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NUMERICAL SIMULATIONS OF HURRICANE-OCEAN INTERACTION WITH A HIGH RESOLUTION COUPLED MODEL

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INTRODUCTION

The topic of tropical cyclone-ocean interaction has received increased attention in the tropical meteorology community over the past several years. It is widely recognized that the major energy source for tropical cyclones is the evaporation from the ocean. The sea surface temperature (SST) is a crucial parameter in this process. A negative feedback mechanism in the tropical cyclone-ocean system affects the SST. Namely, as the tropical cyclone strengthens the increasing winds will generate strong turbulent mixing in the upper ocean, causing significant decreases in the SST due to entrainment of the cooler waters from the thermocline into the mixed layer. The observed SST anomalies induced by the tropical cyclone have been observed to vary from 1°C up to 6°C (e.g., Black, 1983). The cooling of the sea surface results in reduction in the total heat flux directed into the atmosphere leading to a decrease in storm intensity.

In order to simulate the hurricane-ocean interaction during passage of a hurricane over the open ocean, the GFDL 18-level triply-nested movable mesh hurricane model was recently coupled with a multi-layer high resolution primitive equation ocean model. The hurricane model spanned 55 degrees in both the latitudinal and longitudinal directions. The innermost grid, with finest resolution of one-sixth degree, moved with the hurricane and covered an area of about 8 degrees square. The ocean model consisted of 8 layers with uniform horizontal resolution of one-sixth degree. Coupling between the hurricane and ocean model was carried out by passing into the ocean model the wind stress, heat and moisture fluxes computed in the hurricane model. The new SST calculated by the ocean model was then used in the hurricane model.

2. EXPERIMENTAL DESIGN

In the experimental design used for these experiments, a hurricane was embedded in easterly and westerly environmental flows of 7.5, 5.0 and 2.5 m

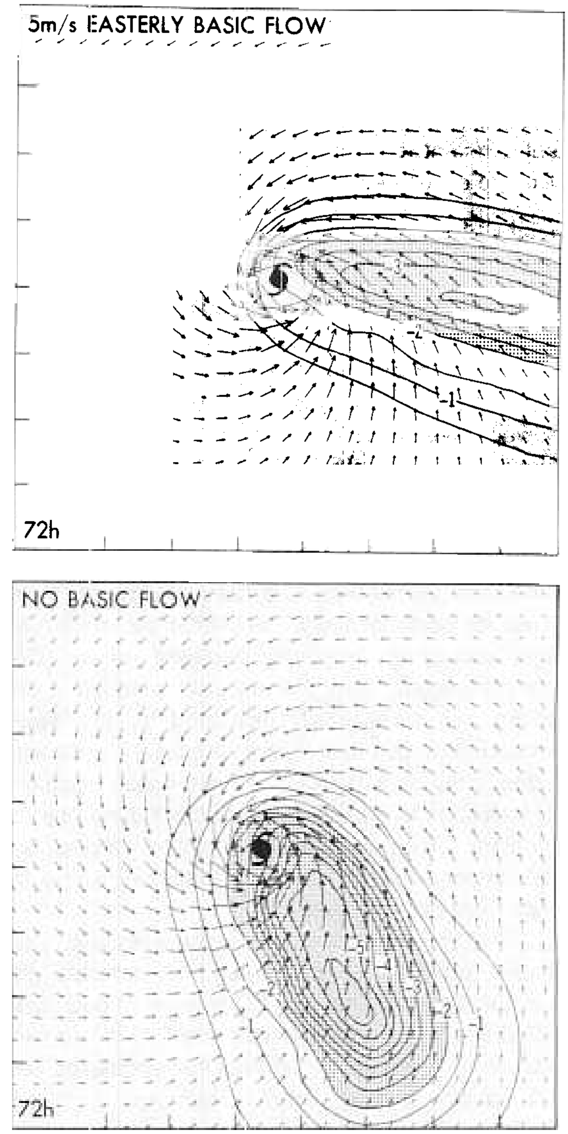

Figure 1. The SST anomalies (°C) and wind vectors of the low-level (σ=.995) wind at 72h. The area shown is for the region of the innermost nest, with the tick marks drawn at one degree intervals. The regions with anomalies larger than 2° and 5° are indicated with different shading. The storm center at 72h is shown.

s^{-1} with a fourth experiment run with no basic flow specified initially (storm motion was only due to the beta effect). Most of the discussion, however, will be limited to the cases with either easterly flow or the no basic flow case. For each of the experiments, the profile of the tangential wind for Hurricane Gloria at 1200 UTC 22 September, 1985 (just after the storm was first upgraded to a hurricane) was used as the initial condition of the hurricane. The model ocean was initially horizontally homogenous and quiescent. The SST was initially set to 302 K everywhere with a vertical temperature profile specified which is typical for tropical regions of the Atlantic. In order to clarify the impact of the ocean response to the hurricane's behavior, analogous experiments were also carried out with the SST kept constant (control experiments without coupling). All of the experiments were integrated to 72h.

3. NUMERICAL RESULTS

The results indicated that the SST cooling produced by the tropical cyclones was largest for the case with no basic flow (Table 1) consistent with other earlier studies (e.g., Khain and Ginis, 1991) which showed greater SST response for slower moving storms. The maximum SST cooling at 72h for the experiments presented here was 5.9^{o} for the no basic flow case and about 3.5^{o} for the 5 m s^{-1} easterly flow. The maximum sea surface cooling occurred to the rear of the storm center (Fig. 1), since the entrainment continued for some period of time after the storm passage, producing additional decrease of the SST behind the storm. Also, the width of the region of SST cooling was substantially increased for the slower moving storm, due to the increased time that the wind forcing acted on a fixed point in the ocean leading to intensification of the ocean currents induced by the hurricane. This generated turbulent mixing and entrainment even at the storm periphery where the winds were relatively weak.

The cooling of the sea surface resulted in significant reduction of total heat flux (sensible plus latent) into the hurricane in the regions of decreased SST (Fig. 2). For example with the 5 m s^{-1} easterly basic flow the maximum net heat flux decreased from 1.25 kw/m^2 in the control experiment (hurricane model) to about 0.9 kw/m^2 with the hurricane-ocean coupling included. The pronounced asymmetry in the distribution of this quantity is very evident in the coupled experiment with the net heat flux greatly reduced in the regions above the cold wake. The resulting reduction in the moist static energy in the boundary layer directly impacted the warm core temperature, producing a decrease of the 250 mb level equivalent

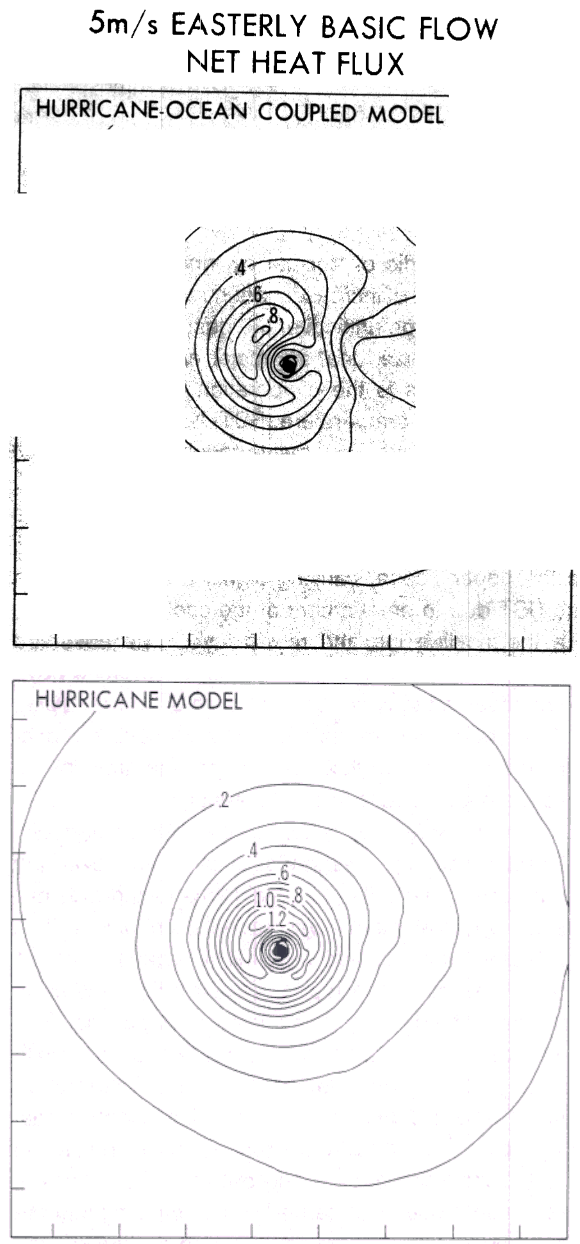

Figure 2. Distribution of the net heat flux (kw/m^2) directed into the atmosphere, averaged for the entire 72h of the integration and computed relative to the moving storm for the experiments run with (top) and without (bottom) coupling. The area shown is for the region of the innermost nest, with the tick marks drawn at one degree intervals. The 72h hurricane center position is indicated by the hurricane symbol.

potential temperature of 4 degrees in the case of the 5 m s^{-1} easterly flow and almost 7 degrees for the experiment with no basic flow.

The impact on intensity is clearly seen in Fig. 3 for these 2 experiments. In the no basic flow experiment the average minimum sea level pressure with the ocean coupling was about 16 hPa higher than the control run during the final 2 days. For the experiment with the 5 m s^{-1} easterly flow the SST response was significantly weaker and the difference was only about 10 hPa. Likewise the average maximum low-level winds also decreased about 7 m s^{-1} and 4 m s^{-1} respectively.

The differences in minimum sea level pressure, maximum low-level wind and maximum SST

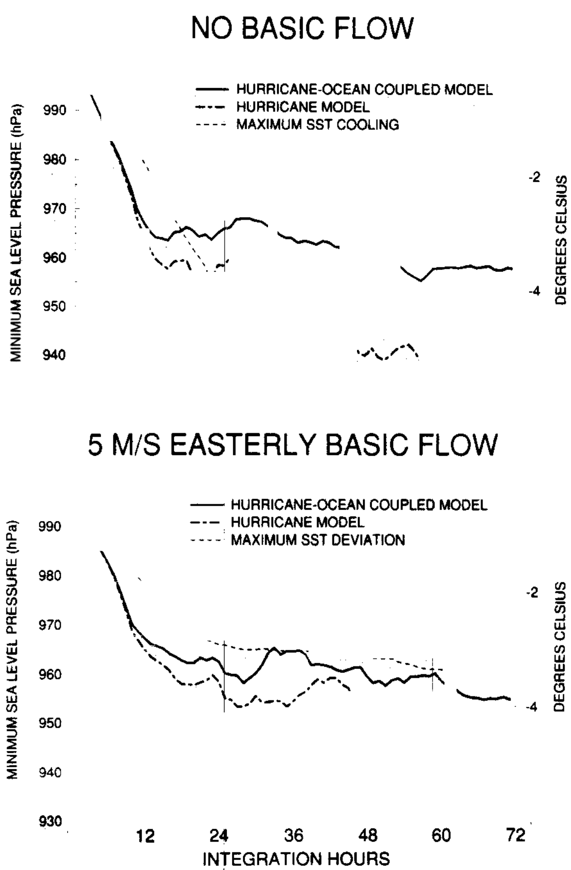

Figure 3. Time series of minimum sea level pressure (hPa) for the experiments run with hurricane-ocean coupling (solid line) and without coupling (dashed line) for both the no basic flow (top) and the 5 m s^{-1} easterly basic flow (bottom) integrations. The maximum SST cooling (°C) is also plotted (thin dashed line) for both of the coupled experiments.

cooling are summarized in Table 1 for the set of experiments performed in this study. The storms embedded in the westerly basic flows moved slightly slower than those with easterly flow since the basic flow in these cases was oriented in a direction almost opposite to the flow produced by the beta effect. This resulted in larger SST cooling with the westerly moving storms and a greater decrease in intensity for these cases. A strong correlation was found between the maximum SST cooling and the changes in storm intensity with both the easterly and westerly moving storms. In both sets of experiments the faster moving storms produced a progressively smaller SST response and smaller reduction in strength measured by the minimum sea level pressure and maximum low-level winds.

Finally, the hurricane-ocean coupling significantly impacted the storm track only for the cases with no basic flow and the 2.5 m s^{-1} easterly flow (Fig. 4). In these cases the storms with the ocean interaction turned more to the northeast (no basic flow) or the north (2.5 easterly flow). In the first case the storm was located about 70 km to the east-southeast of the control experiment by 72h. A possible explanation for this track deviation is related to a systematic weakening of the circular averaged tangential flow at all radii of the storm induced by the interaction with the ocean which may have altered the beta drift. This effect was greatest in the experiments with no basic flow where decreases of almost 2 m s^{-1} in the winds in the outer

TABLE 1. Average differences between the coupled and non-coupled model for the final 48h period of the integrations presented in this study.

	COUPLED - NON COUPLED		
Basic Flow (ms^{-1})	Minimum sea level pressure difference (hPa)	Maximum surface wind difference ($m\ s^{-1}$)	Maximum SST cooling (^oC)
NO BASIC FLOW	**16.4**	**-7.0**	-5.6
WESTERLY FLOW:			
2.5	15.6	-6.7	-4.6
5.0	12.0	-4.8	-3.7
7.5	7.0	-2.6	-3.0
EASTERLY FLOW:			
2.5	11.8	-5.0	-4.1
5.0	9.7	-3.7	-3.2
7.5	7.7	-2.8	-2.6

radii of the storm were found (Fig. 5). This is in agreement with results obtained by Fiorino and Elsberry (1989) from a non-divergent barotropic model in which small reductions in the tangential wind in the 300 to 700 km radii of the storm produced a similar change in the storm track. For the storms with the 5 m s^{-1} and 7.5 m s^{-1} easterly and westerly flows, the difference in the storm tracks remained small throughout the entire integration.

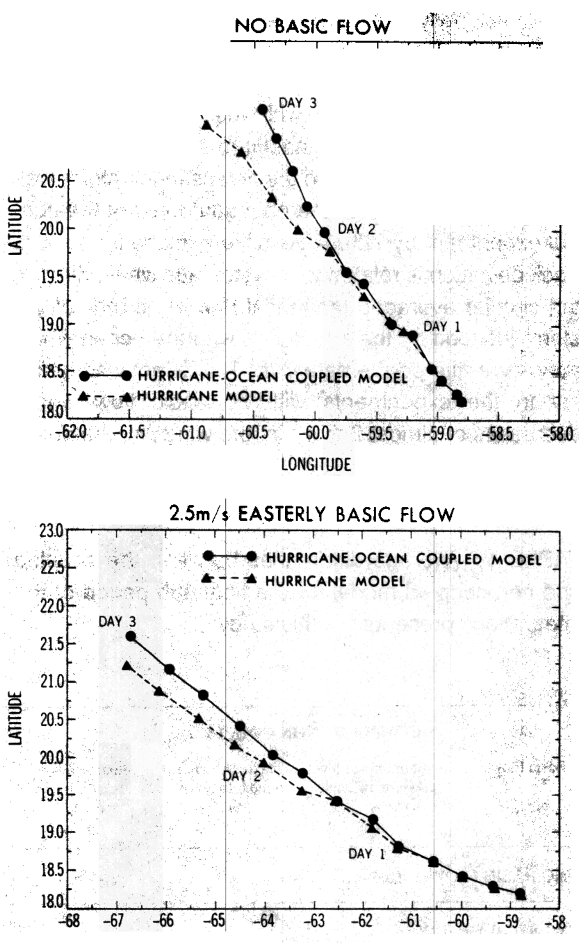

Figure 4. The 72h storm tracks for the experiments with no basic flow (top) and the 2.5 m s^{-1} easterly flow (bottom). The storm track for the experiments with hurricane-ocean coupling is indicated by a solid line (circles) with the control experiment indicated with a dashed line (triangles). The storm positions at 6h intervals are plotted.

4. SUMMARY

A high resolution tropical cyclone-ocean coupled model was used to study the tropical cyclone-ocean interaction. It was demonstrated that the ocean coupling produced a significant reduction in hurricane intensity by cooling of the sea surface and decreasing of the net heat fluxes directed into the hurricane. The storm weakening was consistently greater for the slower moving storms where the SST decrease was larger.

The hurricane-ocean coupling significantly impacted the storm track only for the cases with no basic flow and the 2.5 m s^{-1} easterly flow, possibly through a systematic weakening of the tangential flow at all radii of the storm induced by the ocean interaction.

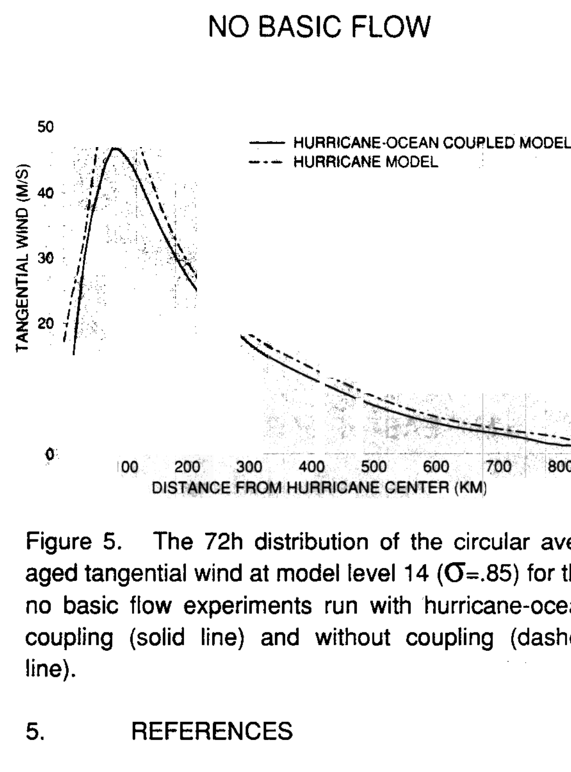

Figure 5. The 72h distribution of the circular averaged tangential wind at model level 14 (σ=.85) for the no basic flow experiments run with hurricane-ocean coupling (solid line) and without coupling (dashed line).

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