A numerical study of the nonlinear interaction of Hurricane Camille with the Gulf of Mexico Loop Current

Coastal circulation
Ocean modeling
Response to a hurricane
Hurricane currents
Coastal simulation

Circulation côtière
Modélisation océanique
Réponse à un cyclone
Courants dans un cyclone
Simulation côtière

Le Ngoc LY [a] and Lakshmi H. KANTHA [b]

[a] Department of Oceanography, Code Oc/Le, Naval Postgraduate School, Monterey, California 93943-5100, USA.

[b] University of Colorado, Boulder, Colorado 80431, USA.

Received 15/12/92, in revised form 26/03/93, accepted 4/07/93.

ABSTRACT

A three-dimensional, primitive equation, ocean general circulation model is used to study the response of the Gulf of Mexico to Hurricane Camille (1969). The free-surface dynamics and the mixed-layer features are included in the model. The numerical model incorporates the realistic coastline and bottom topography. The sigma coordinate model has eighteen levels in the vertical and 0.2° x 0.2° horizontal resolution for the entire gulf. The study focuses on nonlinear interaction between hurricane induced currents and the Loop Current.

The numerical simulations show that there is a strong nonlinear interaction between the hurricane and the Loop Current in the southern and central parts of the eastern gulf. The surface currents due to nonlinear interaction obtain a maximum of over 1 m s^{-1} in the southern gulf. The numerical results also show that the hurricane interaction with the Loop Current strongly affects current, mixed-layer depth, and elevation fields. There is a strong current response to Hurricane Camille in the surface layer on the shelf with a peak velocity approximately 2.2 m s^{-1}. There is a definite right hand bias in the mixed-layer depth field with a maximum of about 90 m.

Oceanologica Acta, 1993. **16**, 4, 341-348.

RÉSUMÉ

Étude numérique de l'interaction non linéaire entre le cyclone Camille et le courant de la boucle du golfe du Mexique

La réponse du golfe du Mexique au cyclone Camille (1969) est étudiée à l'aide d'un modèle tridimensionnel aux équations primitives de la circulation générale océanique. La dynamique de la surface libre et les caractéristiques de la couche de mélange sont incluses dans le modèle. Le modèle numérique prend en compte la ligne de côte réelle et la topographie du fond. Le modèle en coordonnée sigma comporte dix huit niveaux de résolution verticale et horizontale pour tout le golfe. L'étude porte sur l'interaction non-linéaire entre les courants induits par le cyclone et le courant de la boucle.

Les simulations numériques révèlent une forte interaction non-linéaire entre le cyclone et le courant de la boucle dans le sud et le centre de la partie orientale du golfe. Les courant superficiels dus à l'interaction non-linéaire atteignent un maximum qui dépasse 1 m s^{-1} dans le sud du golfe. Les résultats numériques montrent aussi que l'interaction du cyclone avec le courant de la boucle affecte fortement les champs de courant, de profondeur de la couche de mélange et d'élévation.

La réponse du courant au cyclone Camille est forte dans la couche superficielle sur le plateau continental avec un pic de vitesse voisin de 2,2 m. s^{-1}. Une déviation est bien marquée vers la droite dans le champ de profondeur de la couche mélangée, avec un maximum d'environ 90 m.

Oceanologica Acta, 1993. **16**, 4, 341-348.

INTRODUCTION

The response of the ocean to hurricane forcing has been studied numerically by a number of investigators. A detailed review of this subject was done by Cooper (1987). There are two numerical studies of the Gulf of Mexico response to hurricanes that are of interest to our work. Cooper and Thompson (1989 *a*; *b*) studied hurricane-generated currents for hurricanes Eloise, Frederic and Allen on the outer continental shelf, using a four-layer primitive equation model with a free surface. Using a model with zero shear assumption that included inertia, Coriolis term, advection, thermodynamics, topography, and barotropic and baroclinic modes, they found that there is a strong baroclinic response even in the shallow water of 250 m depth, and also that substantial shelf waves can be generated in the Gulf of Mexico by hurricanes. The effect of the free surface on the near-inertial ocean current response to Hurricane Frederic has been studied by Shay *et al.* (1990). They used both an analytical model and a primitive equation model capable of simulating the combined barotropic and baroclinic response to a hurricane. Their models were forced with an idealized wind pattern based on the observed storm parameters of the hurricane. They found that Hurricane Frederic excited a significant barotropic current at near-inertial frequency in depths of about 600 m. They also found that the barotropic response to the passage of a moving hurricane is governed by linear processes. It is noted that these works assumed all lateral boundaries to be land. This was done to avoid the complexity associated with open boundary conditions.

Our research concerns the response of the Gulf of Mexico to the 1969 Hurricane Camille with realistic topography and open boundaries at the Yucatan and Florida Straits. The model used is the three-dimensional, thermodynamic, primitive equation, ocean general circulation model described by Blumberg and Herring (1987), and Blumberg and Mellor (1987). The sigma coordinate has eighteen levels in the vertical with increased resolution in the mixed layer. Sigma coordinates can adequately model domains with large bathymetric irregularities, such as the entire Gulf of Mexico. It resolves both the mixed-layer and deep ocean features. The free surface is included in the model to study sea level changes. The model has a second order turbulence closure to parameterize vertical mixing and Smagorinsky eddy viscosity to parameterize horizontal mixing. Ly (1992) used this same model to study the Gulf of Mexico shelf waves and currents generated by Hurricane Frederic (1979). Ly and Kantha (1992) studied the Hurricane Camille shelf wave in the Gulf of Mexico, also using the same model.

Our study focuses on nonlinear interaction between hurricane-induced current and the Loop Current. The second section describes the model equations. The third section describes the model initialization, forcing and the hurricane background. The fourth section will give the results of the numerical simulation. The final section is a discussion and summary.

MODEL EQUATIONS

The velocity, surface elevation, salinity, and temperature fields in the ocean are described by the model equations. The Boussinesq approximation (hydrostatic and incompressible) is assumed for the ocean. The model equations are described here in terms of Cartesian coordinates with x eastward, y northward, and z upward. The free surface is located at $z = \eta\ (x, y, t)$ and the bottom is at $z = -H\ (x, y)$.

$$\frac{\partial \vec{V}}{\partial t} + \vec{V}.\nabla\vec{V} + W\frac{\partial \vec{V}}{\partial z} + 2\vec{\Omega} \times \vec{V} = -\frac{1}{\rho_0}\nabla P + \frac{\partial}{\partial z}\left(K_m \frac{\partial \vec{V}}{\partial z}\right) + \vec{F} \quad (1)$$

$$\frac{\partial P}{\partial z} = -\rho g \quad (2)$$

$$\nabla.\vec{V} + \frac{\partial W}{\partial z} = 0 \quad (3)$$

$$\frac{\partial \theta_i}{\partial t} + \vec{V}.\nabla\theta_i = W\frac{\partial \theta_i}{\partial z} = \frac{\partial}{\partial z}\left(K_h \frac{\partial \theta_i}{\partial z}\right) + F_{\theta_i} \quad (4)$$

The equation of state (Fofonoff, 1962) in a general form as

$$\rho = \rho_\theta\ (\theta, S) \quad (5)$$

is used to compute density in the ocean.

The Coriolis force is denoted as $2\vec{\Omega} \times \vec{V}$, where $\vec{\Omega}$ is the earth's angular momentum vector, $\vec{V}$ is the horizontal velocity vector with components (U, V), ∇ is the horizontal gradient operator, ρ_0 is the reference density, ρ is the *in situ* density, g is the gravitational acceleration, P is the pressure, K_m and K_h are the vertical turbulent exchange coefficients for momentum, and for heat and salt, respectively. Here θ_i represents mean potential temperature, θ (or *in situ* temperature for shallow water application) or salinity, S. The potential density, ρ_i, is used here as an approximation since it excludes effects of pressure variation (*see*, Blumberg and Mellor, 1981).

The pressure at depth z can be written in the following form

$$P\ (x, y, z, t) = g\rho_0\ (\eta, \eta_a) + g\int_z^0 \rho\ (x, y, z', t)\, dz' \quad (6)$$

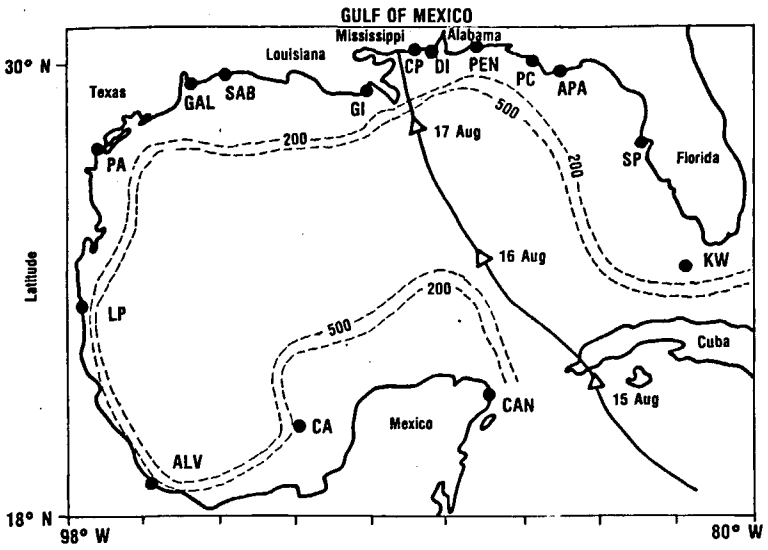

Figure 1

The path of Hurricane Camille and the stations used in the hurricane study: KW (Key West, FL); SP (St. Petersburg, FL); APA (Apalachicola, FL); PC (Panama City, FL); PEN (Pensacola, FL); DI (Dauphin Island, AL); CP (Point Cadet, MS); GI (Grand Isle, LA); SAB (Sabine Pass, TX); GAL (Galveston, TX); PA (Port Aransas, TX); LP (La Pesca, MEX); ALV (Alvarado, MEX); CA (Cayos Arcas, MEX); CAN (Cancun, MEX). The dashed lines are 200 and 500 m isobaths.

where $\eta_a = - P'_a/\rho g$ is the inverse barometer surface elevation, approximately 1 cm sea level increase for every millibar decrease of atmospheric pressure P'_a.

The horizontal mixing terms in (1) and (4) can be written (Blumberg and Mellor, 1981) as

$$F_x = \frac{\partial}{\partial x}(2A_m \frac{\partial U}{\partial x}) + \frac{\partial}{\partial y}[A_m (\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x})] \quad (7)$$

$$F_y = \frac{\partial}{\partial y}(2A_m \frac{\partial V}{\partial y}) + \frac{\partial}{\partial x}[A_m (\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x})] \quad (8)$$

and

$$F_{\theta_i} = \frac{\partial}{\partial x}(A_h \frac{\partial \theta_i}{\partial x}) + \frac{\partial}{\partial y}[A_h (\frac{\partial \theta_i}{\partial y})] \quad (9)$$

where A_m and A_h are the horizontal turbulent exchange coefficients for momentum and for heat, respectively.

The parameterization of turbulence in the model is based on the the work of Mellor and Yamada (1982). At the free surface, $z = \eta\ (x, y)$, the surface wind stress, heat, and salinity fluxes are prescribed. At the bottom, zero heat and salinity fluxes are used. At land boundaries we use the condition of no diffusive fluxes of any property across the interface. The details of the open boundary conditions at the Yucatan and Florida straits will be discussed next.

THE MODEL INITIALIZATION AND FORCING

The domain is the entire gulf with a horizontal resolution of 0.2° x 0.2°, represented with 86 x 65 grid points. The time step for the external (barotropic) mode is 30 *s* and for the internal (baroclinic) mode is fifteen minutes. The gulf bathymetry is obtained from the global DBDB5 bathymetry dataset with 5' x 5' resolution (National Geophysical Data Center, 1985) and is interpolated to the gulf 0.2° x 0.2° grid. The DBDB5 bathymetry is not accurate for depth less than 200 m. It was updated with over 600 grid points along the US coastal region using bathymetry charts provided by the Naval Oceanographic Office. A Shapiro (1970) filter was used on the bathymetry to remove high-frequency noise.

Temperature and salinity from the Levitus (1982) climatology, and wind stress from the Hellerman and Rosenstein (1983) climatology were used to initialize the model. At the Straits of Florida (outflow boundary) radiation open-boundary conditions for temperature and salinity are used. At the Yucatan Straits (inflow boundary), temperature and salinity are prescribed from climatological data. A 30 *Sv* (1 *Sv* = 10^6 m^3 s^{-1}) mass flux is specified in the upper layers through the Yucatan straits to produce the Loop Current. The boundary condition for surface elevation at the Yucatan straits is zero gradient normal to boundary.

The model is then run forward in time 190 days to produce the Loop Current. The resulting Loop Current is shown in Figure 2. It is noted that the exact position of the Loop Current for August 1969 (Camille) is not known with certainty (Cochrane, 1972). We assume the Loop Current produced by the model after the 190-day run is close to the position for August 1969. The Loop Current used here, may be more representative of the five year average position for the period 1980-1984 (Vukovich, 1988).

The sea-level pressure and two components of wind stress are specified on the (0.2° x 0.2°) grid at a time interval of thirty minutes for the period of hurricane passage across the gulf. These data for hurricanes Camille and Frederic (Ly, 1992) were provided by Dr. Cardone of Oceanweather, Inc. The same forcing and track for hurricanes Camille and Frederic were described in the study of the WAMDI Group (WAMDI Group, 1988). Hurricane wind fields were derived from application of a dynamical numerical model of the planetary boundary layer in hurricanes (Cardone *et al.*, 1979).

Camille was a very strong hurricane that passed western Cuba with 115-mph winds and ten inches of rain. Camille passed through the eastern part of the Gulf of Mexico between 15 and 17 August 1969 (Fig. 1). The winds decreased to 100-mph (about 50 m s^{-1}) and the forward movement decreased from 15-10-mph as Camille crossed the gulf.

NUMERICAL SIMULATIONS

Nonlinear interaction between Hurricane Camille and the Loop Current

The interaction of a hurricane with the Loop Current in the Gulf of Mexico is an important and interesting feature to investigate when studying the ocean response to a hurricane with a numerical model. For this study, the path of Hurricane Camille is nearly along the axis of the model Loop Current. It is expected that nonlinear interaction between the hurricane currents and the loop current is important during a hurricane passage.

In the southeast part of the gulf, the Loop Current has a speed of over 1 m s^{-1} (Fig. 2). The surface currents for the position of the hurricane at 1200 EST, 17 August 1969, are shown in Figure 3. The maximum currents at this time are greater than 2 m s^{-1} on the continental shelf. It is seen from this figure that strong currents are induced by hurricane winds in the northern part of the gulf where the hurricane is located. There is a strong interaction between the hurricane-induced current and the Loop Current in the central region where both currents are strong. In the eastern part of the gulf and along the shelf from Florida to Louisiana, the dominant currents are a response to the hurricane forcing. In the western half of the gulf the surface currents are not directly affected by the hurricane.

Hurricane-induced surface currents, obtained by vector subtraction of the initial current (Fig. 2) from the surface currents with Loop Current present (Fig. 3), are shown in Figure 4. The maximum current is greater than 2 m s^{-1} in the northern part of the gulf where the hurricane has most influence at this time. A strong interaction between the Loop Current and hurricane-induced current is indicated by Figure 4. This is a result of a strong activity of the Loop Current in the central and the southern regions of the eastern gulf.

For the purpose of studying nonlinear interaction, the hurricane passage was run under the same climatological conditions without the presence of the Loop Current (closed boundary conditions at the Yucatan and Florida straits). The surface currents at 1200 EST, 17 August 1969, without the Loop Current present are shown in Figure 5. From this figure, we can see strong hurricane-induced currents (but weaker than those shown in Figure 3 with the Loop Current present) mostly in the central and northern parts of the eastern gulf. The maximum current is greater than 2m s^{-1} on the Louisiana and Mississippi shelf (Fig. 5). It is interesting to compare the surface currents with (Fig. 3) and without (Fig. 5) the Loop Current present. It is seen from these two figures that the Loop Current interacts with the hurricane induced currents. The Loop Current is very strong and dominates the southeast part of the gulf at this time (Fig. 3).

The currents in Figure 3 are stronger in the central part of the eastern gulf and with more horizontal shear than those in Figure 5. This is clearly because of the interaction with the Loop Current.

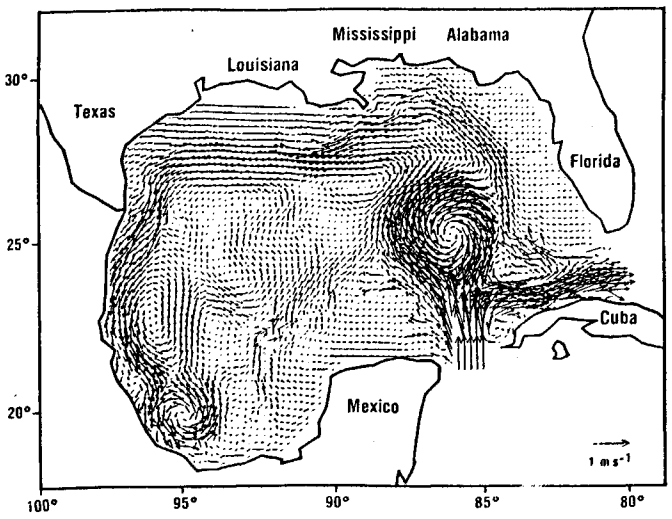

Figure 2

Loop Current produced by 190 day model run, with a 30 Sverdrup inflow through the Yucatan Straits.

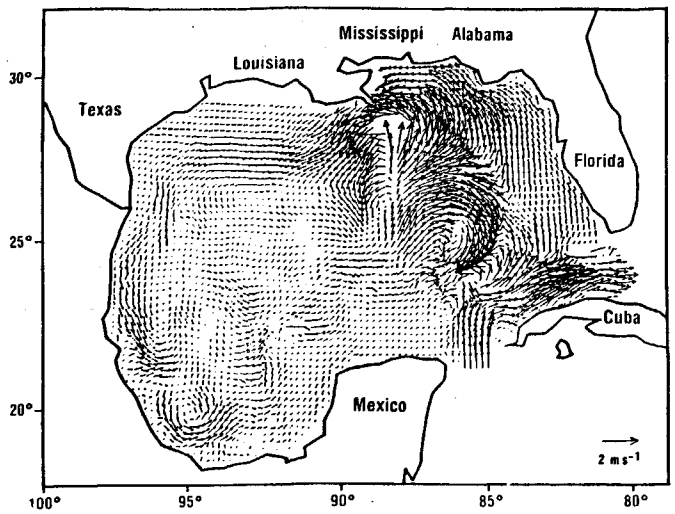

Figure 3

Hurricane-generated surface currents with Loop Current present in model simulation. The maximum currents are greater 2.

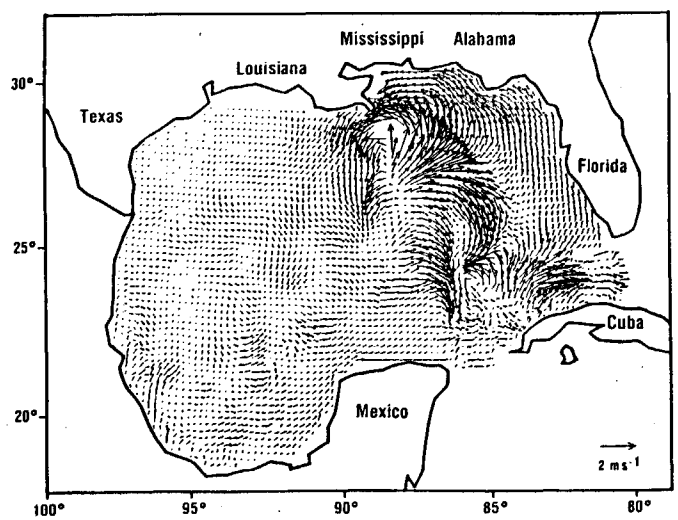

Figure 4

Hurricane-induced surface currents, obtained by vector subtraction of the Loop Current (Fig. 2) from the hurricane currents with Loop Current present (Fig. 3).

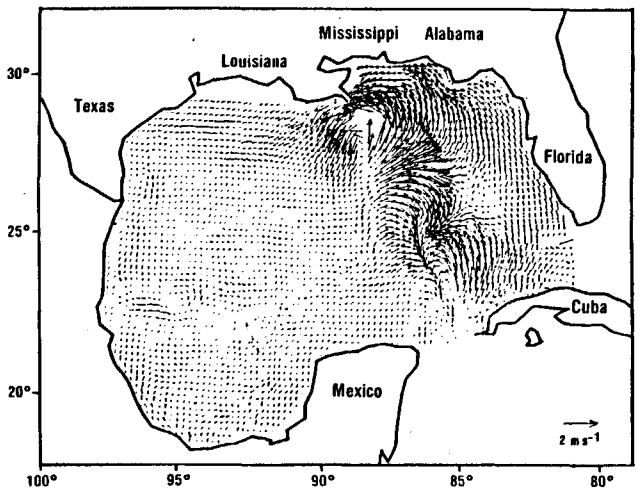

Figure 5

Hurricane-generated surface currents without Loop Current (closed boundaries) for 17 August. The maximum currents are greater 2 .

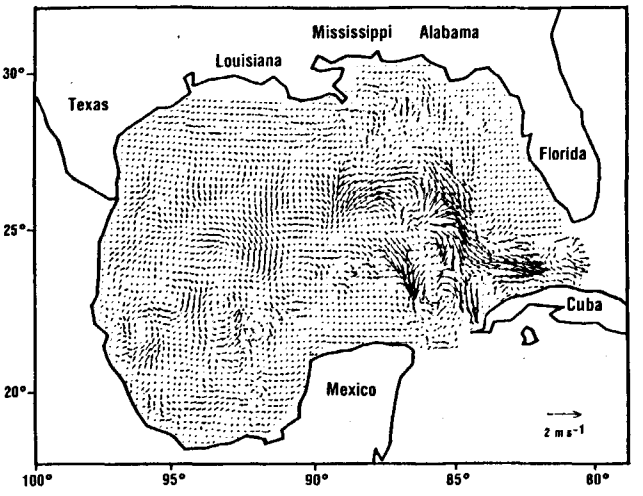

Figure 6

Surface currents due to nonlinear interaction of Hurricane Camille with Loop Current, obtained by vector subtraction of hurricane currents without Loop Current present (Fig. 5) from the hurricane-induced currents with Loop Current present (Fig. 4).

The surface currents due to nonlinear interaction of hurricane-induced currents with the Loop Current, obtained by vector subtraction of surface currents without the Loop Current present (Fig. 5) from the surface currents in Figure 4, are shown in Figure 6. It is noted that if the interaction between these currents were linear, then the currents in Figure 6 would be zero. It is clear that the interaction between hurricane induced currents and the Loop Current is nonlinear. The surface currents due to nonlinear interaction obtain a maximum speed of over 1 m s^{-1} and have opposite direction to the Loop Current in the southern gulf near the Yucatan Strait where the Loop Current is strong (Fig. 2). This shows that the nonlinear interaction between hurricane induced current and the Loop Current is an important feature during a hurricane passage. It is interesting to see that the nonlinear interaction between the currents in Figure 6 is greatest along the shelf break (Fig. 1) and near the high sea-level contours (Fig. 10). This may be caused by the surface elevation (surface pressure gradient terms) becoming large and the advective acceleration terms in equation (1) becoming significant relative to the other terms. The nonlinear interaction mechanism is very complex and requires more theoretical and experimental study.

Hurricane-induced current structure

Here we will study the current response of the Gulf to Hurricane Camille. The model current outputs at depths 7 m, and 50 m are shown in Figures 7, and 8, respectively. For the period 14-23 August, the model current vectors at five sites are plotted at hourly intervals. The sites are located on the 200-m and 500-m isobaths. To show the model current output at these two levels, we choose five sites where there is a definite current response to the hurricane. These sites are on the shelf off St. Petersburg (FL), Apalachicola (FL), Pensacola (FL), Dauphin Island (AL),and Sabine Pass (TX).

Time series of the model output current at the 7 m depth for five sites located on the 200-m isobath are shown in Figure 7. The current vectors consist of along-shelf (V) and cross-shelf (U) components. It is difficult to define the peak current velocities on the shelf off St. Petersburg and Apalachicola. From Figure 7 we can see that the currents become stronger off Pensacola, and obtain a maximum velocity approximately 2.2 m s^{-1} off Dauphin Island close to Camille's landfall on the Mississippi coast. Currents

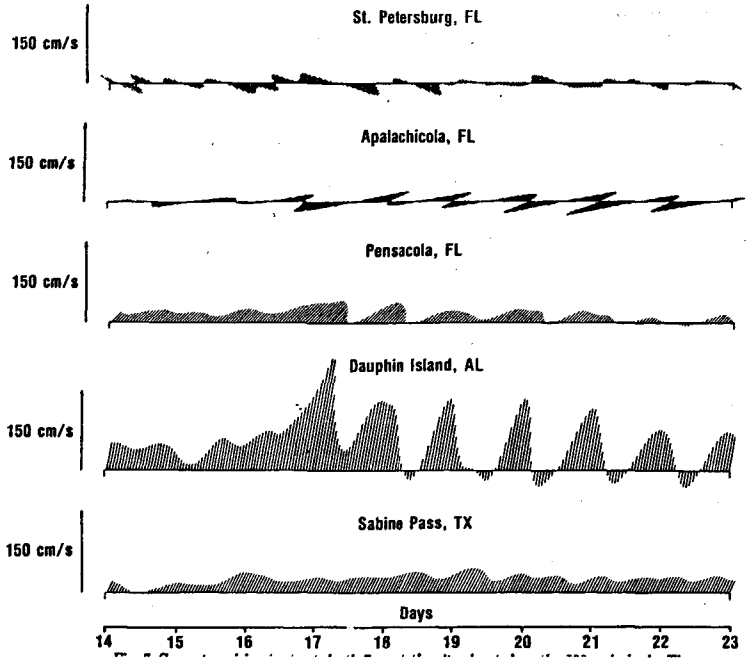

Figure 7

Current model outputs at depth 7 m at the sites located on the 200 m isobath. The vectors with along-shelf (V) and cross-shelf (U) components are plotted for hourly intervals from 14-23 August, 1969.

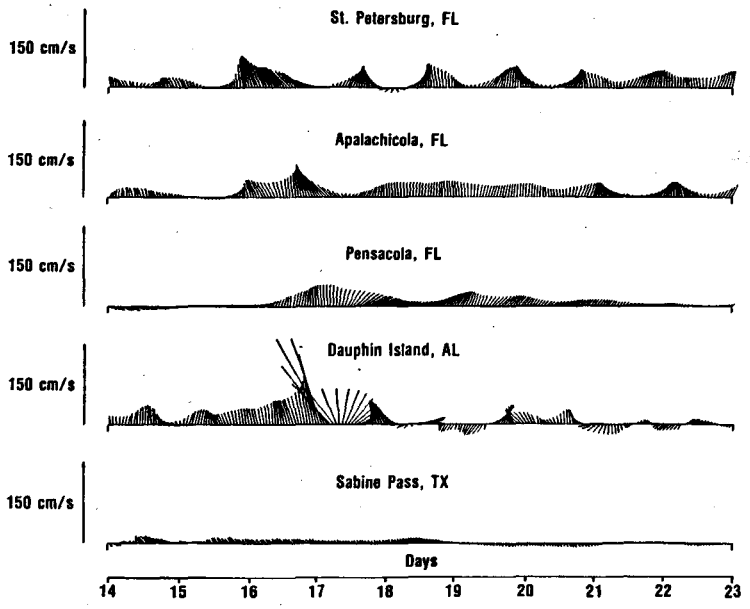

Figure 8

Same as Figure 7 but for the 50 m depth at the sites located on the 500 m isobath.

show a very strong response to Hurricane Camille's forcing at the sites close to the hurricane track. Off Sabine Pass the currents are less than 1.0 m s^{-1}. Currents become less at the sites in the western gulf (not shown) where the hurricane-induced currents are weaker.

The model current vectors for 50-m depth are plotted in Figure 8 for hourly intervals at the sites located on the 500-m isobath. Figures 7 and 8 show many similar features in current structure. Off St. Petersburg, Apalachicola, and Pensacola, the current velocities have peaks approximately 1.0 m s^{-1} at almost the same time. The 50-m currents obtain a maximum of over 2.0 m s^{-1} off Dauphin Island and decrease westward.

We can see from Figures 7 and 8 that the current vectors strongly change their directions off Dauphin Island. This is also true of results from sites off the Texas coast which are not shown here. This may be the result of the strong change of continental shelf direction.

Figures 7 and 8 clearly show inertial motion with approximately a 24-hour period generated by the sudden strong onset of the hurricane wind field in the surface layer of the eastern gulf. In the western gulf, the inertial oscillations in the current field are very small. These oscillations are also shown in the observations of Shay *et al.* (1990) and the numerical simulation of Hurricane Frederic (Ly, 1992). Presumably because of the vertical stratification and bottom friction, the current vectors change their directions and become small at the bottom layer (not shown) in comparison with surface layer currents. Current response to the hurricane is strongest in the surface layer where shear is small and there is less stratification and friction.

Mixed-layer and free surface responses

The mixed-layer depth produced by the model at 1200 EST 17 August 1969, is shown in Figure 9. This depth obtains a maximum of almost 90 m in the center of the eastern gulf to the right of the hurricane track. We can see from Figure 9 that the hurricane strongly deepens the mixed layer in the region to the right side of Camille's track. This is known as the right-hand bias, which is shown very clearly in the study by Price (1981). He indicated that the right-hand bias occurs because the hurricane wind stress vector turns clockwise with time on the right side and anticlockwise on the left side of the track, and is roughly resonant with the mixed-layer velocity. The winds are strongest on the right side of the hurricane. Thus the current field is highly asymmetric, with much stronger velocities on the right of the storm track. Furthermore, water parcels on the right move in the same direction as the hurricane while parcels on the left move in the opposite direction. The mixed layer depth on the right side of the hurricane has increased

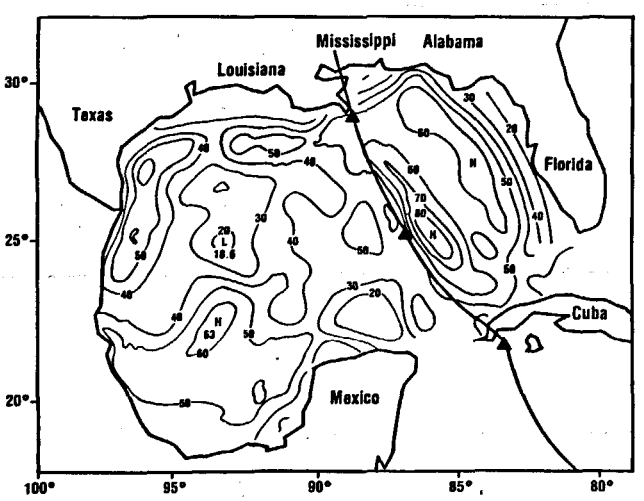

Figure 9

Mixed layer depth on 17 August. Maximum depth of 90 m is to the right of the Hurricane Camille track.

because of vertical mixing. Comparing the mixed-layer depths with and without (not shown here) the presence of the Loop Current we see that the nonlinear interaction of hurricane Camille with the Loop Current deepens the mixed layer. The Loop Current strengthens the mixed layer response to the hurricane, due to a nonlinear response. It can be seen as that both advection and vertical mixing must be stronger where hurricane winds have strong horizontal shear.

The model output of the free-surface response for 1200 EST 17 August 1969 is shown in Figure 10, as the hurricane approaches the coast. The sea level in the deep gulf (as opposed to the coastal storm surge) has reached its maximum of about one meter. The Loop Current elevation reaches a maximum of approximately 45 cm. The comparison of the surface elevation fields with and without the presence of the Loop Current shows that the interaction of the hurricane with the Loop Current has a significant role in the distribution of surface elevation in the eastern gulf.

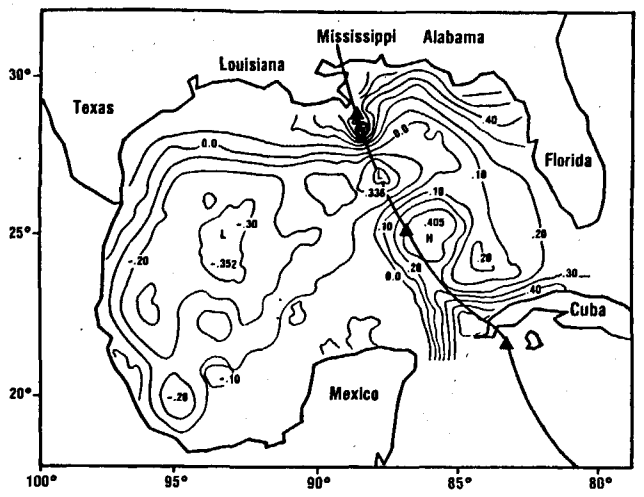

Figure 10

Surface elevation on 17 August.

SUMMARY AND DISCUSSION

A three-dimensional, primitive equation, ocean general circulation model with free surface dynamics is used to study the response of the Gulf of Mexico to Hurricane Camille. Realistic coastline and bottom topography were used for the numerical model. The sigma coordinate model has 18 levels in the vertical and 0.2° x 0.2° horizontal resolution for the entire gulf. The open boundary conditions specified inflow through the Yucatan Straits and outflow through the Straits of Florida. The study focuses on nonlinear interaction between hurricane-induced currents and the Loop Current. Hurricane generated current structure, mixed-layer depth, and sea surface elevation responses to Hurricane Camille are also studied.

The numerical simulations show that there is a strong nonlinear interaction between the hurricane and the Loop Current in the southern and central regions of the eastern gulf. The surface currents due to nonlinear interaction obtain a maximum of over 1 m s^{-1} and have opposite directions to the Loop Current in the southern gulf near the Yucatan Straits. The hurricane-induced surface currents obtained maximum values greater than 2 m s^{-1} in the northern region of the eastern gulf where the hurricane has most influence. In the southern gulf, the Loop Current dominates the circulation pattern with velocities over 1 m s^{-1}. The nonlinear interaction makes hurricane-induced currents stronger and with more horizontal shear.

There is a strong current response to Hurricane Camille in the surface layer off Dauphin Island located close to the hurricane track. At this location the current has a peak velocity approximately 2.2 m s^{-1}. Current vectors strongly change their directions off Dauphin Island following the passage of the hurricane. A clear inertial motion with approximately a 24-hour period is observed in the surface layer of the eastern gulf. This motion is generated by the sudden onset of the hurricane wind field.

The model output of the mixed layer depth on 17 August indicates a maximum depth of almost 90 m in the center of the eastern gulf, to the right of the hurricane track. Results indicate a clear right hand bias in the mixed-layer depth field. The numerical results show that the nonlinear interaction between Hurricane Camille and the Loop Current strengthens the mixed-layer depth response to the hurricane. It is also clear that the interaction of the hurricane with the Loop Current has a significant role in the distribution of surface elevation in the eastern gulf. Overall, there is a clear nonlinear interaction between the hurricane and the Loop Current, and it strongly affects hurricane-induced currents, mixed-layer depths, and elevation fields.

Acknowledgements

The authors acknowledge the support of the Navy Ocean Modeling and Prediction Program (NOMP) of the Office of Naval Research (ONR) under Mr. Robert Peloquin's Program. LNL acknowledges the support, in part, of the Department of Oceanography, Naval Postgraduate School. They are indebted to Dr. William P. O'Connor, NOAA Great Lakes Environmental Research Labs, for his help in the work, and also wish to thank Dr. Vince J. Cardone, Oceanweather, Inc. for providing the hurricane wind-stress data, and Dr. Fred M. Vukovich, Research Triangle Institute, for information on the Loop Current position. The comments of two anonymous reviewers were helpful.

REFERENCES

Blumberg A.F. and G.L. Mellor (1981). A numerical calculation of the circulation in the Gulf of Mexico. Dynalysis of Princeton, Report No. 66.

Blumberg A.F. and G.L. Mellor (1987). A description of a three-dimensional coastal ocean circulation model. Three Dimensional Coastal Models, Coastal and Estuarine Sciences, 4, N. S. Heaps, editor. AGU Geophysical Monograph Board, 1-16.

Blumberg A.F. and J. Herring (1987). Circulation modeling using orthogonal curvilinear coordinates, in: *Three-Dimensional Models of Marine and Estuarine Dynamics*, J.C.J. Nihoul and B.M. Ramart, editors. Elsevier Oceanography Series, 45, Amsterdam, 55-88.

Cardone V.J., C.V. Greenwood and J.A. Greenwood (1979) A unified program for the specification of hurricane boundary layer winds over surfaces of specific roughness. Final Report, Contract DACW-39-78-C-0100, Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, MS, USA.

Cochrane J.D. (1972). Separation of an anticyclone and subsequent developments in the Loop Current (1969), in: Contributions on the Physical Oceanography of the Gulf of Mexico, Vol. 2, L.R.A. Capurro and J.L. Reid, editors. Texas A. & M. University Oceanographic Studies, Gulf Publishing Co., Houston, USA, 91-10.

Cooper C.K. (1987). Hurricane generated currents on the outer continental shelf. *Ph. D. Thesis, University of Maine, Orono, USA*, 183 pp.

Cooper C. and J.D. Thompson (1989 *a*). Hurricane-generated currents on the outer continental shelf. Part 1: Model formulation and verification. *J. geophys. Res.*, **94**, 12513-12539.

Cooper C. and J.D. Thompson (1989 *b*). Hurricane-generated currents on the outer continental shelf. Part 2: Model sensitivity studies. *J. geophys. Res.*, **94**, 12540-12554.

Fofonoff N.P. (1962). Physical properties of sea-water, in: *The Sea, Vol. 1*, Wiley-Interscience, New York, USA, 3-30.

Hellerman S. and M. Rosenstein (1983). Normal monthly wind stress over the world ocean with error estimates. *J. phys. Oceanogr.*, **13**, 1093-1104.

Levitus S. (1982). Climatological atlas of the world ocean. National Oceanic and Atmospheric Administration. Professional Paper No. 13, US Government Printing Office, Washington D.C., USA.

Ly N.L. (1992). The Gulf of Mexico response to Hurricane Frederic simulated with the Princeton numerical ocean circulation model. Institute for Naval Oceanography, Stennis Space Center, MS. Technical Report, 42 pp.

Ly N.L. and L.H. Kantha (1992). Hurricane Camille shelf wave simulation using a numerical ocean circulation model. *Proceedings: Estuarine and Coastal Modeling, Second International Conference/WW Div., American Society of Civil Engineers*, 586-593.

Mellor G.L. and T. Yamada (1982). A hierarchy of turbulence closure models for planetary boundary layers. *J. atmos. Sci.*, **31**, 1791-1896.

National Geophysical Data Center (1985). Worldwide Gridded Bathymetry DBDB5 5-minute Latitude/Longitude Grid, Data Announcement 85-MGG-01, NOAA/NGDC, Boulder, Colorado, USA.

Price J.F. (1981). Upper ocean response to hurricane. *J. phys. Oceanogr.*, **11**, 153-175.

Shapiro R. (1970). Smoothing, filtering, and boundary effects. *Revs Geophys. Space Phys.*, **8**, 359-386.

Shay L.K., S.W. Chang and R.L. Elsberry (1990). Free surface effects on the near-inertial ocean current response to a hurricane. *J. phys. Oceanogr.*, **20**, 1206-1218.

Vukovich F.M. (1988). Loop Current boundary variations. *J. geophys. Res.*, **93**, 15, 585-15, 591.

The WAMDI Group (1988). The WAM model. A third generation ocean wave prediction model. *J. phys. Oceanogr.*, **18**, 1775-1810.