# THE INTERACTION BETWEEN HURRICANE OPAL (1995) AND A WARM CORE RING IN THE GULF OF MEXICO

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## 1. Introduction

It is well known that ocean supplies most of the energy for the development and intensification of tropical cyclones through interfacial transfers of heat fluxes. Tropical cyclones weaken quickly when cut off from these fluxes as they move into land or over cold ocean surface. The dependence of tropical cyclone on ocean conditions, especially the surface and sublayer temperature is well documented. Hurricane Opal of 1995 presents a unique opportunity to study the interaction between tropical cyclones and the ocean. Hurricane Opal experienced a sudden and unpredicted intensification 24 hour before its landfall, severely reduced the effectiveness of coastal evacuation procedure and, as a result, caused considerable damage along Mississippi, Alabama and Florida coasts. During the rapid deepening from 965 hPa (with maximum wind of 110 mph) to 916 hPa (130 mph) over 14 hours, Opal moved over a warm core ring (WCR) that had separated from the Loop Current in the Gulf of Mexico.

The purpose of this study is to analyze simulated interactions between Hurricane Opal and the WCR with a 3-D coupled numerical model with a realistic initial condition. Sensitivity tests will be performed to examine the air-sea coupling of Hurricane Opal and the effect of the WCR in the coupling.

## 2. The Coupled Model

The Naval Research Laboratory (NRL) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) and the Geophysical Fluid Dynamics Laboratory's (GFDL) Modular Ocean Model Version 2 (MOM2) form the coupled system used in this study. The COAMPS atmospheric model is based on non-hydrostatic, compressible dynamics. The parameterized physics include subgrid scale, boundary and surface layer formulation, explicit moist physics for grid-scale precipitation, cumulus parameterization, and the radiative transfer of long- and short-waves. A detailed description of the model can be found in Hodur (1997). For this study, a doubly nested grid covering a domain from 0 to 54 $^{o}$ N and from 121.0 to 29.4 $^{o}$ W is set up to include the tropical and mid-latitude large environmental flow around Opal (Fig. 3). The outer coarse grid has 137 × 91 × 30 points with 0.6 $^{o}$ longitude and latitude resolution horizontally. The inner finer grid has 247 × 136 × 30 points with 0.2 $^{o}$ resolution with an inner grid domain extending from 9 to 36 $^{o}$ N and from 98.2 to 49.0 $^{o}$ W to encompass the immediate area covered by Opal's circulation. The vertical coordinate is in sigma-z with 30 vertical levels in the model. The heights for any grid points over the ocean are 10, 30, 55, 90, 140, 215, 330, 500....m, etc.

The GFDL's MOM2 is a three-dimensional primitive equation ocean model (Bryan 1969, Semtner 1974, Cox 1984, Paconowski 1996). The governing equations consist of the Navier-Stokes equations using the Boussinesq, hydrostatic approximations. A nonlinear equation of state uses the temperature and salinity to calculate the ocean density. A free surface equation is solved for surface height perturbations. A staggered B grid is used with the vertical coordinate in depth z. The Scripps 1 $^{o}$ bathymetry is interpolated to the oceanic grid. For our study, 20 vertical levels are set up in MOM2, where the depths are 5, 17, 36, 67, 113, 179, 267, 381, 522, 692, 892,... m, etc.

In the coupled model, the time step of inner atmospheric grid is three times smaller than that used in the coarse atmospheric grid, which equals the time step of the limited-area ocean model. Thus, fluxes of heat, moisture, momentum, and mass from the atmospheric are summed over three time steps of the inner atmospheric grid before exchanges with the upper ocean. During the three time steps, the ocean conditions are held constant for the calculation of the fluxes.

## 3. The Initial Condition and Experimental Design

The first-guess fields for the initial condition are obtained from the Navy Operational Global Atmosphere Prediction System (NOGAPS) analysis valid for 1200 UTC 2

October 1995. In the NOGAPS analysis, a bogus vortex (Goerss and Jeffries 1994) representing the inner circulation of Opal is introduced to represent Opal on the NOGAPS grid. The first guess fields are re-analyzed for COAMPS grids by a multivariate optimum interpolation (MVOI) analysis technique (Lorenc 1986).

The initial ocean condition that realistically describes the Gulf of Mexico prior to Opal is obtained by first integrating for two years a global MOM2 at a horizontal resolution of 1 $^{o}$ latitude and 2 $^{o}$ longitude. A regional MOM2 is then run with a resolution of 0.2 $^{o}$ long and lat covering the area of interest. Both of the integrations are forced by climatic surface fluxes. The spin-up provides the "correct" boundary and gap flows, including the Gulf of Mexico Loop Current and the Gulf Stream. The prominent features in the initial ocean fields are the anticyclonically-rotating WCR shed from the Loop Current. The WCR is located at 25 $^{o}$ N and 89 $^{o}$ W. SST, ocean surface height anomaly, and the salinity fields are similar to available observations.

Many numerical experiments with various model configurations have been conducted. Due to page limitation, only some of the experiments will be discussed, these are the coupled (C1) and uncoupled (U1) with the WCR and the coupled (C2) and uncoupled (U2) without the WCR.

## 4. Results

### *a. Evolution of Opal's Intensity*

As shown in Fig. 1, the observed and simulated tracks of Hurricane Opal in Exps C1 and U1 are superimposed on the initial model SST (shaded) and surface height (contour) in the Gulf of Mexico. The observed and simulated minimum central sea-level pressures (MSLP) over the period of 72 h are given in Fig 2.

The simulated track is located to the east of the observed, passing right through the central point of the WCR. The simulated storm moves at a lower speed. The simulated land fall time is 11 h behind the observed. At 72 h, the position error is approximately 440 km, a typical position error in operational numerical prediction of tropical cyclones. The evalution of Opal's minimum MSLP follows the general trend of the observed, but differs in details. First, the observed minimum MSLP of Opal has a relatively steady MSLP near 970 hPa for about 24 h before undergoing a rapid intensification during the second 24 h period during the window of interest. The maximum intensification of 41 hPa to 916 hPa occurred during an 11 h period from 0000 to 1100 UTC Oct 4, upon encountering the WCR. By contrast, the intensification of the simulated Opal is much smoother. The MSLP starts from 985 hPa, which is 12 hPa higher than the observed due to the coarse resolution of the global analysis, and deepens to 917 hPa around 1800 UTC 4 October. The delay in reaching the maximum intensity of approximately 7 h and the subsequent weakening (due to cooler SST and land fall) is related to the slower translation speed of about 7 m $s^{-1}$ in the simulation compared to the observed translation speed of 8.5 m $s^{-1}$. It is not surprising that the observed and simulated Opal reaches its maximum intensity as its center moves over and exits the WCR, outlined by the zero SHA contour.

### *b. Opal Induced Response in the Gulf of Mexico*

As Opal moves past the WCR at 0000 UTC Oct 5 (Fig 3), the maximum current speed is accelerated to 200 cm $s^{-1}$ located to the east of the WCR between the cyclonic and anticyclonic pattern. The SHA of the WCR is reduced to 10 cm from the pre-storm height of 40 cm, in good agreement with the altimeter observation from TOPEX (Shay et al. 1998). As Opal moves further north and makes landfall, the maximum SHA is restored to 30 cm and the induced asymmetry lessens. There is a long swath with storm-induced ocean current well over 100 cm $s^{-1}$ to the right of the storm track between the WCR and the Florida panhandle, similar the earlier numerical studies (e.g., Chang and Anthes 1978, Price 1981, Shay et al. 1990) with horizontally homogeneous initial ocean field.

The SST and salinity changes induced by Opal are depicted in Fig 4. In early numerical simulations with initially homogeneous ocean, the induced cool pool is in an elongated pattern located on the right side of the storm track, centered at approximately 2 $R_{max}$. Here, the distribution of the SST changes are modulated by the WCR. As shown in Fig 4, the maximum cooling of more than 2 $^{o}$ C is located to the southwest of the WCR, where the initial mixed layer is shallower (<50m) with stronger stratification below the mixed layer. Over the WCR, the induced cooling is less than 0.5 $^{o}$ C, due to the 200-m deep mixed layer and a stronger stratification below.

### *c. The Effect of the WCR on Opal*

Exp C2 is a coupled experiment with an ocean initial condition otherwise identical to Exp C1 except without the WCR, is conducted. In both Exps C1 and C2 (Fig. 5), the minimum SLP deepens nearly identically from the initial value of 985 hPa at 1200 UTC Oct 2 to 934 hPa 36 h later at 0000 UTC Oct 4. As the center of Opal encounters the WCR regime, the two experiments differ markedly. Opal in Exp C1 continues to intensify by 17 hPa over the next 18 h, reaching a minimum central MSLP of 917 hPa. In the absence of the WCR in Exp C2, Opal decelerates its intensification phase after 0000 UTC Oct 4; its central pressure decreases only another 7 hPa to 927 hPa. Based upon these simulated resuls and agreement with observed changes in the atmosphere and the ocean, *the WCR is responsible for 60% of the final intensification of Opal.*

As expected, the stronger total surface heat flux, both sensible and latent, from the WCR supports a stronger precipitation in C1 as compared to C2. The typical pattern of precipitation is over 90% on the grid-scale, especially in the northern semi-circle where strong precipitation occurs, and less than 10% convective. The effect of the WCR is also evident in the inner core structure of the inner core represented by the equivalent potential temperature (EPT), as a measure of moist static energy, and the wind velocity component tangential to the cross-section through the storm center. In the eye region from C1 experiment, the 370 $^{o}$ K contour is at the 450-hPa level, the 365 $^{o}$ K contour is at 600 mb, and the EPT of the entire eye region is above 360 $^{o}$ K. In Exp C2, these contours occur at higher altitudes at 200, 500 and 700 hPa, respectively. The EPT in the inner core is at least 3 $^{0}$ K cooler than that in C1 below the 500-hPa-level. These results suggest that the tropical cyclone in C1 is more active, robust and intense.

*d. The Effect of Opal on the WCR*

The considerable differences in intensity and structure of the simulated Opal in Exp C1 and C2 discussed above are mostly due to the large heat content of the WCR, which supports the sensible and especially the latent heat transfers to Opal. The heat content Q at a point is as the vertical integration of ocean temperature excess relative to 26 $^{o}$ C. The quantity Q at a selected point (25 $^{0}$N, 89 $^{0}$W) in the pre-storm WCR in Exp C1 is 43 Kcal cm$^{-2}$ as compared to is 10 Kcal cm$^{-2}$ in the common water. These numbers agree with the observed values (Shay et al. 1998). At 0000 UTC Oct 4 as Opal just begins to encounter the WCR in Exp C1, the maximum heat content of the WCR is 43 units ($10^{3}$ cal cm$^{-2}$ ) at the center of the WCR (Fig. 6). The total surface flux is closely correlated to the surface wind field with maxima in the range of 1500-2000 watt m$^{-2}$. At 1800 UTC as Opal begins to exit the WCR, the maximum flux is increased to nearly 2842 watt m$^{-2}$ (Fig. 6). The maximum heat content has decreased to 25 units at 00 UTC Oct 5. In Exp C2 without the WCR, the maximum flux remains just over 1500 watt m$^{-2}$ without the contribution from the WCR as a reservoir.

The air-sea interaction between Opal and the WCR can be further examined by using temporal variations of several parameters--depth of 26 $^{0}$ C isotherm, ocean heat content, surface heat fluxes, and the surface wind stress--are best shown by first normalized with their maximum and minimum values due to their large difference in magnitude. The maximum and minimum values sampled at (25 $^{o}$ N, 89 $^{o}$ W) are listed in Table 2. As shown in Fig. 6, the four parameters stay relatively unchanged to 1800 UTC 3 Oct before Opal encounters the WCR. At 0600 UTC 4 Oct as the northern eyewall moves over the sampling point at 25 $^{0}$ N and 89 $^{0}$, both the total heat flux and wind stress increase suddenly to 60-70% of their respective maximum values. This very large decrease and increase signifies the passing of the eye and the southern section of the eyewall of Opal. During this rapid change, the heat flux and wind stress increase by 1313 watt m$^{-2}$ and 10 dyne cm$^{-2}$ from the pre-storm levels and attain their maximum values of 2597 watt m$^{-2}$ and approximately 82 dyne cm$^{-2}$ at approximately 1500 UTC 4 Oct. Rapid decreases of the mixed-layer depth and total heat content coincide with the eys's arrival. The heat loss rate is about 32 Kcal cm$^{-2}$ d$^{-1}$.

Without the WCR, the temporal variations of the heat content in Exp C2 is similar in their evolution but not as dramatic as compared to that in C1 shown in Fig 6. The available heat content defined in (6) is only approximately 10 Kcal cm$^{-2}$ at the same sampling point at 25 $^{o}$ N and 89 $^{o}$ W. The maximum heat flux in C2 is 1711 watt m$^{-2}$, 30% less than that in Exp C1.

*e. Feedback Effects*

The behavior of Hurricane Opal is undoubtedly coupled to the underlying SST. The effect of the *feedback* of the induced ocean response is examined, mainly, the SST cooling, to the overlying tropical cyclone. (This is not to be confused with the response of tropical cyclone to varying SST field.) Conversely, we can also examine the effect of the weakening of the tropical cyclone--due to the ocean response--on the ocean.

Two numerical integrations of the atmospheric component of the coupled model are conducted to elucidate the effect of the feedback between Opal and the Gulf of Mexico. Exp U1 is run in which the initial SST with the WCR is held constant throughout the integration, whereas Exp U2 is run with the initial SST without the WCR. The minimum SLPs of the simulated Opal are plotted in Fig. 5.

Comparing C1 and U1, the effect of coupling to the ocean on Opal is small, albeit noticeable, after the first 24 h of integration. At the maximum intensity at around 1800 UTC 4 October for both experiments, the difference is 5 hPa. *This is not to be interpreted that Hurricane Opal is insensitive to the SST, it is merely that the effect of the feedback from the cooled ocean makes Opal 5 hPa weaker.* That is, less heat is available for Opal because of storm-induced mixing and active entrainment at the mixed layer base.

The feedback effect without the presence of WCR can be examined by comparing Exps C2 and U2. As shown in Fig. 5, the maximum intensity is 8 hPa at 0000 UTC Oct 5. *The negative feedback effect is stronger without the presence of the WCR.* The average induced SST cooling near the track is closer to 1.5 $^{o}$ C in Exp C2. It is evident that the WCR decreases the ocean thermal response, thereby reducing the feedback effect to the tropical cyclone.

5. Summary

A coupled atmosphere and ocean model, the COAMPS and MOM2, has been used to investigate the interaction between Hurricane Opal (1995) and the Gulf of Mexico in early October of 1995. Hurricane Opal moved almost directly over a WCR shed from the Loop Current. A control numerical experiment was first conducted in which the atmosphere was allowed to interact with the ocean. The simulated Opal moved slower and took a path slightly to the east of the observed storm track, placing itself directly over the WCR. The central pressure decreased from the initial 985 hPa to a minimum of 917 hPa in 54 h as the storm center exited the northern edge of the WCR. The maximum intensity nearly matched the observed intensity level, but the phase was 6 h late due to the slower movement of the simulated storm. The thermal and dynamic response of the Gulf of Mexico was similar to earlier idealized simulations, except over the WCR where the maximum SST decrease was less than 1 $^{o}$ C as compared to the 2 $^{o}$ C cooling elsewhere. The induced surface current field in the wake was altered by the anticyclonic circulation around the WCR, which was temporarily turned into cyclonic rotation in the front-half of hurricane Opal as it passed over the feature. Shay et al. (1998) showed that the circulation associated with the WCR had to be removed from current profiles to examine the near-inertia response.

Further analyses and additional numerical experiments indicated that approximately 40% of the available heat content of the WCR was extracted by Opal via enhanced air-sea fluxes. The heat transfer was converted into an increase of grid-scale precipitation (hence higher equivalent potential temperatures) and into an intensification of Opal. The WCR is responsible for 60% of the intensification of 17 hPa when Opal interacted with the WCR. A series of uncoupled numerical experiments were also conducted. As expected the uncoupled experiments resulted in stronger intensity of Opal and stronger response of the ocean. Uncoupled experiments suggested that the negative feedback of the induced ocean response to Opal was on the order of 5-8 hPa. Considering the average induced SST cooling, the feedback agreed with the linear theory. It is worth noting that *the hurricane-ocean coupling is stronger but the feedback is weaker in the case with the WCR* due to its deep and warm mixed layer as suggested by observational results (Shay et al. 1998).

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Table 1. List of Numerical Experiments

| Exp | Coupling | Atmosphere | Ocean |
|---|---|---|---|
| C1 | coupled | with Opal | with WCR |
| U1 | uncoupled | with Opal | fixed with WCR |
| C2 | coupled | with Opal | with no WCR |
| U2 | uncoupled | with Opal | fixed with no WCR |

Table 2. The Maximum and minimum values of $x(t)$ at (25 $^0$N, 89 $^0$W)

| | Depth of 26 $^0$C isotherm (m) | Heat content (Kcal cm$^{-2}$) | Heat fluxes (Watts m$^{-2}$) | Wind stress (dyne cm$^{-2}$) |
|---|---|---|---|---|
| Max (Exp C1) | 200 | 43 | 2597 | 82 |
| Max (Exp C2) | 71 | 8 | 1711 | 7 |
| Min (Exp C1) | 129 | 23 | 0 | 0 |
| Min (Exp C2) | 0 | 0 | 0 | 0 |

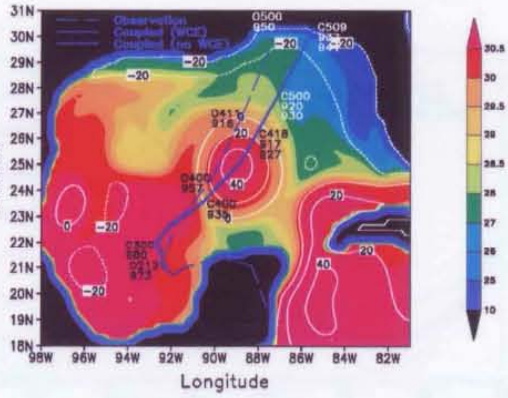


Fig 1. Observed and simulated tracks of Hurricane Opal in Exps C1 and U1 superimposed on the initial model SST (shaded) and surface height (contour) in the Gulf of Mexico.

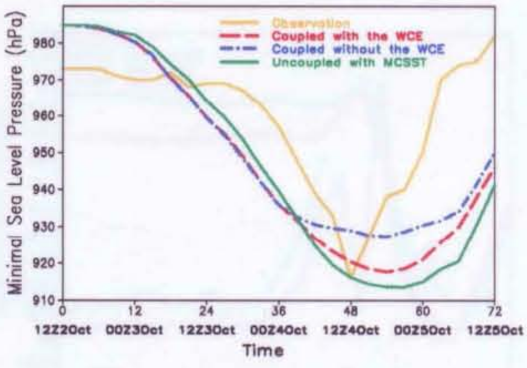


Fig 2. Observed and simulated minimum sea level pressures from the Exps C1, U1 over the period of 72 h.



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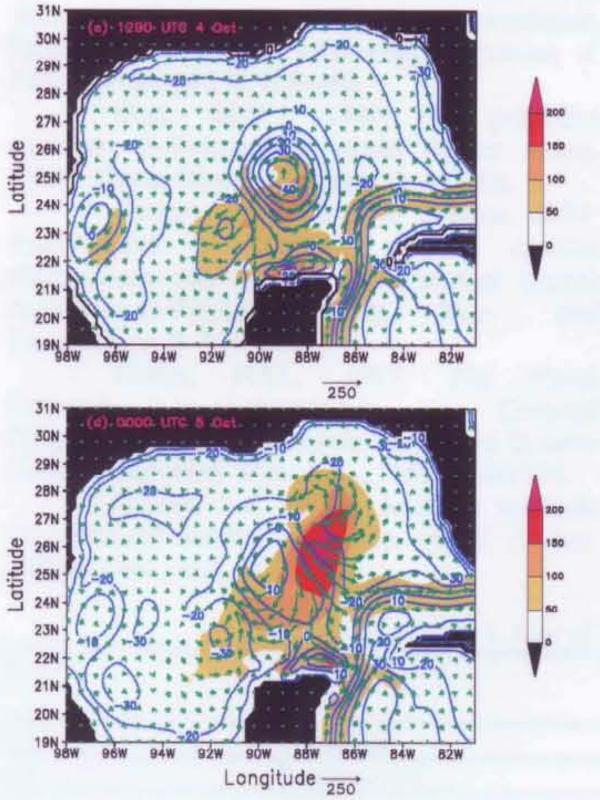


Fig 3. Surface current isotach (shaded), surface current vectors and surface height (contour) for Exp C1 at (a) 12 UTC Oct 4 and (b) 00 UTC Oct 5.

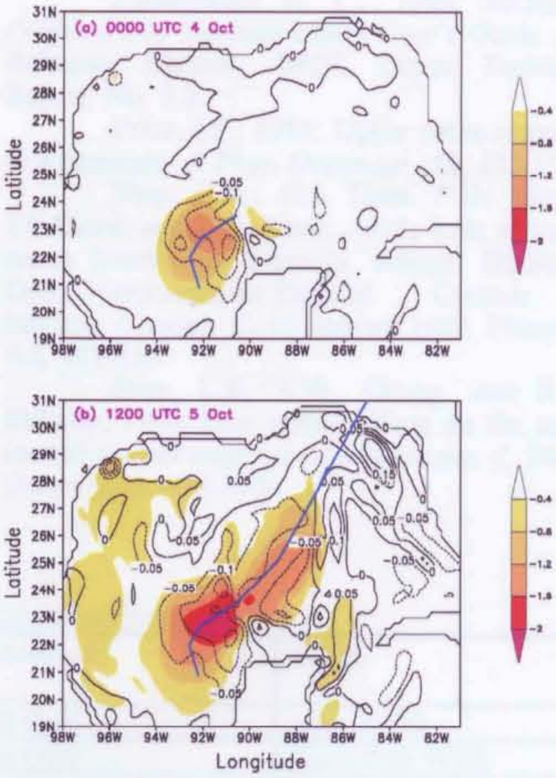


Fig 4. Changes of the sea surface temperature (shaded) and the sea surface salinity (contours) at (a) 00 UTC Oct 4 and (b) 12 UTC Oct 5 for Exp C1.

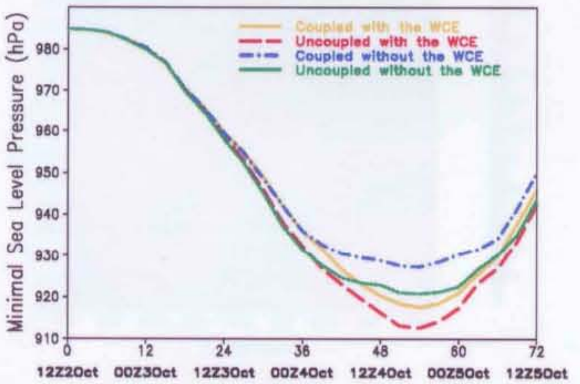


Fig 5. Simulated minimum sea level pressures from the Exps C1, U1, C2 and U2 over the period of 72 h.

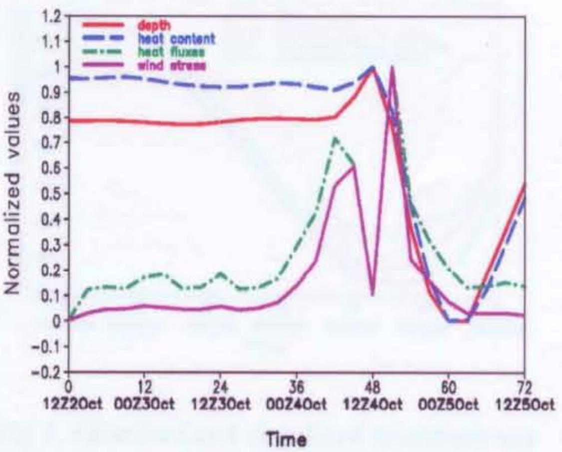


Fig 6. Normalized variables (table 2) including the depth of 26 C isotherm, ocean heat content, surface heat fluxes and the surface wind stress for Exp C1.



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# THE INTERACTION BETWEEN HURRICANE OPAL (1995) AND A WARM CORE EDDY IN THE GULF OF MEXICO

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Hurricane Opal of 1995 experienced a rapid, unexpected intensification in the Gulf of Mexico that coincided with its encounter with a warm core eddy (WCE). The relative positions of Opal and the WCE and the timing of the intensification suggest that there is strong air-sea interaction between the tropical cyclone and the ocean. A coupled atmosphere and ocean model, the COAMPS and MOM2, was used to investigate the interaction between Hurricane Opal (1995) and the Gulf of Mexico.

We first generated a control numerical experiment in which the atmosphere was allowed to interact with the ocean. The simulated Opal moved slower and took a path slightly to the east of the observed storm track, placing itself directly over the WCE. The central pressure decreased from the initial 985 hPa to a minimum of 917 hPa in 54 h as the storm center exited the northern edge of the WCE. The maximum intensity nearly matched the observed but the phase was 6 h late due to the slower movement. The thermal and dynamic response of the Gulf of Mexico was similar to earlier idealized simulation, except over the WCE. The maximum SST decrease over the WCE was less than 1 degree C as compared to 2 degree C cooling elsewhere. The induced surface current field in the wake was broken by the anticyclonic circulation around the WCE, which was temporarily turned into cyclonic direction as Opal was passing.

Further analyses and additional numerical experiments indicated that approximately 40% of the available heat content of the WCE was extracted into Opal. The heat transfer was converted into an increase of grid-scale precipitation (hence higher equivalent potential temperatures) and into an intensification of Opal. We found the WCE is responsible for 60% of the intensification of 17 hPa when Opal interacted with the WCE. A series of uncoupled numerical experiments were also conducted. As expected the uncoupled experiments resulted in stronger intensity of Opal and stronger response of the ocean. The uncoupled experiments suggested that the feedback of the induced ocean response to Opal was on the order of 5-8 hPa. Considering the average induced SST cooling, the feedback agreed with the linear theory. It is worth noting that the hurricane-ocean coupling is stronger but the negative feedback is weaker in the case with the WCE due to its deep and warm mixed layer.

KEY words: Hurricane, air-sea interaction, coupled model.