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FIELD EXPERIMENT AND HYDRODYNAMIC MODELING OF AN STRATIFIED ESTUARY IN FLORIDA, USA

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Abstract: A field experiment study was conducted to investigate the density-induced currents in Apalachicola estuary, USA. Observed time series of surface and bottom salinity and were used to characterize the stratified flow at the measurement location. By removing the tidal signal using low-passing filtering, sub-tidal currents were obtained to investigate the density-induced currents responding to the changes of fresh water input. Regression analysis of data indicated good linear relationship between subtidal salinity stratification and the bottom currents. In order to have better understand of the vertical structure of the density and currents, a three-dimensional hydrodynamic model was used to investigate the temporal and spatial distributions of the circulation and salinity response to the changes of river flow. Comparison between model predictions and observations show that the model provides satisfactorily predictions of spatial and temporal changes of salinity and currents in the strongly stratified estuary.

Key words: Estuary, Stratified flow, Salinity, Hydrodynamic modeling

1. INTRODUCTION

When fresh water discharges into the saline estuarine receiving waters in tidal rivers, stratified two-layer flow occurs due to effects of density gradients (Thomann and Mueller 1987; Lung 1993; Martin and McCutcheon, 1998). The principle feature of the stratified flow is that it consists of a net seaward transport in a surface layer and a net landward transport in a bottom layer of the estuary (Fig. 1). The surface flow is fresh and the bottom flow is more saline and thus more dense. The mixing mechanics of fresh and salt in the stratified river is usually affected by the surface gravity gradient, turbulent diffusivity, and both horizontal and vertical density gradients. The surface gravity gradient is dependent on the upstream freshwater input and downstream tidal elevations as well as the density gradients. Due to the effects of density gradients, tidally-averaged estuarine currents in the upper layer are typically in seaward direction, while in the lower layer currents are in up-estuary direction. In real estuaries, currents and density stratification may vary if river flow and tides are time dependent. Generally, simple analytical solutions are not available to describe the complex structures in transient stratified flow in a real estuary. Field observations of salinity and currents are often needed to characterize the estuarine stratified flow and salinity. Since the duration of a field data collection usually ranges from a few weeks to several months, advanced measurement instruments with pre-programmable and automatic data recording capability are often required in field data collections.

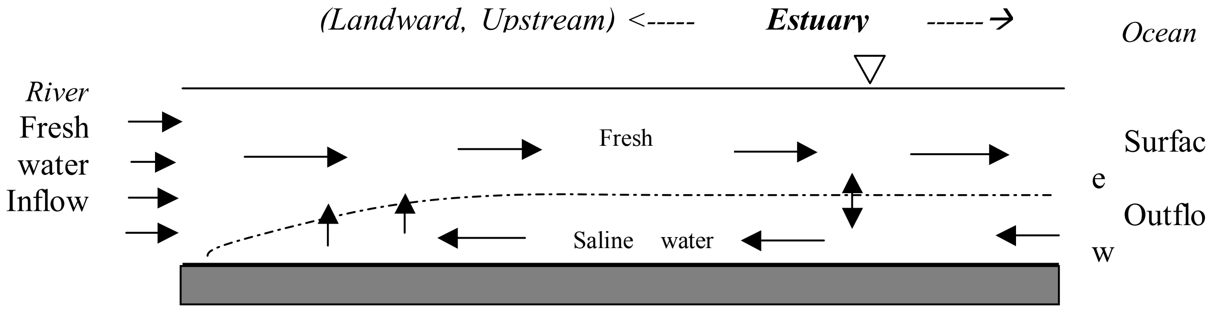

Fig. 1 Schematic of stratified flow in estuary

The vertical stratification in estuarine circulation has significant environmental effects on dissolved oxygen and nutrient recycling. The landward bottom currents may also have an effect on navigation channel by recycling the estuarine suspended sediment upstream to the river navigation channel. Accurate modeling and predictions of salinity and current stratification are also important for estuarine ecological study. For an example, Livingston et al (2000)'s study indicates that salinity is an important factor predator-induced oyster mortality. Incorporating salinity predicted from a hydrodynamic model (Huang and Jones, 2001), Livingston et al. (2000) derived a oyster mortality model for estuarine ecological assessment.

In the following sections, a field experiment and hydrodynamic modeling for a stratified estuary is presented. The experiment set-up and the instrument were described. Field measurement data were analyzed to characterize the vertical structures of salinity stratification and currents. Results from hydrodynamic model predictions were used to describe the spatial distributions of the stratified flow.

2. STUDY SITE

The study site was located in the lower Apalachicola River estuary in the Florida panhandle (Fig. 2). Saline water enters the river from the Gulf of Mexico through Apalachicola Bay. The Apalachicola River system is the largest in Florida in terms of flow and is the third largest river system in the Gulf of Mexico behind the Mississippi and Mobile Bay systems. Historically, higher river flows occur in the late winter and early spring, and lower flows occur in the late summer and early fall. Stratified flow occurs in the lower Apalachicola River due to the density gradient effects and the mixing between fresh and salt water. As part of the large data collection program for Apalachicola Bay, field data collection at Apalachicola River station was conducted by personnel at the Northwest Florida Water Management District (Jones, et al., 1994). Electromagnetic measuring instruments were installed at a field station to measure the time series of surface and bottom salinity and velocity. River flow was obtained from USGS and tidal data was from National Ocean Survey.

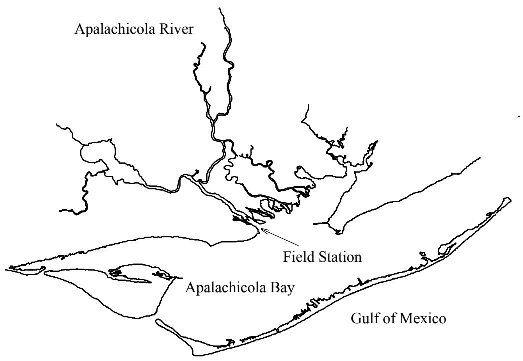

Fig. 2 Apalachicola River, Florida, USA

3. EXPERIMENT STATION SET-UP

Advanced measurement instruments with pre-programmable and automatic data recording capability were required in field data collections. The S4 Current Meter is a self-contained field-deployable electromagnetic instrument (InterOcean Systems, 2001). It is capable of performing remotely controlled real-time data logging and/or pre-programmed automatic data sampling for long deployments (e.g. several weeks to a month). Two S4 current meters were installed in a fixed field location in Apalachicola River as shown in Fig. 3a. Water depth at the measurement station was 12.4 feet at low tide and the typical tidal range was about 4.5 feet. A concrete base block was placed on the riverbed to support a metal bar for mounting the current meter for the measurements of bottom currents and salinity. A cantilever attached to a vertical pile was used to support another S4 meter near the surface to measure surface currents and salinity. The distance was 2.1 feet between the bottom meter and the riverbed, and 1.8 feet between the surface meter and the low tide surface. The S4 current meters (Fig. 3b) were calibrated in house before it was deployed to the field experiment station. The instruments were preprogrammed to automatically log data at 30-minute intervals. An internal battery provided power that allowed continuous data measurement for the period between July 2 and August 2 of 1993 without interruption.

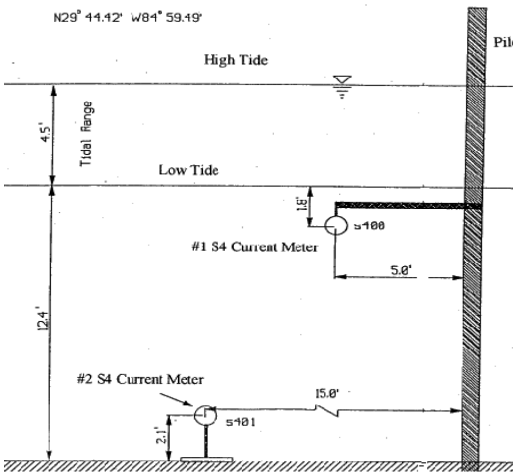

Fig. 3a Field experiment station set up

Fig. 3b Standard S4 current meter

4. CHARACTERISTICS OF ESTUARINE STRATIFIED FLOW

At the end of the data collection lasted from July 2 to August 2 of 1993, time series data were downloaded into electronic files. Due to the adequate setup and operations of the current meters, the quality of the data set was satisfactory. The pre-programmed instruments performed automatic data logging at pre-set time intervals. No data gaps were observed for the data collection period. River flow data was obtained from USGS and tidal data from NOS. This complete hydrographic data set can be used to examine the effects of freshwater input and tides on the stratification and currents (Fig. 4).

During the study period, river flow (Fig. 4-a) increased from approximately 300 m^3/s to 400 m^3/s in the first five days, remained an almost constant 400 m^3/s for 10 days, and then fell to 300 m^3/s. Tidal fluctuation (Fig. 4-b) ranged from 0.3 m to 0.9 m, and was dominated by diurnal and semi-diurnal tidal constituents. Salinity (Fig. 4-c,d) was generally in phase with tidal variations. Salinity increased at flood tide when saltier water moved upstream, and decreased at eddy tide when water moved seaward. In addition to the diurnal and semidiurnal salinity variation, the low frequency trend showed that salinity decreased as river flow increased. Bottom salinity was considerably larger than the surface salinity, which showed strong stratification in the water column. The vertical salinity difference (or stratification) varied in response to the changes of tide and river forces. In general, stratification increased at flood tide when saltier water intruded upstream from the lower water column. Salinity stratification at high tide was generally stronger than that at low tide. Currents (Fig. 4-e,f) were in phase with surface elevation, which is consistent with the progressive wave theory (Officer, 1976) in this long tidal river. Bottom currents were weaker than the surface currents due to the effects of bottom friction. In addition, during the period of low river flow (day 20-30), the tidally averaged bottom currents were negative, which indicates that they were towards upstream and opposite to the surface current direction. This showed the typical estuarine stratified flow due to the effects of density gradients and stratification.

Time series data were filtered using72-hr low-pass filter to remove tidal effects. Then, the relationship between subtidal bottom current and vertical salinity difference was analyzed. The regression equation (Eq. 1) indicates that the density-induced bottom current 'u_b' were linearly proportional to the vertical salinity stratification 'ΔS'. The stronger is the vertical salinity stratification, the stronger the density-induced bottom currents. Fig. 5 shows the observed vertical distributions of currents and salinity at different river flow conditions.

$$u_b = -1.3585\Delta S + 6.0281 \quad (1)$$

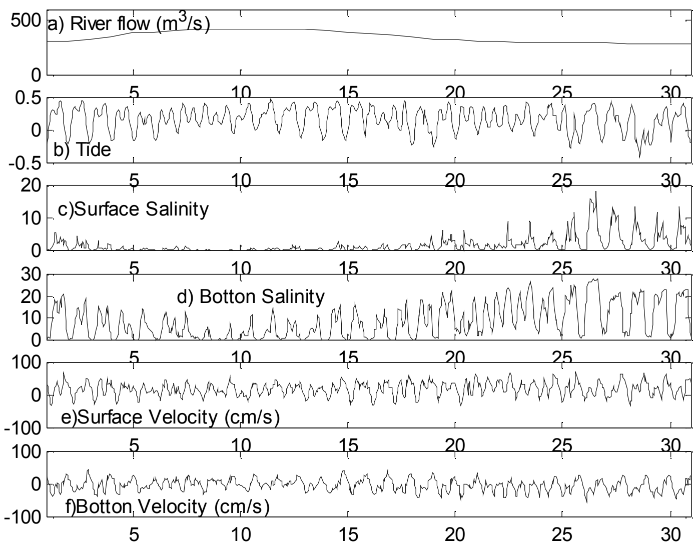

Fig. 4 Time series data from field observations

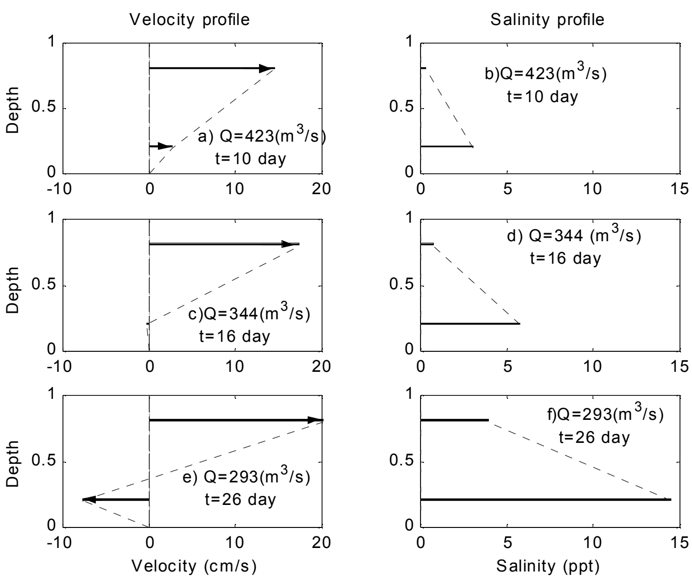

Fig. 5 Vertical distributions of subtidal velocity and salinity

5. 3D DRODYNAMIC MOFDELING

A three-dimensional hydrodynamic model (POM, Blumberg and Mellor, 1987) was improved and applied to Apalachicola Estuary. It is a semi-implicit, finite-difference model that can be used to determine the temporal and spatial changes of surface elevation, salinity, temperature, and velocity in response to wind, tide, buoyancy, and Coriolis forces. The model solves a coupled system of differential, prognostic equations describing conservation of mass, momentum, heat and salinity at each horizontal and vertical location determined by the computational grid. The model was improved by using an algorithm (Huang and Spaulding, 1996, 2002a) to reduce numerical diffusion error for steep slope cells. The model incorporates a second-order turbulence closure sub-model that provides eddy viscosity and diffusivity for the vertical mixing (Mellor and Yamada, 1982). The calibrations of model coefficients are satisfied in most stations in the bay (Huang and Jones, 2001) except for the stations in the lower Apalachicola River. In the early stage of model validation, it was shown that using the original default turbulence model parameters, model predictions overestimated velocity stratification and bottom upstream-ward current. Consequently, salinity intrusion from the higher salinity bottom water layers was over predicted. Sensitivity study of the eddy viscosity is given in the following sections. Through model sensitivity study, a factor of 1.12 was used to correct the turbulent eddy viscosity (Huang, 2001). Model predictions of surface and bottom salinity and currents matched well with time series observations (Fig. 6). The validated hydrodynamic model was used to investigate the spatial distributions of the stratified currents and salinity in the estuary. Fig. 7 shows the horizontal distributions of salinity and currents, which shows strong salinity gradient (or density gradient) near the river mouth. Fig. 8 indicates that the water column was strongly stratified in the river mouth, and well mixed in the bay areas near the tidal inlets.

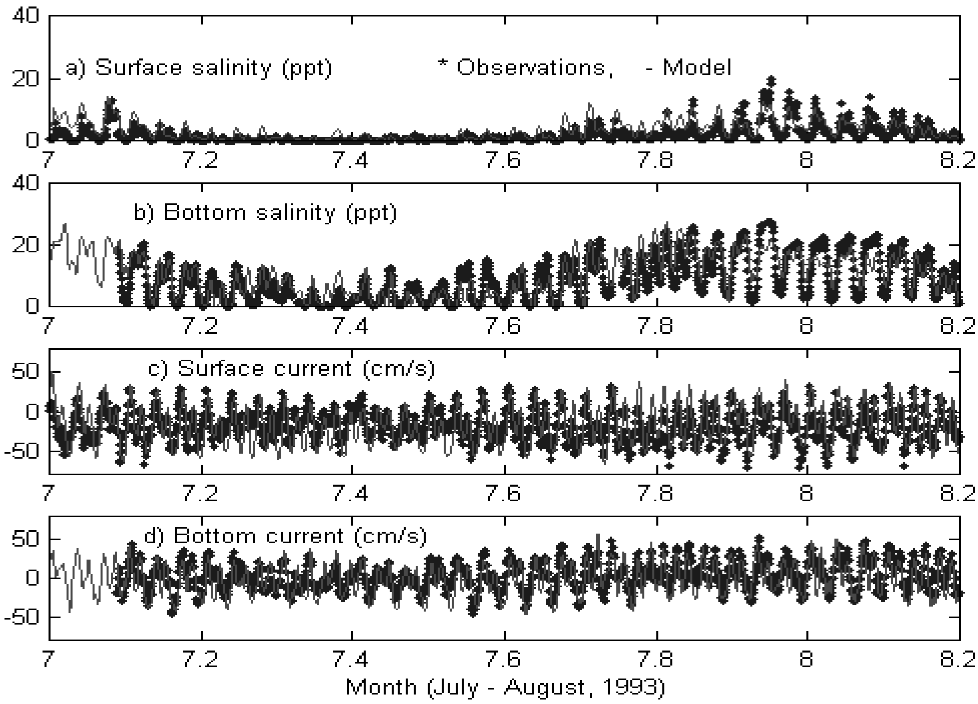

Fig. 6 Comparison of model predictions of salinity and currents to observations

6. SUMMARY

A field experiment study was conducted in an stratified estuary using S4 current meter that features automatic data recording. Using the field observation data, the characteristics of salinity stratification and currents were analyzed. Data showed that the stratification of currents and salinity in the Apalachicola River were affected by tides and river flow. During a tidal cycle, maximum salinity stratification was observed at high tide while the minimum stratification was observed at low tide. Subtidal stratification characteristics were studied after removing the tidal effects through low-pass filtering. Regression analysis indicates that a linear relationship exists between vertical salinity stratification and the bottom currents.

Experiment data set was used to calibrate a three-dimensional hydrodynamic model. The turbulent closure in the hydrodynamic models plays an important role in the accurate predictions of vertical stratification, fresh and salt water mixing, and density-induced current. Using the data set obtained from this study, a correction factor of 1.12 was obtained to correct the turbulent eddy viscosity determined from Mellor-Yamada turbulent model. Comparison between model predictions and observations indicated that, after employ the correction factor, the hydrodynamic model was able to accurately predict the dynamics of stratify flow in Apalachicola River.

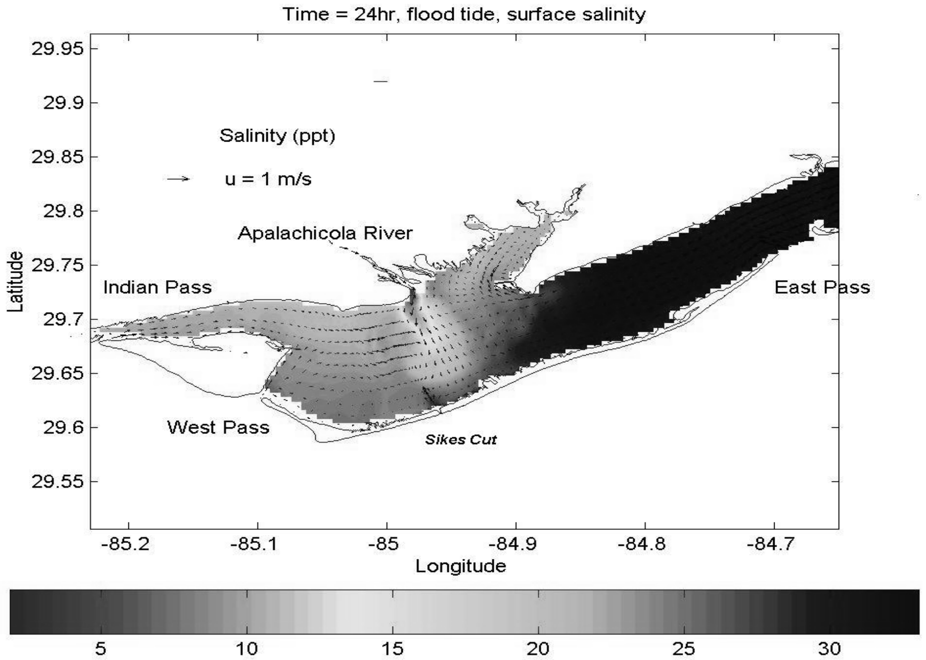

Fig. 7 Model predictions of horizontal distributions of salinity and currents.

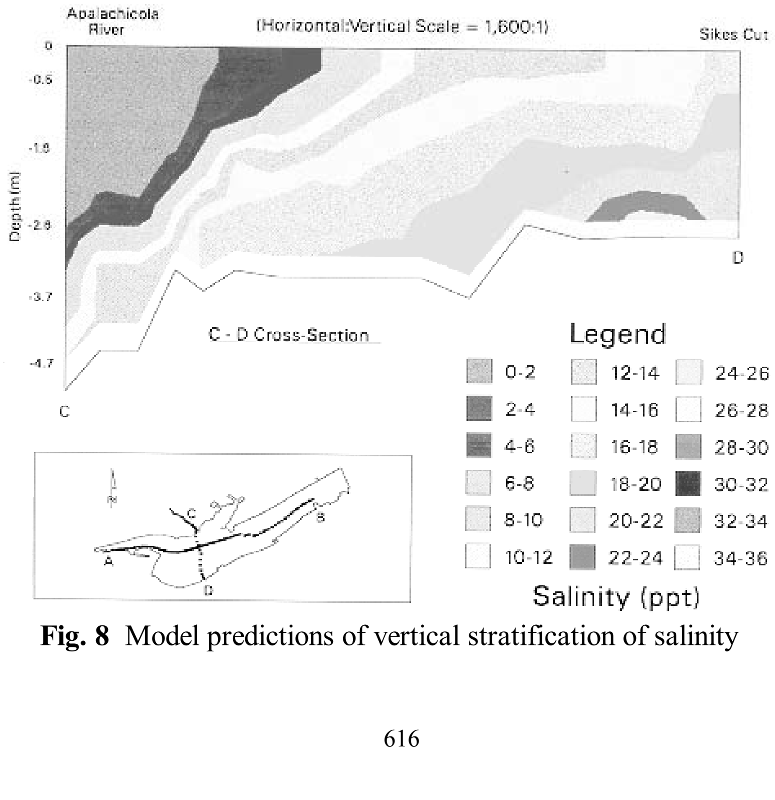

Fig. 8 Model predictions of vertical stratification of salinity

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