The survey model comparisons showed that the feature-based simulation with AXBT assimilation had the best agreement with the data. The results were less conclusive when assessing the model response to hurricane conditions during Hurricane Isaac. Both simulations have locations where they have good skill, but no initialization out-performed the others overall. Both of the simulations overestimate the sea surface temperature cooling; the feature-based

simulation typically underestimates the mixed layer depth whereas the HYCOM simulation overestimates it.

1. Introduction

The ability to forecast accurately hurricane track and intensity is an important and complex issue. It has been well established that the ocean is a driving force behind hurricane genesis and evolution (e.g. Price 1981, Ginis 2002). Idealized and real case studies of coupled tropical cyclone models have shown that storm intensity is sensitive to ocean coupling, especially for slow moving storms or those over shallow mixed layers (Bender and Ginis 2000, Ginis 2002).

Many studies compared observations to models for specific storms (eg. Bender and Ginis 2000, Bender et al. 2007, D'Asaro et al. 2007, Sanford et al. 2007, Halliwell et al. 2008, Mainelli et al. 2008, Sriver et al. 2008, Halliwell et al. 2011, Lloyd et al. 2011) or specifically in the vicinity of the Loop Current in the Gulf of Mexico (eg. Leben 2005, Oey et al. 2005, Vukovich 2007, Hamilton et al. 2011, Shay et al. 2011). The response of an ocean model to hurricane forcing is very sensitive to initial conditions. This study examines two different initialization procedures, Global HYCOM and Feature-Based (FB), in the Princeton Ocean Model (POM). One of the key differences between these methods is the degree and method of data assimilation. Data assimilation is essential for accurate ocean forecasting because 1) many ocean phenomena are due to flow instabilities and therefore are not simply a deterministic response to atmospheric forcing, 2) there are errors in atmospheric forcing, and 3) ocean models are also imperfect, especially due to

limitations in resolution (Chassignet et al. 2006). Section 2 will discuss the details of these initialization methods. Section 3 will evaluate the initialization initial fields compared to an array of Airborne eXpendable BathyThermographs (AXBTs) dropped in July of 2009. Section 4 will examine the modeled ocean response to Hurricane Isaac (2012). Section 5 will summarize the conclusions.

Section 2: Model Initialization Methods

Two different model initialization methods will be compared: Global HYCOM and Feature-Based. HYbrid Coordinate Ocean Model (HYCOM) is a free-running global ocean model that is nudged daily towards NCODA (Chassignet et al. 2006, Chassignet et al. 2009). NCODA, or Navy Coupled Ocean Data Assimilation, is a daily real-time global ocean product distributed by the Fleet Numerical Meteorological and Oceanography Center (FNMOC) and Naval Oceanographic Office (NAVOCEANO). Its output is comprised of 3-dimensional temperature, salinity, and geostrophic current fields, as well as the 2-D geopotential. The fields are created from short-term forecasts to which available observations are assimilated. The interpolation method used to assimilate the data is an oceanographic implementation of the multivariate optimum interpolation technique (MVOI). Table II.1 lists global operational ocean observation data sources (Cummings 2005). NCODA has $1/6^\circ$ horizontal resolution and 34 vertical levels.

HYCOM wind and thermal forcing inputs are provided by Navy Operational Global Atmospheric Forcing System (NOGAPS) (Chassignet et al. 2006). HYCOM has $1/12^\circ$ horizontal resolution and 32 vertical levels. The vertical coordinates are a

hybrid of isopycnal, sigma-level, and z-level. It has been running in real time since February 2007 (Chassignet et al. 2009) and daily fields are available at ftp.hycom.org.

The feature-based (FB) initialization method initially reads in the Generalized Digital Environmental Model (GDEM) climatology (Falkovich et al. 2005, Yablonsky and Ginis 2009, Gopalakrishnan et al. 2011). GDEM is a monthly temperature and salinity climatology, with a horizontal grid spacing of $1/2^\circ$ and 33 vertical levels. The data in the version of GDEM used operationally in Hurricane Weather Research and Forecasting (HWRF) model are mostly taken from the 1986 Master Oceanographic Observational Data Set (MOODS) (Teague et al. 1990). Climatology does a poor job representing mesoscale oceanic features that do not follow an annual or regular cycle, such as the penetration of the Loop Current into the Gulf of Mexico and the shedding and reattachment of Loop Current eddies (Yablonsky and Ginis 2009). The correct location of these features is important for hurricane prediction; the Loop Current separates the two water masses of different properties. The Gulf of Mexico waters have a shallower mixed layer, while the Caribbean Sea waters have a deeper mixed layer. This difference in mixed layer depth could affect storm intensity and SST cooling as the storm crosses the Loop Current. A key assumption in the FB modeling approach is that the cross-frontal temperature, salinity, and velocity structures in the upper and main thermocline do not change significantly along the strong oceanic front (Falkovich et al. 2005). The FB method involves a cross-frontal “sharpening” procedure to yield more realistic ocean structure. The Loop Current position and structure and associated eddies are manually placed during model initialization based on real time in situ or remotely sensed

observations. One data source frequently used is the Colorado Center for Astrodynamic Research (CCAR) sea surface height (SSH), which is based on satellite altimetry (Leben et al. 2002: http://eddy.colorado.edu/ccar/ssh/hist_gom_grid_viewer). Based on Leben's findings (2005), the 17 cm SSH contour is used to define the feature boundaries. Other available data sources such as AXBTs can then be used to refine feature position and structure (Yablonsky and Ginis 2008). During spin-up of the FB model, the 1° resolution NCEP GFS SST daily product (Reynolds and Smith 1994) is assimilated. In the operational HWRF hurricane model, the FB method is used for the ocean model with 1/6° horizontal spacing and 23 vertical levels (Gopalakrishnan et al. 2011). For this study, a version of this code has been adapted for research purposes with 1/12° horizontal grid spacing.

All of these initialization procedures were tested in the Princeton Ocean model (POM). POM is a 3D, primitive equation, numerical ocean model with sigma coordinates in the vertical and curvilinear orthogonal horizontal coordinates on an Arakawa C grid (Mellor 2004). There are two phases to model operation. During phase 1 (historically phase 3), the ocean is spun up for 48 hours, while the SST is held constant. The temperature and salinity fields are dynamically adjusted and geostrophically-adjusted currents are generated. In phase 2 (historically phase 4), wind stress is applied and the cold wake is generated. Currently, wind information from the National Hurricane Center (NHC) message files is used (Bender and Ginis 2000). The model was run for the United Domain for FB and for a transatlantic subset of the Global HYCOM (Figure II.1). The Global HYCOM was run on an mpi-

version of POM. It has 18 years of community upgrades, including the ability to run on multiple processors (URI July 2012 HFIP report).

3. Evaluation of HYCOM/Feature-Based Initial fields using AXBT data

Remotely sensed satellite data and in-situ data are useful for assimilation into the model and for model verification. Two sources of in situ data are used in this study: AXBTs and buoys. Airborne eXpendable BathyThermographs (AXBTs) are launched from aircraft flying above the storm. Once they hit the sea surface, the AXBTs float on the surface and deploy a long wire with thermistors, or temperature sensors, which collect and transmit the vertical temperature profile through the water column at that location at the time of the drop. Figure II.2 shows an AXBT and a schematic of its deployment. Buoys are also a good source of in situ data; while they only collect temperature data at the surface. AXBT data is only available at a one location at one time; buoy data is available at one location but frequently with temporal resolution of an hour.

Fifty-seven AXBTs were deployed in a lawnmower pattern in the Gulf of Mexico on July 16, 2009 by NOAA/AOML Hurricane Research Division (HRD). Figure II.3 shows the AXBT locations. The goal was to collect information on sea surface temperature and ocean heat content as background for any tropical activity in the Gulf of Mexico during the 2009 season.

(http://www.aoml.noaa.gov/hrd/Storm_pages/misc2009/20090716I1.html)

In early July 2009, a large warm core ring (WCR), known as Eddy Ekman, broke off from the Loop Current (Horizon Marine, Hamilton et al. 2011). This array of AXBT

observations allows the validation of model initialization in pre-storm conditions and the examination of feature position and structure of the WCR. One of the goals of the NOAA/AOML/HRD 2009 Hurricane Field Program was to collect information that spans the tropical cyclone lifecycle in a variety of environments as part of the Intensity Forecasting EXperiment (IFEX) Program. The purpose of IFEX was a better understanding of storm genesis and ocean-atmospheric interaction; this would hopefully lead to refinements in forecasting storm intensity. They used a variety of instruments including radar, Stepped Frequency Microwave Radiometer (SFMR), and AXBTs to collect measurements of ocean and atmospheric conditions.

The AXBT information is used in NCODA if it is available by forecast hour, which is then used in HYCOM. In the FB initialization, AXBTs can be used to refine the position and structure of the Loop Current and any Loop Current Eddies present. The temperature field is initially taken from GDEM monthly climatology, shown for July in Figure II.4. Next, satellite altimetry data is used to create an initial approximation of the position of the Loop Current and any eddies in the Gulf of Mexico, Figure II.5. Here, CCAR SSH is used to define the northern extent of the Loop Current, the points at either end of the major axis of any rings, and the radius of the minor axis. Caribbean Common Water temperature profile is used to define the vertical temperature profile at the center of the WCR. The result of the above steps is shown in Figure II.6.

At this stage, AXBTs can be used to refine the structure and position of the warm core ring. The edge of the ring can be located where there is a transition from a deeper mixed layer and the water is warmer at depth to the shallower mixed layer and

colder water at depth of the Gulf Common Water. Figure II.7 shows three AXBTs in a row that are used to bound the WCR. While the temperature profile measured by AXBT #33 shown in Figure II.7 is characteristic of Gulf Common Water, the temperature profile measured by AXBT #31 is clearly located within the WCR as evidenced by the deep thermocline and warmer water at 300 m. We can therefore locate the edge of the ring near AXBT #32. Adjusting based on AXBT information resulted in the eastern extent of the WCR being relocated 0.3° farther east, the center of the ring shifting 0.35° north, and the radius of the minor axis shrinking by 0.2° . The center of the ring was identified by the location with the deepest mixed layer and the warmest temperature at 75 m depth. In this case, AXBT #54 marks that location and is used to define the water profile at the center of the ring instead of the default Caribbean profile as shown in Figure II.8. The Caribbean profile is the default because the WCR breaks off from the Loop Current which originates in the Caribbean. Finally, the GFS SST is assimilated. Figure II.9 shows the SST and temperature at 75 m depth after the AXBT and SST assimilation.

This study will compare three different FB initializations that use 1) only CCAR SSH information to define feature position (FB-CCAR), 2) AXBT information to refine the WCR position (FB-AXBT-POSONLY), and 3) AXBT information to refine the WCR position and to define the temperature structure in the center of the ring (FB-AXBT). The location of the Loop Current and the CCR are not changed in all three FB initializations; the differences are only in the position and structure of the WCR.

Figure II.10 compares the sea surface heights from the Global HYCOM and

the three FB initializations to the CCAR SSH data. The model comparisons were done using the output fields from the end of phase 1, after a 48-h spin-up. It is important to note that the FB initialization only allows for elliptical types of eddies. Eddies with more complex geometry cannot be accurately represented. On 16 July, 2009, the CCAR SSH incorporated data from three satellites: Envisat, Jason1, and Jason2. The five panels in Figure II.10 show the differences in size, shape, and location of Eddy Ekman in the observations and in the model with different data assimilation procedures. The Global HYCOM eddy is the closest in size and shape to the CCAR SSH, as it is not constrained to be elliptical in shape. FB-CCAR results in a ring that is too weak; this is remedied by using the center profile defined from AXBT data (FB-AXBT). FB-AXBT-POSONLY has the same WCR position as the FB-AXBT but the structure is too weak like FB-CCAR.

While the sea surface height is a good indicator of ring position, for ocean modeling and especially for hurricane modeling, the thermal structure is of greater importance. The sea surface temperature is the immediate driver, as it is in contact with the atmosphere (Figure II.11). In addition to the AXBTs, the simulated SST can be compared to remotely sensed satellite data. The Tropical Rainfall Measuring Mission (TRMM) radiometer, the TRMM Microwave Imager (TMI), retrieves sea surface temperature. The advantage of the microwave retrieval over infrared observation is that SST can be measured through clouds. Data is available on a 0.25° grid (www.ssmi.com/tmi/tmi_description.html). The TMI data shown below is a 3-day average 14 July through 16 July 2009 inclusive.

The TMI satellite SST is much warmer than the blended AXBT temperature

field, so there is some discrepancy between the direct observations. The sea surface temperature for all of the feature-based simulations is identical to the GFS SST, and it is much cooler than the TMI, AXBT, and HYCOM SSTs. The sea surface temperature in the Gulf of Mexico has small horizontal variability during the summer (Yablonsky and Ginis 2008), but the mixed layer depth and upper thermocline depth will vary with feature and Loop Current positions so larger differences are expected in temperature fields below the surface.

Figure II.12 shows the temperature at a depth of 75 meters from the surface for the AXBTs and for the different simulations. Both the Global HYCOM and FB without AXBT assimilation of center temperature structure (FB-CCAR and FB-AXBT-POSONLY) overestimate the temperature at 75m. The simulation with AXBT assimilation at the center (FB-AXBT) shows a similar size and temperature to the blended AXBT field. In all instances, the more complex spatial pattern cannot be captured by the FB model.

Eddy Ekman has a complex vertical structure. Figure II.13 shows the AXBT locations overlaid on the 75 meter blended temperature field, and the vertical temperature profiles at three locations: inside the warm core ring, at the edge of the ring, and Gulf Common Water. The four closest grid points to the AXBT location were identified in the model output, and a weighted average was used to calculate the model temperature profile at each AXBT location. All of the model initializations accurately simulate Gulf Common Water (AXBT #33). Within the ring (AXBT #28), only FB-AXBT accurately represents the entire vertical structure. FB-AXBT-POSONLY does not capture well the thermocline structure. It has a much deeper

mixed layer and is colder at depth. The HYCOM profile is too warm for the upper approximately 200 meters. Only FB-AXBT accurately places the edge of the ring (AXBT #31). HYCOM and the FB-CCAR and FB-AXBT-POSONLY situate the ring edge farther to the east, as evidenced by the colder temperature profile, which more closely resembles Gulf Common Water.

The observed vertical temperature structure of the center of the ring is markedly different from the Caribbean profile, as shown in Figure II.6. This ring separated from the Loop Current early in July (Hamilton et al. 2011, horizonmarine.com), so on 16 July it had not been separated from the Caribbean source water for long. Also, it is early enough in the summer season that the water has not reached its peak temperature. While the ring only recently broke off, the center of the ring had been isolated from the source water for a few months. This timing was determined by looking at the closed contour lines in the CCAR altimetry data from March through July. The deeper thermocline reflects a very deep Caribbean mixed layer, while the upper mixed layer could be due to summer solar radiation. Shay et al. (2011) found a similar structure with a deep thermocline down to 80 to 120 m straddling 19 to 20 degrees C in Eddy Franklin in 2010. They hypothesized that the structure was due to insolation. The full thermal structure across the ring can be seen at a vertical cross-section taken through the center of the ring (Figure II.14). In the AXBT field, the FB-AXBT output, and HYCOM field, the complex structure of the mixed layer and the thermocline is visible, whereas the mixed layer is more homogeneous in the FB-CCAR and FB-AXBT-POSONLY. The warm ring in FB-CCAR does not penetrate as deep as in the measurements. Changing the ring position

(FB-AXBT-POSONLY) appears to make the ring wider, which is more consistent with the observed AXBT field. The ring in the HYCOM output is much warmer than that measured by the AXBTs. FB-AXBT best captures the structure and magnitude of the warm core ring in this cross-section.

Although FB-AXBT performs better than the other initialization procedures within this ring, there are other locations where this is not the case, as shown in Figure II.15. The largest challenges in using FB initialization is representing the ring position and defining the edge. The only inputs to the model in defining a WCR position are two points and a radius; therefore, complex geometry is impossible to represent realistically. AXBTs #16 and #48 are two examples where the FB model is unable to represent realistically the ring position. At AXBT #16, the FB-CCAR is closest to the AXBT profile; the profile appears more similar to the Gulf Common Water profile than the ring profile, while the FB-AXBT simulation shows a profile more characteristic of a WCR. At AXBT #52, FB-CCAR is again closer to the AXBT profile. Here, it is more characteristic of a boundary point than the Gulf Common Water profile as shown by FB-AXBT-POSONLY and FB-AXBT. At both AXBT #52 and AXBT #40, the FB SST is too low, highlighting perhaps some deficiencies in the GFS SST. At AXBT #40, it is possible that if the SST were corrected for the FB-AXBT simulation, the entire profile would be warmer and align better with the AXBT profile. At this location, all of the FB simulations reflect a WCR profile; however, the FB-AXBT-POSONLY cannot capture the structure that is captured by FB-AXBT. For the model to most closely resemble the AXBT input, both position and structure information must be assimilated.

The ocean thermal field is often represented in hurricane-ocean interaction by a metric termed the upper ocean heat content (OHC). It is calculated as:

$$OHC = \int_0^{D_{26}} \rho c_p (T - 26) dz, \text{ where } \rho \text{ is the density, } c_p \text{ is the heat capacity, } D_{26} \text{ is the}$$

depth of the 26 degree isotherm, T is the temperature, and z is the depth. Figure II.16 shows the ocean heat content for each of the model initializations compared to the ocean heat content calculated from the AXBT measurements. Each vertical profile was interpolated to 1-m spacing before integrating. The ocean heat content is much too high when calculated from HYCOM compared to the AXBTs. It is moderately too high for FB-CCAR and FB-AXBT-POSONLY. It is too weak overall for FB-AXBT. HYCOM, FB-CCAR, and FB-AXBT-POSONLY clearly show a significantly increased OHC within the WCR. However, FB-AXBT shows a much lower OHC and a weaker ring, which is more consistent with the AXBT field.

In addition to comparing the entire field, we can compare the OHC calculated at discrete the AXBT locations (Figure II.17). The trends seen in the fields are also reflected in this figure. Some key statistics are summarized in Table II.2. Root mean square error (RMSE) and bias were calculated by:

$$RMSE = \sqrt{(\overline{OHC_{\text{model}} - OHC_{\text{AXBT}}})^2}$$

$$Bias = \overline{OHC_{\text{model}} - OHC_{\text{AXBT}}}$$

where the overbar represents the mean value.

FB-AXBT shows the most skill in matching the AXBT measurements, with lowest root mean square error and the lowest bias. The simulations initialized with HYCOM and FB-CCAR tend to overestimate the OHC at most locations. They have

the closest fit for mid-values and are farther from observations at the two extremes. FB-AXBT-POSONLY results are similar to those of FB-CCAR. The simulation initialized with FB-AXBT underestimates the OHC value at low values of OHC and overestimates the value for high OHC, within the WCR. This error in part is due to errors in the sea surface temperature; in many locations it is too low. Therefore, the continued use of GFS SST must be evaluated. Large differences are also seen at the edges of the WCR. Simply adjusting ring position does not have as large an effect as accurate specification of the center temperature profile, although the RMSE is a bit lower in FB-AXBT-POSONLY than FB-CCAR. Therefore, it is important in planning future AXBT deployments in front of a hurricane in the Gulf of Mexico that AXBTs are dropped at the center of the ring as well as at the periphery.

4. Evaluation of Simulated Ocean Response Under Hurricane Conditions

Different initialization schemes affect not only the initial fields but also the ocean response under hurricane conditions. Hurricane Isaac in 2012 was selected as a test case due to the high volume of AXBT data available for verification. The AXBT data set was made available to us by Cdr. Beth Sanabia and her group at the United States Naval Academy. Figure II.18 shows the AXBT drop locations for two days during Hurricane Isaac, August 28th and August 29th, and the location of a buoy that will also be used for comparison. Buoy data was downloaded from the National Data Buoy Center.

Hurricane Isaac caused severe damage in the Caribbean and along the Gulf of Mexico coast. It originated from a tropical wave that moved into the Atlantic Ocean

from the west coast of Africa. On August 21st, it was upgraded to Tropical Depression Nine and later to Tropical Storm Isaac (<http://www.nhc.noaa.gov/archive/2012/ISAAC.shtml>). Isaac became a category 1 Hurricane around 1620 UTC on August 28th and maintained hurricane force winds for about a day. The storm moved northwestward across the Gulf of Mexico due to a subtropical ridge to its north. The air was dry, preventing the inner core of convection to develop. A ragged eye developed multiple times but was unable to persist. Isaac was a large, slow-moving storm that made landfall in the mouth of the Mississippi River at 2345 on August 28th. The storm moved back to water shortly after and made the second landfall at 0715 on August 29th in the southwest Louisiana.

Before comparing the ocean response with the in situ data, it is instructive to compare the ocean initial conditions created by the HYCOM and FB initializations. Figure II.19 compares the sea surface height from the different initial conditions with the CCAR SSH on August 26, 2012. On this date, CCAR used altimetry data from three satellites: Cryosat, Jason1, and Jason2. The AXBTs are too disparate in space to make a blended field for comparison. Also, the time of the drop matters when examining AXBTs in the context of a storm; the drop times are divided into pre-, post-, and during the storm relative to the storm track. HYCOM shows the highest sea surface height, and the warm core ring is oriented closer to the meridional direction than the feature-based initialization and CCAR altimetry. FB is constrained to have an elliptical ring, so it cannot closely match the shape of the warm core ring from the altimetry data, but the SSH shows a similar magnitude.

The results of the spin-up are used for the initial conditions for the model.

Wind data (hurricane “extended” track file) provided by NOAA’s National Hurricane Center (NHC) is used to calculate the wind forcing. The extended track record for Hurricane Isaac is shown in Table II.3. At each model time step, the hurricane track data are interpolated to determine the current position, the storm speed and size. If there is missing data in any of NE/SE/NW/SW quadrants for both the 34 and 50 knot wind radii, an idealized Holland profile (1980) is used based on the maximum wind speed and radius of maximum wind. It is calculated according to:

$$B = W_{\max}^2 * e * \rho_{air} / \Delta P$$

$$A7 = r_{\max}^B$$

$$Wind = (A7 * B * \Delta P * \exp(-A7/R^B)) / (\rho_{air} * r^B) + r^2 * f^2 / 4)^{1/2} - r * f / 2$$

where $W_{\max}$ is the maximum wind speed, ρ_{air} is the density of air, ΔP is the difference between the environmental pressure and the pressure at the center of the storm, $r_{\max}$ is the radius of maximum wind, r is the radius from the storm center to the location where the wind is being calculated, and f is the Coriolis parameter at that location (Holland 1980). Half the translation speed is added to the wind field on the right side of the storm. If there is wind information for both 34 and 50 knot radii in the relevant quadrant, the wind speeds and radii are used in the formulas below. Otherwise, if only either the 34 or 50 knot wind is available, only that is used in the calculation and the other is set to zero. The wind is calculated by (Moon et al. 2003):

$$r > r_{\max} :$$

$$b = (r_{\max} - \frac{r_{34} + r_{50}}{2}) / \log(\frac{34 + 50}{2} / W_{\max})$$

$$Wind = W_{\max} * \exp((r_{\max} - r) / b)$$

$$r < r_{\max} :$$

$$Wind = r * W_{\max} / r_{\max}$$

The wind stress magnitude is calculated using the bulk formula, in which case the drag coefficient is calculated as an empirical function of the 10-m wind speed, similar to Moon et al. (2007) but modified to decrease the drag coefficient at high wind speeds to be more consistent with observations as suggested by Tung (2008) (Yablonsky and Ginis 2009). Figure II.20 shows the wind stress at two times along the storm track.

The cold wake is generated by applying the wind stress as the surface boundary condition in the model. No heat flux is applied; therefore, an initialization time close to the time of interest was selected so that the background temperature field does not drift too far. Figure II.21 shows the hurricane-induced cold wake in the sea surface temperature field in the model runs using the FB and HYCOM initial fields and TRMM-TMI observations. While the Gulf Common Water is cooler for the feature-based simulation in general, the storm-induced cooling is less in the wake of Hurricane Isaac. The HYCOM-initialized simulation shows the most cooling in the storm wake.

The subsurface response can also be examined. Figure II.22 shows the temperature at 75 m on 29 August 2012. The temperature in the Loop Current and the WCR are fairly consistent for all of the model initialization schemes. The WCR appears the weakest in HYCOM. The Gulf Common Water is warmer in general in the models initialized with HYCOM. Although it is not the focus of this study, it appears that the currents are stronger and there is more detail structure in the western Gulf of Mexico in the HYCOM initialized model.

Buoy 42003 is located very close to the storm track (Figure II.18). Figure II.23 compares the time series of the sea surface temperature as measured by the buoy to the sea surface temperature model outputs. Hurricane Isaac passed the buoy around 18Z 27 August 2012 (42 hours after 00Z 26 August). The anemometer on this buoy was mounted at 5 m. The model output is the wind speed at 10 m. The buoy winds speed at 10 m was calculated according to:

$$U_{(z=10)} = \frac{u_*}{\kappa} \ln \frac{10g}{z_{ch} u_*^2},$$

where U is the wind speed, u_* is the friction velocity, z_{ch} is the

height calculated by the Charnock relation, κ is the von Karmen constant, and g is the gravitational constant. Neutral stability and $z_{ch}=0.015$ have been assumed. U_* is constant within the boundary layer and can be calculated by $U_{(z=5)} = \frac{u_*}{\kappa} \ln \frac{5g}{z_{ch} u_*^2}$. The

buoy measured less cooling than calculated by any of the simulations. The sea surface temperature was warmer at this location prior to storm passage in the simulations initialized by FB; the simulation that used HYCOM initialization had a pre-storm sea surface temperature closer to buoy observation. Both models show a greater drop in temperature than that measured by the buoy, but the drop is much too large in the simulation initialized with HYCOM.

An AXBT was dropped at (-85.565, 26.183), close to the buoy, on 28 August 2012 at 3:14, approximately 53 hours after 26 August 00Z. Figure II.24 shows the model and AXBT temperature profile at this location. The model output was interpolated to the AXBT location. Output was generated at hourly intervals, and the AXBT was compared to the closest output file in time. HYCOM has colder sea surface temperature by about a degree by the end of hurricane forcing. The FB

initialization is approximately a quarter degree warmer at the surface; the biggest difference is seen at the base of the thermocline. One of the reasons for the differences in the cooling rates could be related to the differences in the magnitudes of the pre-storm currents. The stronger pre-storm currents in HYCOM could have contributed to enhanced mixing during the storm passage and thus stronger SST cooling.

Figure II.25 shows the comparison for AXBT 4, which is located in Gulf Common Water far from the storm track. As with the AXBT July 16 Survey discussed above, all of the simulations accurately capture the AXBT profile away from features and the storm track.

Closer to the storm track, the models have less skill in capturing the complex observed temperature field. For further analysis we divide the AXBTs into 3 categories: along the storm track (Figure II.26), to the right of the track (Figure II.27), and to the left of the track (Figure II.28). The cooling is typically greatest to the right of the track and weakest to the left of the track. This rightward bias is due to the clock-wise rotating wind stress on the right enhancing the inertial motions (Price 1981). The WCR located to the left of the storm adds additional complexity to the ocean response near it. Figure II.29 highlights a few AXBTs dropped near the edge of the WCR; unfortunately, no AXBTs were dropped near the center of the eddy. AXBT#10 was dropped approximately 6 hours after storm passage. AXBT #23 was dropped during the storm passage at that location. At the location of AXBT #10, HYCOM shows too much cooling at the surface. Without a pre-storm drop in a similar location, it is unknown whether this difference is due to errors in initialization

or model physics. The SST in the FB simulation is warmer than the AXBT and has a much shallower mixed layer depth. At the location of AXBT #23, all of the models have an SST that is colder than the AXBT temperature. The mixed layer depth is too shallow in the FB simulation; however, below about 150 m, there is good agreement between the FB simulation and the AXBT. The HYCOM simulation has a deeper mixed layer and is warmer than the AXBT at depth.

There are four AXBTs located near each other to the right of the track: AXBT #7, #15, #24, and #27 (Figure II.27). AXBT #7 was dropped at 6:07 on August 28; AXBT #15 was dropped at 13:15 on August 28, AXBT #24 was dropped at 23:26 on August 28, and AXBT #27 was dropped at 2:42 on August 29. The storm track was closest to this cluster between 12:00 and 18:00 on August 28. Before the passage of Hurricane Isaac (AXBT #7), all of the models slightly underestimate the sea surface temperature and underestimate the mixed layer depth. Therefore, we would expect more cooling in the simulations than measured by the AXBTs. At AXBT #15 (under the storm), the sea surface temperature is similar between the simulations and the AXBT. The mixed layer depth is greater in the simulations using HYCOM than that measured by the AXBT. Some sea surface cooling is seen in all of simulations as compared to the pre-storm conditions measured by AXBT #7. About 10 hours after storm passage (AXBT #24), the AXBT does not show any additional cooling. However, the sea surface has cooled more than 2° in the HYCOM simulation. The FB simulation shows some SST cooling but much less than HYCOM. The mixed layer depth is shallower in the FB simulation and slightly greater in the HYCOM

simulation than that of the AXBT. The same trends as seen at AXBT #24 are found at AXBT #27.

The AXBTs to the left of the track include AXBTs #19, #20, #26, and #29 (Figure II.28). The locations of AXBTs #19 and #26 are close to each other; they are also close to the shelf. The bathymetry is different for each of the initializations. AXBT #19 and AXBT #26 are separated by 10 hours. AXBT #19 is deployed more than a 1 degree ahead of the storm center so it can be used to represent pre-storm conditions at this location; the storm center is a little bit north and slightly east at the time of AXBT #26 deployment (01:03 on August 29). AXBT #29 was deployed at 03:22 on August 29 2012. The simulations show lower SST and shallower mixed layer in front of the storm (AXBT #19). All the simulations overestimated sea surface cooling in the cold wake. The mixed layer depth is too shallow for the FB simulation and too deep for the HYCOM simulation. These trends are similar to the ones seen to the right of the track in Figure II.27.

A couple of AXBTs were dropped near the edge of the warm core ring (Figure II.29). The HYCOM simulation shows better agreement in the thermal structure of the water column at these locations. As we discussed in Section 3, the FB initialization is more constrained in the types of feature geometry it can accurately represent.

Ocean heat content calculations were performed at all 30 AXBT locations using the same methodology described in Section 3. Figure II.30 shows the ocean heat content for each AXBT as well as the comparisons of the simulations to the AXBT calculated values. The simulation with feature-based initialization tends to

underestimate the value of the OHC, especially at higher values. The simulation that used HYCOM initialization underestimates the value of the OHC at very low values, slightly overestimates at intermediate values, and is inconsistent at higher values.

Table II.4 summarizes some key statistics for the OHC calculations. The root mean square error is similar for both of the simulations; the skill of the feature-based model might be improved if there were AXBT measurements in the center of the warm core ring prior to the storm that could be assimilated into the model.

5. Summary

Temperature fields from the Princeton Ocean Model using three different initialization methods were compared to in-situ data collected during a survey on 16 July 2009 and Hurricane Isaac in 2012. Temperature fields measured during the survey were compared with the feature-based initializations using 1) only CCAR SSH data, 2) CCAR SSH and AXBT profiles to refine WCR position, and 3) CCAR SSH and AXBT profiles to refine WCR position and thermal structure. The addition of AXBTs to define feature position and structure greatly improved the skill of the feature-based model. Assimilating information on both WCR position and structure improved the model much more significantly than only assimilating data pertaining to WCR position. In addition, comparisons were made with the model initializations using data-assimilative Global HYCOM data analysis. We found that FB-AXBT initialization method had the smallest RMS errors in simulating the observed ocean heat content (OHC) compared to the HYCOM initializations

To evaluate the ocean model response under storm conditions simulations of Hurricane Isaac (2012) initialized with the feature-based method and Global HYCOM, were compared to satellite, buoy, and AXBT measurements. No initialization method was overall more skillful than the others, although each model had locations where it outperformed the others. Both of the simulations tended to overestimate the sea surface temperature cooling. The feature-based simulation generally underestimated, while the HYCOM overestimated the mixed layer depth. These trends held for both the right and left of the track. Future work is needed to understand fully these differences. The wind forcing could also be improved by using the HRD HWIND product instead of the hurricane message files. More case studies should be conducted to evaluate how the model initializations fare under differing storm and oceanic conditions.

References

- Bender, M. A. and I. Ginis, 2000: Real-case simulations of hurricane-ocean interaction using a high-resolution coupled model: effects on hurricane intensity. *Monthly Weather Review*, **128**, 917-946.
- Bender, M.A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The operational GFDL coupled hurricane-ocean prediction system and a summary of its performance. *Monthly Weather Review*, **135**, 3965-3989.
- Chassignet, E.P., H.E. Hurlburt, O.M. Smedstad, G.R. Halliwell, P.J. Hogan, A.J. Wallcraft, R. Baraille, and R. Bleck, 2007: The HYCOM (Hybrid Coordinate Ocean Model) data assimilation system. *Journal of Marine Systems*, **65**, 60-83.
- Chassignet, E.P., H.E. Hurlburt, E.J. Metzger, O.M. Smedstad, J.A. Cummings, G.R. Halliwell, R. Bleck, R. Baraille, A.J. Wallcraft, C. Lozano, H.L. Tolman, A. Srinivasan, S. Hankin, P. Cornillon, R. Weisberg, A. Barth, R. He, F. Werner,

- and J. Wilkin, 2009: US GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM). *Oceanography*, **22**, no. 2, 64-75.
- Colorado Center for Astrodynamic Research, cited 2012: Gulf of Mexico Historical SSH Grid Viewer. [Available online at http://eddy.colorado.edu/ccar/ssh/hist_gom_grid_viewer]
- Cummings, J., 2005: Operational multivariate ocean data assimilation. *Quarterly Journal of the Royal Meteorological Society*, **131**, 3583-3604.
- D'Asaro, E.A., T.B. Sanford, P.P. Niiler, E.J. Terrill, 2007: Cold wake of Hurricane Frances. *Geophysical Research Letters*, **34**, L15609, doi:10.1029/2007GL030160.
- Environmental Modeling Center Marine Modeling and Analysis Branch, cited 2012: About RTOFS Global. [Available online at polar.ncep.noaa.gov/global/about]
- Falkovich, A., I. Ginis, and S. Lord, 2005: Ocean data assimilation and initialization procedure for the coupled GFDL/URI hurricane prediction system. *Journal of Atmospheric Oceanic Technology*, **22**, 1918-1932.
- Ginis, I., 2002: Tropical cyclone-ocean interactions. *Atmosphere-Ocean Interactions, Advances in Fluid Mechanics Series*, No. 33, WIT Press, 83-114.
- Ginis, I., R. Yablonsky, B. Thomas, and M. Kaufman, 2012: July 2012 Hurricane Forecast Improvement Project (HFIP) Progress Report.
- Gopalakrishnan, S., Q. Liu, T. Marchok, D. Sheinin, N. Surgi, M. Tong, V. Tallapragada, R. Tuleya, R. Yablonsky, and X. Zhang, 2011: Hurricane Weather Research and Forecasting (HWRF) Model: 2011 Scientific Documentation. L. Bernardet, Ed., 81 pp. Available from DTCenter.org.
- Halliwell, G.R. Jr., L.K. Shay, S.D. Jacob, O.M. Smedstad, and E.W. Uhlhorn, 2008: Improving ocean model initialization for coupled tropical cyclone forecast models using GODAE nowcasts. *Monthly Weather Review*, **136**, 2576-2591.
- Halliwell, G.R. Jr., L.K. Shay, J.K. Brewster, W.J. Teague, 2011: Evaluation and sensitivity analysis of an ocean model response to Hurricane Ivan. *Monthly Weather Review*, **139**, 921-945.
- Hamilton, P., K.A. Donohue, R.R. Leben, A. Lugo-Fernandez, and R.E. Green, 2011: Loop Current observations during spring and summer of 2010: description and historical perspective. *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record Breaking Enterprise, Geophysical Monograph*, Vol. 195, American Geophysical Union, 117-130.

- Holland, G.J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Monthly Weather Review*, **108**, 1212-1218.
- Horizon Marine, cited 2012: Loop Current Eddies. [Available online at www.horizonmarine.com/loop_current_eddies.php]
- Hurricanes: Science and Society, cited 2012: Expendable Airborne Instrument. [Available online at <http://www.hurricanesociety.org/science/observation/aircraftrecon/expendable-airborneinstruments/>]
- Hurricane Research Division, cited 2012: 20090716I1 Mission. [Available online at http://www.aoml.noaa.gov/hrd/Storm_pages/misc2009/20090716I1.html].
- HYCOM, cited 2012: HYCOM + NCODA Global 1/12° Analysis (GLBa0.08/expt_90.0). [Available online at http://hycom.org/dataserver/glbanalysis/expt_90pt9]
- Leben, R.R., G.H. Born, and B.R. Engebret, 2002: Operational Altimeter Data Processing for Mesoscale Monitoring. *Marine Geodesy*, **25**, 3-18.
- Leben, R. R., 2005: Altimeter-derived Loop Current metrics. *Circulation in the Gulf of Mexico: Observations and Models, Geophysical Monograph*, No. 161, American Geophysical Union, 181-201.
- Lloyd, I.D., T. Marchok, and G.A. Vecchi, 2011: Diagnostics comparing sea surface temperature feedbacks from operational hurricane forecasts to observations. *Journal of Advances in Modeling Earth Systems*, **3**, M11002, 17 pp.
- Mainelli, M, M. DeMaria, L.K. Shay, G. Goni, 2008: Application of oceanic heat content estimation to operational forecasting of recent Atlantic category 5 hurricanes. *Weather and Forecasting*, **23**, 3-16.
- Mellor, G. L., 2004: *Users guide for a three-dimensional, primitive equation, numerical ocean model (June 2004 version)*. Program in Atmospheric and Oceanic Sciences, Princeton University, 56 pp.
- Moon, I.-J., I. Ginis, T. Hara, H. Tolman, C.W. Wright, and E.J. Walsh, 2003: Numerical simulation of sea surface directional wave spectra under hurricane wind forcing. *Journal of Physical Oceanography*, **33**, 1680-1706.
- Moon, I.-J., I. Ginis, T. Hara, and B. Thomas, 2007: A physics-based parameterization of air-sea momentum flux at high wind speeds and its impact on hurricane intensity predictions. *Monthly Weather Review*, **135**, 2869-2878.

- National Data Buoy Center, cited 2012. [Available online at www.ndbc.noaa.gov]
- National Weather Service National Hurricane Center., cited 2012: Hurricane ISAAC Advisory Archive. [Available online at www.nhc.noaa.gov/archive/2012/ISAAC.shtml]
- Oey, L-Y, T. Ezer, and H-C Lee, 2005: Loop Current rings and related circulation in the Gulf of Mexico: A review of numerical models and future challenges. *Circulation in the Gulf of Mexico: Observations and Models, Geophysical Monograph*, Vol. 161, American Geophysical Union, 31-56.
- Price, J., 1981: Upper ocean response to a hurricane. *Journal of Physical Oceanography*, **11**, 153-175.
- Remote Sensing Sytems, cited 2012: TMI Data. [Available online at <ftp:ssmi.com/tmi>]
- Reynolds, R.W., and T.M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. *Journal of Climate*, **7**, 929-948.
- Sandford, T.B., J.F. Price, J.B. Girton, and D.C. Webb, 2007: Highly resolved observations and simulations of the ocean response to a hurricane. *Geophysical Research Letters*, **34**, L13604, doi:10.1029/2007GL09679.
- Shay, L.K., B. Jaimes, J. Brewster, P. Meyers, E.C. McCaskill, E. Uhlhorn, F. Marks, G. Halliwell, O.M. Smedstad, and P. Hogan, 2011: Airborne ocean surveys of the Loop Current Complex from NOAA WP-3D in support of the *Deepwater Horizon* Oil Spill. *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record Breaking Enterprise, Geophysical Monograph*, Vol. 195, American Geophysical Union, 131-151.
- Sriver, R.L., M. Huber, and J. Nusbaumer, 2008: Investigating tropical cyclone-climate feedbacks using the TRMM Microwave Imager and the Quick Scatterometer. *Geochemistry, Geophysics, and Geosystems*, **9**, Q09V11, doi:10.1029/2007GC001842.
- Teague, W. J., Carron, M.J., and P.J. Hogan, 1990: A comparison between the Generalized Digital Environmental Model and Levitus Climatologies, *Journal of Geophysical Research*, **95**, 7167-7183.
- Tung, C.-A., 2008: Impact of reduced air sea momentum flux on hurricane and wave modeling. M.S. thesis, Graduate School of Oceanography, University of Rhode Island, 69 pp. [Available from Graduate School of Oceanography, University of Rhode Island, South Ferry Rd., Narragansett, RI 02882.]

- Vukovich, F.M., 2007: Climatology of ocean features in the Gulf of Mexico using satellite remote sensing data. *Journal of Physical Oceanography*, **37**, 689-707.
- Yablonsky, R. and I. Ginis, 2008: Improving the ocean initialization of coupled hurricane-ocean models using feature-based data assimilation. *Monthly Weather Review*, **136**, 2592-2607.

Table II.1: Data Sources used for assimilation into NCODA (Cummings 2005)

Data source	Specifications	Estimated number of daily observations	Measurement-error standard deviations
AVHRR GAC ¹ Infrared Satellite SST	8 km day, night, relaxed day retrievals NOAA-16, 17, 18	1 200 000	variable
AVHRR LAC ² Infrared Satellite SST	2 km day, night retrievals NOAA-16, 17, 18	4 000 000	variable
GOES Infrared Satellite SST	12 km day, night retrievals GOES-10, 12	5 000 000	variable
Microwave Satellite SST	AMSR-E 25 km retrievals	5 000 000	variable
Thermosalinograph	<i>in situ</i> SST, SSS ³	1 800	1.1 degC, 0.5 PSU
Sea surface height anomaly	Satellite altimeters (Jason, GFO ⁴ and Envisat)	150 000	0.03, 0.08, 0.08 m
Sea ice concentration	<i>T</i> and <i>S</i> profiles SSM/I 25 km retrievals DMSP ⁵ F13, F14, F15	300 1 200 000	0.01 m 5%
Ship SST	Engine room intake	4 000	1.3 degC
	Hull contact sensor	800	0.6 degC
	Bucket temperature	200	1.2 degC
Buoy SST	Fixed	6 000	0.05 degC
	Drifting	32 000	0.12 degC
CMAN ⁶ Stations	<i>in situ</i> SST	120	1.1 degC
XBT	Temperature profiles	100	0.12 degC
Argo Floats	Temperature and Salinity profiles	200	0.002 degC 0.01 PSU
CTD ⁷ Stations (TESACs ⁸)	Temperature and Salinity profiles	50	0.002 degC 0.01 PSU
Drifting Buoy	Temperature profiles	700	0.12 degC
Fixed Buoy	Temperature and Salinity profiles	1 000	0.003 degC 0.02 PSU

Table II.2: Root mean square error and bias of OHC values for simulations compared to AXBT calculated value for 16 July 2009 Survey

	Bias	RMSE
HYCOM	16.5	34.4
FB-CCAR	13.9	26.4
FB-AXBT	3.2	23.8
FB-AXBT-POSONLY	14.8	26.3

Table II.3: Extended track file for Hurricane Isaac. The first column is the reporting agency (National Hurricane Center). The second column is the storm ID; the third column is the storm name. The fourth column is the date (year, month, day). The fifth column is the hour and minutes. The sixth column is the latitude measured in tenths of a degree. The seventh column is the longitude west in tenths of a degree. The eighth column is the direction of the storm motion in degrees from North; the ninth column is the storm speed in tenths of a m/s. The tenth column is the storm central pressure in mb; the eleventh column is the environmental pressure in mb. The twelfth column is the estimated radius of the outermost closed isobar in km. The thirteenth column is the estimated maximum wind speed in m/s and the fourteenth column is the estimated radius of maximum wind in km. Columns 15 through 18 are the estimated radius of 34 knot winds in NE/SE/NW/SW quadrants; columns 19 through 22 are the same for the 50 knot winds. -999 indicates that there is no estimate or the data are missing.

(http://www.emc.ncep.noaa.gov/mmb/data_processing/tcvitals_description.htm)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
NHC	09L	ISAAC	120825	0000	173	0720	315	051	0992	1008	0463	28	102	0371	0167	0139	0371	0111	-999	-999	-999
NHC	09L	ISAAC	120825	0600	181	0727	315	057	0991	1008	0463	28	083	0371	0167	0139	0371	0111	-999	-999	-999
NHC	09L	ISAAC	120825	1200	197	0737	320	077	0998	1007	0510	26	111	0334	0167	0111	0334	0111	-999	-999	-999
NHC	09L	ISAAC	120825	1800	208	0753	310	093	1000	1008	0510	23	111	0334	0167	-999	0334	-999	-999	-999	-999
NHC	09L	ISAAC	120826	0000	217	0767	305	088	0997	1008	0510	26	111	0334	0278	-999	0334	0111	-999	-999	-999
NHC	09L	ISAAC	120826	0600	228	0782	305	088	0995	1008	0482	26	111	0334	0334	-999	0334	0111	-999	-999	-999
NHC	09L	ISAAC	120826	1200	235	0800	300	088	0995	1008	0482	28	111	0334	0334	-999	0334	0111	-999	-999	-999
NHC	09L	ISAAC	120826	1800	239	0815	295	077	0994	1008	0482	26	093	0334	0334	-999	0334	0111	-999	-999	-999
NHC	09L	ISAAC	120827	0000	240	0825	285	062	0992	1007	0482	28	093	0334	0222	0148	0334	0111	-999	-999	0111
NHC	09L	ISAAC	120827	0600	249	0837	295	062	0990	1007	0426	26	074	0334	0222	0148	0334	0093	-999	-999	0093
NHC	09L	ISAAC	120827	1200	258	0848	305	067	0988	1007	0426	28	074	0334	0222	0148	0334	0093	-999	-999	0093
NHC	09L	ISAAC	120827	1800	261	0859	300	051	0984	1007	0426	31	056	0334	0278	0148	0334	0093	-999	-999	0093
NHC	09L	ISAAC	120828	0000	267	0865	310	046	0981	1008	0426	31	056	0278	0297	0185	0334	0093	0111	0093	0074
NHC	09L	ISAAC	120828	0600	274	0877	305	051	0978	1012	0556	31	056	0334	0297	0222	0334	0111	0111	0093	0093
NHC	09L	ISAAC	120828	1200	278	0882	305	031	0976	1012	0556	31	056	0334	0297	0222	0334	0148	0111	0093	0093
NHC	09L	ISAAC	120828	1800	285	0889	310	046	0975	1012	0556	33	093	0297	0278	0222	0278	0148	0130	0093	0093
NHC	09L	ISAAC	120829	0000	290	0895	315	041	0968	1008	0510	36	074	0297	0278	0278	0259	0148	0130	0093	0093
NHC	09L	ISAAC	120829	0600	290	0900	305	031	0968	1008	0510	36	074	0278	0278	0259	0241	0148	0130	0093	0093
NHC	09L	ISAAC	120829	1200	294	0905	305	026	0970	1008	0510	36	065	0278	0278	0259	0185	0148	0130	0074	0074
NHC	09L	ISAAC	120829	1800	298	0908	310	026	0974	1007	0510	31	083	0278	0278	0259	0148	0093	0093	-999	-999
NHC	09L	ISAAC	120830	0000	301	0911	320	026	0977	1006	0510	26	074	0241	0278	0259	0130	0093	0148	-999	-999
NHC	09L	ISAAC	120830	0600	305	0913	325	021	0981	1006	0510	23	074	0185	0278	0259	0130	-999	-999	-999	-999
NHC	09L	ISAAC	120830	1200	313	0919	330	041	0985	1006	0510	21	185	-999	0315	0259	-999	-999	-999	-999	-999

Table II.4: Root mean square error and bias for OHC values of simulations compared to AXBT calculated value for Hurricane Isaac

	RMSE	Bias
FB	21.19	-14.82
HYCOM	18.61	-6.06

Figure II.1: Transatlantic and United Domains.

Figure II.2: AXBT instrument (left). Schematic diagram of AXBT deployment (right). (hurricanescience.org)

Figure II.3: AXBT locations for July 16, 2009 survey.

Figure II.4: GDEM Climatology for July SST (left) and temperature at 75 m (right).

Figure II.5: CCAR SSH for 16 July 2009. The Loop Current is in the lower right. There is a large warm core ring and a smaller cold core ring (CCR). The block dots are the positions of the northern extent of the Loop Current and the ends of the major axes of the rings used in the FB method. The black lines are the radii of the minor axes of the rings. Contours are every 10 cm. The marked locations are based on the 17 cm contours.

Figure II.6: Sea surface temperature (left) and 75 m temperature (right) after Loop Current, WCR, and CCR have been assimilated using the FB method.

Figure II.7: AXBT # 33, 32, 31 (left to right).

Figure II.8: Temperature profile at center of WCR.

Figure II.9 : Sea surface temperature (left) and 75 m temperature (right) after GFS SST and AXBTs have been assimilated.

Figure II.10: Sea surface height (cm) from CCAR (top), Global HYCOM (middle left), FB-CCAR (middle right), FB-AXBT (bottom left), and FB-AXBT-POSONLY (bottom right). Contours are every 10 cm.

Figure II.11: Sea surface temperature on 16 July 2009 from observed TMI (top left), blended from 57 AXBT observations (top right), HYCOM (bottom left), FB-CCAR (bottom right).

Figure II.12: Sea surface temperature on 16 July 2009 blended from 57 AXBT observations (top), HYCOM (middle left), FB-CCAR (middle right), FB-AXBT(bottom left), and FB-AXBT-POSONLY (bottom right). Contour lines are every 1°.

Figure II.13. Observed temperature at 75-m depth using a blend of 57 AXBTs on 16 July 2009 (upper left); temperature profiles at the locations of AXBT #28 (upper right), AXBT #31 (lower left), and AXBT #33 (lower right).

Figure II.14: Vertical cross-section of temperature through center of ring from AXBT # 33-24 (top), HYCOM (middle left), FB-CCAR (middle right), FB-AXBT(bottom left), and FB-AXBT-POSONLY (bottom right). Contour lines are every 1°.

Figure II.15. Temperature profiles at the locations of AXBT #16 (upper left), AXBT #52 (upper right), AXBT #40 (lower left), and AXBT #48 (lower right).

Figure II.16: Ocean heat content calculated from 57 AXBT observations (top), HYCOM (middle left), FB-CCAR (middle right), FB-AXBT (bottom left), and FB-AXBT-POSONLY (bottom right). Contour lines are every 10 kJ/cm².

Figure II.17: Ocean heat content for the model output at the AXBT location versus the AXBT location for the simulations initialized with HYCOM (upper left), FB-CCAR (upper right), FB-AXBT (lower left), and FB-AXBT-POS ONLY (lower right). The dashed line is the 1:1 line.

Figure II.18: AXBT drop position for August 28 (red) and August 29 (blue) during Hurricane Isaac (2012). Buoy 42003 is marked by a black circle. The thick black line is the storm track, with the storm position marked every 6 hours. The top figure covers the entire Gulf of Mexico; the bottom figure is zoomed in on the AXBT drop locations.

Figure II.19: Sea surface height on August 26th 2012 from CCAR altimetry (top), simulation run with feature-based initialization (lower left) and Global HYCOM initialization (lower right).

Figure II.20: Wind stress (N m^{-2}) on 26 August 2012 (left) and 28 August 2012 (right).

Figure II.21: Sea surface temperature and currents on August 29, 2012 for TRMM-TMI (top), FB (lower left), HYCOM (lower right). The black line is the track of Hurricane Isaac.

Figure II.22: Temperature and currents at 75 m on August 29, 2012 for FB (left), HYCOM (right). The black line is the track of Hurricane Isaac.

Figure II.23: Time series of sea surface temperature as measured by buoy 42003 compared to model output at (-85.612, 26.044). The time is measured as hours after 00Z on 26 August 2012.

Figure II.24: Temperature profile on 28 August 2012 for AXBT #2 and model output.

Figure II.25: Temperature profile on 28 August 2012 for AXBT #4 and model output.

Figure II.26: Temperature profile for AXBT #10 (left) and AXBT #23 (right) and model output along the storm track.

Figure II.27: Temperature profile for AXBT #7 (top left), AXBT #15 (top right), AXBT #24 (bottom left), AXBT #27 (bottom right) and model output on the right of the storm track.

Figure II.28: Temperature profile for AXBT #19 (top left), AXBT #26 (top right), AXBT #20 (bottom left), AXBT #29 (bottom right) and model output – on the left of the storm track.

Figure II.29: Temperature profiles at AXBT #16 (left) and AXBT #17 (right) – near the edge of the WCR.

Figure II.30: Ocean heat content for each AXBT (top). Comparisons of OHC for the Feature-based initialized simulation to AXBTs (lower) and OHC HYCOM-AXBT (lower right). The dashed line is 1:1 line.

BIBLIOGRAPHY

- Bender, M. A., and I. Ginis, 2000: Real case simulation of hurricane-ocean interaction using a high-resolution coupled model: Effects on hurricane intensity. *Monthly Weather Review*, **128**, 917-946.
- Bender, M. A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The operational GFDL Coupled Hurricane-Ocean Prediction System and a summary of its performance. *Monthly Weather Review*, **135**, 3965-3989.
- Chassignet, E.P., H.E. Hurlburt, O.M. Smedstad, G.R. Halliwell, P.J. Hogan, A.J. Wallcraft, R. Baraille, and R. Bleck, 2007: The HYCOM (Hybrid Coordinate Ocean Model) data assimilation system. *Journal of Marine Systems*, **65**, 60-83.
- Chassignet, E.P., H.E. Hurlburt, E.J. Metzger, O.M. Smedstad, J.A. Cummings, G.R. Halliwell, R. Bleck, R. Baraille, A.J. Wallcraft, C. Lozano, H.L. Tolman, A. Srinivasan, S. Hankin, P. Cornillon, R. Weisberg, A. Barth, R. He, F. Werner, and J. Wilkin, 2009: US GODAE: Global Ocean Prediction with the HYbrid Coordinate Ocean Model (HYCOM). *Oceanography*, **22**, no. 2, 64-75.
- Colorado Center for Astrodynamics Research, cited 2012: Gulf of Mexico Historical SSH Grid Viewer. [Available online at http://eddy.colorado.edu/ccar/ssh/hist_gom_grid_viewer]
- Cummings, J., 2005: Operational multivariate ocean data assimilation. *Quarterly Journal of the Royal Meteorological Society*, **131**, 3583-3604.
- D'Asaro, E.A., T.B. Sanford, P.P. Niiler, E.J. Terrill, 2007: Cold wake of Hurricane Frances. *Geophysical Research Letters*, **34**, L15609, doi:10.1029/2007GL030160.
- Dare, R.A. and J.L. McBride, 2011: Sea surface temperature response to tropical cyclones. *Monthly Weather Review*, **139**, 3798-3808.
- Emanuel, K., 2001: Contribution of tropical cyclones to meridional heat transport by the oceans. *Journal of Geophysical Research*, **106**, 14771-154781.
- Environmental Modeling Center Marine Modeling and Analysis Branch, cited 2012: About RTOFS Global. [Available online at polar.ncep.noaa.gov/global/about]
- Falkovich, A., I. Ginis, and S. Lord, 2005: Ocean data assimilation and initialization procedure for the coupled GFDL/URI hurricane prediction system. *Journal of Atmospheric Oceanic Technology*, **22**, 1918-1932.

- Ginis, I., 2002: Tropical cyclone-ocean interactions. *Atmosphere-Ocean Interactions, Advances in Fluid Mechanics Series*, No. 33, WIT Press, 83-114.
- Ginis, I., R. Yablonsky, B. Thomas, and M. Kaufman, 2012: July 2012 Hurricane Forecast Improvement Project (HFIP) Progress Report.
- Gopalakrishnan, S., Q. Liu, T. Marchok, D. Sheinin, N. Surgi, M. Tong, V. Tallapragada, R. Tuleya, R. Yablonsky, and X. Zhang, 2011: Hurricane Weather Research and Forecasting (HWRF) Model: 2011 Scientific Documentation. L. Bernardet, Ed., 81 pp. Available from DTCenter.org.
- Halliwel, G.R. Jr., L.K. Shay, S.D. Jacob, O.M. Smedstad, and E.W. Uhlhorn, 2008: Improving ocean model initialization for coupled tropical cyclone forecast models using GODAE nowcasts. *Monthly Weather Review*, **136**, 2576-2591.
- Halliwel, G.R. Jr., L.K. Shay, J.K. Brewster, W.J. Teague, 2011: Evaluation and sensitivity analysis of an ocean model response to Hurricane Ivan. *Monthly Weather Review*, **139**, 921-945.
- Hamilton, P., K.A. Donohue, R.R. Leben, A. Lugo-Fernandez, and R.E. Green, 2011: Loop Current observations during spring and summer of 2010: description and historical perspective. *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record Breaking Enterprise, Geophysical Monograph*, Vol. 195, American Geophysical Union, 117-130.
- Holland, G.J., 1980: An analytic model of the wind and pressure profiles in hurricanes. *Monthly Weather Review*, **108**, 1212-1218.
- Horizon Marine, cited 2012: Loop Current Eddies. [Available online at www.horizonmarine.com/loop_current_eddies.php]
- Hurricanes: Science and Society, cited 2012: Expendable Airborne Instrument. [Available online at <http://www.hurricanesociety.org/science/observation/aircraftrecon/expendableairborneinstruments/>]
- Hurricane Research Division, cited 2012: 20090716I1 Mission. [Available online at http://www.aoml.noaa.gov/hrd/Storm_pages/misc2009/20090716I1.html].
- HYCOM, cited 2012: HYCOM + NCODA Global 1/12° Analysis (GLBa0.08/expt_90.0). [Available online at http://hycom.org/dataserver/glbanalysis/expt_90pt9]

- Jansen, M.F., R. Ferrari, and T.A. Mooring, 2010: Seasonal versus permanent thermocline warming by tropical cyclones. *Geophysical Research Letters*, **37**, L03602.
- Leben, R.R., G.H. Born, and B.R. Engebret, 2002: Operational Altimeter Data Processing for Mesoscale Monitoring. *Marine Geodesy*, **25**, 3-18.
- Leben, R. R., 2005: Altimeter-derived Loop Current metrics. *Circulation in the Gulf of Mexico: Observations and Models*, *Geophysical Monograph*, No. 161, American Geophysical Union, 181-201.
- Lloyd, I.D., T. Marchok, and G.A. Vecchi, 2011: Diagnostics comparing sea surface temperature feedbacks from operational hurricane forecasts to observations. *Journal of Advances in Modeling Earth Systems*, **3**, M11002, 17 pp.
- Mainelli, M, M. DeMaria, L.K. Shay, G. Goni, 2008: Application of oceanic heat content estimation to operational forecasting of recent Atlantic category 5 hurricanes. *Weather and Forecasting*, **23**, 3-16.
- Mellor, G. L., 2004: *Users guide for a three-dimensional, primitive equation, numerical ocean model (June 2004 version)*. Program in Atmospheric and Oceanic Sciences, Princeton University, 56 pp.
- Moon, I.-J., I. Ginis, T. Hara, H. Tolman, C.W. Wright, and E.J. Walsh, 2003: Numerical simulation of sea surface directional wave spectra under hurricane wind forcing. *Journal of Physical Oceanography*, **33**, 1680-1706.
- Moon, I.-J., I. Ginis, T. Hara, and B. Thomas, 2007: A physics-based parameterization of air-sea momentum flux at high wind speeds and its impact on hurricane intensity predictions. *Monthly Weather Review*, **135**, 2869-2878.
- Manucharyan, G.E., C.M. Brierley, and A.V. Fedorov, 2011: Climate impacts of intermittent upper ocean mixing induced by tropical cyclones. *Journal of Geophysical Research*, **116**, C11038.
- Mao, Q., S.W. Chang, and R.L. Pfeffer, 2000: Influence of large-scale initial oceanic mixed layer depth on tropical cyclones. *Monthly Weather Review*, **128**, 4058-4070.
- National Data Buoy Center, cited 2012. [Available online at www.ndbc.noaa.gov]
- National Weather Service National Hurricane Center., cited 2012: Hurricane ISAAC Advisory Archive. [Available online at www.nhc.noaa.gov/archive/2012/ISAAC.shtml]
- Northern Gulf Institute/NOAA Developmental Ecosystem Data Assembly Center, cited 2012: Intra Americas Sea Nowcast Forecast System. [Available online at

www.northerngulfinstitutue.org/edac/IASNFS.php]

- Oey, L-Y, T. Ezer, and H-C Lee, 2005: Loop Current rings and related circulation in the Gulf of Mexico: A review of numerical models and future challenges. *Circulation in the Gulf of Mexico: Observations and Models, Geophysical Monograph*, Vol. 161, American Geophysical Union, 31-56.
- Pasquero, C. and K. Emanuel, 2008: Tropical cyclones and transient upper-ocean warming. *Journal of Climate*, **21**, 149-162.
- Price, J., 1981: Upper ocean response to a hurricane. *Journal of Physical Oceanography*, **11**, 153-175.
- Remote Sensing Sytems, cited 2012: TMI Data. [Available online at <ftp.ssmi.com/tmi>]
- Reynolds, R.W., and T.M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. *Journal of Climate*, **7**, 929-948.
- Sandford, T.B., J.F. Price, J.B. Girton, and D.C. Webb, 2007: Highly resolved observations and simulations of the ocean response to a hurricane. *Geophysical Research Letters*, **34**, L13604, doi:10.1029/2007GL09679.
- Shay, L.K., B. Jaimes, J. Brewster, P. Meyers, E.C. McCaskill, E. Uhlhorn, F. Marks, G. Halliwell, O.M. Smedstad, and P. Hogan, 2011: Airborne ocean surveys of the Loop Current Complex from NOAA WP-3D in support of the *Deepwater Horizon* Oil Spill. *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record Breaking Enterprise, Geophysical Monograph*, Vol. 195, American Geophysical Union, 131-151.
- Sriver, R.L. and M. Huber, 2007: Observational evidence for an ocean heat pump induced by tropical cyclones. *Nature*, **447**, 577-580.
- Sriver, R.L., M. Huber, and J. Nusbaumer, 2008: Investigating tropical cyclone-climate feedbacks using the TRMM Microwave Imager and the Quick Scatterometer. *Geochemistry, Geophysics, and Geosystems*, **9**, Q09V11, doi:10.1029/2007GC001842.
- Teague, W. J., Carron, M.J., and P.J. Hogan, 1990: A comparison between the Generalized Digital Environmental Model and Levitus Climatologies, *Journal of Geophysical Research*, **95**, 7167-7183.
- Tung, C.-A., 2008: Impact of reduced air sea momentum flux on hurricane and wave modeling. M.S. thesis, Graduate School of Oceanography, University of Rhode Island, 69 pp. [Available from Graduate School of Oceanography, University of Rhode Island, South Ferry Rd., Narragansett, RI 02882.]

- Vincent, E., M., M. Lengaigne, G. Madec, J. Vialard, G. Samson, N. Jourdain, C. E. Menkes and S. Jullien, 2012: Processes setting the characteristics of sea surface cooling induced by Tropical Cyclones, *Journal of Geophysics Research*, **117**, C02020, doi:10.1029/2011JC007396.
- Vukovich, F.M., 2007: Climatology of ocean features in the Gulf of Mexico using satellite remote sensing data. *Journal of Physical Oceanography*, **37**, 689-707.
- Yablonsky, R. and I. Ginis, 2008: Improving the ocean initialization of coupled hurricane-ocean models using feature-based data assimilation. *Monthly Weather Review*, **136**, 2592-2607.
- Yablonsky, R. and I. Ginis, 2009: Limitations of one-dimensional ocean models for coupled hurricane-ocean model forecasts, *Monthly Weather Review*. **137**, 4410-4419.