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MET/OCN 665 term-project

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Is Warm Core Rings (WCR) the Major Reason Inducing the Rapid Intensification of Hurricane Opal

1. Introduction

Hurricane Opal became a tropical storm on 30 September 1995 and intensified from 965 to 916 hPa in 14 hours when crossed the Gulf of Mexico on 4 October. This rapid and dramatic intensification attracts many experts to explain this phenomenon. Since hurricane development is easy to be influenced by the external effects, these issues can be mainly divided into atmospheric and oceanic two parts. The atmospheric issues were proposed such as the jet, trough and hurricane interacted in a low-shear environment by analyzing the data from European Centre for Medium-Range Weather Forecasts (ECMWF) and National Centers for Environmental Prediction (NCEP) (L. F. Bosart et al. 2000) and the gradient of angular momentum which was induced by the mesoconvective precipitation in the lower-tropospheric inflow layer adjusts the Potential Vorticity (PV) (T. N.Krishnamurti et al. 1998). As announced by the previous research, the ocean also plays an important role in the hurricane intensifying and decaying. Hence, a warm core rings (WCR) right in the track when Opal passing the Gulf of Mexico was also a hot issue. (Xiaodong Hong et al., 2000, Lynn K. Shay, 2000) At the same time, the internal effect, the concentric eyewall displacement may also play a role in the intensification process (L. F. Bosart et al. 2000, T. N.Krishnamurti et al. 1998). In this study, I will focus on the ocean WCR influence to the Opal intensification.

Recently, it is noticed that the oceanic upward heat flux is the major energy source to support tropical cyclone. The surface wind under the tropical cyclone accelerates these fluxes through the increased surface turbulence and at the same time, the increased upward heat flux generates the low pressure. However, the lower pressure inhibits the heat flux by decreasing the water vapor pressure and lower saturation mixing ratio. Hence the thermodynamic disequilibrium is generated.

Though this theory was known more than 50 years ago (e.g., Riehl 1950; Kleinschmidt 1951), the sensitivity between Sea Surface Temperature (SST) and tropical cyclone intensity is still an open question. On the one hand, from the dynamic theory, there is less sensitivity between the tropical cyclone maximum intensity and SST. On the other hand, in the thermodynamic theory, SST is a very important factor to influence the maximum intensity of the tropical cyclone. Even more, when SST is altered by the tropical hurricane surface wind, it becomes more complex, although there exists almost explicitly relationship between the SST and Maximum Potential Intensity (MPI) (e.g. K.A. Emanuel 1991; G. J. Holland 1997) For this paper, I will investigate if SST anomaly plays a crucial role in the intensification process of Hurricane Opal. In the section 2, I will introduce the supporting standpoint from two articles. Then I will state the opposing opinions in section 3. In the last section 4, it is the conclusion section.

2. The Effect of WCR to Opal intensification

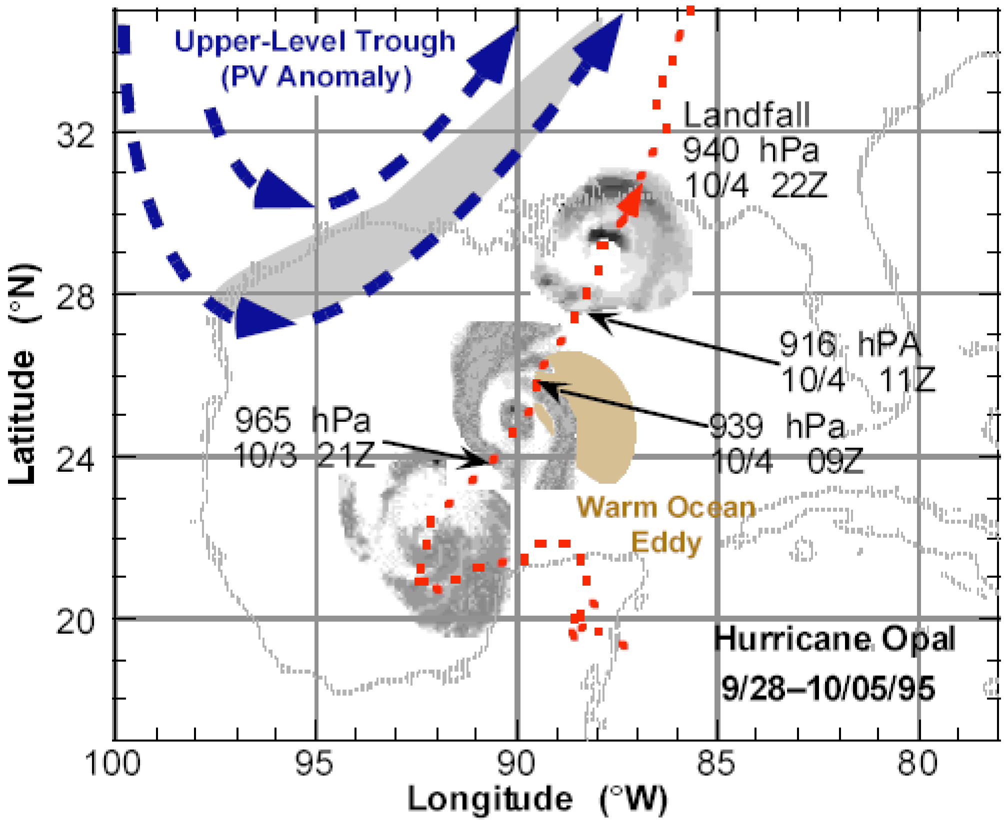

Fig1: Track of Hurricane Opal from 28 September to 5 October 1995. The storm track is drawn as a bold dotted line. The warm core ocean eddy location derived from TOPEX altimeter data is depicted by the dark stippling. The storms internal structure is represented by SSM/I 85-GHz imagery at 1629 UTC 3 October, 0337 UTC 4 October, and 1555 UTC 4 October. The 85-GHz black body temperatures are depicted as shades of gray, the darker shades denoting cooler temperatures. The SSM/I data was provided by Jeff Hawkins (Naval Research Laboratory/Monterey), and the TOPEX/Poseidon imagery used to find the location of the warm core eddy was provided by Gustavo Goni (Remote Sensing Group, University of Miami/Rosenstiel School for Marine and Atmospheric Science). (adopted from Marks et al. 1998).

As the Fig1 shown by Marks et al.1998, it is easy to find out that there is a warm core ocean eddy ring touched the Hurricane Opal intensification track. Hong et al. (2000) and Shay et al. (2000) thought it was a good example to show the interaction between the warm ocean temperature anomaly and tropical cyclone.

They used different models to simulate this intensification and got the conclusion that because of the warm core ring (WCR) heat content, the negative feedback of SST effect which was induced by the surface wind under the hurricane Opal turned into the positive feedback. And "the WRC is responsible for 60% of the intensification of 17hPa when Opal interacted with the WRC" (Hong et al., 2000). Looking at Hong et al.(2000)'s paper, they used a model which couples a nonhydrostatic atmospheric component of the Naval Research Laboratory's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) and the hydrostatic Geophysical Fluid Dynamic Laboratory's Modular Ocean Model version 2 (MOM 2), together with a realistic initial condition to analyze the interaction between the WCR and Hurricane Opal. The following presented are their model mechanism, initial condition and results.

I) model introduction:

The COAMPS atmospheric model was based on nonhydrostatic, comprehensible dynamics of Klemp and Wilhelmson (1978). The parameterized physics include subgrid-scale mixing (Deardorff 1980), boundary and surface-layer formulation of Louis et al. (1982), explicit moist physics (Rutledge and Hobbs 1983) for grid-scale precipitation, cumulus parameterization of Kain (1990) and Kain and Fritsch (1993), and the radiative transfer of Harshvardan et al.(1987). The model specific description can be found in Hodur (1997) and Xu (1995). In their study, two-nested grids were used with an outer coarse resolution 0.6^o longitude and latitude horizontally in the domain from 0^o to 54^o N and from 121^o to 39.4^oW and an inner fine resolution 0.2^o from 9^o to 36^oN and from 98.2^o to 49.0^oW, which covered Gulf of Mexico, Caribbean Sea and the western of Atlantic Ocean. The vertical coordinate was in sigma z with 30 vertical levels.

The coupled ocean model was GFDL's MOM2, a three-dimensional primitive equation ocean model (Bryan 1969; Semtner 1974; Cox 1984; Paconowski 1996). MOM 2 circulation was forced by interfacial fluxes of momentum, sensible and latent heat, and shortwave and longwave radiation. And the depth coordinate was set up to 20 vertical levels in MOM 2. At the same time, the simulated domain in MOM 2 was the same as the atmospheric model inner domain, as well as the resolution.

II) Initial conditions:

The initial atmospheric conditions were verified by multivariate optimum interpolation (MVOI) analysis technique (Lorenc 1986) from the Navy Operational Global Atmosphere Prediction System (NOGAPS) data on 1200 UTC 2 October 1995. In MVOI, the wind, heights and thickness were obtained from the real situation, but the boundary conditions were not reanalyzed by MVOI, 12 hours intervals from NOGAPS analyses.

The initial ocean conditions were not real conditions from the ocean, but integrated from the climatological forcing (Esbensen and Kushnir 1981) and a fixed boundary condition from a 2-year global MOM2 simulation. The simulation result is shown in fig2 and the most distinct feature is that there was a anticyclonically rotating WCR which located at 25°N and 89°W departs from the Loop Current. But it was 1° south of the observation data. (Shay et al. 2000) At the same time, the simulated SST was $2^{\circ}-3^{\circ}$ less than the AVHRR derived the real SST on 29 September 1995 (fig4). But it could be explained by the integrated climatological forcing. And there wasn't cold SST in the AVHRR figures. But authors suggested that it was a realistic situation since the streamers of colder west Florida shelf water flows into the loop current and WCR. And then they did some sensitive experiments and compared the simulated results with the hurricane Gilbert (1988). Most of them were matched with observation data.

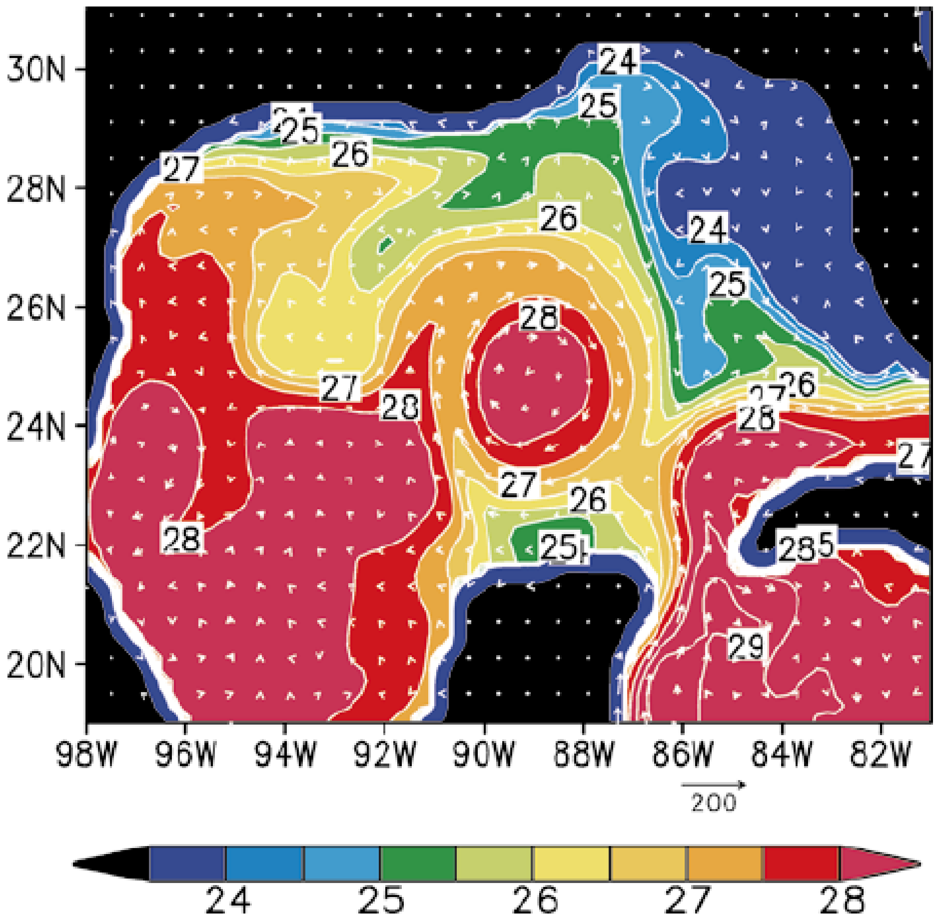

FIG. 2. Sea surface temperature (contours) and current speed (vectors in cm s21) obtained from a 690-day simulation in the Gulf of Mexico basin. (Hong et al. 2000)

III) Results:

After doing the control experiment and several comparable experiments, coupled/uncoupled ocean model, with/without WCR and fixed with WCR, they got several results. Figure 3was one of their results.

The simulated Opal crossed the center of the WCR with a slower speed which led the time reaching the maximum intensity delayed 6 hours. But the minimum central pressure was quite similar, and the time period of deepening and weakening was agreed with the observation. Hong et al. (2000) also demonstrated that "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 about 0.5^oC as compared to the $2^o C$ cooling elsewhere." However, according to the Shay et al. (2000), the 0.5^oC cooling was quite agreed with the buoy measurements in the WCR.

They also achieved the effect of the WCR on Opal through comparing the experiments with WCR to without WCR. The experiment with WCR didn't affect the Opal's track but obvious influence the maximum intensity. It deepened the maximum intensity 10hPa more than the experiment without WCR and matched the observation. Based on these simulated results, they got the conclusion that WCR is the major reason inducing Opal intensified between Oct 3rd and 4th. They also tested the wind field and precipitation to prove that the results were good enough. Then they also showed that the weaker negative feedback is congruent with the theory of Emanuel.

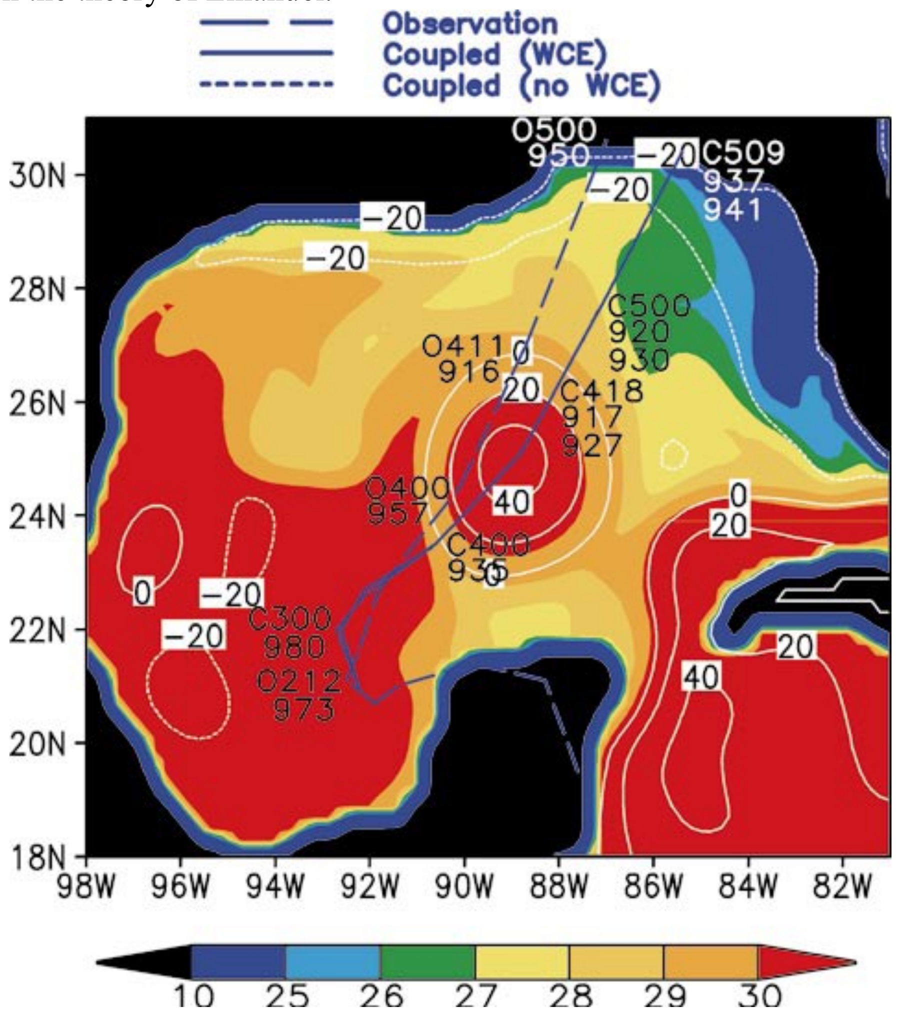

Fig3. Observed and simulated tracks of Hurricane Opal in expts C1 and U1 superimposed on the initial model SST (shaded) and surface height (contour) in the Gulf of Mexico. The letters O and C, followed by time (i.e., 212 gives the time 2 Oct 1200 UTC), represent the observed and model output, respectively. The numbers in the second and third lines represent the minimum sea level pressure. (adopted by Hong et al.2000)

3. Discussion:

Though we know the warm SST is quite important to hurricane intensification (Emanuel 1991; Holland 1997), is WCR the main reason inducing this rapid intensification of Hurricane Opal?

The observed ocean data in 1995 is very rare, so most data are modified by interpolating or simulating based on the other years' data. During the period of Opal passing over Gulf of Mexico, two different images of sea surface temperatures are showed by National Aeronautics and Space Administration (NASA) oceanographic Topography Experiment (TOPEX) mission and Advanced Very High Resolution Radiometer (AVHRR) derived. From the TOPEX data and poststrom satellite data, a WCR was shown when Opal intensified (fig 2); while in the AVHRR derived image, in the area of Opal deepening, there was not any ocean eddies but uniformly 29^o SST distribution (fig 4) due to strong solar radiation occurring during the past summer in the Gulf of Mexico. (Shay et al. 1992)

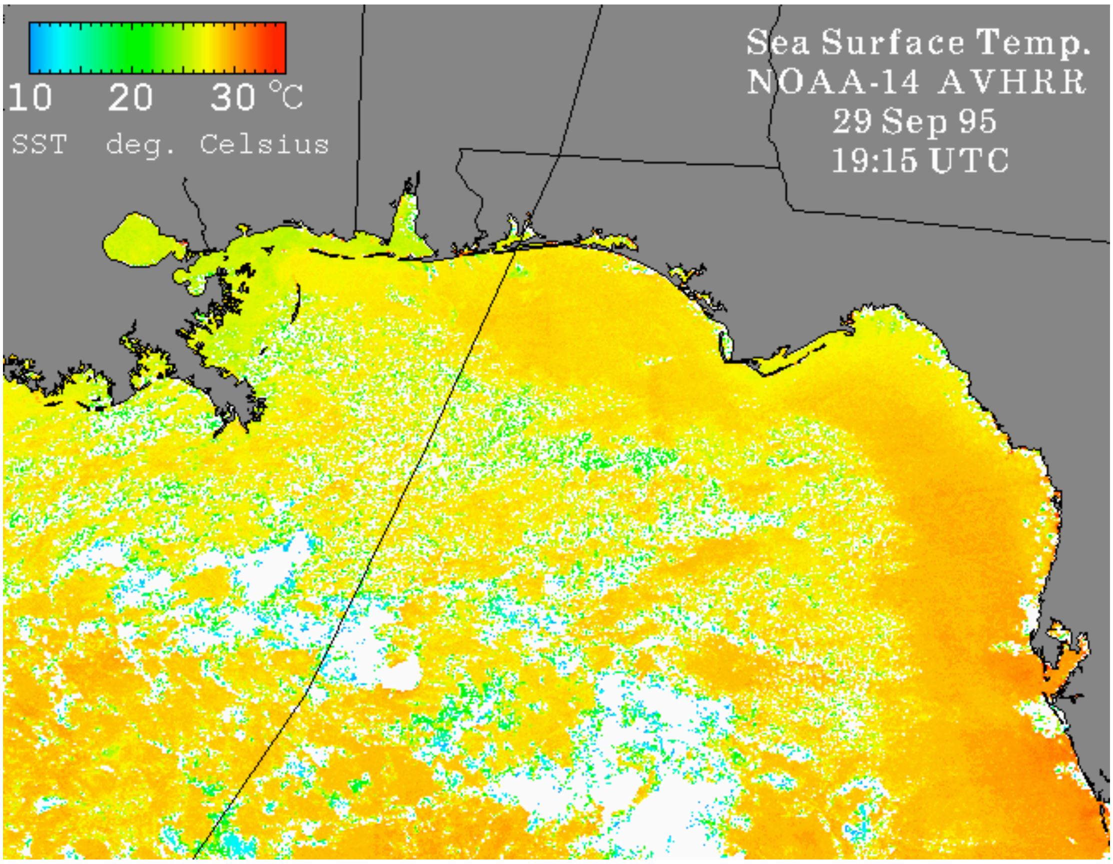

Fig4: Satellite NOAA-14 AVHRR SSTs obtained on 29 Sep 1995 over the Gulf of

Mexico during Hurricane Opal.

Therefore, Bender and Ginis (2000) tried to use a high-resolution coupled model with AVHRR SST to simulate the Hurricane Opal. In their paper, the GFDL movable triply nested mesh hurricane model was coupled with a high-resolution version of the Princeton Ocean Model. This GFDL hurricane-ocean coupled model was tested by 163 hurricanes during the 1995-1998 seasons and proved that it was 26% more accurate than the operational GFDL model. The hurricane model's two inner grid followed the hurricane center with a higher resolution $(1/3)^o$ and $(1/6)^o$. And it included more physical parameters than the atmosphere model in Hong et al. (2000), for example, surface flux, vertical diffusion, diurnal radiation cycle. At the same time, in order to illustrate the influence of the oceanic feedback, they chose the Princeton Ocean Model which emphasized the upper ocean mixed layer physics. Similarly, the ocean model resolution was the same as the coupled hurricane model. And the most important part was model initial conditions. For the hurricane model, it used the NCEP T126 global analysis and the storm message with fixed SST, provided by the National Hurricane Center. And for the ocean model, the initialization was relatively more reliable, although they also relied on a climatological ocean data and real-time SST data from NAVOCEANO Generalized Digital Environmental Model (GDEM). Because it included the realistic inflow/outflow open ocean boundary condition which was important for upper ocean currents, SST displacement/adjustment and the cold wake at the sea surface produced by the hurricane wind stress. During the experiments, they added the cold wake as an initial condition when needed since it was the direct response of the interaction between ocean and hurricane. Therefore, the coupled model in Bender and Ginis (2000) is relatively more reliable than the coupled model used in Hong et al. (2000)

The simulated results are shown as figure 5. We can see that during Oct 2 0Z to Oct 3 12Z, the simulated hurricane moved slowly which was quite matched the observation, as well as the Opal intensity which kept a very small decrease in the first one and a half day. From 3 Oct 12Z, the model which was integrated from 1200 successful simulated the hurricane speed and a rapid intensification which was agreed with the observation quite well although the intensity at a smaller rate. This gave them the conclusion that "the main reason for Opal's rapid intensification was due to the storm's acceleration from 2-3 m/s to about 10m/s over a 12-h period"(Bender and Ginis, 2000). What we need to notice that the simulated track was in the west side of the real track about 100km, the WCR eddy affected little on these results. Hence, without WCR the hurricane Opal intensification still can be simulated.

Furthermore, comparing to Hong et al(2000)'s ocean model, the Princeton Ocean model is relatively more precise to simulate the Ocean Planetary Boundary Layer since it is the key to simulate hurricane Opal intensification. Hence, the results of Bender and Ginis (2000) are more reliable.

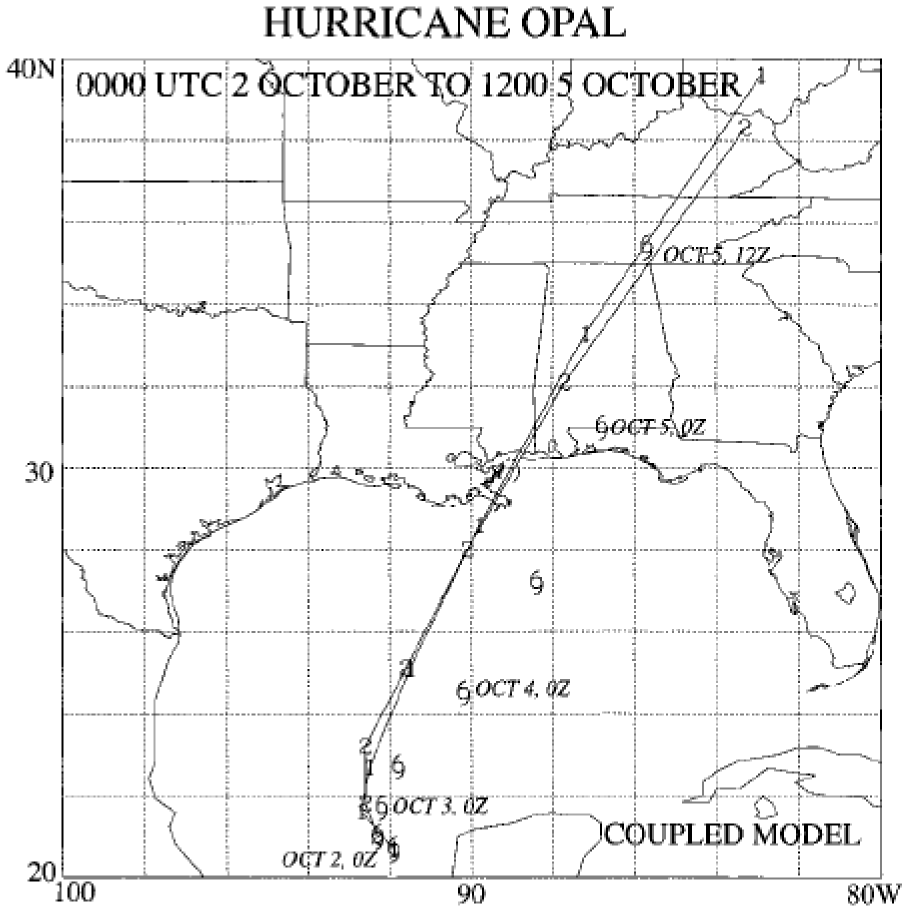

Fig5: The 72-h storm tracks (thin lines) for the two forecasts of Hurricane Opal made by the coupled model starting at 0000 and 1200 UTC 2 Oct. The storm positions at 12-h intervals are indicated by the symbols 1 and 2 for the forecasts starting at 0000 and 1200, respectively. The observed positions at 12-h intervals are indicated by the storm symbols. (Bender and Ginis, 2000)

Besides, as it is stated in the first section, there are many other attributions may induce this intensification. For example, Bosart et al. (2000) suggested that a subsynoptic-scale trough-jet-hurricane interaction may benefit the rapid intensification based on the averaged 200-hPa Balanced Vorticity outflow results. Krishnamurti et al. (1998) thought that the interior construction, like concentric eyewall, also played a role in this intensification.

Except the Bender and Ginis (2000) model and previous studies, now back to the Hong et al. (2000) paper, we may find some other questions. First, the WCR in the figure1 in Hong et al. (2000)(fig6), they adopted by Marks et al.(1998)(fig1), wasn't exact the same with the figure in Marks et al.(1998). While the figure in Marks et al. (1998) was almost the observation data due to its strong data source and tool, which is shown in table 1. In the original data (fig1), the Hurricane just went around the WCR and the intensity only achieved 939hPa at 10/4 09Z. But in Hong et al.,(2000) paper (fig6), the location of WCR changed right in the track center of the Hurricane Opal and the hurricane intensity is 3hPa more intensive than the original one due to the WCR. At the same time, the location of the Hurricane in 10/4 11Z when the hurricane reached its Maximum Intensity was about 500 km out of the WCR in the Marks et al.(1997). However, in Hong et al. paper, the maximum intensity was still in the WCR close to the 09Z location. It means the data is relatively unreliable. Moreover, from the Marks et al.(1998), when the hurricane started to intensify in 21Z 3 Oct, it was still far away from the WCR 200km. Also when the hurricane stopped deepen at 11Z 4 Oct, it was more than 100km far from the WCR. That suggests that the effect of WCR isn't very important. And before the hurricane touching the WCR, the intensity change was 26 hPa in the 12 hours. Then when it moved out of WCR, it deepened almost the same intensity and moved almost the same distance from where it started to deepen. But it only spent 2 hours to finish these.

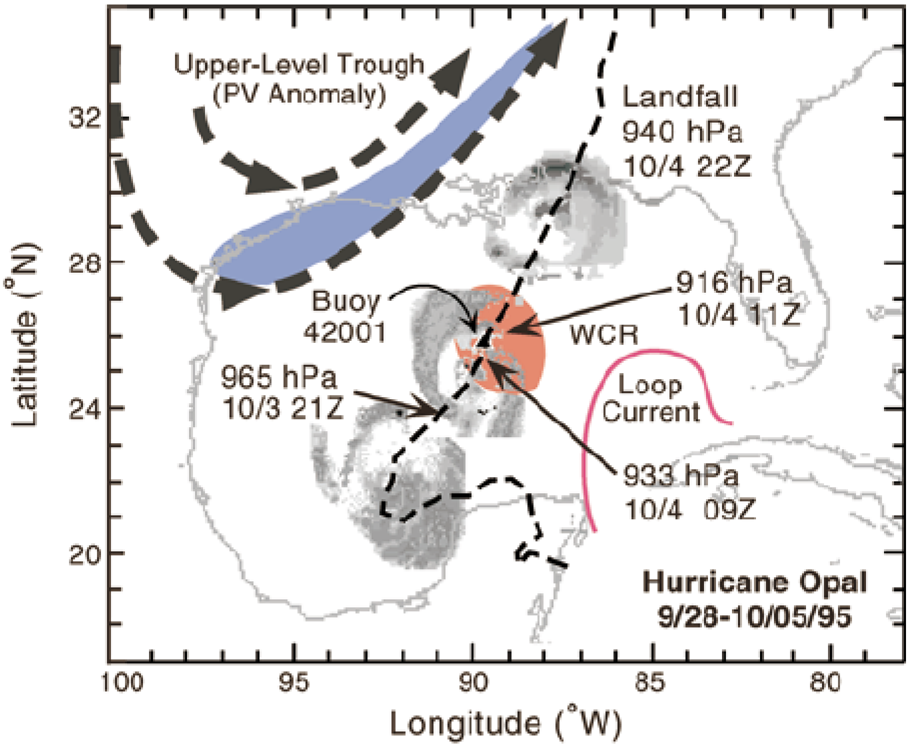

Fig 6 Observed track of Hurricane Opal and locations of upperlevel trough and the Loop Current warm core ring (WCR). Track (a bold dotted line) is from 28 Sep to 5 Oct 1995. The upper-level trough location at 1200 UTC 4 Oct (the bold dashed line) and the positive PV anomaly associated with the trough (the blue area) is derived from upper-level analyses. The WCR is derived from TOPEX altimeter data (the red area in the center of Gulf). The storm's internal structure is represented by SSM/I 85-Ghz imagery at 1629 UTC 3 Oct, 0337 UTC 4 Oct, and 1555 UTC 4 Oct. The 85-Ghz blackbody temperatures are depicted as shades of gray (adopted from Marks et al. 1998). (Hong et al. 2000)

Tool	*Benefit*
Aircraft-based or deployed observing systems	
G-IV Aircraft	High altitude data and dropsondes
Expendables (GPS dropsondes, AXCP, drifting buoys)	Atmospheric and oceanic profiles
Airborne remote sensors (C-SCAT, SRA, SFMR)	Surface wind and current observations
Ground-based observing systems	
Upgrading surface observations (C-MAN, ASOS)	Improved surface observations
WSR-88D network	Wind profiles, Doppler winds, rainfall estimates
Portable remote sensors: OSCR, truck-mounted radars (DOW), and profilers (with RASS)	Surface wind and current observations. Wind and thermodynamic profiles and dual-Doppler winds
NLDN	Number of lightning flashes as an indicator of intensity change or severe weather
Satellite-based observing systems	
GOES WV and 1-min rapid-scan data	Irradiance fields, motion vectors
TOPEX and ERS-1 altimeter	OML heat potential
SSM/I	Surface winds and microphysics
ERS-1	Surface winds and waves
OTD	Number of lightning flashes as an indicator of intensity change
Numerical Guidance	
GFDL, ETA , and NOGAPS model output	Improved use of all simulated fields
Research Models (e.g., RAMS, MM5, ARPS)	Compare research model simulations to operational models
Operational and Research Objective Analysis Systems	Develop improved techniques to integrate mobile observations into models
Telecommunications (WWW)	
Data storage and telecommunications	Disseminate data and model output

Table 1: Tools readily available for addressing specific science issues relating to the forecast of track, intensity change and storm damage from landfalling TCs. (Marks et al. 1998)

In the other hand, the heat content also can show us some , in Hong et al.(2000), the heat content Q is calculated by

$$Q = \rho c_p \Delta T \Delta z$$

Where ρ is the oceanic density taken as $1\, gm/m^3$, c_p is specific heat at constant pressure taken as 1 cal/(gK), ΔT is the maximum of zero or the difference of ocean temperature and $26^o C$, and Δz is the maximum of zero or the depth of the $26^o C$ isotherm. Since only ocean water temperature larger than $26^o C$ attributes the intensification. (DeMaria and Kaplan 1994) The depth of the $26^o C$

thermocline was set 180m. From the simulated results, they got that "the rate of heat loss is 15 kWm^{-2}, and given the heat flux of about 2600 Wm^{-2} near the region of maximum fluxes the percentage of heat loss is approximately 17% via air-sea fluxes." And Shay et al.(2000) simulated the heat content loss was 20 kWm^{-2}. But both of their available upper-ocean heat results were larger than the buoy measurements (Cione et al.2000). I think it maybe because there was not a WCR with a deep $26^o C$ thermocline, but uniform high SST with a shallow mixed layer. Since in the Gulf of Mexico in October, the 26^o thermocline is around 50 meter, only in the ocean water warm eddy, the 26^o thermocline can reached more than 150 meter.

4. Conclusion

The exact reason why Hurricane Opal intensified is still an open question. Both the track and intensity change rely on the interaction between the environmental condition and hurricane's interior convection. Owing to the lack of available observation data, all those reasons are possible. Mostly, the intensification is due to the interaction of all those factors. Hence, we can infer that this narrow warm SST eddy can accelerate the intensification but it isn't the crucial factor for the rapid intensification of Hurricane Opal.

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