Simulation of Hurricane-Ocean Interaction for Hurricane Katrina: Coupling WRF with a 1-D Ocean Model

Kimberly R. Trent

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Science Research Mentors: Greg J. Holland and Richard Rotunno
Writing and Communication Mentor: Catherine Shea

ABSTRACT

Given the drastic increase in shoreline habitation in hurricane zones and recent hurricane disasters such as Katrina (2005), every effort should be made to improve the accuracy of hurricane simulations. In this research project, a simulation of Katrina was run using the WRF (Weather Research and Forecasting) atmospheric, numerical model coupled with the 1-D PWP (Price-Weller-Pinkel) isolated-column ocean model. The goal of this study was to determine the sufficiency of coupling with a 1-D ocean model in terms of the accuracy of the ocean response to the hurricane and the ocean feedback (the hurricane response). There are two parts of the ocean response, local mixing and upwelling. Both components bring deeper, colder water up to the surface, decreasing the temperature of the warmer, surface mixed layer. This cooling decreases the amount of energy available to the storm. The PWP ocean model is only able to simulate the local mixing element of the ocean response. However, a full 3-D ocean model is needed to account for the upwelling factor as well. Results show that coupling WRF with the PWP ocean model does not produce a significant hurricane response. This result can be attributed to how the PWP has to be initialized due to its simplicity, and to the model’s inability to capture the upwelling component of the ocean response. We anticipate that using a 3-D ocean model will produce a simulation that more closely follows actual events in terms of the physics of the hurricane-ocean interaction due to the 3-D model’s ability to use a more complete initialization procedure, and its ability to capture both aspects of the ocean response.

1. Introduction

This paper will present and analyze the results from a Hurricane Katrina (2005) simulation which was run using the WRF (Weather Research and Forecasting) numerical, atmospheric model coupled with the PWP (Price-Weller-Pinkel) 1-D isolated-column ocean model. By analyzing this simulation, the adequacy of coupling WRF with a simple 1-D ocean model when running hurricane simulations will be evaluated. Each year hurricanes demonstrate their disastrous impact on coastal regions. Over the last several decades, shoreline habitation, in regions affected by hurricanes, has increased dramatically and is one of the factors which has caused actual hurricane damage to increase over the years (Pielke & Landsea, 1998). Given the drastic increase in shoreline habitation in hurricane zones; and recent hurricane disasters,
such as Katrina 2005, every effort should be made to improve the accuracy of hurricane simulations. Coastal communities, meteorologists, and decision-makers would benefit greatly from improved hurricane forecasts, because the public could be more accurately warned about a pending hurricane danger, communities could be better advised as to how to prepare and whether to evacuate, and more lives could be saved.

With recent improvements in supercomputing, numerical weather prediction and observational data collection, researchers have made significant improvements to hurricane simulations. Forecasters can run these models in real-time on supercomputers using the current atmospheric and oceanic conditions as input data so that forecasts can be made for hurricanes that are threatening coastal communities. With this information meteorologists can issue the proper forecasts and public advisories.

Still, these models are far from perfect, and there is much work to be done to make hurricane simulations and forecasts more precise and reliable. One of the issues facing researchers and forecasters is the trade-off between the complexity of the model used and the time needed to run a simulation using the model. An example of this trade-off is determining the complexity of the ocean model that is to be coupled with the atmospheric model in order to make the hurricane simulation as accurate as possible.

The purpose of this research project is to analyze the results obtained from running a simulation of Hurricane Katrina (2005) using the WRF numerical, atmospheric model coupled with the 1-D PWP ocean model to see how the coupled model performs in simulating the key dynamics of the hurricane-ocean interaction. Evaluating this simulation will determine whether it is necessary to try simulations with a full 3-D model.

This paper will unfold as follows:
- In Section 2, a brief overview of hurricane dynamics will be given. In this overview, some of the key characteristics of hurricanes that numerical models need to capture will be highlighted including the effect of the ocean response on hurricanes.
- In Section 3, the WRF atmospheric model, and the PWP ocean model will be described and the data used to initialize the models will be explained. In addition, the coupled run will be outlined in detail.
- In Section 4, the results from the coupled model simulation will be presented and analyzed using a simulation that was run without ocean coupling. This will be followed by the conclusion and a description of future work.

2. Hurricane Dynamics and Ocean Feedback

a. General Hurricane Dynamics

Hurricanes are rotating storm systems that form over the Atlantic or the eastern part of the Pacific and have maximum winds greater than 32 m/s. Hurricanes travel at speeds of 5-10m/s with rainfall rates up to 5cm/h. After formation, they tend to drift westward, and then turn poleward. These tropical cyclones evolve from low-pressure, mesoscale convective systems. The low-pressure centers of these systems drive the boundary layer inflow (which is the frictional inflow layer that is ~1km high). The Coriolis force, which is due to the earth’s rotation, causes the cyclonic (counterclockwise) rotation of the inflow. This inflow spirals towards the center of the convective system while picking up water vapor and sensible heat from the ocean surface. Then this inflow rises in the eyewall and rainbands. This rising of the inflow causes the water vapor in the air to condense and release latent heat which supplies the hurricane with its primary source of energy.
In order for the cyclone to form and intensify, the sea surface temperatures (SSTs) need to be above ~26.5ºC so that the low-level inflow can absorb enough water vapor and latent heat to fuel the storm (Wallace & Hobbs, 2006). While the SST affects the potential development of hurricanes, one of the factors that affects the actual intensity of a hurricane is the depth of the warm water beneath its path. This warm surface stratum is called the mixed layer (ML) where the temperature is approximately uniform (to within no less than 0.02ºC of the SST) (Price et al., 1986).

In the Gulf of Mexico (GOM), the loop current and Warm Core Rings (WCRs) have the deepest mixed layer depth. The loop current is a current that flows northward between Cuba and the Yucatán peninsula, then around the GOM in a clockwise direction, and then exits to the east through the Florida Straits. A WCR develops when part of the loop current breaks off in the GOM and forms an eddy that travels to the west at a speed of around 5 cm/s.

The effect of the loop current and WCRs on hurricane intensity has been seen repeatedly in past events. Hurricane Camille (1969) was a category 3 when it entered the Gulf. It traveled along the loop current which allowed it to intensify to a category 5 before landfall in Mississippi. Hurricane Opal (1995) crossed a WCR and went from a category 2 to a category 4 in 14 hours a day before making landfall. Officials did not have enough time to modify coastal evacuations because they did not take the effect of these features on hurricane intensity development into account when forecasting the storm (Hong et al., 2000). During the 2005 hurricane season, Katrina and Rita greatly increased in intensity when they passed over the loop current and WCR. Katrina increased from a category 1 to a category 5 (Shen et al., 2006). Rita also passed over this WCR and intensified from a category 2 to a category 5. That same year, Wilma was predicted to make landfall as a category 2 because mixed layer topography was not taken into account when the forecast was made; but as a result of passing over the loop current, it hit Florida as a category 3.

These warm oceanic features play a key role in hurricane intensity development and forecasters need to take this into account when running real-time simulations by coupling with an ocean model that can accurately simulate the key aspects of the hurricane-ocean interaction.

b. Ocean Response

A tropical cyclone is affected by the mixed layer depth through the process of ocean feedback. This feedback is the result of the ocean’s response to the passage of the hurricane, and this response has two main parts: mixing and upwelling.

As the cyclone moves along the ocean surface, its boundary layer inflow gives the upper ocean waters an initial velocity, through friction and a transfer of momentum, which is tangential to this lower level circulation. This transfer of momentum from the hurricane wind stress sets up a vertical shear in the upper ocean which causes vertical mixing (entrainment). This mixing occurs at each point in the upper ocean independent of its surroundings. Therefore, this mixing is a local process that can be modeled with even the most simple 1-D isolated column ocean model.

The second part of the ocean response is upwelling. The upper ocean’s initial circulation, due to the hurricane winds, becomes deflected to the right at each point by the Coriolis force (which is rightward pointing in the Northern Hemisphere). This divergence of the upper ocean circulation causes the deeper waters to be
brought to the surface underneath the center of the hurricane’s circulation to replace the departing surface waters. This upwelling causes the isotherms to rise in a dome-like shape that is centered on the track. Therefore, the upwelling decreases the depth of the ML allowing mixing and upwelling to blend even more of the colder deeper waters with the upper ocean. For slowly moving hurricanes, upwelling is greatly augmented. This decreases the depth of the mixed layer even more causing entrainment to be enhanced even more (Wallace & Hobbs, 2006; Price, 1981).

Upwelling is not a local process, because it results from the deflection that occurs at each point, or within each column, in the upper ocean underneath the hurricane. Since the water is diverging away from the center within each of the columns, the law of continuity stipulates that water has to come up form below to fill in that space. The 1-D ocean model can not simulate this process because the columns are isolated and therefore the law of continuity is not held for the simulated ocean. A 3-D ocean model would be needed to simulate the upwelling component of the ocean response.

1.) A DEEPER LOOK AT MIXING (ENTRAINMENT)

As the upper ocean circulation is deflected to the right at each point, and as the hurricane moves along its track, this deflection is reinforced on the right hand side of the track by the new position of the storm. Since the water is diverging away from the center within each of the columns, the law of continuity stipulates that water has to come up from below to fill in that space. Therefore, on the left-hand side, the updated hurricane position counteracts the deflected ocean flow. The increased mixed layer velocity, on the right side, increases the velocity shear in the layer and this causes a larger amount of vertical mixing (entrainment). This near-resonant coupling that causes the deflected upper ocean flow to be reinforced by the updated position of the storm on the right-hand side causes the upper ocean water to obtain a clockwise rotation.

On the left-hand side, the upper ocean and boundary layer flows are pointing downward or southward. In the frame of reference of the upper ocean velocity, a rightward deflection by the Coriolis force is actually to the left when looking down on the flow with North pointing up. Therefore, on the left side, the “rightward” deflection of the upper ocean velocity, is in the opposite direction to the circulation of the updated direction of the boundary layer inflow. So, as the hurricane moves along its track, the leftward component of the upper ocean’s velocity is counteracted by the rightward component of the boundary layer circulation; and entrainment is not as strong on this side (Wallace & Hobbs, 2006; Price, 1981).
c. Ocean Feedback

Mixed layer depth topographic features, such as WCRs, positively affect hurricane intensity because a deeper mixed layer means that more water with the SST is available to the storm. The upwelling and entrainment that occurs under the hurricane will not bring cooler water to the surface as quickly, as the hurricane passes over these features. Therefore more energy, in the form of latent and sensible heat, is supplied to the hurricane through the lower level inflow. This strengthens the storm—increasing the lower level inflow and heat flux into the vortex—in a repeating pattern that intensifies the hurricane (Wallace & Hobbs, 2006).

On the other hand, cool wakes left by previous hurricanes, and shallow mixed layer depths negatively affect hurricane intensity. If the ocean mixed layer is relatively shallow, the colder thermocline water below this layer will be quickly pulled to the surface, mixing with the warmer water and decreasing the SST underneath the hurricane’s track.

The decrease in SST that results from the passage of the hurricane can range from 1º to 6ºC. The slower the translational speed of the hurricane and the greater the intensity of the hurricane, the greater the decrease in SST will be. In addition, a very sharp upper thermocline temperature gradient will increase the negative change in SST. In a study by Black (1983) referenced by Bender, “observations were grouped according to slow, medium, and fast moving storms, with average cooling for the three groups of 5.3º, 3.5º, and 1.8ºC, respectively” (Bender, 2000; Price, 1981). If the cyclone is moving slowly enough, it can be weakened by this upwelling (Wallace & Hobbs, 2006).

For rapidly moving hurricanes (>6m/s), the maximum SST decrease occurs several tens of kilometers to the right of the hurricane track. This is because the clockwise rotation of the upper ocean, tangential to the circulation of the boundary layer inflow is reinforced by the wind-stress vector which also turns clockwise on the right hand side which increases entrainment on this side. This rightward bias of the SST decrease is only slightly dependent on the asymmetry of the 10m hurricane winds due to the translational speed of the hurricane which increases the magnitude of the winds and the magnitude of the wind-stress vector on the right-hand side.

Under slow moving hurricanes (<4m/s), the more sustained upwelling increases entrainment and reduces the rightward shift of the maximum SST reduction. However, the magnitude of the mixed layer cooling is still greatest on the right side, because of the fact that the wind stress vector is resonant with the ML velocity on the this side.

Below the deepened mixed layer that results from the passage of the hurricane, the temperature change is mainly due to upwelling. The most cooling, in this region, is therefore directly beneath the track where upwelling is the strongest.

Price (1981) specifically investigated the response of the upper ocean to a hurricane moving over it using observational data from Hurricane Eloise (1975) and a 3-D, three layer, numerical ocean model. The upper layer of the model was the mixed layer which entrained the deeper waters according to a velocity dependent parameterization, and the two lower layers simulated the response of the thermocline. For the boundary conditions of the ocean model, Hurricane Eloise was estimated to have a translational velocity of 8.5m/s and a maximum wind speed of about 30m/s. Model results showed that upwelling and entrainment caused...
the majority (~85%) of the changes to the ML depth and temperature, while that latent and sensible heat fluxes were responsible for the rest.

Bender et al. (2000) explored the effect of the hurricane-ocean interaction on hurricane intensity. They used the GFDL model with movable triple nesting coupled with the Princeton Ocean Model, and ran simulations of Hurricane Opal (1995), Gilbert (1988), Felix (1995), and Fran (1996) with and without ocean coupling. The Princeton Ocean Model is a 3D, multilayer, primitive equation model. Their results confirmed that the cooling of the sea surface caused by the hurricane significantly affects the cyclone’s intensity especially for slow moving storms and for shallower mixed layer depths.

Due to the relationship between hurricane intensity and ocean feedback, an ocean model that is able to account for the essential processes that provide positive and negative feedback to the storm is essential for accurately simulating changes in hurricane intensity. This study will determine whether a 1-D ocean model accurately simulates these processes or whether a 3-D ocean model is called for.

3. Methods

a. The WRF model and Initial Conditions

The Advanced Research WRF (Weather Research and Forecasting) [ARW] was designed to be used for the forecasting and in the research of mesoscale (2km to 2000km) weather systems. It is the collaborative effort of NCAR’s Mesoscale and Microscale Meteorology (MMM) Division, the National Oceanic Atmospheric Administration’s (NOAA) National Centers for Environmental Prediction (NCEP) and Forecast System Laboratory (FSL), the Department of Defense’s Air Force Weather Agency (AFWA), and a number of other agencies, centers, laboratories, and universities (Skamarock et al., 2005). The ARW is a flexible, portable code that can be executed in a parallel computing environment. It is a community model that has become a common tool among scientists in universities and operational centers. Therefore, the use of this model in research establishes commonality and a base-level degree of confidence in the results.

In the ARW model, initial atmospheric and oceanic surface conditions can be defined analytically when running idealized simulations, or they can be defined using observational data when running real simulations. In this study, initial atmospheric conditions were set using Geophysical and Fluid Dynamics Laboratory (GFDL) observational data from hurricane Katrina. The initial SST field was set using National Centers for Environmental Protection’s (NCEP’s) real-time, global, SST analysis data.

The ARW is composed of two main parts, the WRF Preprocessing System (WPS), and the ARW dynamics solver. First, the WPS is run to define the simulation domains and to reformat the input data so that it can be understood by the model. WPS creates one file for every six hours within the simulation time domain. The first file contains the oceanic and atmospheric state and boundary conditions that will be used to initialize the model, and the rest of the files contain the boundary conditions that will be used by the model throughout the simulation. These files are created by mapping the terrestrial and meteorological observational data to the domain and filling in any missing data using interpolation (Skamarock et al., 2005).

The second part of the model is the ARW dynamics solver. It initializes and runs the model using the reformatted input data generated by the WPS. The ARW solver integrates the fully compressible, non-hydrostatic governing Euler equations at each time step to generate the
simulation. The model’s governing equations describe the evolution of the variables that define the atmospheric state (pressure, temperature, relative humidity, wind velocity, etc.). These equations also account for different atmospheric processes such as evaporation, rainfall, surface friction, radiative cooling, and solar heating; and are based on the laws of nature such as the conservation of mass, energy, momentum and moisture (Hoffman, 2004). In addition, the earth’s rotation and curvature are fully accounted for through the inclusion of the full Coriolis term and curvature terms in the equations where these terms are needed. The boundary condition at the top of the model domain (in the z-direction) is that it is a surface of constant pressure (Skamarock et al., 2005).

The ARW has a telescoping feature which allows the area of interest to have a higher resolution. This is done by nesting a grid with finer resolution within the coarser, parent grid. For these simulations, a 12km grid was used for the coarse domain which includes the mid-Atlantic (Fig. 3.1, larger red box), and a 4km nested domain was used for the area of interest which was the GOM (18ºN to 31ºN latitude and 80ºW to 98ºW longitude) (Fig. 3.1, smaller red box). In addition, WRF’s moving nest routine was used for the 4 km inner domain. This routine uses the Automated Tropical Cyclone Forecasting (ATCF) system’s automatic vortex-following algorithm to update the position of the inner grid every fifteen minutes so that the finer resolution moves with and stays centered on the eye of the storm, allowing an even more accurate simulation to be produced.

b. The PWP Ocean Model and Initial Conditions

The PWP is a 1-D, upper-ocean model. The upper ocean is made up of the mixed layer and the thermocline (Fig 3.2). The PWP model consists of an array of isolated columns where there is a column under each water point in a domain. In the simulation carried out for this research, the model covers all of the domains defined for the WRF model, and the columns have a horizontal length and width that corresponds to the horizontal resolution specified in each domain for the WRF model. This ocean model can only simulate motion in the horizontal and vertical directions within each isolated column (Price, 1986 ; Jimy Dudhia, personal communication, 2007).
PWP ocean model is coupled to the WRF atmospheric model through the local heat and momentum fluxes at the surface of each isolated column. The heat flux mainly consists of solar radiation incident on the ocean surface, and latent and sensible heat absorbed from the surface by the boundary level inflow. The momentum flux is the wind stress from the hurricane which causes vertical shear in the upper ocean and leads to entrainment. Therefore, in the model, the parameterization of entrainment is dependent on vertical shear. The Coriolis force is also taken into account in the model, and causes deflection in the upper ocean flow (Price, 1986).

The PWP is a simple upper ocean model that only has two layers. In the first layer a “mixed layer” depth is specified and in the second, a constant temperature gradient for the entire Gulf of Mexico is chosen. Right below the ML, the temperature profile varies too radically in space for a reasonably accurate spatially constant lapse rate to be specified which would not underestimate or overestimate the Ocean Heat Content (OHC) in different parts of the GOM. Therefore, in this simple two-layer model, the depth of the 26°C isotherm (26C ID) is used to approximate the depth of water that has the SST instead of the actual MLD. Since the SSTs in the GOM were warmer than 26°C in August of the 2005 hurricane season, this depth is greater than the actual MLD. If this model had more layers and/or the lapse rate was specified for each column, then the lower stratification could be more accurately represented, and the actual MLD could be used instead of the 26C ID (Shuyi Chen, RSMAS, University of Miami, personal communication, 2007).

The oceanic conditions used to initialize the PWP model were set using mixed layer altimeter-derived data. This data specifies the depth of the 20°C and 26°C isotherms, and the OHC for the pre-Katrina state at 0000 UTC Aug 27 in 0.5 degree latitudinal-longitudinal grid format (L. Shay, RSMAS, University of Miami, personal communication, 2006). The oceanic conditions were incorporated into the WRF meteorological input data using WPS. In the ocean model code, the lapse rate in the transition layer below the 26°C isotherm was set as 5K / 100m.

c. Simulations

First a simulation was run without any ocean coupling (Run 1). Then a simulation was run with WRF coupled to the PWP ocean model (Run 2) (Table 3.1). In both simulations, the model version 2.1.2 was used with the ARW dynamical core option. The simulations were run for 3 days and 6 hours starting at August 27th, 2005 0000 UTC. WRF Single-Moment 5-class scheme (WSM5) was used for the cloud microphysics. This scheme allowed mixed-phase processes and super-cooled water (Hong et al., 2004). The Rapid Radiative Transfer Model (RRTM) was used to simulate the shortwave radiation and the Dudhia scheme was used for the longwave radiation. In addition, the Yonsei University scheme was used for the planetary boundary layer and the Kain-Fritsch scheme was used for the cumulus parameterization. Refer to the ARW Version 2 Modeling System User’s Guide for descriptions of the different physics schemes (Wang et al., 2007)

Below is a table summary of the simulations conducted for this study. The remaining section of this paper will describe and analyze the results obtained from these simulations.
4. Results, Discussion and Conclusion

a. Results for the WRF Katrina Simulation (Run 1) and Discussion

Run 1’s track has a maximum deviation of roughly 0.6 degrees (60 km) from the actual track. This distance is much larger than the inner and outer domain resolutions, so this difference is significant.

The simulated hurricane only reaches category 4 intensity while Katrina at its maximum intensity was a category 5 (Fig 4.1). In addition, the minimum pressure reached by the simulated hurricane was about 911mb while Katrina’s lowest recorded pressure was 902mb. The maximum wind speed the simulated hurricane obtained was about 126kts while the actual maximum was about 150kts. Additionally, the magnitude of the intensity throughout Run 1 was much lower than in actual events (Fig 4.2). It has been shown through other simulations carried out with the ARW at NCAR that this problem, of an underestimated intensity, can be fixed by increasing the resolution used to run the model (Wei Wang and Chris Davis, personal communication, 2007). A higher resolution was not used for the simulations in this paper due to the additional runtime and cost that this would incur.
In addition to the magnitude of the intensity throughout the run being off, the ARW simulation does not capture the rapid intensification of Katrina. In actual events, this intensification was coincident with Katrina passing over the WCR which was the deepest part of the mixed layer in the GOM at the time. The uncoupled WRF model does not take the mixed layer topography into account, but instead assumes an infinite MLD. This may account for the fact that the shape of the intensity profile throughout time is off.

b. Results for the WRF/PWP Katrina Simulation (Run2) and Discussion

With ocean coupling using the PWP model and the initialization procedure explained in section 3, there is only a small change in the simulated hurricane’s track and intensity (Fig 4.3, Fig. 4.4, and Fig 4.5).

Since the hurricane response (ocean feedback) was extremely small, it is necessary to check the ocean response to the passage of the hurricane to determine if the ocean model is reacting in the expected way. If the ocean response is comparable to observations, theory, and the results from other research, then the small hurricane response must be due to other factors. If the ocean response is not reasonable, then this may be part of the reason for the small hurricane response.
Figures 4.6 and 4.7 show the SST and 26°C isotherm depth (hereafter, 26C ID) fields, respectively, for the GOM on Aug. 30th 0000 UTC which is after the simulated hurricane has made landfall. The maximum amount of cooling the SST experienced in any one spot was about 2°C and occurred around 87.5°W and 28°N. The maximum amount of 26C ID deepening was about 100m and occurred around the same location. Most of the cooling and deepening occurred on the right hand side of the track.

The massive cooling and deepening that occurred near the coast (as seen in Figures 4.6 & 4.7) was not considered, when estimating the maximum cooling and deepening, because it is not realistic. This massive cooling is a result of the simple initialization procedure used for the PWP ocean model where a constant lapse rate was specified under the 26C ID over the entire GOM including along the coast. Since the 26C ID was very small along the coast due to the fact that the water is shallower there, this lapse rate allowed a large amount of cooling to take place. In reality, there is no cold water beneath the ML near the coast because the ocean floor is under the ML. Therefore, in reality, barely any cooling of the SST takes place near the coast as the hurricane approaches land.

Figure 4.8 shows the surface current vector field (in m/s) against the 26C ID scalar field. The plot is for Aug. 29th 1200 UTC just before the simulated hurricane makes landfall. It can be seen more easily from this plot that the ocean response has the greatest extent on the right hand side of the track. In a perpendicular cross section across the track through the area of maximum cooling and deepening, the length of the ocean response is 250km on the right hand side while the length of the ocean response was only about 50km on the left hand side.

This rightward bias of the ocean response is consistent with the effects of entrainment (vertical mixing) since there is a near-resonant coupling of the boundary layer circulation with the wind and Coriolis force driven rotating ML velocity on the right hand side of the track (as explained in section 2). The surface current pattern, seen in Figure 4.8, results from this near-resonant coupling, and this pattern is similar to that obtained in a simulation carried out by Shay et al. (1990, hereafter SH90) (Figures 4.8 & 4.9).
FIG. 4.8 This diagram shows the surface current vector field (in m/s) against the final 26°C ID scalar field. This plot is for Aug. 29th 1200 UTC just before the simulated hurricane of Run 2 makes landfall.

In the simulation carried out by SH90, they used a 3-D, non-linear, hydrostatic, 17 layer primitive equation model that had a free surface with a horizontal resolution of 20km. The model was forced with an idealized wind stress pattern created by delineating a Rankine vortex based on the average observed parameters in hurricane Frederic. Their idealized storm had a translational speed of 6.5 m/s and a maximum wind speed of 23 m/s (a low category 2).

In SH90’s simulation, they obtained a ML current perturbation field that had a perpendicular length, from the storm’s track, of 300 km on the right and left hand sides. In Run 2, as stated earlier, this field was 250 km on the right hand side, but only 50 km on the left hand side. This difference in results is due to the fact that SH90 used a 3-D ocean model which is also able to simulate the upwelling component of the ocean response.

Upwelling (as described in section 2), is a process that causes the deeper waters to be brought to the surface below the center of the hurricane’s circulation. This upwelling (vertical advection) causes the isotherms to rise in a domelike shape that is centered on the track, and this rising of the isotherms also enhances entrainment. Therefore, upwelling causes the surface current perturbation field to have the same extent on both sides of the track. Since the PWP ocean model used in Run 2 can not simulate upwelling, the ocean response does not have the same extent on both sides of the track.

In SH90’s simulation, the maximum ML current was 1.4 cm/s and was located about

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1 The category of the idealized storm was calculated using the maximum wind stress they gave in their paper (33 dyn/cm² or 3.3 N/m²). Wind stress is equal to \( \tau = c_a \rho_a |u|^2 \) where \( \rho_a \), the density of air, is equal to 1.2 kg/m³, \( c_a \), a dimensionless drag coefficient, is equal to 0.0015, and \( u \) is the wind speed.
60km (3R_{\text{max}}) to the right of the storm’s track. In Run 2, on Aug. 29 at 6000 UTC, the hurricane was a low Category 4 with a wind speed of 59.7m/s and a translational speed of 5.7m/s. The maximum ML current was 1.41m/s and was located about 70km to the right of the storm. Even though these numbers are comparable, Shay et al.’s idealized hurricane was a Category 2 and in Run 2 at this point in the simulation, the hurricane was a Category 4. Therefore, Run 2’s maximum surface current speed should be larger than that obtained in SH90’s simulation. In addition, Run 2’s larger Category storm should have produced an ocean response that was even larger on the right hand side than its 250km perpendicular length, and SH90’s 300km perpendicular length.

As stated earlier, in Run 2, the maximum SST cooling was about 2°C and the 26C ID deepened by a maximum of 100m. As mentioned in section 2, observations analyzed by Black (1983) showed that the average cooling over the extent of the ocean response for a fast moving storm (>6m/s) is 1.8°C. Since the maximum cooling for Run 2, which was over a small area of the entire cooling, was only 2°C, and since at this point the storm was a Category 4, the magnitude of the ocean response may have also been underestimated by the 1-D PWP ocean model due to the fact that the upwelling component can not be simulated.

This analysis is consistent with what Price (1981) found. He used a 3-D model to determine the effect of non-local dynamic processes (such as upwelling) on the ocean response. When upwelling was omitted from the 3-D ocean model, it was the equivalent of each grid point operating independently and the 3-D model becoming an array of 1-D models. When the model was rerun under these stipulations, the change in the SST near the track was underestimated by ~35%.

c. Conclusion and Justification for Further Research

Many key aspects of the ocean response in Run 2 were inconsistent with observations, theory, and other research. These inconsistencies may be due to the fact that the upwelling component of the ocean response can not be simulated with this 1-D isolated column ocean model, and the simple initialization procedure used for the model since it only has 2-layer. The weak and narrow ocean response the model produced which was a product of these inconsistencies, may have contributed to the weak hurricane response that was obtained in Run 2.

Coupling WRF with a 3-D ocean model may produce a simulation that is more consistent with observations, theory and other research in terms of the physics of the hurricane-ocean interaction since a 3-D model is able to use a more complete initialization procedure, and to capture both aspects of the ocean response.

d. Description of Future Research

In future research, a Katrina simulation with WRF coupled to a 3-D ocean model, should be carried out using the same atmospheric initial conditions used to initialize the model in Runs 1&2. The HYCOM (Hybrid Coordinate Ocean Model) would be a good choice for this experiment.

HYCOM is a 3-D hybrid model in that it has z-level coordinates in the ML, a density following coordinate system (isopycnal) under the ML (where the ocean is stratified), and sigma coordinates (which are terrain-following) in the shallow coastal regions. In addition, this model is adaptive in time and space, because it uses the layered continuity equation to allow transition between the different vertical coordinate types during the simulation depending on the changing conditions.
In order to more easily compare the two simulations, the oceanic initial conditions used for the PWP ocean model should be as realistic and as comparable to the HYCOM initialization as possible—given the simplicity of the model. In this paper, the 26C ID was used as the mixed layer depth so as not to overestimate or underestimate the OHC since a constant thermocline lapse rate was used for the entire GOM (as explained in section 3). However, the actual MLD can be used instead if a different constant lapse rate is used to initialize each column of the ocean model. These lapse rates can be extrapolated from the 3-D temperature field used to initialize HYCOM and/or based on the integrated OHC for each column. In addition, this more realistic initialization procedure, for the PWP, may improve the hurricane response compared to the results obtained in Run 2.

Running a WRF/HYCOM simulation presents many difficulties. The PWP ocean model was able to be incorporated into WRF as a subroutine so it did not change the way the WRF model was set up and run. However, HYCOM is a separate entity that has to be coupled to WRF through a program called MCEL which handles the communication between the two models throughout the simulation. This arrangement changes the way WRF is set up and run, and it complicates the entire process making it very difficult to make adjustments to the model, and to carry out simulations. The WRF/HYCOM system needs to be made more user friendly, and more compatible with other systems such as WRF, if it is to be used for extensive research.

Another difficulty that will be encountered when carrying out research using WRF coupled to HYCOM is the increase in time and hence the increase in cost of the simulations that will be incurred due to the increase in ocean complexity. At this point, the increase in cost is so drastic that in its current configuration setup on NCAR’s supercomputers, HYCOM is only coupled to the inner grid of the WRF model domain, and the outer grid is forced by oceanic satellite data that has to be updated on a periodic basis throughout the simulation (personal communication, John Michalakes, 2007). This current configuration would produce a simulation that could not be easily compared to the WRF/PWP simulation. Therefore, the WRF/HYCOM coupled model needs to be rebuilt and reconfigured, so that HYCOM can be fully coupled to WRF without incurring unmanageable runtimes and cost, before this next phase of this research project is carried out.

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