THE EFFECT OF THE OCEAN EDDY ON TROPICAL CYCLONE INTENSITY

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1. INTRODUCTION

It has been widely recognized that the ocean supplies surface heat fluxes and therefore energy to tropical cyclones (TCs). The TC can induce the sea surface temperature (SST) cooling (Price 1981) associated with both the entrainment/mixing and upwelling processes. In turn, the SST cooling near the storm core exerts influence on the TC intensity. This negative feedback to the TC intensity is clearly a function of the oceanic thermal conditions (Bender et al. 1993; Schade and Emanuel 1999). In particular, the role of warm ocean eddies or rings in the above-mentioned typhoon-ocean interaction has been underscored (Shay et al. 2000; Goni and Trnanes 2003; Emanuel et al. 2004; Lin et al. 2005). Studies of Hurricanes Opal (1995), Mitch (1998), and Bret (1999) in the Atlantic and of Supertyphoon Maemi (2003) in the North western Pacific have consistently seen rapid TC intensification when the storms moved across warm ocean eddies. Hurricane Katrina (2005) which devastated the Gulf States is yet another case in point that intensified from a Category-1–to a Category-5 within two days while passing the warm Loop Current over the Gulf of Mexico (Scharroo et al. 2005).

Recently Lin et al. (2005) have integrated the satellite altimetry data into a very simple coupled model to show that the presence of the warm ocean eddy can serve as an efficient insulator against the ocean's negative feedback, helping maintain and even boost the TC intensity. Note that the coupled model used by Lin et al. (2005) is a rather simplified atmospheric model (Emanuel 1999) coupled with a one-dimensional ocean model (Schade 1997). To elaborate the findings of Lin et al. (2005), we adopt a slightly more sophisticated coupled-model, though still simple enough (Emanuel 1989; Schade and Emanuel 1999; Korty 2002) to systematically evaluate the role of the oceanic thermal structure in TC intensity evolution. In particular, we wish to quantify the influence of the ocean eddy on TC intensity and to provide a new perspective on the physics therein. The experiment design is presented in section 2. Results are detailed in section 3, followed by the conclusion and future work in the final section. A more detailed description of this work is shown in Wu and Lee (2006).

2. EXPERIMENT DESIGN

The hurricane-ocean coupled model used here was constructed by Schade and Emanuel (1999) from two independently developed and tested models, namely the axisymmetric hurricane model of Emanuel (1989) and the four-layer ocean model of Cooper and Thompson (1989).

The foci of this study are to address the effects of the ocean eddy on TC intensity. Note that TC intensity is influenced not only by oceanic structure but also by atmospheric environment and the history of each storm (Schade and Emanuel 1999). Here the atmospheric environment is fixed (ambient relative humidity is 80%) to discuss the role of the oceanic environment. Shade and Emanuel (1999) suggested that the slower the storm moves, the stronger the ocean's negative feedback. Therefore, the control value of storm's translation speed in this study is set at 5 m s^{-1} to allow stronger ocean's negative feedback.

Each experiment is started with initial low pressure disturbance,the maximum azimuthal wind speed of 17 m s^{-1}, the radius of the maximum wind of 100 km, and the minimum sea-level pressure of 1003 hPa. The distributions of the azimuthal wind speed and the sea-level pressure satisfy the conservation of the angular momentum and the gradient wind balance.

Experiments are conducted to evaluate the evolution of the TC when it encounters the ocean eddy for finite time and then returns to the standard oceanic structure for the rest of the model integration (Fig. 1). To quantify the eddy's contribution to the intensity feedback, the eddy feedback factor is defined as $F_{EDDY-T,}$ .i.e.,

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$$F_{EDDY-T} = \frac{\Delta p_{out} - \Delta p_{in}}{\Delta p_{in}} \quad (2)$$

where the "Δp_{in}" ("Δp_{out}") is the amount of the sea-level central pressure deepening at the moment when the storm encounters (leaves) the ocean eddy. F_{EDDY-T} could be positive (warm eddy) or negative (cold eddy). The eddy feedback factor of $F_{EDDY-T} = 0.5$ represents that storm's intensity is further strengthened by 50% due to an encounter with the warm ocean eddy.

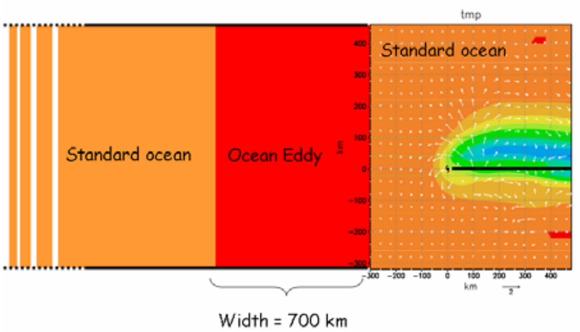

Figure 1. A sketch of the transient-eddy experiment. The sign of typhoon represents the location of the model storm and the horizontal black line shows its trajectory. The storm encounters the 700-km (transient) eddy (red block) from the standard ocean (orange block) and then goes back to the standard ocean.

3. RESULTS

We first let a storm enter a 700-km-wide warm ocean eddy and then return to the standard oceanic structure for the rest of the model integration. The standard oceanic thermal structure and the specified eddy's thermal structure are further depicted in Fig. 2. We switch the ocean to the eddy conditions on the 5th day. Figure 3 shows the time series of the sea-level central pressure and the maximum azimuthal wind. The TC strengthens from 978 to 962 hPa (45 to 56 m s^{-1}) during the episode it moves across the warm eddy. The corresponding F_{EDDY-T} is 0.64, which implies that the TC intensity is further strengthened by 64% due to an encounter with that warn ocean eddy. This intensification is attributed both to the more heat flux the warm eddy supplies and to the less SST cooling induced in the eddy's structure.

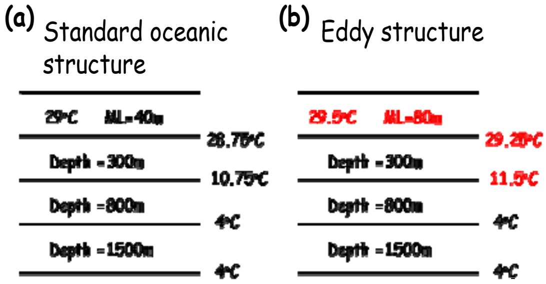

Figure 2. The standard oceanic structure (left) and the eddy structure (right). The SST and mixed-layer depth in eddy structure increase by 0.5 °C and 40 m respectively while other conditions remain unchanged.

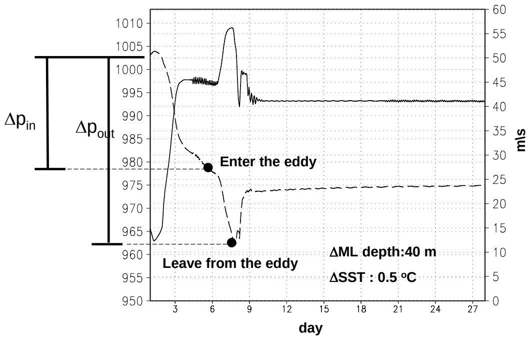

Figure 3. Time series of the sea-level central pressure (dashed line) and the maximum azimuthal wind (solid line) in the experiment which introduces a 700-km wide warm eddy on the 5th day. Δp_{in} and Δp_{out} indicate the pressure depression in the eye of the storm as it enters and leaves that warm eddy. ΔML and ΔSST account for the differences of the mixed-layer and SST between the standard ocean and the warm ocean eddy.

Clearly the ocean eddy's structure would affect the magnitude of the eddy feedback effect and we find out that F_{EDDY-T} increases with both rising SST and deepening mixed layer. Besides, the interaction time between the TC and the ocean eddies, which depends both on the storm's translation speed and the size of the eddy, also affects the magnitude of eddy feedback effect. Figure 4 shows the F_{EDDY-T} as a function of the eddy size and the translation speed. In general, F_{EDDY-T} increases either with the increase of eddy size or the decrease of the storm's translation speed due to the longer interaction time.

According to previous discussions, F_{EDDY-T} depends not only on the eddy structure but also on storm's property and atmospheric environment, such as the translation speed and the relative humidity. To find out the functionality of F_{EDDY-T}, some key parameters are chosen. The ambient SST (*SST*), unperturbed mixed-layer depth (*ML*), and the stratification below the mixed layer (Γ) represent the large-scale oceanic conditions which affect the magnitude of the ocean's negative feedback. The storm size (η) and the translation speed (U_H) determine the interaction timescale between the atmosphere and ocean's negative feedback. Besides, U_H also determines the interaction timescale between the TC and the ocean eddy. The boundary layer relative humidity (RH) is also an important parameter because it affects the steady-state TC intensity and determines the thermodynamic disequilibrium at the sea surface (Shade and Emanuel 1999). Last, the SST (SST_{EDDY}) and the mixed-layer depth (ML_{EDDY}) in the eddy are chosen to represent the eddy's character. Table 1 lists the range of those eight dimensional parameters.

	Parameter	Unit	Range
D_1	$SST - 26^oC$	^oC	2 – 3
D_2	$SST_{EDDY} - 26^oC$	^oC	2.2 – 3.6
D_3	ML	M	20 – 40
D_4	ML_{EDDY}	M	40 – 100
D_5	η	1	0.6 – 1.0
D_6	$1-RH$	1	75% – 85%
D_7	Γ	$^oC\ m^{-1}$	0.04 – 0.06
D_8	U_H	$m\ s^{-1}$	3 – 7

Table 1. Dimensional parameters.

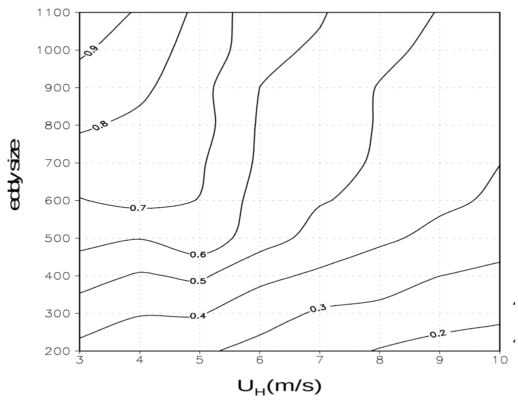

Figure 4. F_{EDDY-T} as a function of the eddy size (km) and the TC's translation speed (m s^{-1}).

Based on the results from the 1944 model experiments and the linear least-squares technique, the best-fit function of F_{EDDY-T} is defined as,

$$F_{EDDY-T} = 0.38\left(SST_{EDDY} - 26^oC\right)^{2.08}\left(SST - 26^oC\right)^{-1.88}\left(ML_{EDDY}\right)^{0.98} \times \left(ML\right)^{-0.97}\left(\eta\right)^{0.22}\left(1-RH\right)^{-0.74}\left(\Gamma\right)^{0.45}\left(U_H\right)^{-0.83} \quad (3)$$

The exponents of Eq. (3) reveal that F_{EDDY-T} highly depends on the SSTs of the large-scale ocean and the ocean eddy. We rewrite Eq. (3) as,

$$F_{EDDY-T} = 0.38\left(\frac{SST_{EDDY} - 26^oC}{SST - 26^oC}\right)^{1.88}\left(SST_{EDDY} - 26^oC\right)^{0.2}\left(ML_{EDDY}\right)^{0.98} \times \left(ML\right)^{-0.97}\left(\eta\right)^{0.22}\left(1-RH\right)^{-0.74}\left(\Gamma\right)^{0.45}\left(U_H\right)^{-0.83}$$
$$\approx 0.37\left(SST_{EDDY} - 26^oC\right)^{0.2}\left(ML_{EDDY}\right)^{0.98}\left(ML\right)^{-0.97}\left(\eta\right)^{0.22} \times \left(1-RH\right)^{-0.74}\left(\Gamma\right)^{0.45}\left(U_H\right)^{-0.83} \quad (4)$$

In Eq. (4), we combine *SST* and SST_{EDDY} and find out that the ratio of the SSTs in these two oceanic structure affects F_{EDDY-T} drastically. From observation, the SST in warm eddies typically differs slightly from that outside the eddy region, therefore the first term in Eq. (4) is very much close to 1 and the influence of the first term on F_{EDDY-T} could be ignored. The exponent of other parameters indicates that the mixed-layer depths of the large-scale ocean and of the eddy are two most important factors in determining the magnitude of eddy feedback effect, while the translation speed, the ambient relative humidity, and the stratification below the mixed layer are the next three.

Equation (3) shows that in this coupled model, a stronger eddy feedback effect occurs in either of the following conditions:

(1) higher eddy's SST;
(2) thicker eddy's mixed-layer depth;
(3) lower unperturbed SST;
(4) shallower unperturbed mixed-layer depth;
(5) stronger thermal stratification below the oceanic mixed layer;
(6) larger storm size;
(7) higher relative humidity;
(8) lower translation speed.

The first four conditions imply that when the difference between the standard oceanic and the eddy's thermal structure is greater, and the eddy feedback effect is more significant. In the 5^{th}, 6^{th}, 7^{th} and 8^{th} conditions, the ocean's negative feedback is also more prominent (Schade and Emanuel 1999). It is suggested that while the condition is favorable to the TC to induce stronger ocean's negative feedback, the influence of eddies on the TC intensity would be more significant. The 6^{th} and 8^{th} conditions closely correspond to our physical intuition, i.e., when the TC encounters the eddy for a shorter time period, the eddy feedback effect is less significant.

Figure 5 shows the scatter plot of the model's F_{EDDY-T} and the best-fit F_{EDDY-T}. The correlation coefficient of 0.97 shows that Eq. (3) is a very good approximation to the distribution of eddy feedback factor in our experiments. In other words, Eq. (3) can account for the dependence of the eddy feedback factor on the above eight dimensional parameters in this simple coupled model.

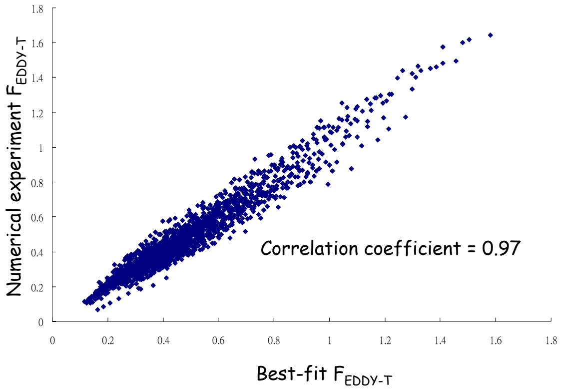

Figure 5. Scatter plot of the modeled F_{EDDY-T} and the best-fit F_{EDDY-T}. The correlation coefficient is 0.97.

4. CONCLUSION AND FUTURE WORK

It is well known that the interaction between the TC and ocean eddies is critical to the TC's evolution. This study aims to systematically address the above important issue by a simple ocean-coupled model. Result shows that stronger eddy feedback effects exists while

(1) the difference of SST and the mixed-layer depth between the standard oceanic and eddy's structures is larger;
(2) the eddy's mixed layer is deeper;
(3) the interaction timescale between the TC and ocean eddy is longer; or
(4) the ambient condition is more favorable for a TC to induce stronger SST cooling.

Based on a simple ocean-coupled model, in this study we have conducted a useful investigation into the ocean's upper thermal structure, particularly the warm eddy, as a factor in affecting the TC intensity. Note that the negative effect of the cold eddies on the TC intensity can also be found based on the same model (not shown here).

In conclusion, this paper has used the simple typhoon-ocean-coupled model to assess the effect of the warm ocean eddy on the intensity of typhoons. We believe that this work will aid in improving our basic understanding of the factors influencing TC intensity and perhaps lead to better observation strategies for future forecasts of TC intensify. Note that, however, owing to the simplicity of the three-layer axisymmetric hurricane model used, some important processes in the atmosphere have been neglected. Therefore, we plan to use a more sophisticated atmospheric model to address the above issues. Meanwhile, the current study only focuses on the ocean initiated from a rest condition. In addition to the ocean eddy, the potential impact of the strong ocean currents, such as the strong horizontal heat transport from the Kuroshio or Loop Current, on the TC intensity would also be a very interesting topic for future investigation.

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