A HYDRODYNAMIC MODEL FOR THE BACK BAY OF BILOXI

***Ranjit M. Passi, *Igor Shulman, *Robert Willems and **James K. Lewis**

***Center for Ocean & Atmospheric Modeling**
Stennis Space Center, Mississippi

****Ocean Physics Research & Development**
Long Beach, Mississippi

INTRODUCTION

Objective

The Back Bay of Biloxi, located on the Mississippi Gulf Coast, is an estuarine system whose waters of late are coming under increasing stress. Waters in the study area are used for recreational activities and support fish and aquatic life. The environment quality of the region is of major concern, and steps are being designed to protect and balance it against wastewater discharges from industrial and municipal sources located around the Bay. Objective and scientific approaches are being taken to determine the assimilative capacity of the Bay, which will lead to an equitable allocation of wastewater discharge permits so that the ecosystem is maintained without inhibiting economic growth. The water quality model currently used by the Office of Pollution Control at the Department of Environmental Quality (Shindala et al. 1973) is not applicable to the current complex environment and cannot provide satisfactory guidance for issuing permits for wastewater allocation.

The University of Southern Mississippi and Mississippi State University are collaborating to develop a Water Quality Model (WQM) which will provide the relationship between waste inputs and their impact on the receiving waters. The WQM consists of two modeling components: (1) a hydrodynamic model (HDM) that predicts the circulation of the Bay based on winds, tides, and freshwater inflow from the tributaries; and (2) a pollutant fate model that uses mass transports across grid cells predicted by the HDM to determine the fate of the pollutants introduced into the system. This paper provides preliminary results on the development of the HDM of the Bay.

Description of the Area

The Back Bay of Biloxi region is a narrow estuary (average three quarters of a mile from north to south shores), separated from the Mississippi Sound by the narrow Biloxi Peninsula (Figure 1). The area extends about 16 km from the mouth of the Bay in the east to the confluence of the Biloxi and Tchoutacabouffa Rivers in the west. The main drainage into the Bay is provided by four tributaries: the Biloxi and Tchoutacabouffa Rivers, and Bernard Bayou flowing into the Big Lake located at the northwestern edge of the Bay; and Fort Bayou in the eastern part of the Bay. In addition, there are several small creeks and bayous that have been incorporated in the HDM. Except for a navigational channel, the Bay is shallow, mostly less than 3 m, with an average depth near one meter. In the navigational channel, the depth varies from 3 m to >7m.

Dominant Forcings

The dynamics of the region are controlled by the tides, winds, and freshwater inflow. The tides are primarily diurnal in nature, with little difference in the phase of the tide throughout the Bay. As expected, flood tide brings the saltier water from the Mississippi Sound. However, the salinity of the Mississippi Sound is low. As a result, we do not see the large salinity differences between the bottom and surface waters of the Bay as in most other estuaries.

The influence of the winds comes as a result of the shallow nature of both the Biloxi Bay and the coastal Mississippi Sound. Strong northerly or southerly winds can result in a significant setup or setdown of the water level along the Mississippi coast. The Bay responds to the direct wind forcing and the change in the coastal sea level height by discharging (entrapping) more (less) than usual water during northers (strong southerly winds). As a result, the flushing of pollutants may be significantly enhanced or degraded depending on wind conditions.

As for freshwater inflow, it is the seasonal variation of the inflow of the Biloxi Bay tributaries that result in varying estuarine dynamics. During rainy weather, the freshwater tends to enhance the vertical salinity structure of the Bay. These are distinct periods during which the Bay has a salt wedge estuarine structure, albeit less dramatic as in many other bays. During low rainfall periods, the tributaries have less influence on the salinity structure, and many segments of the Bay reflect the characteristics of the Mississippi coastal waters.

The Model Development

Although the WQM needs only the vertically-averaged transports, there is a clear need for a three-dimensional model to simulate the circulation of subregions that may be affected by wastewater discharge. In the past, wastewater effluent tracer studies have been conducted by releasing dye solutes to evaluate the spatial and temporal extents of such discharges (Gaines et al. 1987). Currently, the Mississippi Department of Environmental Quality is being asked to consider a license to discharge in the vicinity of Keegan Bayou (near point C, Figure 1). Tracer studies indicate that such discharges would affect oyster beds downstream. A dye study is being planned in the near future. The HDM will be evaluated for its capability to simulate the three-dimensional dye plume so that the model could be used for such studies in the future.

The HDM for the Back Bay of Biloxi is based on the Princeton Ocean Model. The model possesses all the necessary physics for shallow and deep water modeling. Versions of the models have been successfully applied in varied applications. The model will be forced with tidal forcing at the two open boundaries and winds, and it will incorporate freshwater inflow from the tributaries. The rivers are incorporated as a part of the model grid. The model parameters will be fine-tuned using observations from an intensive observing period marked by low flow (13-19 September 1994). The model validation will be performed using observations from an intensive observing period planned for April 1995.

This paper provides simulation results of our preliminary investigation using estimated forcing parameters. The main objective here is to demonstrate the capability of the model to adequately respond to the tidal and wind forcings with rivers and bayous incorporated into the model grid. We will first describe the salient features of the model, followed by the basic setup of the model including the model grid, bathymetry, and the formulation of the open boundary conditions. The inclusion into the model of rivers and bayous up to the tidal boundaries is of import, so a special effort has gone into the development of their depths. With this setup, the results of the computer simulations indicate a satisfactory model response to the external forcings.

MODEL DESCRIPTION

Governing Equations and Numerical Scheme

The Princeton coastal numerical model (Mellor and Blumberg 1987) has been successfully used for modeling lakes, estuaries, and coastal areas: Chesapeake Bay, Massachusetts Bay, Delaware Bay, Hudson-Raritan Estuary (Blumberg and Goodrich 1990; Signell et al. 1993; Galperin and Mellor 1990; Oey et al. 1985). The main model characteristics are as follows: finite-difference analog of the three-dimensional momentum and continuity equations, assuming incompressibility, hydrostatic and Bousinesq approximations; free upper surface with the barotropic mode; baroclinic mode; prognostic equations for temperature and salinity; Smagorinsky horizontal diffusion; and turbulence model for vertical mixing (Mellor and Yamada 1982). Numerically, the model uses the Arakawa-C staggard grid (Mellor and Blumberg 1987), a leapfrog numerical scheme (centered in space and time) and an implicit time scheme for vertical mixing. Equations are written using a terrain following, vertical coordinate system. For computational efficiency, time-integration is split into a two-dimensional, external mode with a short time step, and a three-dimensional, internal mode with a long time step. Therefore, the model can be run in the two-dimensional, vertically-integrated mode, or a fully three-dimensional mode. In the three-dimensional case, the model can be run in the diagnostic and prognostic modes. In the diagnostic mode, the temperature and salinity are held fixed, while the velocity field is allowed to adjust to the baroclinic field. The diagnostic mode is usually used to spin up the model from rest. In the prognostic mode, the integration of the equations for temperature and salinity is performed.

MODEL GRID, BATHYMETRY, INITIAL CONDITIONS, BOUNDARY CONDITIONS

The model grid is a curvilinear orthogonal grid containing 70 x 35 grid points (Figure 2). The grid resolution ranges from 200 m to 400 m. The model uses a sigma coordinate system in the vertical: $\sigma = (z - \eta)/(H + \eta)$, where H is the bottom depth and η is the surface height elevation. In this case, we have a very accurate representation of the irregular bottom topography and free surface elevation in the model. In this study, the model has five active vertical layers, corresponding to σ intervals: (0.0 -0.333), (-0.333 -0.5), (-0.5 -0.666), (-0.666 -0.833), and (-0.833 -1.). Bathymetry for the main Bay was estimated from navigation charts by averaging all depths within a model grid cell (the bathymetry for rivers and creeks will be discussed below). The depth ranges from 40 cm to 7.8 m (in the deep channel). The initial fields for temperature and salinity were taken from observations (February 7,

1973) at stations along the Bay (Eleuterius 1973) and interpolated to the model grid. The model has the following boundaries: free surface, rigid bottom, closed lateral boundaries, and open lateral boundaries. At the free surface, the following atmospheric forcing can be specified: wind stress components, heat flux, and the difference between evaporation and precipitation. At the bottom, momentum flux is balanced by matching the computed velocity near the bottom with a logarithmic boundary layer:

$$\frac{K_M}{D}\left(\frac{\partial U}{\partial \sigma}, \frac{\partial V}{\partial \sigma}\right) = C_z [U^2 + V^2]^{1/2} (U, V),$$

$$C_z = \max\left[\frac{k^2}{(\ln((1+\sigma_{b-1}) H/z_0))^2}, C_{\min}\right]$$

where $k = 0.4$ is the von Karman constant and z_0 is the roughness parameter, U and V are horizontal components of the velocity, H is the depth, K_M is the vertical kinematic viscosity momentum mixing coefficient. $C_{\min}$ is the minimal value of the bottom friction drag coefficient, and σ_{b-1} is the bottom sigma layer. The salinity and heat fluxes are set to zeros at the bottom boundary. At all closed lateral boundaries, the normal velocities are set to zero, as well as the tangential velocities at half a grid distance inside the closed boundaries. The model has two open boundaries (Figure 1). In the numerical experiments described below, we used the radiation condition (Ippen 1966) or the radiation/forcing condition of Reid and Bodine (1968) for the barotropic mode. Temperature and salinity were prescribed from data at the inflow boundaries, and the upstream advection was used at the outflow boundaries (Blumberg and Mellor 1987).

RIVERS, BAYOUS AND CREEKS MODELING

The major tributaries, viz. Bayou Bernard, Biloxi River, Tchoutacabouffa River, and Fort Bayou, have been incorporated into the model grid. For each tributary, freshwater inflow will be specified at the tidal boundary. To set up a grid for these tributaries, the Gulf Coast Research Laboratory provided strip charts of the depths in separate transects, which were digitized and average depths of the transects were computed. The various transects were sectioned or grouped to form grids that, on average, preserve the length, depth, and volume. The gridding was performed so that orientation and the dimensions of the sections included in a grid were similar. A one-to-one correspondence has been set up between the grid locations and the arc-length distance from a reference point in the Bay. However, the emplacement of these gridded sections on the numerical grid has been so that the tributaries lie along straight lines. Computer simulations have been made with this grid configuration, and the model results seem reasonable. Further simulations will be made to validate the overall grid. The overall bathymetry of the entire system will be modified to incorporate the geodetic elevation above sea level of the various sections of the rivers. This will allow the freshwater to drain into the Bay under the influence of gravity.

THE MODEL SETUP

The time step for the vertically-integrated, barotropic, external mode is restricted by the grid size and the depth of the Bay and can be determined from the Courant-Friederics-Levy (CFL) computational stability condition (Blumberg and Mellor 1987). In our simulations, the external time step was set to equal 15 sec. For the three-dimensional, internal mode, the time step was equal to 600 sec. As we mentioned before, the model uses the Smagorinsky diffusivity for horizontal diffusion. The coefficient multiplying the horizontal diffusivity term was set at 0.075. The minimum bottom friction drag coefficient $C_{\min}$ was equal to 0.0025. The background diffusivity was set at 0.00002. The model was spun up over 1.5 inertial periods. In some experiments, the model was forced on the open boundary by the major diurnal and semi-diurnal tidal constituents for the Biloxi tidal station.

NUMERICAL EXPERIMENTS AND RESULTS

In the first numerical experiments, the model was run in the three dimensional case: prognostic and diagnostic modes. In the prognostic mode, the dynamical equations for temperature and salinity were integrated. In the diagnostic run, the velocity field was allowed to adjust to the spatial distribution of the density field (the temperature and salinity fields were held fixed). We forced the model with the K_1 diurnal tidal constituent on the open boundaries. Because of the lack of temperature and salinity data in the rivers and creeks, this run was performed without the rivers and creeks. The distribution of the surface height elevation and vertically-averaged velocity are very close for the prognostic and diagnostic runs. In both simulations, the solutions stabilized after 30 hours, with the amplitude equal to the amplitude of the diurnal tide K_1 (17 cm). The maximum amplitude of the vertically-averaged velocity was about 12 cm/sec; but, the vertical distribution of the velocity for the prognostic run was significantly different from that of the diagnostic run. For the six locations along the Bay (Figure 1), the velocities at the top, middle, and bottom layers are shown in Figures 3-5. The values for the surface velocity are greater than what we had in the diagnostic run, and a larger flux at the surface was directed out of the Bay than in the diagnostic run. At the same time, the bottom flux is directed into the Bay (except location F, close to the open boundary). We can see small, higher frequencies oscillations on top of the tidal variations. These three-dimensional simulations in the diagnostic and prognostic runs show that the density distribution in the Bay can significantly influence the vertical mixing and diffusion, that are important for water quality analysis. It can be especially critical in the situation of the significant salinity flux due to river runoff and rain.

In our next simulation, we tested the response of the Bay to all major tidal constituents K_1, O_1, M_2, S_2, P_1 and Q_1. In this barotropic, two-dimensional experiment, we modeled the main Bay together with the rivers and bayous. The total amplitude of the surface height is around 30 cm for all the constituents, which restricts the depth the model can handle (the drying of the grid cells is not allowed in the model). In Figure 6, the vertically averaged velocities are shown for the last 30 days of the 45-day run, for six locations (Figure 1) (four of them, A, D, E and F are the same as in the previous experiments). The amplitudes of the velocity are largest at the rivers' mouths (locations G and H). The amplitudes at locations D and E are between 15 and 30 cm/sec.

The influence of idealized wind stress on the Bay and estuarine system of the Biloxi Back Bay was tested in the following experiment. We forced the model with the wind velocity linearly increasing from zero to 10 m/sec over half of the day, then linearly decreasing over the second half of the day. To calculate the corresponding wind stress, we used the Large and Pond (1982) formulation for the drag coefficient. The wind was blowing from west to east. At the open boundaries, an energy radiation condition was used (Ippen 1966). To model the wind influence for the rivers and bayous, the angles between the physical orientations of the rivers and bayous and the corresponding computational grids were used. It was noted that the flow direction at the mouth of the Industrial Seaway (location G) is opposite to the flow direction at the mouth of Bernard Bayou (location H). This can be explained by the fact that the Industrial Seaway and the Bernard Bayou are connected. The influence of the 10 m/sec wind spike on the sea level in the deep channel of the bay is not as significant (less than 5 cm for locations A, D, E, F), but about twice as large at the entrance of the bayous (locations G and H).

CONCLUDING REMARKS

Preliminary results from computer simulations of a hydrodynamic model of the Back Bay of Biloxi have been presented. This model is a component of a Water Quality Model of the region being developed for the Mississippi Department of Environmental Quality. The model simulations show that the model is capable of reproducing the regional dynamics. Qualitatively, the neap and spring-tide amplitude pattern matches well with observations. However, the simulations also indicate potential difficulties in modeling in such a shallow region. The combined effect due to tides (~30 cm amplitude) and winds (~10 cm setdown) could be lowering the water level of the Bay by as much as 40 cm. Since the model does not have wetting and drying capability, this restricts the model bathymetry to be at least 40 cm.

Two intensive periods for observing the Bay have been planned. The data collected during the first period (11-19 September 1994 -- low flow period) will be used to calibrate the model parameters. Observations from the next observing period, planned for late April 1995 during a high flow regime, will be used to validate the model. The final model will be able to provide both the vertically averaged transports and the three-dimensional predictions.

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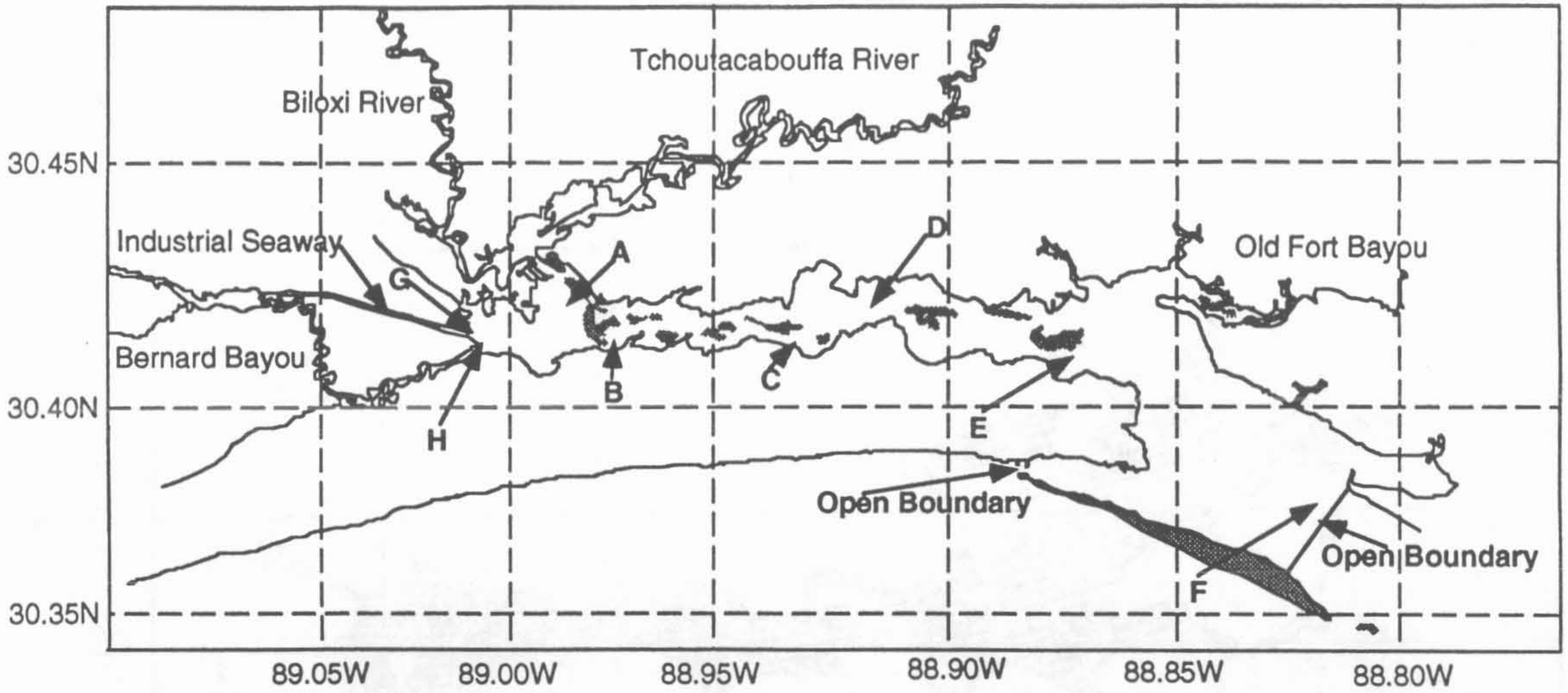

Fig. 1: The Back Bay of Biloxi and its tributaries. Letter locations are the model grid points where simulation results are presented in later figures.

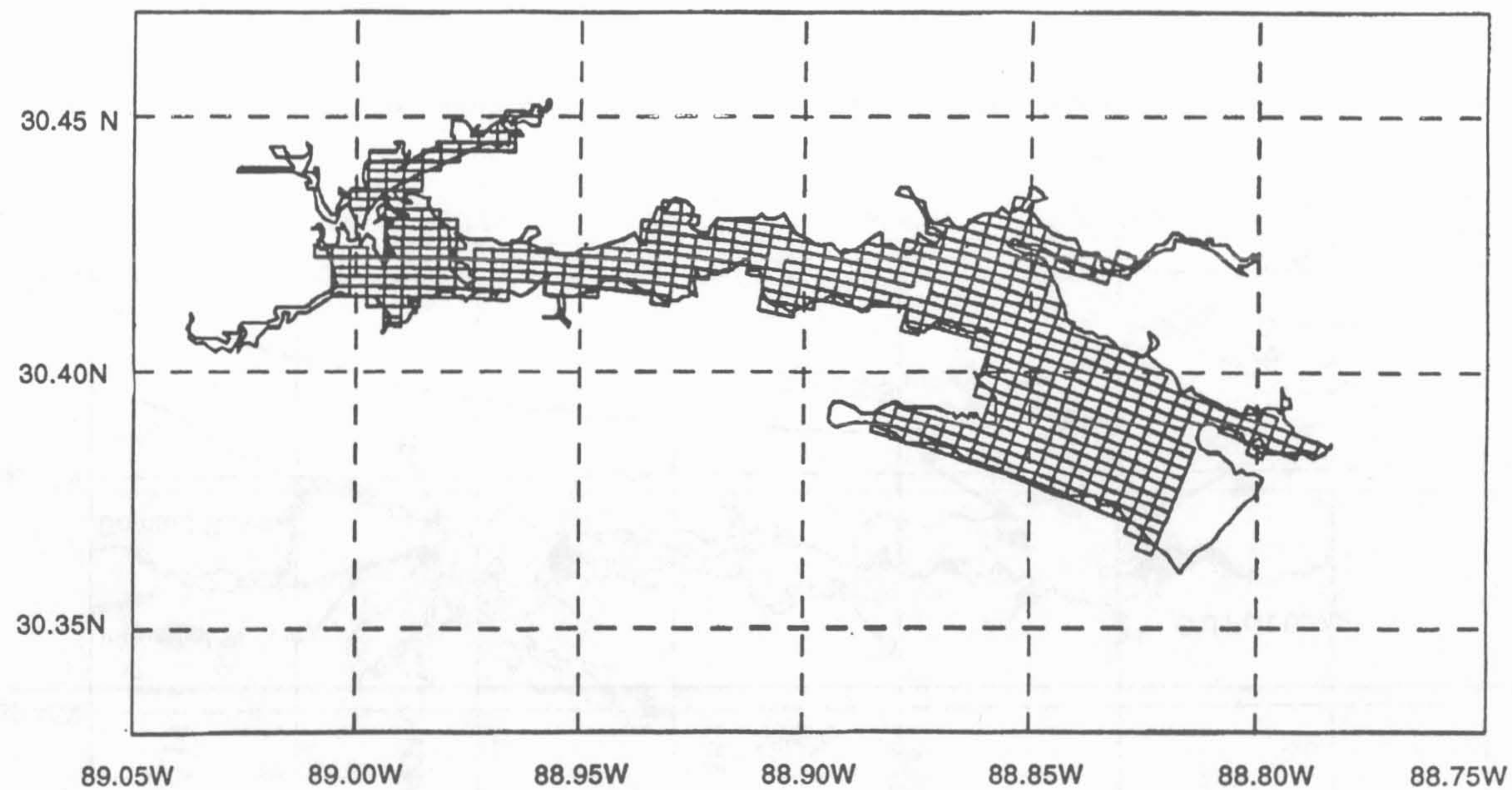

Fig. 2: Curvilinear orthogonal grid of the Back Bay of Biloxi.

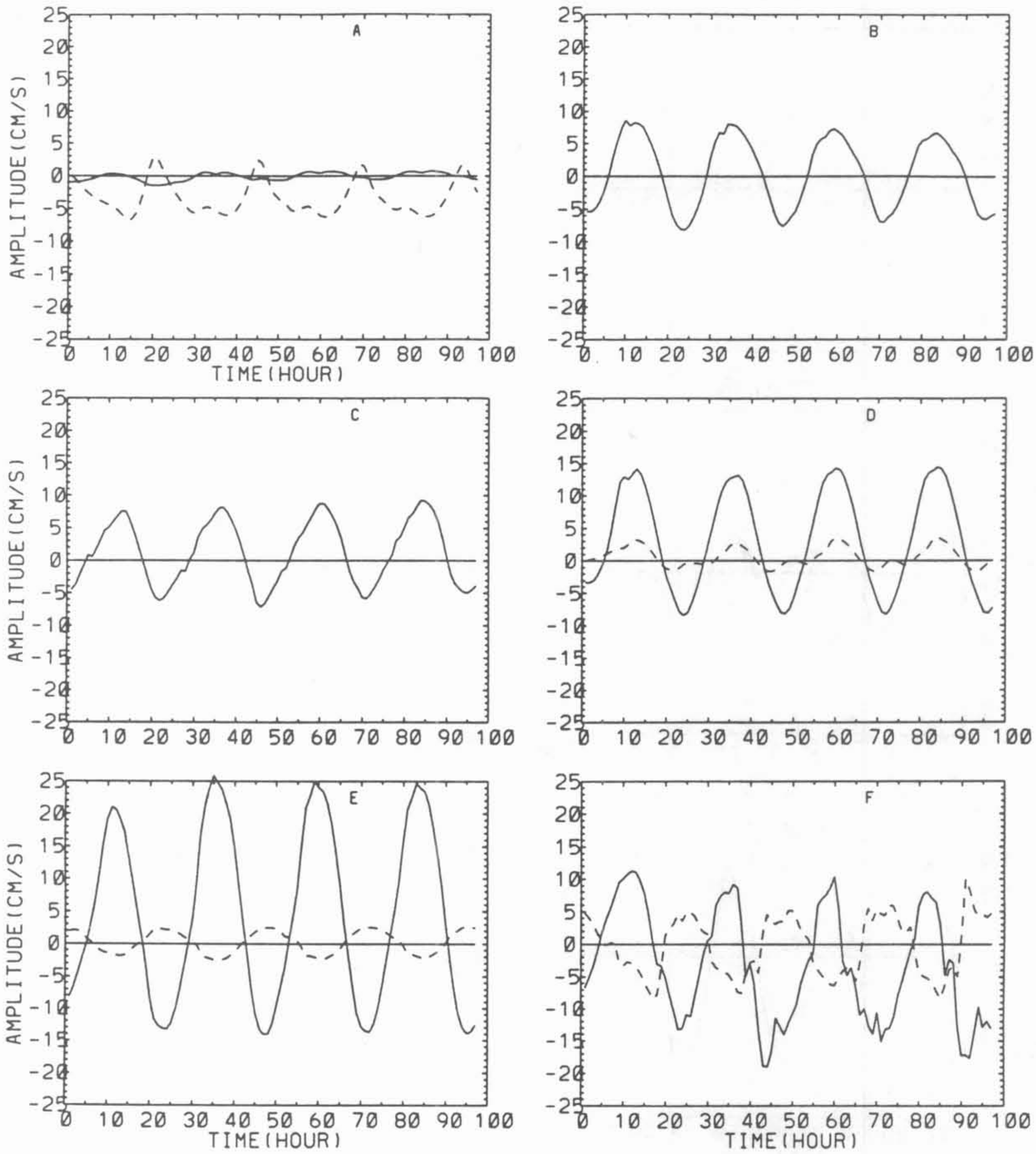

Fig. 3: The results of the three-dimensional simulations. Components of the velocity for the top layer and for the six locations shown in Fig. 1. The solid line is the X-component (along the Bay) of the velocity; dashed line is the Y-component (across the Bay) of the velocity.

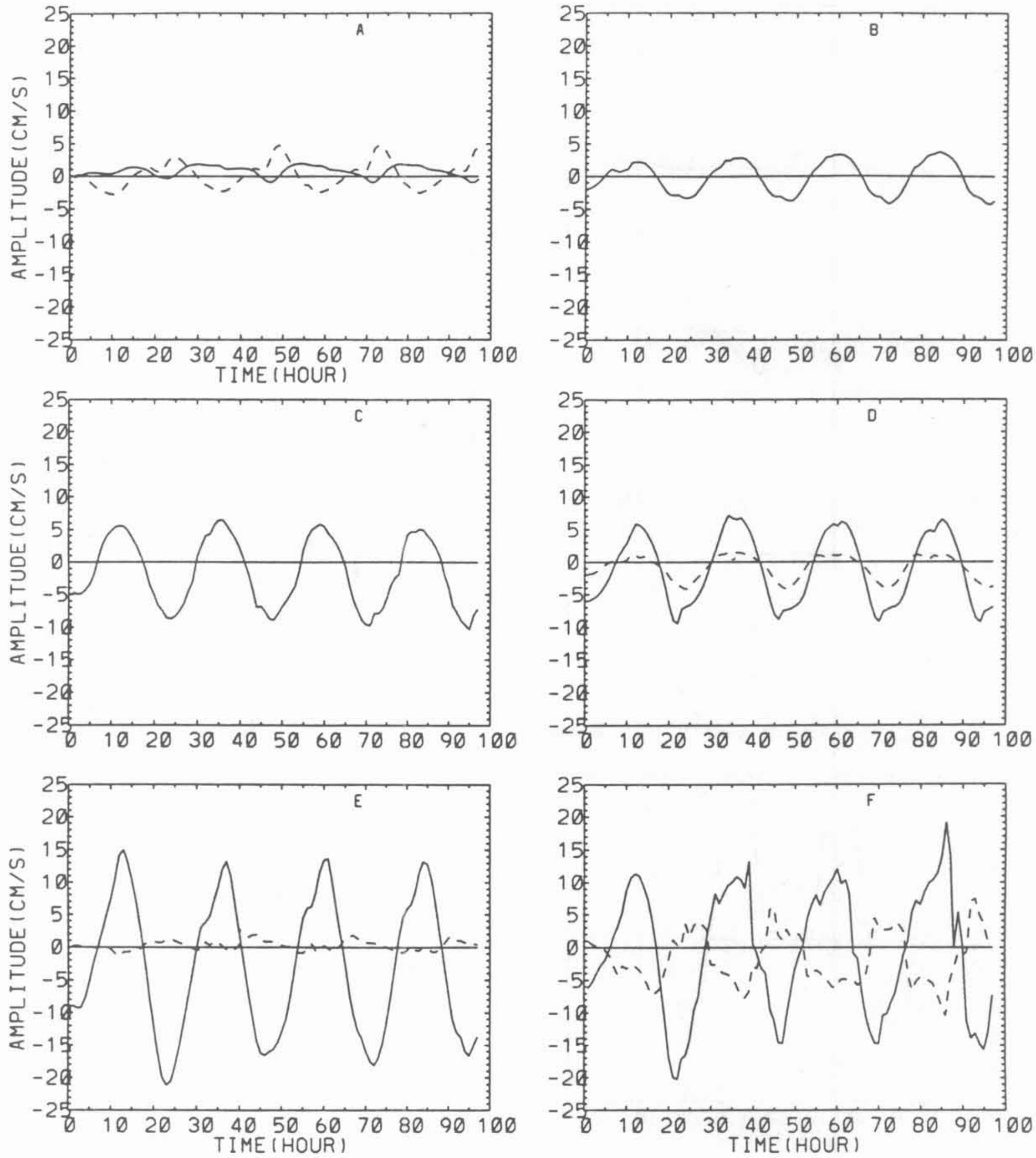

Fig. 4: The same as Fig. 3, but for the middle layer.

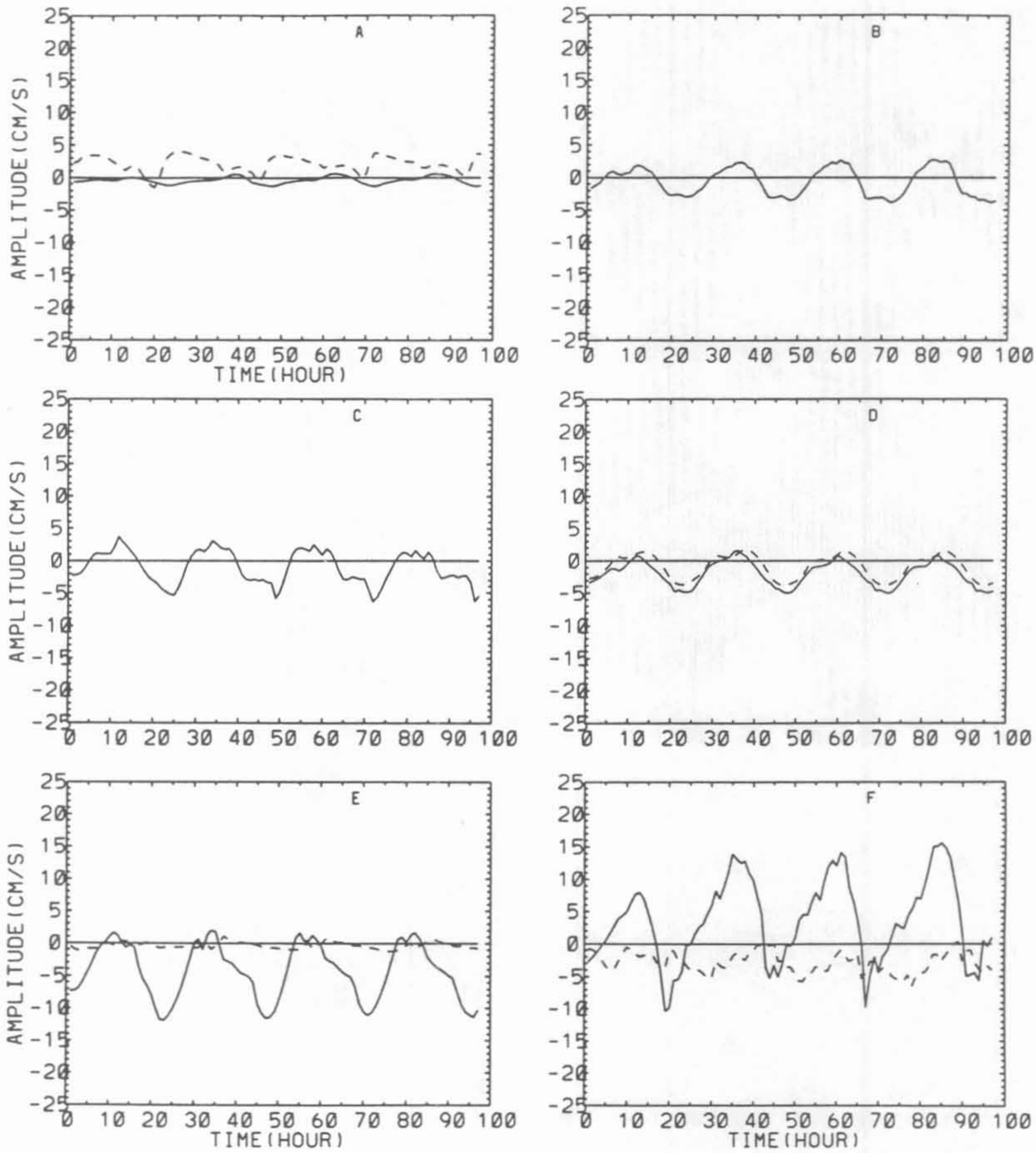

Fig. 5: The same as Fig. 3, but for the bottom layer.

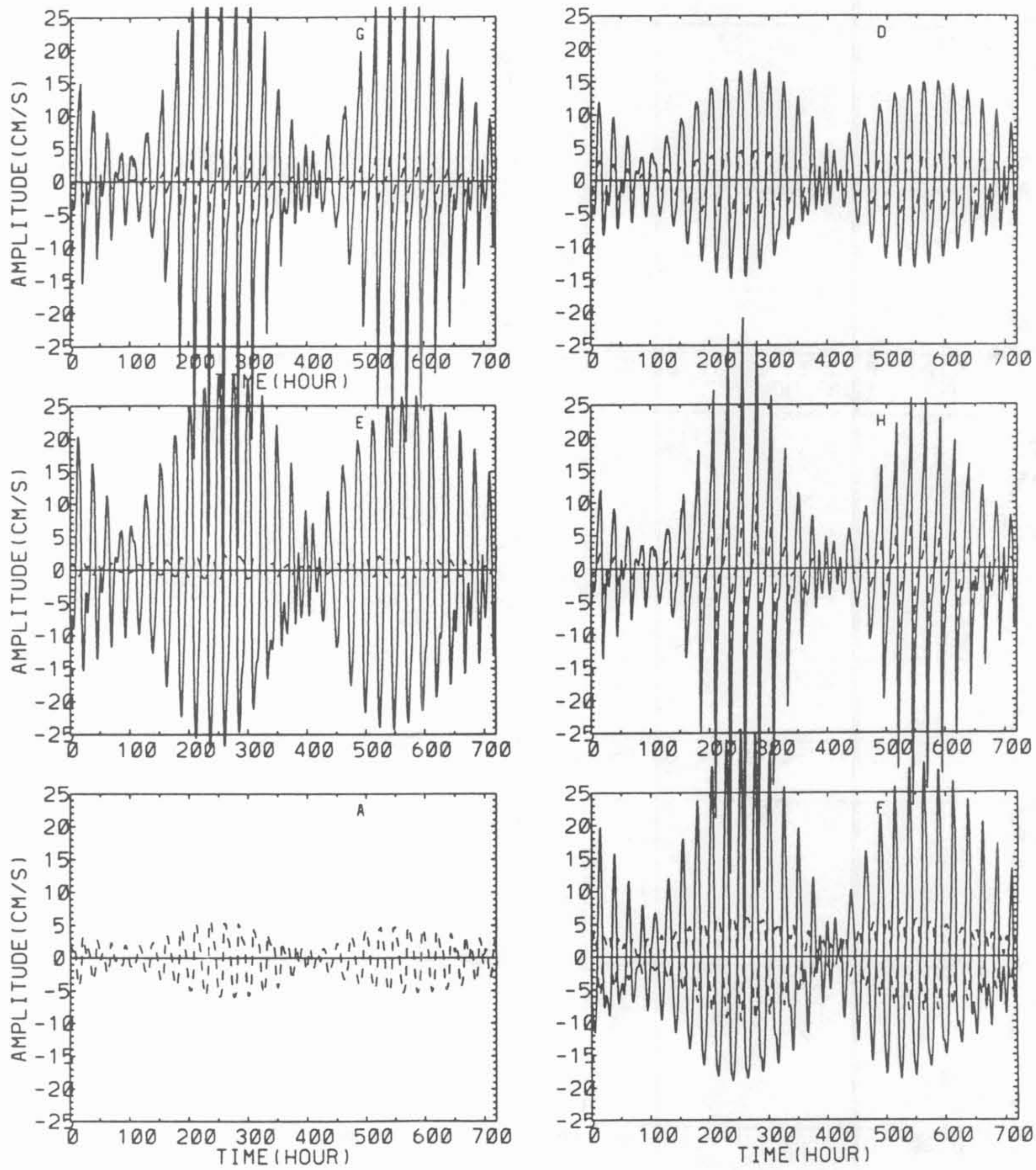

Fig. 6: Components of the vertically-averaged velocity. Solid line is the X-component (along the Bay) of the velocity; dashed line is the Y-component (across the Bay) of the velocity.