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A Numerical Simulation of the South China Sea Response to Tropical Cyclone Ernie 1996

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1 INTRODUCTION

The South China Sea (SCS) is one of the largest marginal seas of the Western Pacific Ocean, extending across both tropical and subtropical zones and encompasses a total surface area of 3.5×10^6 km^2 (Fig. 1). The SCS thermal structure is highly connected to the surface wind forcing (Chu et al., 1997a, b). A moving tropical cyclone is an intense source of surface wind stress and stress curl that produces many significant responses in the ocean environment. Three of the most distinctive are changes to the ocean thermal structure, upper ocean currents and sea surface elevation. Our goal of this research is to identify if those effects occurring in the open ocean still exist in the SCS using the Princeton Ocean Model (POM). Earlier usage of the POM for the SCS (Chu et al., 1998) successfully simulated the variability of the SCS circulation and multi-eddy structure with the changing monsoonal winds. Here, we study the SCS responses to Tropical Cyclone Ernie (1996) using the POM forced by a high-resolution wind field computed by a Tropical Cyclone Wind Profile Model (TCWPM) proposed by Carr and Elsberry (1997).

Figure 1 – Geography and isobaths showing the bottom topography of the South China Sea.

2 TROPICAL CYCLONE ERNIE 1996

Tropical Storm Ernie initially formed about 1300 km to the east of the Philippine island of Mindanao on November 4, 1996 (Fig. 2.) After formation, Ernie slowly intensified as it tracked westward through the Philippine Sea toward the central Philippine Islands. On November 6 Ernie made landfall over Mindanao and intensified to tropical storm strength, 18 m/s. Ernie continued moving westerly through the Philippine Islands, intensifying at a slow rate because of frictional interaction with the land. The storm entered the SCS on November 8 and reached an intensity of 25 m/s. Ernie began moving northerly toward a break in the mid-latitude ridge and Tropical Depression 39W (TD 39W), which had formed during the previous day over Luzon, to the northeast of Ernie. The storm merged with TD 39W and became quasi-stationary on November 11, as the mid-latitude ridge strengthened.

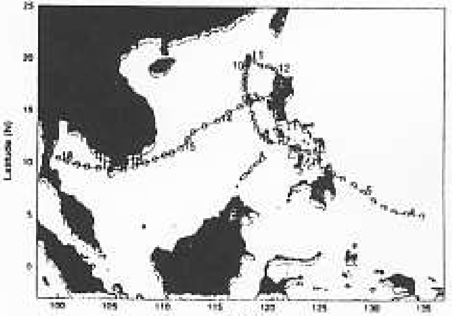

Figure 2 – Track of tropical cyclone Ernie (1996) with position plotted at six hour intervals. Number next to storm position indicate date of November, 1996.

3 TROPICAL CYCLONE WIND PROFILE MODEL (TCWPM)

Consider a tropical cyclone moving in the atmosphere. The wind field associated with the tropical cyclone has two components: (1) $\mathbf{V}_c$, the wind vector relative to the center of the tropical cyclone, and (2) $\mathbf{V}_t$, the tropical cyclone translational velocity (Fig. 3.) The two components of the storm wind produce the distinct asymmetrical wind structure of a moving tropical cyclone. The translational vector component causes enhanced wind flow on the right side of the moving storm and diminished wind flow on the left side. This asymmetrical forcing contributes significantly to the production of the unique oceanic thermal and current patterns generated by the storm. We use a recently developed wind profile model (Carr and Elsberry, 1997) to determine the relative velocity $\mathbf{V}_c$, and use the best track storm course and speed from post-storm analysis by the United States Navy Joint Typhoon Warning Center at Guam (JTWC) to determine the translational velocity $\mathbf{V}_t$.

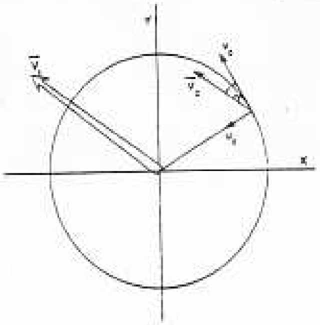

Figure 3 – Tropical cyclone wind field. The angle gamma is the wind inflow angle, spiraling inward toward the storm center.

4 PRINCETON OCEAN MODEL

The POM is a time dependent, primitive equation circulation model on a three dimensional grid that includes realistic topography and a free surface (Blumberg and Mellor, 1987). The horizontal spacing of our model is 0.179° by 0.175° (approximately 20 km resolution) and there are 23 vertical sigma coordinate levels. The model domain is from 3.06°S to 25.07° N, and 98.84°E to 121.16°E, which encompasses the SCS and the Gulf of Thailand, and uses realistic bathymetry data from the Naval Oceanographic Office Digital Bathymetry Data Base 5 minute by 5 minute resolution (DBDB5). Consequently, the model contains 125 × 162× 23 horizontally fixed grid points. The horizontal diffusivities are modeled using the Smagorinsky (1963) form with the coefficient chosen to be 0.2 for this application.

Closed lateral boundaries, i.e., the modeled ocean bordered by land, were defined using a free slip condition for velocity and a zero gradient condition for temperature and salinity. No advective or diffusive heat, salt or velocity fluxes occur through these boundaries. Open boundaries, where the numerical grid ends but the fluid motion is unrestricted, were treated as radiative boundaries. Volume transport through the Luzon Strait, Taiwan Strait, and Gasper/Karimata Strait was defined according to observations (Table 1). However, the Balabac Channel, Mindoro Strait, and Strait of Malacca are assumed to have zero transport. When the water flows into the model domain, temperature and salinity at the open boundary are likewise prescribed from the climatological data (Boyer and Levitus, 1994). When water flows out of the domain, the radiation condition was applied,

Month	Feb	Apr	Jun	Aug	Oct	Dec
Karimata Str.	4.4	0.0	-4.0	-3.0	1.0	4.3
Luzon Str.	-3.5	0.0	3.0	2.5	-0.6	-3.4
Taiwan Str.	-0.9	0.0	1.0	0.5	-0.4	-0.9

Table 1. Bi-monthly variation of volume transport (Sv) at the lateral open boundaries. The positive/negative values mean outflow/inflow and were taken from Wyrtki (1961).

$$\frac{\partial}{\partial t}(\theta, S) + U_n \frac{\partial}{\partial n}(\theta, S) = 0$$

where the subscript n is the direction normal to the boundary.

For computational efficiency, the mode splitting technique (Blumberg and Mellor, 1987) is applied with a barotropic time step of 25 seconds, based on the Courant-Friederichs-Levy (CFL) computational stability condition and the external wave speed; and a baroclinic time step of 900 seconds, based on the CFL condition and the internal wave speed.

5 NUMERICAL SIMULATION

The model year consists of 360 days (30 days per month), day 361 corresponds to 1 January. The integration was divided into pre-experimental and experimental stages. During the pre-experimental stage, the model was integrated for 34 months and three days from an initial at rest state with three-dimensional climatological January temperature and salinity fields (Levitus, 1984), forced by the climatological monthly mean wind stress (Hellerman and Rosenstein, 1983). The final state from the pre-experimental run was taken as the SCS condition for 4 November 1996, the initial condition for the experimental stage. During the experimental stage, the POM model was forced by TCWPM modeled wind field, simulating Tropical Cyclone Ernie, for eighteen days.

6 SIMULATION RESULTS

Ernie first entered Area One late on November 7 from the southeast after passing through the central Philippine Islands. The storm size, R_0, was approximately 850 km. The radius of maximum winds, R_m, was 20 km and the maximum wind speed was 25 m/s. Initial ocean responses occurred almost immediately as the storm crossed the coast.

Outflow from the storm produced very strong divergent upper layer currents (Fig. 4) and significant upwelling along the coast. A strong barotropic cyclonic circulation was noted near 13°N on November 8 in a cross section of the u velocity field taken along 119.5°E (Fig. 5). Velocities were 60 to 100 cm/s at the surface, decreasing to 20 cm/s at 100 m. The model produced very intense vertical current shear across the base of the mixed layer, with 180 cm/s northerly flow in the mixed layer and 100 cm/s southerly flow in the thermocline (Fig. 5). Shay et al. (1992) saw a similar pattern in current meter data from Hurricane Gilbert. This 180° phase reversal between the mixed layer and thermocline indicates that wind stress generated the near-surface currents, whereas pressure gradient effects generated the thermocline currents (Price, 1983). Along the 119.5°E cross section the v velocity field shows very strong divergence at 40 to 50 m. This divergence generated an intense, narrow upwelling plume, with velocities reaching 300 cm/hr at 100 m near 13°N, 119.5°E. This intense upwelling produced large SST and subsurface temperature changes.

SST decreases of 1.5°C were noted to the right of the storm track (not shown), which is consistent with past observation of tropical cyclone SST cooling (Jordan, 1964; Hazelworth, 1968; Black, 1983) . Subsurface temperature changes were more pronounced however. The largest subsurface temperature changes occurred to the right of the storm track near 50 m, the approximate depth of the thermocline, with a decrease of 3.5°C (not shown). Pudov et al. (1978) reported a similar subsurface cooling pattern in the wake of Typhoon Tess. The storm produced subsurface cooling of up to 1.5°C to a depth of 200 m.

7 CONCLUSIONS

This study used the Princeton Ocean Model to investigate ocean responses generated by Tropical Cyclone Ernie, which affected the SCS from November 8 to 18, 1996. A model was developed to simulate Tropical Cyclone Ernie's wind stress forcing and used to force the POM for this fourteen day period. POM velocity, temperature, salinity and surface elevation fields were then analyzed to investigate ocean responses produced by the storm.

The model satisfactorily simulated the unique asymmetrical upper-ocean current pattern produced by a moving tropical cyclone, which researchers have seen in many past studies. The model generated strong near-inertial, anticyclonic turning upper-ocean currents to the right of the storm track. These highly divergent upper-layer currents also generated the typical bias of maximum sea surface temperature cooling to the right of the storm track. Sub-surface responses were also consistent with observations and numerical studies of other storms. The highly divergent surface currents produced strong upwelling. Maximum cooling associated with this upwelling was also found to the right of the storm track at the base of the mixed layer. The model fields depicted intense current shear between the mixed layer and thermocline, with 180o reversal of these currents. Sea surface depressions developed in the wake of the storm were also similar to studies of other storms.

The model also simulated several unique features, apparently caused by coastal interactions with storm forcing. Along the coast of Luzon storm forcing formed a sub-surface alongshore jet near the coast. Northward alongshore surface flow, produced by the divergent near-surface currents, significantly enhanced a warm anomaly off the northern tip of Luzon.

8 ACKNOWLEDGMENTS

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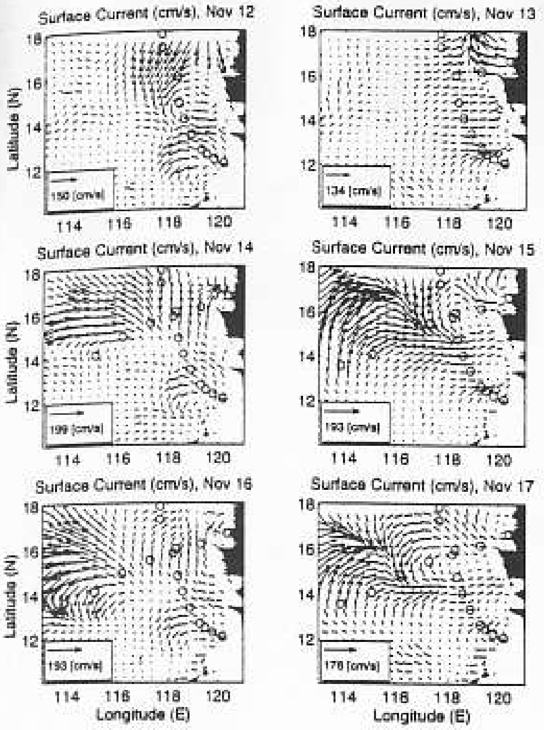

Figure 4 – Time variation of the surface currents near Lozon Island. Here the symboal 'o' indicates the location of Ernie.

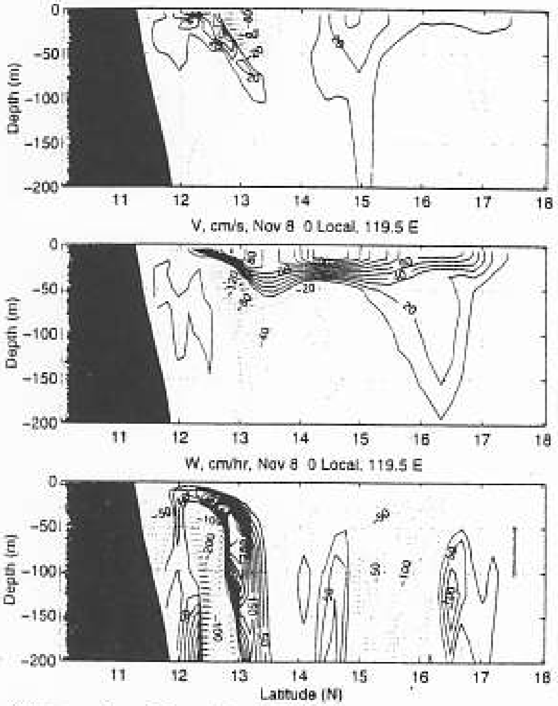

Figure 5 – Longitudinal cross section of simulated u, v (cm/s), and w (cm/hr) along 119.5 deg E on Novemer 8, 1996.

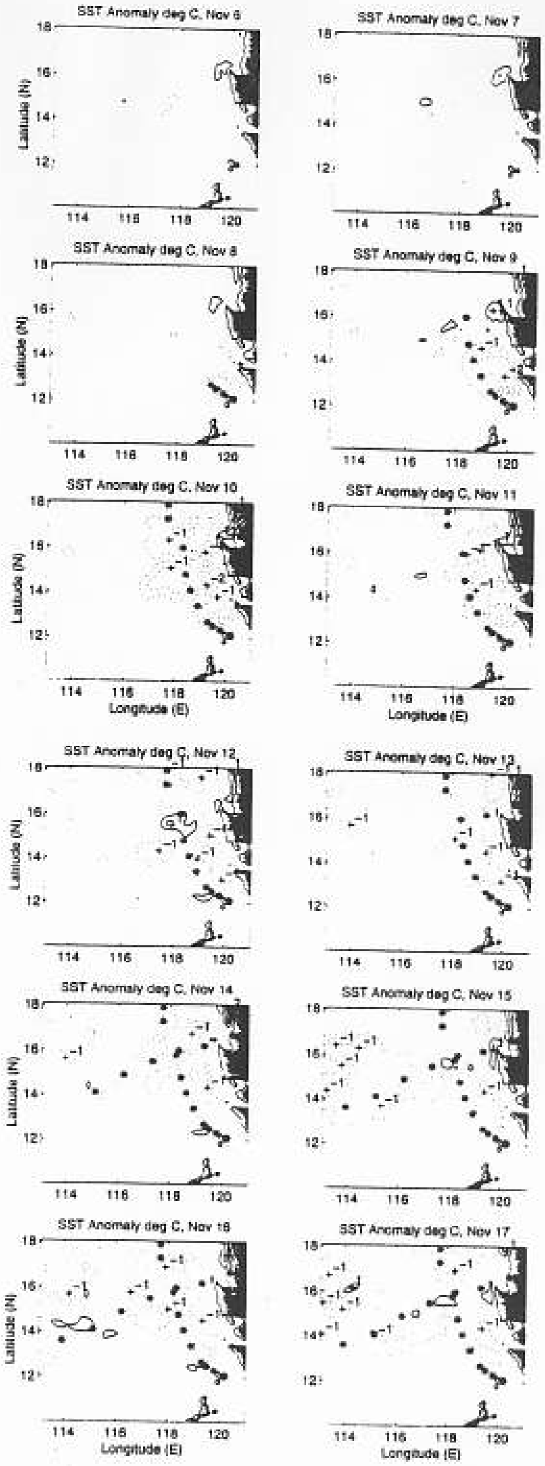

Figure 6 – SST change (deg C) from 4 November. Here the symboal '*' indicates the location of Ernie.