CHAPTER 236

WAVE-INDUCED SEDIMENT RESUSPENSION AND MIXING IN SHALLOW WATERS

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ABSTRACT

A field and modeling study on the resuspension and vertical mixing of sediments in Tampa Bay, a large shallow estuary, and Lake Okeechobee, a large shallow lake in Florida, U.S.A. has been studied. The study was aimed to obtain a quantitative understanding of the fundamental processes controlling resuspension and vertical mixing of sediments in the water column and to develop models for simulating resuspension and mixing of sediments in shallow waters. For the field study, field data (including wind, wave, currents, suspended sediments and water quality parameters) were collected from Tampa Bay and Lake Okeechobee during several episodic events. These data were then used for the development of a one-dimensional water column model of hydrodynamics, sediment dynamics and water quality dynamics. Results of the study indicate that during episodic events, bottom stresses induced by the wind waves are very effective in causing significant resuspension of sediments and nutrients from the bottom of shallow estuaries and lakes. Vertical turbulent mixing due to wind-driven and tidal currents, however, are more effective in distributing suspended sediments through the water column.

INTRODUCTION

A field and modeling study on the resuspension and vertical mixing of sediments has been conducted in a large shallow estuary (Tampa Bay in Figure 1) and a large shallow lake (Lake Okeechobee in Figure 2) in Florida. The primary objectives of the study are: (i)to quantify the fundamental processes controlling resuspension and vertical mixing of sediments in the water column, (ii)to compare the

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processes controlling resuspension and vertical mixing of sediments in the shallow estuary to those in the shallow lake, (iii)to develop models for simulating resuspension and mixing of sediments in shallow waters, and (iv)to quantify the effects of sediment resuspension and vertical mixing on contaminant transport in shallow waters.

To accomplish the objectives of the study, field experiments and numerical simulations were conducted. Because of scaling problems in laboratory simulation of field processes, only limited laboratory experiments were conducted.

FIELD EXPERIMENTS

Field studies were conducted in Tampa Bay (Sheng et al., 1993a) and Lake Okeechobee (Sheng et al., 1993b) during episodic events in 1992 and 1993. For example, a no-name storm passed the Tampa Bay area in February 1992. A front passed Lake Okeechobee in January 1993. A "Storm of the Century" passed Tampa Bay in March 1993. To obtain data during the storms, instrument platforms (Figure 3) were deployed in the water bodies prior to the storms. For example, platforms were deployed at Site A and Site B (Figure 1) in Tampa Bay during 1993, while platform was deployed at Site A in Tampa Bay during 1992. Platform was deployed in Lake Okeechobee at Site L002 during 1993.

On each platform, instruments were mounted to measure wind (anemometer), wave (underwater pressure gauge), current (2-3 Marsh McBirney EM current meters), water level (vented pressure gauge), salinity and temperature (2-3 SeaBird CTD sensors), and suspended sediment concentration (2-3 OBS sensors). In addition, various instruments were mounted to measure such water quality data including dissolved oxygen concentration, pH, and concentration of various nitrogen and phosphorus species. With the exception of instruments for measuring nutrient concentrations, most instruments can be connected to a data logger to collect continuous data with 2-Hz sampling frequency over several (e.g., 5-7) days using battery power. 15-minute averaged data are also recorded. However, since the storms usually last less than 1-2 days, it is extremely difficult for the instruments to "capture" the storms. The instrument platforms usually have to be deployed in the water body 1-2 weeks prior to the arrival of a forecasted storm, activated 1-2 days before the storm, and retrieved a few days after the storm. The collection of nutrient data is particularly difficult since it requires immediate filtering of water samples at the data site.

The field data were used to provide information on the dominant forcing mechanisms for sediment resuspension/erosion and vertical mixing. In particular, statistical analysis was performed to determine the dominant frequencies and correlations of various physical parameters. In addition to the data analyses, numerical models were used to assist the interpretation of field data and to quantify the various processes.

NUMERICAL MODELING

Three-dimensional numerical models of sediment transport have been developed by Sheng (1986) and Sheng et al. (1991). In this study, since the focus is on the fundamental processes in the vertical water and sediment columns, a vertical one-dimensional numerical model was used. Basically, the vertical 1-D model developed by Sheng and Villaret (1989) and Sheng et al. (1989) was significantly modified to simulate the current, turbulence, and sediment dynamics in the water column. Basically, the one-dimensional model includes a hydrodynamic component and a sediment component. The hydrodynamic component of the 1-D model computes the horizontal velocities forced by wind, wave, and pressure gradients (associated with tidal circulation and baroclinic circulation). In order to simulate the vertical turbulent mixing throughout the water column, we developed a procedure which determines the horizontal pressure gradients (associated with tidal, wind-driven and density-driven circulations) in the water column by assimilating the measured 15-minute averaged currents into 1-D model simulation which uses a relatively large time step (e.g., 15 minutes). These slowly varying pressure gradients are then combined with the fast-varying wave-induced pressure gradients to drive the water column in the 1-D model simulation which uses a very small time step (about 1/100 of the wind wave period). These model simulations produce accurate vertical turbulent mixing and bottom shear stress under combined current-wave motion without resorting to ad-hoc wave-averaging procedure.

The sediment component of the 1-D model includes the following processes: vertical turbulent mixing, gravitational settling, resuspension/erosion, deposition and a fluid mud layer at the bottom. One important feature of the present 1-D model is that simultaneous deposition and resuspension/erosion are allowed, while the critical stress for deposition is generally several times larger than the critical stress for erosion. The resuspension/erosion rate of sediments is modeled as a linear function of the excess bottom shear stress (Sheng et al., 1989), while the deposition rate is computed by combining the deposition velocity formula of Sheng (1986) with the deposition probability of Krone (1993).

The 1-D models were used to simulate the measured suspended sediment data and to determine the resuspension/erosion rate during the storm events. The 1-D models were also used to test various hypotheses concerning dominant processes for sediment resuspension/erosion and mixing. A sensitivity study was also conducted to examine the effects of various model parameters on model results. Resuspension/erosion rates determined by the 1-D models were used in a three-dimensional model of sediment transport to simulate the long-term sediment transport in the estuary and the lake.

RESULTS

Using the field data measured at 2 Hz sampling frequency, analysis was performed to determine the dominant forcing for sediment resuspension. For both the estuary and the lake, wind wave was found to be the dominant mechanism for sediment resuspension. In both the tidal estuary and the lake, currents played little role in causing sediment resuspension, but are primarily responsible for the vertical mixing of sediments.

For example, Figure 4 shows the wind speed and direction in Tampa Bay during a storm event (Julian day 30 to 40) in 1992. Figure 5 shows the measured horizontal North-South velocities and suspended sediment concentration at two vertical levels at Station A in Tampa Bay during Julian day 35.6 to 36.6, 1992. Because of the strong wind from the south on Julian day 36, significant wave-induced bottom stress caused resuspension of sediments. As shown in Figure 5, suspended sediment concentration increased from 10 mg/l to more than 40 mg/l in less than 2 hours. The simulated horizontal velocities and suspended sediment concentration at Station A as shown in Figure 6 compare very well with the measured data.

The sediments in the vicinity of Station A in Tampa Bay are composed primarily of silt with a small amount of clay. The resuspension of sediments led to release of ammonium adsorbed on the sediments into the water column. The one-dimensional model was used to simulate the currents, suspended sediment concentration, and ammonium concentration in the water column during the episodic event. Model results also suggest that fully turbulent boundary layer only exists during part of a tidal cycle. Thus, the presence of viscous sublayer should be incorporated into the model for accurate estimation of bottom stress and vertical mixing.

Three-dimensional flow fields in Tampa Bay have been simulated using a three-dimensional curvilinear-grid hydrodynamics model CH3D (Sheng 1989), which is capable of resolving the complex shoreline and navigation channel in Tampa Bay. As shown in Figure 7, the vertically-averaged currents in Tampa Bay during a typical flood tide are generally less than 50 cm/sec. During storm conditions, however, currents could be stronger and contribute to resuspension of sediments.

The resuspension event in Lake Okeechobee showed different behavior since the bottom sediments are consisted primarily of cohesive mud particles and flocs. Wind wave is also the driving force for resuspension of sediments. However, suspended sediment concentration can reach 100-2000 mg/l, depending on the location in water column. Near the bottom, there exists a very thin "lutocline" where sharp suspended sediment concentration gradient is found. The thickness of the lutocline varies significantly with time, as a result of variations in hydrodynamic forcing. As an example, results of a three-day simulation and field data at the Center-Lake Station C are shown in Figure 8. Erosion/resuspension and deposition of fine sediments were described by relationships similar to those used in the Tampa Bay model. Flocculation apparently had a more significant effect on the gravitational settling of sediments in Lake Okeechobee than in Tampa Bay. Resuspension of sediments led to the subsequent release of phosphorus into the water column (Sheng 1993).

DISCUSSIONS

The study demonstrated the significance of wind wave in causing resuspension of sediments and contaminants in shallow estuaries and lakes. The effect of wave groups on sediment resuspension was found to be insignificant. Wind-driven currents and tidal currents are generally insufficient to cause sediment resuspension, but are more effective in causing vertical mixing of suspended sediments. The process-based one-dimensional models were able to successfully simulate the mean flow, turbulent mixing, and suspended sediment dynamics in Tampa Bay and Lake Okeechobee. Model simulations showed that flocculation and lutocline dynamics are important processes in Lake Okeechobee but not in Tampa Bay.

ACKNOWLEDGEMENT

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REFERENCES

Krone, R.B, 1993: "Sediment Revisited," In (A.J. Mehta, Ed.), *Coastal and Estuarine Studies 42: Nearshore and Estuarine Cohesive Sediment Transport.* American Geophysical Union, Washington, DC, pp. 108-125.

Sheng, Y.P., 1986: "Modeling Bottom Boundary Layers and Cohesive Sediment Dynamics," in *Estuarine Cohesive Sediment Dynamics*, Springer-Verlag, pp. 360-400, 1986.

Sheng, Y.P., 1989: "Evolution of a Three-Dimensional Curvilinear-Grid Hydrodynamic Model for Estuaries, Lakes and Coastal Waters: CH3D," *Estuarine and Coastal Modeling* (M.L. Spaulding, Ed.), ASCE, pp. 40-49.

Sheng, Y.P., 1993: "Hydrodynamics, Sediment Transport and Their Effects on Phosphorus Dynamics in Lake Okeechobee," in *Nearshore, Estuarine and Coastal Sediment Transport* (A.J. Mehta, Ed.). Coastal and Estuarine Studies, **42**, American

Geophysical Union, pp. 558-571.

Sheng, Y.P. and C. Villaret, 1989: ''Modeling the Effect of Suspended Sediment Stratification on Bottom Exchange Processes,'' *Journal of Geophysical Research*, **94:C10**, pp. 14429-14444, 1989.

Sheng, Y.P., V. Cook, S. Peene, D. Eliason, S. Schofield, K.M. Ahn, and P.F. Wang, 1989: ''A Field and Modeling Study of Fine Sediment Transport in Shallow Waters,'' in *Estuarine and Coastal Modeling* (M.L. Spaulding, Ed.), ASCE, pp. 113-112.

Sheng, Y.P., D.E. Eliason, X.-J. Chen, and J.-K. Choi, 1991: ''A Three-Dimensional Numerical Model of Hydrodynamics and Sediment Transport in Lakes and Estuaries: Theory, Model Development, and Documentation,'' *Final Report for Environmental Research Laboratory*, U.S.E.P.A., Athens, GA.

Sheng, Y.P., X.-J. Chen, E. Yassuda, K.R. Reddy, and M.M. Fisher, 1993a: ''Quantifying Sediment Resuspension Flux of Nutrients and Contaminants in Estuaries due to Episodic Events,'' *Final Report to Florida Sea Grant,* Coastal & Oceanographic Engineering Department, University of Florida, Gainesville, Florida 32611.

Sheng, Y.P., X.-J. Chen, S. Schofield, and E. Yassuda, 1993b: ''Hydrodynamics and Sediment and Phosphorus Dynamics in Lake Okecchobee During an Episodic Event.'' *Final Report to South Florida Water Management District,* Coastal & Oceanographic Engineering Department, University of Florida, Gainesville, Florida 32611.

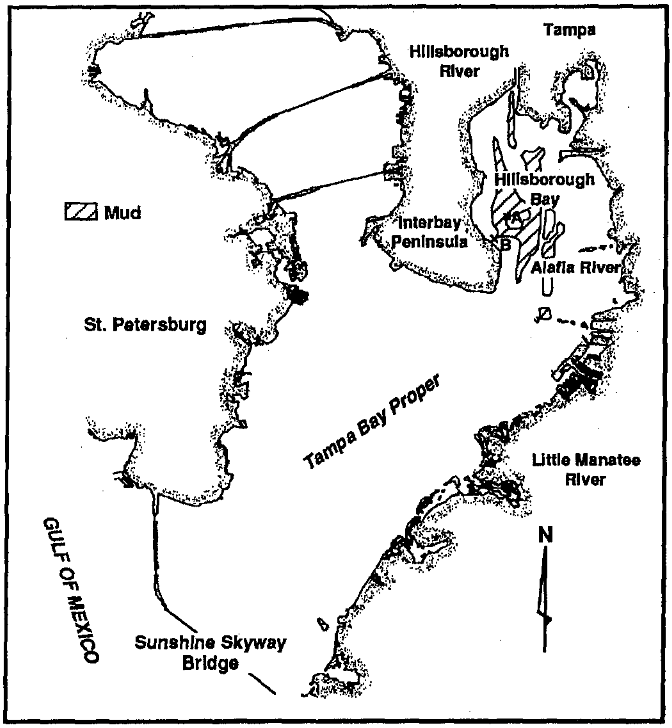

Figure 1. Map of Tampa Bay, Florida Showing Field Stations A and B (from Sheng et al. 1993a).

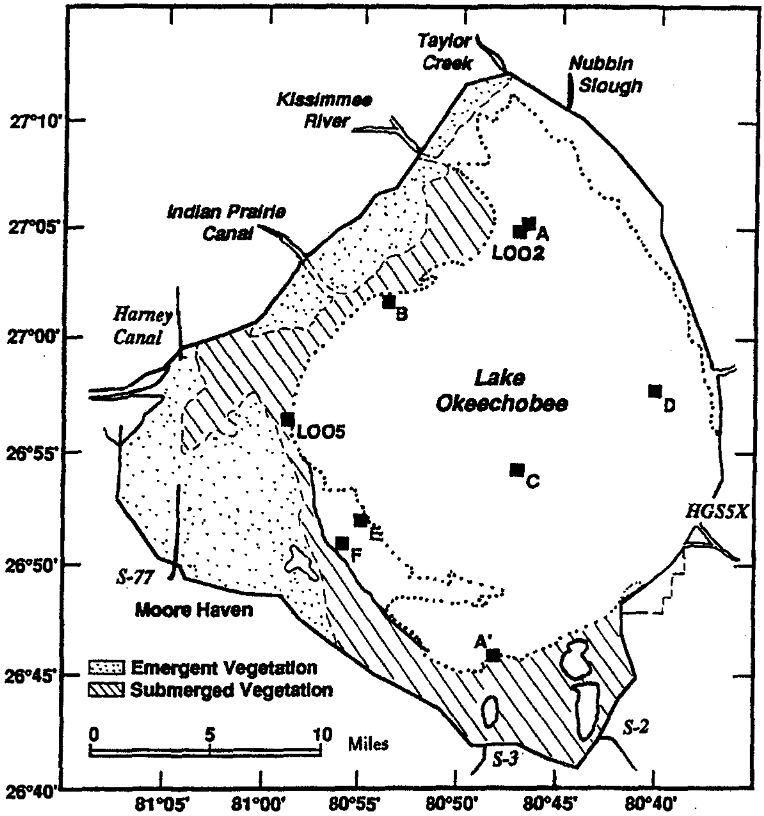

Figure 2. Map of Lake Okeechobee, Florida Showing Locations of Field Stations (from Sheng et al. 1993b).

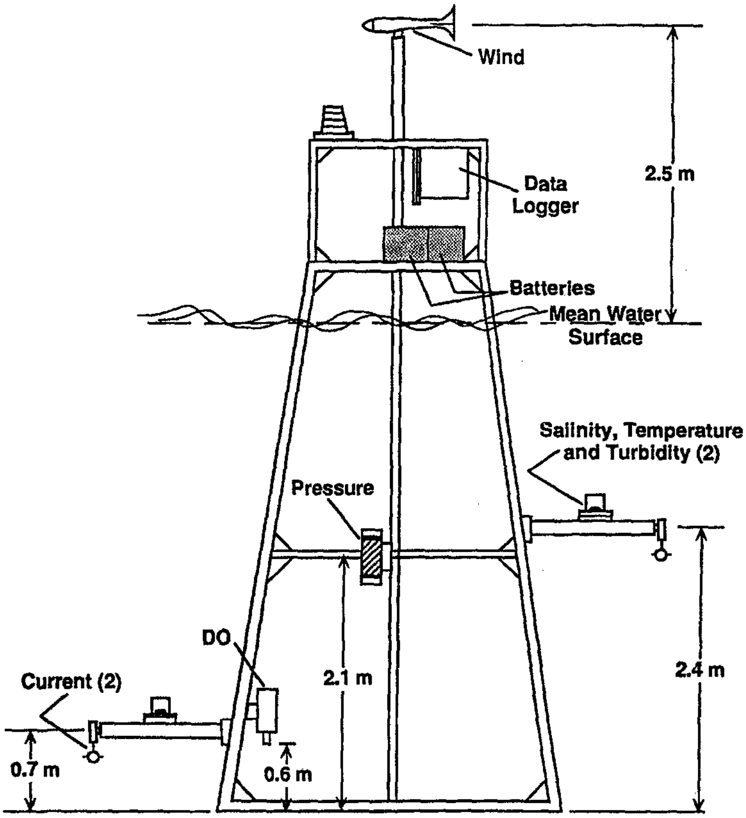

Figure 3. Instrument Platform and Some Hydrodynamic Instruments Used for the Tampa Bay and Lake Okeechobee Studies. Water Quality Instruments Are Not Shown.

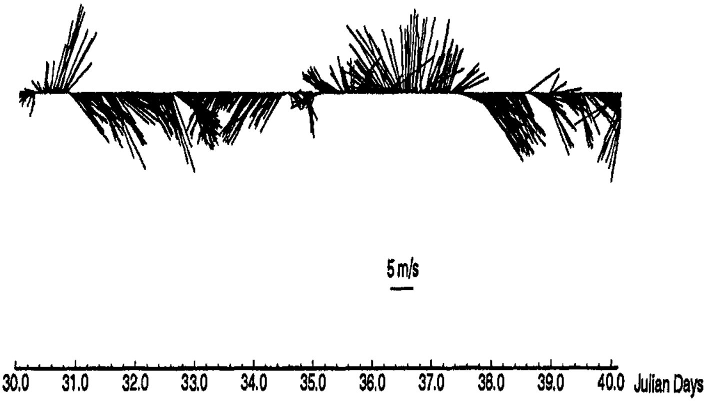

Figure 4. Stick Diagram of Wind Speed and Direction in Tamapa Bay During Julian Day 30 to 40, 1992.

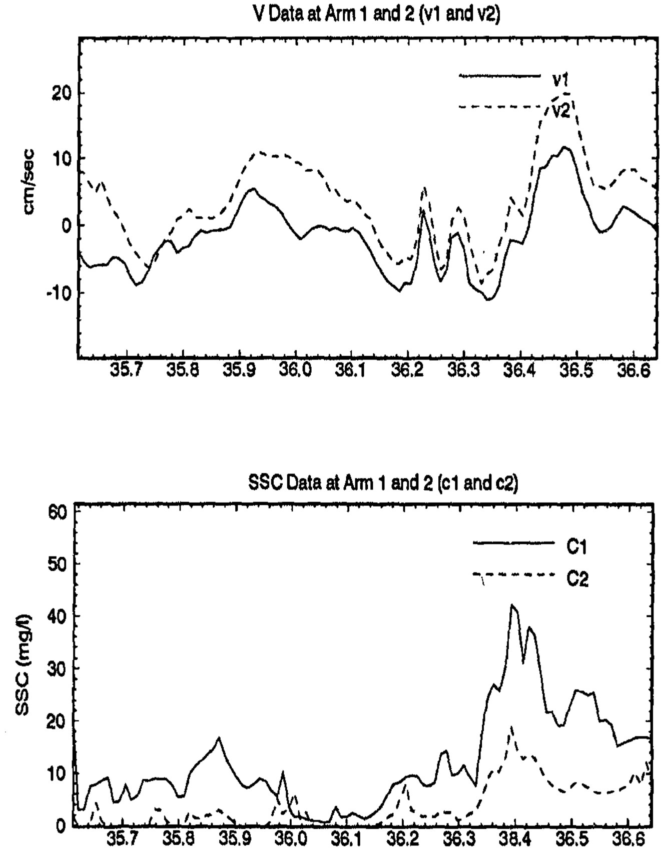

Figure 5. Measured North-South Velocity and Suspended Sediment Concentration at the Near-Surface (C1) and Near-Bottom (C2) Arms at Station A in Tampa Bay During A 1992 Storm between Julian Day 35.6 and 36.6.

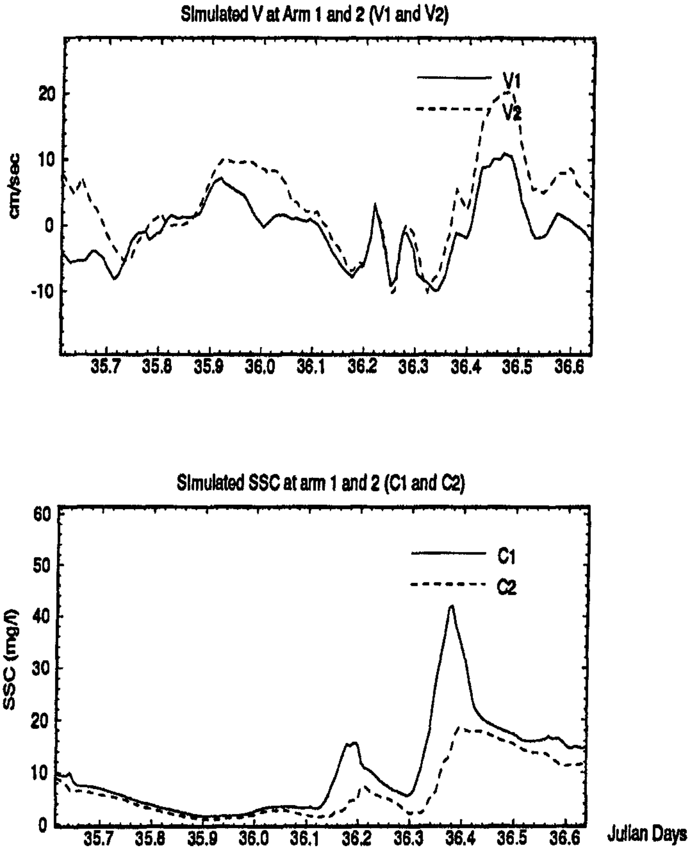

Figure 6. Simulated North-South Velocity and Suspended Sediment Concentration at the Near-Surface (C1) and Near-Bottom (C2) Arms at Station A in Tampa Bay During a 1992 Storm between Julian Day 35.6 and 36.6.

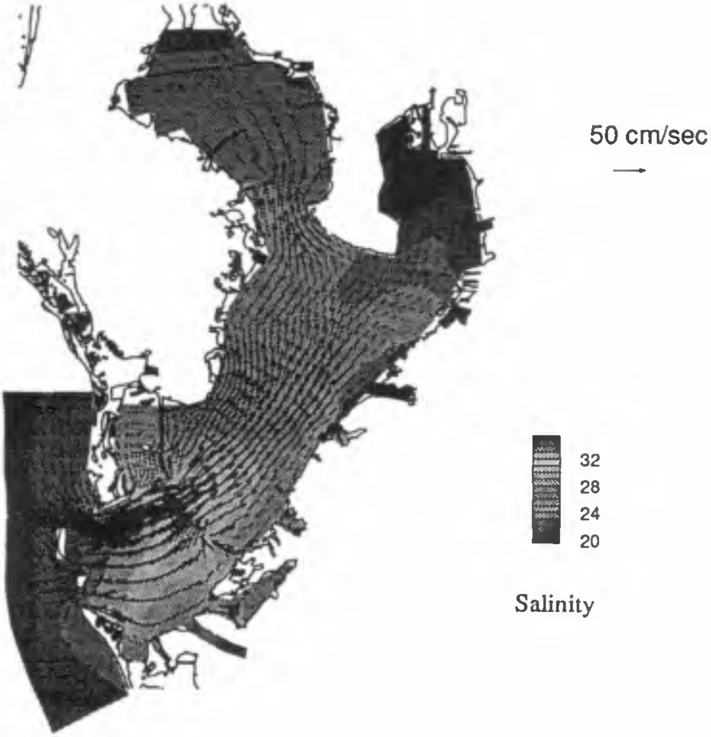

Figure 7. Simulated Tide- and Density-Driven Vertically-Averaged Currents and Near-Surface Salinity During a Typical Flood Tide in Tampa Bay. Results Obtained With a 3-D Curvilinear-Grid Hydrodynamics Model CH3D.

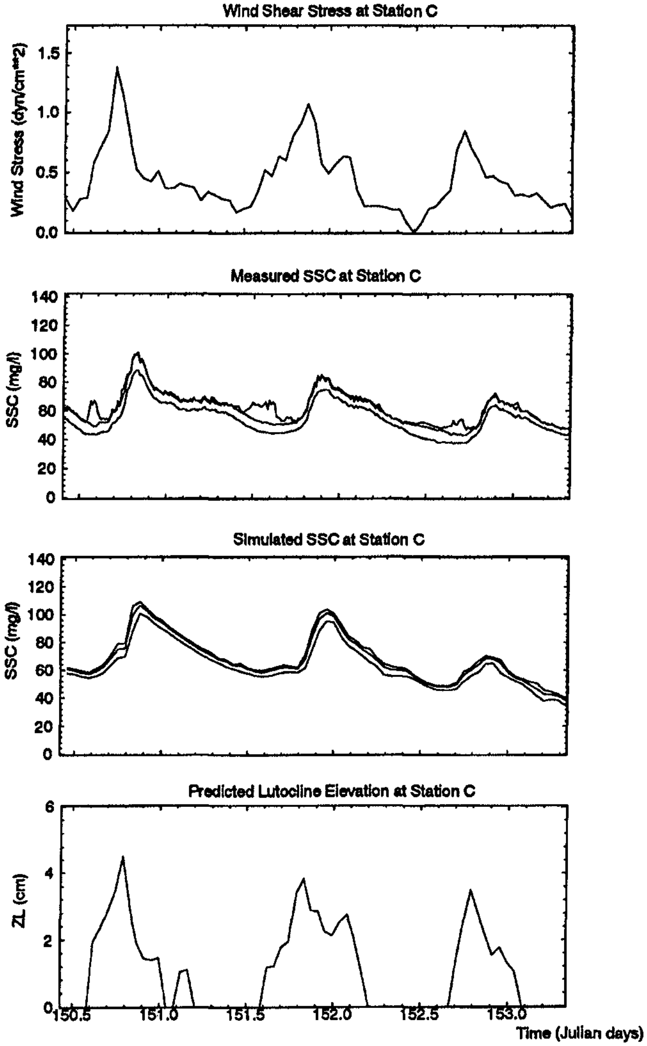

Figure 8. Wind Stress, Measured Suspended Sediment Concentration at 3 Depths, Simulated Suspended Concentrationat 3 Depths, and Simulated Lutocline Thickness at Station C in Lake Okeechobee During a 3-Day Event in Spring 1989.