2007

3D Numerical Modeling of Hydrodynamics and Sediment Transport in Estuaries

Xiaohai Liu
3D Numerical Modeling of Hydrodynamics and Sediment Transport in Estuaries

By

Xiaohai Liu

A Dissertation submitted to the
Department of Civil and Environmental Engineering
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

Degree Awarded:
Summer Semester, 2007

Copyright © 2007
Xiaohai Liu
All Rights Reserved
The members of the Committee approve the Dissertation of Xiaohai Liu defended on April 9, 2007

____________________________________________________________________
Wenrui Huang
Professor Directing Dissertation

____________________________________________________________________
Kaisheng Song
Outside Committee Member

____________________________________________________________________
Amy Chan Hilton
Committee Member

____________________________________________________________________
Gang Chen
Committee Member

Approved:

____________________________________________________________________
Kamal Tawfiq, Chair

Department of Civil and Environmental Engineering
The office of Graduate Studies has verified and approved the above named committee members.
ACKNOWLEDGEMENT

I would like to express my gratitude to Dr. Wenrui Huang, who not only served as my advisor, but also encouraged, supported and challenged me during my study. I also want to thank him for sharing his expertise with me. I also would like to thank my committee members Dr. Hilton, Dr. Song, Dr. Chen and Dr. Dzurik for their guidance and valuable contributions.

Many people have been a part of my graduate education. I am grateful to the faculty, staff and colleagues at FAMU- FSU engineering school for making this journey delightful. This study has been funded by USEPA STAR Grant. Data for deriving correlation regression equation between turbidity and TSS were provided by NOAA Environmental Cooperative Science Center at Florida A&M University; Sid Flannery and Dr. Xinjian Chen from Southwest Florida Water Management District for providing necessary data to support Little Manatee River hydrodynamic modeling project. I would like to thank these organizations for their support.

Most of all, I would like to thank my family back in China, and especially my parents, for their absolute confidence in me. I wouldn’t be who I am now without their endless love and support.
# TABLE OF CONTENTS

List of Figures....................................................................................................................iv
List of Tables.......................................................................................................................vi
Abstract............................................................................................................................vii

Chapter 1: General Introduction.........................................................................................1

Chapter 2:
Enhancement of EFDC Hydrodynamic Model with an Effective Algorithm for Reducing Horizontal Pressure Gradient Errors in σ-coordinate
Introduction.........................................................................................................................4
Horizontal Pressure Gradient in Sigma Coordinate .............................................................5
An Effective Algorithm for Horizontal Pressure Gradient..................................................8
Numerical Test .....................................................................................................................13
Conclusion..........................................................................................................................17

Chapter 3:
Improvement of Horizontal Diffusion Coefficient Equation for Numerical Modeling of Salinity in a Shallow Tidal River
Introduction.........................................................................................................................41
Field Observed Data.............................................................................................................43
Horizontal Diffusion Scheme in EFDC Hydrodynamic Model..........................................43
Comparing Performance of Horizontal Diffusion Equations.............................................46
Verification of the Enhancement Horizontal Diffusion Scheme......................................51
LIST OF FIGURES

Fig.2-1 Sigma grids viewed in physical (x,z) space .............................................................. 19

Fig.2-2 Schematic diagram for 4th order sigma coordinate horizontal gradient viewed in (x-z) space .............................................................. 20

Fig.2-3 Schematic diagram for the sigma coordinate horizontal gradient calculation in the top layer viewed in (x-z) space .............................................................. 21

Fig.2-4 Test case I: Flat bottom basin with 100 meters depth .............................................. 22

Fig.2-5 Test case II: model grids in a coastal shelf ............................................................... 23

Fig.2-6 Initial stratified salinity field for test case II (coastal shelf) ......................................... 24

Fig.2-7 Time series of surface elevations from the original EFDC for test case II .................. 25

Fig.2-8 Surface elevation contour from original EFDC for test case II .................................. 26

Fig.2-9 Velocity field from the original EFDC for test case II .............................................. 27

Fig.2-10 Comparison of analytic solution and interpolation result of salinities ....................... 28

Fig.2-11 Horizontal salinity difference(left) and horizontal pressure difference(right) at the interfaces of the 5th and 6th columns of calculation grids ........................................ 29

Fig.2-12 Comparison of the surface elevations between original and modified models .......... 30

Fig.2-13 Comparison of the surface elevation time series between original and modified EFDC models ........................................................................................................ 31

Fig.2-14 Velocity field from the modified EFDC for test case II ........................................... 32

Fig.2-15 Test case III: model grids for navigation channel ..................................................... 33

Fig.2-16 Salinity distribution for test case III (navigation channel) ........................................ 34

Fig.2-17 Elevation time series from original EFDC for test case III ..................................... 35

Fig.2-18 Surface elevation contour from original EFDC for test case III .............................. 36

Fig.2-19 Velocity field from the original EFDC for test case III .......................................... 37

Fig.2-20 Comparison of the surface elevation(test case III) .................................................. 38
Fig.2-21 Comparison of the surface elevation time series (test case III) ........................................39

Fig.2-22 Velocity field from the modified EFDC (test case III) .........................................................40

Fig.3-1 Comparison of different dispersion coefficients in an analytic test case of salinity intrusion in a uniform flow channel .................................................................54

Fig 3-2 Location of Little Manatee River .......................................................................................55

Fig 3-3 Model Grid and Field Measurement stations ........................................................................56

Fig.3-4 Observations of water levels, water temperature, and salinity .............................................57

Fig.3-5 Locations of gauged and un-gauged freshwater inflow .......................................................58

Fig.3-6a Gauged Inflow from USGS station; and inflow from #1- #2 sub basins ...............................59

Fig.3-6b Inflows from #3- #6 sub basins ....................................................................................60

Fig.3-6c Inflows from #7- #10 sub basins ....................................................................................61

Fig.3-7a Comparison of observations with model predicted salinity based on Smagorinsky diffusion coefficient equation at station 546 .................................................................62

Fig.3-7b Comparison of observations with model predicted salinity based on Smagorinsky diffusion coefficient equation at station 542 .................................................................62

Fig.3-8a Comparison of observations with model predicted salinity based on Overton and Fisher’s diffusion coefficient equation at station 546 .........................................................63

Fig.3-8b Comparison of observations with model predicted salinity based on Overton and Fisher’s diffusion coefficient equation at station 542 .........................................................63

Fig.3-9a Comparison of observations with model predicted salinity based on the enhanced Smagorinsky diffusion equation with variable $A_0(x)$ at station546 ........................................64

Fig.3-9b Comparison of observations with model predicted salinity based on the enhanced Smagorinsky diffusion equation variable $A_0(x)$ at station 542 .................................64

Fig.3-10a Model verification: comparison of model predicted and observed salinity in Station 546 .................................................................65

Fig.3-10b Model verification: Comparison of model predicted and observed salinity in station 542 ..................................................................................65

Fig. 3-11a Salinity field at high tide, 2/19/2005 ..............................................................................66
LIST OF TABLES

Tab.2-1 Test Case II of a coastal shelf: Comparison of errors between existing EFDC model and the enhanced EFDC model ........................................................................................................18

Tab 2-2 Test Case III of navigation channel: Comparison of errors between existing and enhanced EFDC models...........................................................................................................18

Tab.3-1 Statistics of salinity predicted from different diffusion equations in Little Manatee River.................................................................................................................................................68

Tab.3-2 Statistical comparison between observations and model predictions of salinity by using the enhanced horizontal diffusion equation ..................................................................................69

Tab.4-1 Calibrated parameters used in the hydrodynamic model .....................................................................................................................................................................................85

Tab.4-2 Hydrodynamic model statistics analysis ..................................................................................................................................................................................................................85

Tab.4-3 Statistical comparison between observations and model predictions of TSS concentration at Cat Point and Dry Bar .....................................................................................................85
ABSTRACT

As a USEPA recommended hydrodynamic and transport model, EFDC model has been widely used in modeling estuarine and coastal hydrodynamics and transport. EFDC employs sigma coordinate transformation to deal with irregular water depth. However, it is well known that this coordinate transformation introduces additional terms and produces computation errors in calculation of horizontal pressure gradient terms when a steep bottom slope exists in water domains. Errors in pressure gradient calculation can cause errors in velocity field and ultimately results in errors in spurious transports. In this study, a new algorithm is presented to reduce the numerical errors induced by the horizontal pressure gradient term near steep topography. The basic concept of this algorithm is to re-organize the pressure terms in sigma coordinate system to avoid the subtractions of two large horizontal pressure terms. To accomplish this objective, the 4th order Lagrangian interpolation method was firstly used in sigma space to obtain concentration in the corresponding z-level of the water column. Secondly, the horizontal concentration difference was determined. Finally, the horizontal pressure gradient in the water column was directly calculated from the horizontal concentration gradient. A stepwise bottom boundary condition was adopted for steep slopping bottom boundary. The algorithm has been used to enhance the EFDC model. The model code has been tested in three test cases: 1) flat bottom basin, 2) steep sloping channel, and a coastal shelf. Results indicate that conventional approach in current EFDC dealing with horizontal pressure gradient terms causes spurious surface elevation and velocity field. In comparison, the employment of the algorithm presented in this study significantly reduced numerical errors in predicting surface elevation and currents in navigation channels and coastal shelves.

Equations for estimating horizontal diffusion coefficient in 3D numerical modeling of estuarine transport have been evaluated in this study in a shallow tidal river. In the application of a 3D hydrodynamic model to Little Manatee River located in Florida of USA, the popular Smagoringsky diffusion scheme was shown to result in the underestimate salinity in comparison with field observations. Another horizontal diffusion equation by Overton et al was also unable to provide satisfactory results of salinity variations in the shallow and narrow river. In an analytic test case of a non-tidal uniform flow channel, Smargorinsky equation results in unreasonable zero horizontal diffusion and no salinity intrusion in the nontidal one dimensional tidal river. An enhanced horizontal diffusion equation was presented in this study. Decoupled
from the horizontal eddy viscosity, the enhanced horizontal diffusion equation is composed of the Smargorinsky equation with addition of a non-tidal background horizontal diffusion to account for the effects of shallow and narrow effects of streams. The enhanced equation has been calibrated with field observations of hourly surface and bottom salinity at two field stations during 2/15/2005-2/28/2005. It was also satisfactorily verified with field observations for the period of 3/1/2005-6/30/2005. Model predictions of salinity and currents fields from model predictions were presented to support water research. The enhanced horizontal diffusion equation will be helpful for more accurate modeling of other water quality constituents in tidal rivers.

A 3D sediment transport model is applied to Apalachicola Bay to predict temporal and spatial distributions of sediment concentrations in water columns. The model is coupled with the 3D hydrodynamic model in the EFDC model code that provides information on estuarine circulations and salinity transport. The hydrodynamic model has been calibrated with field observations of water levels and salinity. The sediment transport model solves the transport equation with source and sinks terms to represent sediment deposition and re-suspension. The model is capable of predicting dye transport and fecal coliform. Basing on the collection of field observation and data analysis, the main driving force for sediment resuspension in the bay is found to be surface wind drive current. The calibrated hydrodynamic model then was used to simulate the total suspended sediments (TSS) transportation and get a satisfying result. The calibrated model can serve as an effective tool for environmental scientists and resources managers to examine effects of management scenarios on estuarine sediments transport and the aquatic ecosystem.
CHAPTER 1

GENERAL INTRODUCTION

Modeling the physics, chemistry, and biology of the receiving waters of streams, lakes, estuaries, or coastal regions requires a model that incorporates all the major processes. Hydrodynamics and transport processes for this study were simulated using the three-dimensional EFDC hydrodynamic model. The EFDC hydrodynamic model was developed by Hamrick (1992). The model formulation was based on the principles expressed by the equations of motion, conservation of volume, and conservation of mass. Quantities computed by the model included three-dimensional velocities, surface elevation, vertical viscosity and diffusivity, temperature, salinity, and density. The Environmental Fluid Dynamics Code is a general purpose modeling package for simulating three-dimensional flow, transport, and biogeochemical processes in surface water systems including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions. The EFDC model was originally developed at the Virginia Institute of Marine Science for estuarine and coastal applications and is considered public domain software. In addition to hydrodynamic and salinity and temperature transport simulation capabilities, EFDC is capable of simulating cohesive and noncohesive sediment transport, near field and far field discharge dilution from multiple sources, eutrophication processes, the transport and fate of toxic contaminants in the water and sediment phases, and the transport and fate of various life stages of finfish and shellfish. Special enhancements to the hydrodynamic portion of the code, including vegetation resistance, drying and wetting, hydraulic structure representation, wave-current boundary layer interaction, and wave-induced currents, allow refined modeling of wetland marsh systems, controlled flow systems, and near-shore wave induced currents and sediment transport. The EFDC model has been extensively tested and documented for more than 100 modeling studies. The model is presently being used by a number of organizations including universities, governmental agencies, and environmental consulting firms, and is supported and recommended by USEPA for simulating multi-dimensional flow and water quality in surface water systems. The structure of the EFDC model includes four major modules: (1) a hydrodynamic model, (2) a water quality model, (3) a sediment transport model, and (4) a toxics
model. The EFDC hydrodynamic model itself, which was used for this study, is composed of six transport modules including dynamics, dye, temperature, salinity, near field plume, and drifter. Various products of the dynamics module (i.e., water depth, velocity, and mixing) are directly coupled to the water quality, sediment transport, and toxics models.

Although the EFDC model has been widely applied and shown its strong capabilities in hydrodynamic and transport modeling, it still has some problems. First, as a sigma coordinates model, EFDC produces noticeable horizontal pressure gradient numerical errors in steep slope bottom water bodies, which is caused by coordinates transformation. These errors could be in the same order of the expected current and many methods have been developed in the past to reduce the PGF errors (Song, 1998). Many alternative PGF schemes have been proposed, as vertical interpolation schemes, higher-order methods and methods retaining integral properties which are considered important for long term integrations. A number of methods have been applied to reduce the pressure gradient error (Song, 1998). The most common technique adopted in the existing version of EFDC model is to subtract a mean vertical density profile before calculating the gradient Gary (1973). While this might improve the results in those situations where there are only small horizontal density differences within the model domain, it will be of limited effectiveness in regions with large horizontal density gradients (Kliem, Pietrzak, 1999). Another type of approaches to decrease the truncation error is to use high-order differencing. McCalpin (1994) carried out a study using SPE in which he found improved results by implementing a fourth-order discretization of horizontal pressure gradient terms, and Chu and Fan (1997) extended this work to a six-order control volume method. They did reduce some truncation errors at some points, but were not efficient considering the extra computational expanse and complexity for programming. Secondly, most applications of the EFDC model have been conducted in estuaries or coastal regions, and there are not enough verifications of the model in rivers. Adequate estimation of horizontal diffusion coefficient affects the accuracy of water quality modeling. The EFDC hydrodynamic model employs popular Smagorinsky scheme (1963) in determining horizontal diffusion coefficient for concentration transport. However, in an analytic test case of a non-tidal uniform flow channel, Smargorinsky equation results in unreasonable zero horizontal diffusion and no salinity intrusion in the nontidal one dimensional tidal river. The application of the model to Little Manatee River located in Florida also shows that current EFDC model tend to
underestimate salinity variations in the shallow and narrow river and underestimate both mean value and fluctuations of salinity in upstream.

Pointing to those two problems existing in current EFDC model, this dissertation presents the improvements of the model, also an application of the sediment transport modeling. Three objectives are presented in the study. The first part is to enhance the horizontal pressure gradient scheme to reduce numerical errors in modeling flow and transports in steep slope bottom conditions. The 2nd part presents an enhanced horizontal diffusion coefficient for more accurate predictions of the transport process in Little Manatee River. The 3rd part investigates the capability of the model to simulate wind-induced sediment resuspension and transport to support estuarine ecological study in Apalachicola Bay.
CHAPTER 2

ENHANCEMENT OF EFDC HYDRODYNAMIC MODEL WITH AN EFFECTIVE ALGORITHM FOR REDUCING HORIZONTAL PRESSURE GRADIENT ERRORS IN σ-COORDINATE

Introduction

Among several 3D hydrodynamic models, Environmental Fluid Dynamics Code (EFDC, by Hamrick, 1992) is an advanced three-dimensional, time-variable model that provides the capability of internally linking hydrodynamic, water quality and eutrophication, sediment transport and toxic chemical transport and fate sub-models in a unique single source code framework. Sigma vertical coordinate and orthogonal-curvilinear horizontal coordinate are used in the model. As a fully three-dimensional and an USEPA recommended hydrodynamic and transport model, EFDC can be applied to all types of water-bodies and has been applied to over 100 water-bodies cross the states. The EFDC model, as several other 3D estuarine models (e.g. POM, ECOM3D, DELFT-3D), employ sigma coordinate for the numerical approximation in the vertical direction due to its advantage in dealing with irregular bathymetry. By the use of sigma coordinate transformation, the water column is divided into the same number of layers independently of the water depth, which leads to a smooth representation of the topography instead of ‘staircase’ grids in Cartesian coordinate. Moreover, these “terrain-following coordinate” allow an efficient grid refinement near the free surface (in the case of wind-driven flow) and near the bed. This coordinate transformation was first introduced by Phillips (1957) in meteorological forecasting. It was introduced into hydrodynamic calculations in the Great Lakes by Freeman et al. (1972). By now, it has became a commonly used technique for calculation of circulation in estuarine and coastal modeling (Blumberg et al, 1993; 1992; Hamrick, 1992, 1996; Chen and Smith,1990; Sheng,1990).

However, it has been well known that sigma coordinate transformation also induce numerical errors in horizontal pressure gradient force (PGF) in the case of stratified flow over steep topography. Sundquist (1975, 1976) was one of the first to warn about the potential consequences of this error when dealing with steep topography in meteorological models. Haney
(1991) brought this concern to ocean modelers. These errors could be in the same order of the expected current and many methods have been developed in the past to reduce the PGF errors (Song, 1998). The most common technique consists of subtracting a reference density, which is useful in limited area applications but not for large domains and long term simulations where departure from the reference density can be large. Many alternative PGF schemes have been proposed, as vertical interpolation schemes, higher-order methods and methods retaining integral properties which are considered important for long term integrations. A number of methods have been applied to reduce the pressure gradient error (Song, 1998). The most common technique adopted in the existing version of EFDC model is to subtract a mean vertical density profile before calculating the gradient Gary (1973). While this might improve the results in those situations where there are only small horizontal density differences within the model domain, it will be of limited effectiveness in regions with large horizontal density gradients (Kliem, Pietrzak, 1999). Another type of approaches to decrease the truncation error is to use high-order differencing. McCalpin (1994) carried out a study using SPE in which he found improved results by implementing a fourth-order discretization of horizontal pressure gradient terms, and Chu and Fan (1997) extended this work to a six-order control volume method. They did reduce some truncation errors at some points, but were not efficient considering the extra computational expanse and complexity for programming. To avoid subtractions of large terms in sigma coordinate transformation of horizontal diffusion, Huang and Spaulding (2002) reorganized terms in the transformed horizontal gradient equation, and found that horizontal gradient in (x,σ) can be reorganized into the same finite difference forms as that in (x,z) space. The only difference is that the corresponding salinity at z-level is estimated by the Taylor expansion in the sigma grid cells.

In this study, numerical experiments were conducted to examine errors induced by horizontal pressure gradients in sigma coordinate in the existing EFDC model. An effective algorithm was developed. Test cased were conducted to evaluate the reductions of spurious errors of surface elevation and currents induced by horizontal pressure gradients.

**Horizontal Pressure Gradient in Sigma Coordinate**
In three-dimensional shallow water models, a sigma coordinate transformation is often applied. The main advantage of this coordinate system is the fact that it is fitted to both the moving surface and bottom topography, which is essential for the accurate approximation of the vertical flow distribution without a large number of vertical grid points. Governing equations in Cartesian Coordinate in the EFDC model (Harmrick, 1996) are given below:

**Continuity equation,**

\[
\frac{\partial \eta}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial z} = 0
\]  

(1)

The momentum equations in

\[
\frac{\partial}{\partial t}(u) + \frac{\partial}{\partial x}(uu) + \frac{\partial}{\partial y}(vu) + \frac{\partial}{\partial z}(wu) = -g\left(\frac{\partial \eta}{\partial x} + \frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial z}(A_v \frac{\partial u}{\partial z})
\]

(2)

\[
\frac{\partial}{\partial t}(v) + \frac{\partial}{\partial x}(uv) + \frac{\partial}{\partial y}(vv) + \frac{\partial}{\partial z}(wv) = -g\left(\frac{\partial \eta}{\partial y} + \frac{\partial P}{\partial y}\right) + \frac{\partial}{\partial z}(A_v \frac{\partial v}{\partial z})
\]

(3)

where, \(u, v\) and \(w\) are the velocities components with respect to the \(x, y\) and \(z\) direction respectively, \(A_v\) is the vertical eddy viscosity, \(P\) is the physical pressure in excess of the reference density hydrostatic pressure,

\[
P = g \int_z^\xi \frac{\rho}{\rho_0} \, dz = \int_z^\xi b \, dz
\]

(4a)

\[
b = \frac{\rho g}{\rho_0}
\]

(4b)

Where \(b = \rho g / \rho_0\) is the buoyancy, \(\rho\) is the density, \(\rho_0\) is the reference density.

In sigma coordinate system, \((x, y, z)\) space is transformed to \((x, y, \sigma)\) space by the following relationship:

\[
x' = x, \quad y' = y, \quad \sigma = \frac{z + h}{H}
\]

Where \(H = \eta + h\) represents the total water depth, \(z = \eta(x, y, t)\) and the values for sigma at the surface and bed are constant in space and time, with \(\sigma(\eta) = 1, \sigma(-h) = 0\). Then the governing equations can be transformed from \((x, y, z)\) space to \((x, y, \sigma)\) as given below.

**Continuity equation:**
\[
\frac{\partial H}{\partial t} + \frac{\partial H u}{\partial x} + \frac{\partial H v}{\partial y} + \frac{\partial \omega}{\partial \sigma} = 0
\]

(5)

Momentum equations in \((x', y')\) directions:

\[
\frac{\partial}{\partial t} (H u) + \frac{\partial}{\partial x'} (H u u) + \frac{\partial}{\partial y'} (H u v) + \frac{\partial}{\partial \sigma} (w u)
\]

\[
= -H \left( g \frac{\partial \eta}{\partial x'} + \frac{\partial P}{\partial x'} + \frac{1}{H} \frac{\partial h}{\partial x'} \frac{\partial H}{\partial \sigma} \right) + \frac{\partial}{\partial \sigma} \left( \frac{A_\nu}{H} \frac{\partial v}{\partial \sigma} \right)
\]

(6)

\[
\frac{\partial}{\partial t} (H v) + \frac{\partial}{\partial x'} (H u v) + \frac{\partial}{\partial y'} (H v v) + \frac{\partial}{\partial \sigma} (w v)
\]

\[
= -H \left( g \frac{\partial \eta}{\partial y'} + \frac{\partial P}{\partial y'} + \frac{1}{H} \frac{\partial h}{\partial y'} \frac{\partial H}{\partial \sigma} \right) + \frac{\partial}{\partial \sigma} \left( \frac{A_\nu}{H} \frac{\partial u}{\partial \sigma} \right)
\]

(7)

For numerical approximation a grid need to be defined. Due to the sigma transformation, this grid is fitted to the surface and the bottom. In estuaries such a grid may deteriorate quite strongly in the presence of steep bottom slopes and shallow water. This coordinate transformation can cause numerical problems when computing horizontal gradient including horizontal diffusion and horizontal pressure gradient force. The transformation of the horizontal pressure gradient is given as follows:

\[
\frac{\partial P}{\partial x'} = \frac{\partial P}{\partial x} + \frac{1}{H} \frac{\partial h}{\partial x'} \frac{\partial H}{\partial \sigma} \frac{\partial P}{\partial \sigma}
\]

(8)

From Eq.8, small pressure gradient might be the result of the sum of two relatively large terms of opposite sign which tend to cancel each other theoretically near steep bottoms. Small truncation errors in the approximation of both terms result in a relatively large error in the pressure gradient. This might produce spurious density-induced motions and increased velocity fields at depth in variable topography domains (Jalmart et al, 1982; Johnson et al, 1990; Haney, 1991, Beckmann and Haidvogel, 1993; Paul, 1993). These problems have been serious enough to force some modelers to resort to simulating the model in Cartesian coordinate system (Johnson et al, 1990; Sheng, 1990). The horizontal pressure gradient at a depth of \(z\) as used in the internal mode of the EFDC model in Cartesian coordinate can be written as

\[
\left( \frac{\partial P}{\partial x} \right)_z = \int_0^z \frac{\partial b}{\partial x} \, dz = \int_0^z \frac{\partial b}{\partial x} \, dz
\]

(9)
In EFDC, the numerical solution of the vertically discrete momentum equation proceeds by splitting the external depth integrated model associated with external long surface gravity waves from the internal model associated with vertical current structure. So the pressure gradient force also includes these two parts. The vertically averaged horizontal pressure gradient force for the external mode

\[
\frac{\partial \overline{P}}{\partial x} = \frac{1}{\xi} \int_{-H}^{H} \left( \xi \frac{\partial b}{\partial x} \right) dz
\]

(10)

Density is expressed by the equation of state in EFDC model to show an empirical relationship between water density, temperature and salinity. For the purpose of clarity, a linear approximation to this function (Leclerc, et al, 1999) is given by

\[
\rho = \rho_0 (1 + \alpha S + \beta T)
\]

(11)

Here \(\rho_0\) is reference density, \(S\) is salinity and \(T\) is the temperature, and \(\alpha, \beta\) are coefficients for salinity and temperature. The salinity variations produce density gradient that is much greater than those due to temperature variations. These density difference between freshwater and seawater cause estuarine mixing to be distinctly different from mixing in freshwater lakes and oceans (Martin and Mc1999). Then buoyancy shown in Eq. 4b become

\[
b = (1 + \alpha S + \beta T) g
\]

(12a)

\[
\frac{\partial b}{\partial x} = g (\alpha \frac{\partial S}{\partial x} + \beta \frac{\partial T}{\partial x})
\]

(12b)

**An Effective Algorithm for Horizontal Pressure Gradient**

To reduce horizontal gradient errors induced by the subtraction of two large horizontal gradient terms in sigma coordinate transformation, we can re-organize the pressure gradient terms in sigma coordinate. Huang and Spaulding (2002) have demonstrated that the finite different form of the horizontal gradient in \((x', \sigma)\) and \((x, z)\) can be represented in the same form.
The only difference is that, in \((x',\sigma)\) space, the corresponding salinity or pressure in the corresponding z-level can be approximated by the Taylor expansion using salinity in the neighboring sigma layers. Huang and Spaulding’s (2002) analysis indicates that for the 1st order horizontal gradient, the 1st order horizontal gradient in \((x',\sigma)\) space can be rewritten in conventional finite difference form in \((x,z)\) space with corresponding concentrations estimated from the 1st order Taylor expansion, while the 2nd order horizontal gradient in \((x',\sigma)\) space can be rewritten in conventional finite difference form in \((x,z)\) space with corresponding concentrations estimated from the 2nd order Taylor expansion. In modeling 2nd order horizontal diffusion gradient, Huang and Spaulding recommended the 2nd order Lagrangian interpolation method for estimating salinity in the z-equivalent levels for determining horizontal diffusion because of its easy in computer programming and 2nd order accuracy features. This concept was adopted in proposed algorithm in this study to directly use horizontal pressure gradient in term of salinity and temperature gradient as given in Equations 9,10,12 rather than Eq.8 to avoid the subtraction of two large terms in the transformed equation in \((x,\sigma)\) for reducing numerical errors. Instead of calculating horizontal pressure for determining its gradient, the horizontal buoyancy difference at sigma grid can be calculated first based on the 2nd or higher order interpolations of salinity and temperature in the vertical direction of sigma grid cells to get approximation of concentrations at the corresponding z-level position.

To obtain more accurate estimation of horizontal salinity gradient in the water column, the relationship of discretized horizontal gradients in sigma and z coordinate was analyzed firstly. For simplification and clarity, we restrict our discussion in a 2-D vertical cross section (as shown as in Fig. 1 and the horizontal distance of grid cells is equal. The relationship between \((x,z)\) (Cartesian coordinate) and \((x',\sigma)\) coordinate systems can be given by

\[
\begin{align*}
    x &= x' \\
    z &= \sigma H(x') \\
    \frac{\partial C}{\partial z} &= \frac{1}{H} \frac{\partial C}{\partial \sigma} \\
    \frac{\partial c}{\partial x} &= \frac{\partial c}{\partial x'} - \frac{(\sigma - 1)}{H} \frac{\partial H}{\partial x'} \frac{\partial c}{\partial \sigma}
\end{align*}
\]

(13)

Where \(c\) is the concentration of scalar quantities (e.g. salinity or temperature)
Fig. 2-1 shows the geometric relationships between sigma and z coordinate, and the slope of a constant sigma line in \((x, z)\) space can be represented by

\[
\tan \alpha_k = (\sigma_k - 1) \frac{2\partial H}{\partial x}
\]  

(14)

We can also obtain the following equations to describe the vertical deviation \(\Delta z\) of the \(\sigma_k\) layer from the \(z_k\) level

\[
\Delta z_{i-1} = z_k - z_{k-1, \sigma_k} = \tan \alpha_k \Delta x' = (\sigma_k - 1) \frac{\partial H}{\partial x'} \Delta x' = (\sigma_{\xi} - \sigma_k) H_{i-1}
\]

\[- \Delta z_i = z_k - z_{k+1, \sigma_k} = -\tan \alpha_k \Delta x' = - (\sigma_k - 1) \frac{\partial H}{\partial x'} \Delta x' = (\sigma_\eta - \sigma_k) H_i
\]

(15)

where \(\sigma_{\xi}\) and \(\sigma_\eta\) are the sigma values at the \(z_k\) level at \((i, i-1)\) locations as shown in Fig. 1, respectively.

\[
\sigma_{\xi} - 1 = \frac{z_k}{H_{i-1}} = \frac{H_{i-1}}{H_i} \sigma_k, \quad \sigma_\eta - 1 = \frac{z_k}{H_i} = \frac{H_i}{H_i} \sigma_k
\]

(16)

In \((x, z)\) space, the finite difference expression of the horizontal concentration gradient is given by

\[
\frac{\Delta C}{\Delta x} = \frac{C_{i, z_0} - C_{i-1, z_0}}{\Delta x}
\]

(17)

In \((x, \sigma)\) space, the corresponding finite difference form of horizontal concentration gradient as given in Eq 13 can be reorganized (Huang and Spaulding, 2002) as follows

\[
\frac{\Delta C}{\Delta x'} = \frac{(C_{i, \sigma} + \frac{\partial C}{\partial \sigma})(\sigma_\eta - \sigma_k) - (C_{i-1, \sigma} + \frac{\partial C}{\partial \sigma})_{i-1}(\sigma_{\xi} - \sigma_k)}{\Delta x'}
\]

(18)

The finite difference scheme in \((x, \sigma)\) space given in (Eq. 18) can be rewritten into the same form as that used in the \((x, z)\) as shown in Eq. 17:

\[
\frac{\Delta C}{\Delta x} = \frac{C_{i, z} - C_{i-1, z}}{\Delta x}
\]

(19a)

\[
C_{i, z} = C_{i, \sigma} + \frac{\partial C}{\partial \sigma}(\sigma_\eta - \sigma_k) = C_{i, \sigma} + \frac{\partial C}{\partial z}(z_{in, \sigma} - z_{i, \sigma})
\]

(19b)
\begin{align}
C_{i-1,z} &= C_{i-1,\sigma} + \left( \frac{\partial C}{\partial \sigma} \right)_{i-1} (\sigma_{\xi} - \sigma_{k}) = C_{i-1,\sigma} + \left( \frac{\partial C}{\partial \sigma} \right)_{i-1} (z_{i,\sigma} - z_{i-1,\sigma}) \\
\end{align}

(19c)

Therefore, in sigma space system the finite difference scheme can be written in the same form as that in the Cartesian system. The finite differential equations show that the geometric meaning for horizontal gradient remains the same, however, when performing finite differencing along the z-level in sigma coordinate grids, the variables in the finite difference equation are now approximated from the sigma grid cells through the 1st order Taylor series in vertical direction. Alternatively, we also can use other interpolation schemes to find variables at z level from sigma grids. Because that the pressure gradient term is more sensitive than the diffusion term, we applied 4th order Lagrangian interpolation polynomial to approximate the concentrations at z level in sigma grid cells.

The proposed algorithm can be described by following step by step procedures.

(1) Estimate salinity and temperature at z level from sigma grids with 4th order accuracy.

For the computational domain shown in Fig.2-2, concentrations (salinity, temperature) value of $C_{i-1,z}$ and $C_{i,z}$ at $z_k$ level in (x,z) space can be determined from other variables given at the sigma grid cells by using 4th order Lagrangian interpolation polynomial

\begin{align}
C_{i-1,z} &= C(\sigma_{\xi}) = \sum_{i=0}^{4} \left( \prod_{k=0}^{4} \frac{(\sigma_{\xi} - \sigma_{k})}{(\sigma_{\xi} - \sigma_{k})} \right) C(\sigma_{k}) \\
C_{i,z} &= C(\sigma_{\eta}) = \sum_{j=0}^{4} \left( \prod_{k=0}^{4} \frac{(\sigma_{\eta} - \sigma_{j})}{(\sigma_{j} - \sigma_{j})} \right) C(\sigma_{j}) \\
\end{align}

(20)

Where $\sigma_{\xi}$ and $\sigma_{\eta}$ can be calculated from Eq.14. Given the arrays of sigma grids centers $[\sigma_0 = \sigma_{k-2}, \sigma_1 = \sigma_{k-1}, \sigma_2 = \sigma_k, \sigma_3 = \sigma_{k+1}, \sigma_4 = \sigma_{k+2}]$ and the concentration values at the sigma grids centers $[C_0(\sigma_0), C_1(\sigma_1), C_2(\sigma_2), C_3(\sigma_3), C_4(\sigma_4)]$, a simple computer program can be easily developed to determine $C_{i,z}$ and $C_{i-1,z}$ at each sigma computational grid.

(2) Calculate density and the corresponding buoyancy at zk using Eq .4(a) and Eq.12(a)

\begin{align}
\begin{cases}
b_{i,z} = \rho_{i,z} g / \rho_0 \\
b_{i-1,z} = \rho_{i-1,z} g / \rho_0
\end{cases}
\end{align}

(21)
(3) Horizontal buoyancy difference at $z_k$ position is determined basing on Eq.4(b) and Eq.12(b)

$$\Delta b_{z_k} = b_{i,z_k} - b_{i-1,z_k} \quad (22)$$

(4) Compute the horizontal pressure gradient ($\Delta p/\Delta x$) at $z_k$ position in terms of horizontal buoyancy difference $\Delta b$ for the 3D internal mode:

$$\left(\frac{\Delta p}{\Delta x}\right)_{z_k} = \frac{H}{\Delta x} \sum_{j=k}^{K} \Delta b * \Delta \sigma \quad (23)$$

Because salinity is determined from 4th order accuracy Lagrangian interpolation, error in horizontal buoyancy gradient and thus the pressure gradient can be minimized.

(5) Compute vertical averaged horizontal pressure gradient by integrating Eq.24 in vertical direction for the 2D averaged external mode

$$\overline{\left(\frac{\Delta p}{\Delta x}\right)} = \sum_{k=1}^{K} \left(\frac{H}{\Delta x} \sum_{j=k}^{K} \Delta b * \Delta \sigma \right) \Delta \sigma \quad (24)$$

Comparing to Eq.8, the new algorithm avoids the subtraction of two relatively large terms, which can cause significant truncation errors along steep bottoms, instead, the horizontal gradient of concentration ($\Delta C/\Delta x$) and buoyancy ($\Delta b/\Delta x$) is calculated first. This will minimized horizontal pressure gradient error.

**Surface Boundary Approximation**

In EFDC a vertical staged grid is used, hence the z-level of a grid center may actually locate above the first sigma layer while calculating concentration profile at the top. In this case an assumption or extrapolation has to be made to determine an appropriate value. Stelling and Van Kester (1994) made an assumption that the density gradient near the surface was set to zero, however, Slordal (1997) showed that the method underestimate the horizontal pressure gradient force; and if the depth $z_i$ is above the first layer of the deep grid point $\bar{\sigma}_{i-1,i}$ (Fig.2-3) and the concentration need to be extrapolated to $z_i$ level at (i-1) water column, the numerical error caused by extrapolation can be large. To avoid extrapolation, a slight modification is made here to calculate salinity difference at the top layer as shown in Fig.2-3. Instead to estimate salinity at $Z_1$ level from sigma grids at both i and (i-1) water columns, the concentration gradient is
calculated at the deeper grid point of two adjacent grids at \( z_{\sigma_i-1} \) level, so only \( C(\sigma_{i,z_{\sigma_i-1}},1) \) at \( i \) column need to be calculated by interpolation while the real value of \( C(\sigma_{i-1,z}) \) at \( (i-1) \) column is applied, then the horizontal salinity gradient at the top layer can be approximate more accurately.

**Bottom Boundary Approximation**

Similarly, a problem arises since the z-level of a grid center may actually locate under the deepest layer or within the bed when the bottom slope is steep or the horizontal grid is large. At the bottom layer, it is equivalent to a vertical wall boundary physically when using the finite-difference formula in the horizontal direction in conventional z-coordinate models. Huang and Spaulding (2002) proposed a stepwise bottom boundary condition to reduce numerical errors because it keeps the same physical characteristics at the bottom boundary. The method showed good results in diffusive flux calculation and is adopted here, in which zero concentration gradient condition is applied to the wall boundary at bottom layer.

Obviously, basing on Eq.10, when the horizontal gradient of the concentrations (salinity, temperature etc.) are zero, there is no contribution of the horizontal density gradient to the driving force in the momentum equations. By using the proposed algorithm and boundary approximations here, pressure gradient can be calculated from the horizontal concentration gradient directly after the horizontal concentration difference at the interface of sigma grid centers was determined, so the truncation errors from the subtraction of two relatively large terms can be minimized.

**Numerical Tests**

Spurious currents and transport generated by PGE errors can be exactly evaluated by the idealized test in absence of the external forcing with only a vertical stratification, where PGF terms should be null and the steady state of null is the exact solution (Paul, 1993; Huang and Spaulding 2002; Ciappa, 2006). In this section, proposed algorithm was applied in EFDC models for some numerical tests and the results were compared with those from the original EFDC models. As we mentioned before, to evaluate the spurious currents generated by pressure gradient exactly, the only case is the test in absence of external forcing with a horizontally
uniform stratification, here the pressure gradient terms should be null and the quiescent state should be kept, then the numerical errors generated by the coordinate transformation arise and the spurious currents can be quantitatively estimated. The models are tested at two-dimensional lateral-averaged water columns which are vertically stratified. The initial density is the nonlinear function of water depth, so there is no initial horizontal density gradient, which is the only possible factor that can drive horizontal flow when all external forces turned off. Simulations for each case were performed for 5 days by applying existing EFDC model and enhanced model with the proposed algorithm to estimate the pressure gradient error. The results for each case were presented in terms of the artificial surface elevation and artificial current field caused by truncation errors. These values should be null if the model can correctly approximate the horizontal pressure gradient term. Three cases were tested, which are flat bottom basin, steep slope coastal shelf and navigation channel, respectively.

**Test Case I**

First test case is a flat bottom regular channel with 100 meter depth (shown in Fig.2-4). The water column is vertically stratified, and the initial salinity filed is specified by following non-linear function:

\[
S(x, z) = S_{\text{max}} \cdot \left( \frac{z}{H_{\text{max}}} \right)^{1/3} \quad \text{or} \quad S(x', \sigma) = S_{\text{max}} \cdot \left( \frac{\sigma H(x')}{H_{\text{max}}} \right)^{1/3}
\]  

(25)

Where \( H_{\text{max}} \) is maximum depth of the basin, \( H(x') \) is local water depth, and \( S_{\text{max}} \) is maximum salinity of 35 ppt at the maximum depth of the water column \( H_{\text{max}} \), and the temperature remains constant zero in the water domain, then the equation of state for density (Eq.11) is simplified as

\[
\rho = \rho_0 (1 + 0.00075S)
\]

(26)

Where \( \rho_0 \) is the constant reference density and \( \rho_0 = f(S_0, T_0) \). The density is the nonlinear function of water depth also, so there is no initial horizontal density gradient, which is the only factor that can drive horizontal flow without any external forces. After 5 days simulation, the surface elevations remain null and no current either from both existing and enhanced EFDC models, as the expectation. The results show that both existing and enhanced EFDC model do not produce spurious flow while dealing with flat bottom topography water.
regions. So we can use these models to check if there is spurious horizontal pressure gradient from topographic gradients, which can cause pure computational surface elevation and current.

**Test Case II**

The models were conducted in steep slope bottom coast shelf in the second case. The length of coastal shelf is 8000 m. It is approximated by 500*16 grids in horizontal direction and divided evenly into 7 sigma layers in vertical direction. Calculation grids were shown in Fig.2-5. The shelf has flat shelves at both ends and a strong slope bottom basin with the slope of 0.03 in the middle. The water column is vertically stratified with the same initial salinity filed distribution as case I (shown in Fig.2-6).

As expected, a deformation of surface elevation and artificial flow were obtained from existing model. After about 2 days simulations, the model reached the steady state (Fig.2-7) At the deeper end, the surface elevation is about 1 cm under the initial surface, and is about 0.9 cm above the initial level at the shallow end, therefore, there is artificial surface elevation gradient is created (Fig.2-8). Flow current for the steady state solution is shown in Fig.2-9. The maximum velocity obtained near the slope is the order of 0.11 cm/s and the mean velocity is around 0.024 cm/s. Those are entirely due to truncation errors in the approximation of horizontal pressure gradient force. If the transport equations were coupled, the artificial flow current would introduce spurious concentration (salinity, temperature, etc) transport and further change in the density field and additional spurious velocity and surface elevation.

The results from enhanced EFDC model applying proposed algorithm were shown in Fig.2-10-Fig.2-14. After 5 days simulation, the comparison between analytic and calculation values of salinity shows that 4th order Lagrangian interpolation can produce a very accurate approximation (Fig.2-10), and the maximum horizontal salinity difference at the interface of 5th and 6th water columns is only about 0.003 ppt (Fig.2-11 left) and the maximum horizontal pressure difference there is only around 0.001 N (Fig.2-11 right), which are negligible in many cases. The water surface almost remains quiet, and the maximum artificial surface elevation is only around 0.05 cm (Fig.2-12&Fig.2-13), which has been reduced more than 90% compared with the result from existing model. The spurious velocity has also been reduced significantly, and the maximum current is down to 0.02 cm while the mean velocity is reduced to 0.004 cm/s.
(Fig.2-14), which has been reduced more than 80% compared with the spurious current from existing model.

Test Case III

Finally, the numerical experiments were conducted in a small scale symmetric navigation channel. The channel has the depth of 23.5 m at both ends, which drop sharply to a 52 m deep flat bottom in the middle. The length of the channel is 2400 m. The channel is approximated by 100*24 grids in horizontal direction and divided evenly into seven sigma layers in vertical direction (shown in Fig.2-15). The water column is vertically stratified with the same initial salinity filed distribution as former two test cases (shown in Fig.2-16).

The results from existing EFDC model were presented in Fig.2-17, 2-18, 2-19. A deformation of surface elevation and artificial flow were obtained from existing model as expected. After about 2 days simulations, the model reached the steady state (Fig.2-17). The surface elevation is about 0.17 cm above the initial surface at both ends, and is about 0.16 cm under the initial level in the middle of channel, which produced artificial surface elevation gradient (Fig.2-18). The spurious flow current was shown in Fig.2-19. After simulation reached steady state, the maximum velocity can be found near the slope at the order of 0.02 cm/s and the mean velocity of the field is around 0.06 cm/s, those spurious surface elevation and flow current are solely due to the errors in the approximation of horizontal pressure gradient force. If the transport equations (for example, sediments) were coupled, the artificial flow current would introduce unrealistic sediment transport in the channel even if no numerical error occurs in computing the horizontal diffusion flux.

The results from enhanced EFDC model applying proposed algorithm are shown in Figs 2-20, 2-21, 2-22. After 5 days simulation, the water surface almost remains quiet. The artificial surface elevation is only less than 0.015 cm below the initial position in the middle and about 0.017 cm above the initial surface at both ends of the channel, which has been reduce more than 95% compared with the result from existing model (Fig.2-20), the time series of surface elevations at the stations of right end (A) and the middle (B) (Fig.2-21) also show that there is only a negligible fluctuation around equilibrium surface during the time while the elevation at these two stations from existing model increase continuously until reaching the steady state and produce the artificial surface elevation gradient. The artificial flow current has also been reduced
significantly, and the maximum current is down to 0.003 cm while the mean velocity is reduced to 0.001 cm/s (Fig.2-22), which have been reduced more than 80 % compared with the results from existing model.

Conclusion

This paper presents a new algorithm to reduce the numerical errors induced by the calculation of horizontal pressure gradient term near steep topography. The pressure terms in sigma coordinate system was re-organized to avoid the subtractions of two large horizontal pressure terms. The salinity profile was calculated in the convenient sigma grid cells, using the fourth order Lagrangian interpolation method, then, the horizontal salinity difference at sigma grid cell interface was determined instead of calculating horizontal pressure and its gradient, and finally the horizontal pressure gradient in the water column is calculated from the horizontal salinity gradient. The proposed method is easy to program, while it maintains fourth-order accuracy in interpolating variables between sigma and Cartesian coordinate for non-linear vertical stratification structures. When the z-elevation of a sigma grid center lies below the bottom boundary of a neighboring sigma grid, the stepwise bottom boundary applies a wall boundary and no salinity gradient between the two sigma-grid cells.

The proposed algorithm was applied in EFDC model and successfully reduced the spurious flow caused by truncation errors. The initial density field was specified with non-linear function dependent on the vertical elevation only. Numerical simulations were conducted for 5 days to examine the spurious flow by using existing EFDC model and enhanced EFDC model with proposed algorithm. The proposed method in this study reduced more than 90% artificial surface elevation and more than 80% spurious flow current caused by truncation error at both large scale coast shelf and small scale navigation channel test cases compared with the results from existing models (Tab.2-1 and Tab.2-2). Method for EFDC model development can also apply to other sigma-coordinate models (e.g., POM, Delfta3D, ECOM3D, etc) for coastal and estuarine applications.
Tab.2-1 Test Case II of a coastal shelf: Comparison of errors between existing EFDC model and the enhanced EFDC model for modeling surface elevations and velocities

<table>
<thead>
<tr>
<th></th>
<th>Existing EFDC model</th>
<th>Enhanced EFDC Model</th>
<th>Ratio of enhanced model error and existing model error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation error at A (cm)</td>
<td>-0.16</td>
<td>-0.009</td>
<td>5.6%</td>
</tr>
<tr>
<td>Surface Elevation error at B (cm)</td>
<td>0.17</td>
<td>0.009</td>
<td>5.3%</td>
</tr>
<tr>
<td>Maximum velocity error (cm/s)</td>
<td>0.02</td>
<td>0.003</td>
<td>15%</td>
</tr>
<tr>
<td>Mean Velocity error (cm/s)</td>
<td>0.006</td>
<td>0.001</td>
<td>16.7%</td>
</tr>
</tbody>
</table>

Tab.2-2 Test Case III of navigation channel: Comparison of errors between existing EFDC model and the enhanced EFDC model for modeling surface elevations and velocities in

<table>
<thead>
<tr>
<th></th>
<th>Existing EFDC model</th>
<th>Enhanced EFDC Model</th>
<th>Ratio of enhanced model error and existing model error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Elevation error at A (cm)</td>
<td>-1.1</td>
<td>-0.04</td>
<td>3.6%</td>
</tr>
<tr>
<td>Surface Elevation error at B (cm)</td>
<td>0.8</td>
<td>0.05</td>
<td>6.25%</td>
</tr>
<tr>
<td>Maximum velocity error (cm/s)</td>
<td>0.11</td>
<td>0.02</td>
<td>18%</td>
</tr>
<tr>
<td>Mean Velocity error (cm/s)</td>
<td>0.024</td>
<td>0.004</td>
<td>16.7%</td>
</tr>
</tbody>
</table>
Fig. 2-1 Sigma grids viewed in physical (x, z) space
Fig. 2-2 Schematic diagram for 4th order sigma coordinate horizontal gradient viewed in (x-z) space. Salinity at z level is estimated using 4th order Lagrangian interpolation from variables in sigma coordinates.
Fig. 2-3: Interpolation in surface boundary. Surface boundary approximation in the top layer viewed in (x-z) space.
Fig.2-4  Test case I: Flat bottom basin with 100 meters depth. Time series of surface elevation at station A and B were used to check if the model has reached a stable status in model validation.
Fig.2-5 Test case II: model grids in a coastal shelf. Time series of surface elevation at station A and B were used to check if the model has reached a stable status in model validation.
Fig. 2-6  Initial stratified salinity field for test case II (coastal shelf), which is vertically stratified and is non-linear function of the water depth.
Fig. 2-7 The time series of surface elevations from the original EFDC for test case II. The model reaches steady state after 2 days. The artificial surface elevation is about 1.1 cm below the initial and about 0.8 cm above the initial position at the ends, respectively.
Fig.2-8 Surface elevation contour from original EFDC for test case II. After 5 days simulation, the artificial surface elevation is about 1.1 cm below the initial position at the deeper end and about 0.8 cm above the initial position at the shallower end.
Fig. 2-9 Velocity field from the original EFDC for test case II. The maximum velocity obtained near the slope is the order of 0.11 cm/s and the mean velocity is around 0.024 cm/s.
Fig. 2-10 Comparison of analytic solution and interpolation result from 4th order Lagrangian interpolation of salinities at 5th and 6th columns of the calculation grids.
Fig. 2-11 Horizontal salinity difference (left) and horizontal pressure difference (right) at the interfaces of the 5th and 6th columns of calculation grids
Fig. 2-12 Comparison of the surface elevations between original and modified EFDC models. From enhanced model, the artificial surface elevation is about 0.04 cm below and about 0.05 cm above the initial positions at the ends respectively.
Fig.2-13 Comparison of the surface elevation time series between original and modified EFDC. The models reach steady state after 2 days. From the enhanced model, the maximum artificial surface elevation is only about 0.05 cm.
Fig. 2-14 Velocity field from the modified EFDC for test case II. The maximum velocity obtained near the slope is the order of 0.02 cm/s and the mean velocity is around 0.004 cm/s.
Fig. 2-15 Test case III: model grids for navigation channel. Time series of surface elevation at A and B were used to check if the model has reached a stable status in model validation.
Fig. 2-16 Salinity distribution for test case III (navigation channel), which is vertical stratified and is non-linear function of the water depth.
Fig. 2-17 Elevation time series from original EFDC for test case III. The model reaches steady state after 2 days, and the artificial surface elevation is about 0.16 cm below and about 0.17 cm above the initial positions at the ends, respectively.
Fig. 2-18 Surface elevation contour from original EFDC for test case III. The surface elevation is about 0.17 cm above the initial surface at both end, and is about 0.16 cm under the initial level at the shallow end.
Fig. 2-19 Velocity field from the original EFDC for test case III. Near the slope, the maximum velocity can be found at the order of 0.02 cm/s and the mean velocity of the field is around 0.06 cm/s.
Fig. 2-20 Comparison of the surface elevation between original and modified EFDC. From enhanced model, the artificial surface elevation is about 0.01 cm below and about 0.01 cm above the initial positions at the ends, respectively.
Fig. 2-21 Comparison of the surface elevation time series between original and modified EFDC. The models reach steady state after 2 days. From the enhanced model, the maximum artificial surface elevation is less than 0.01 cm.
Fig. 2-22 Velocity field from the modified EFDC for test case III. The maximum velocity obtained near the slope is the order of 0.003 cm/s and the mean velocity is around 0.001 cm/s.
CHAPTER 3

IMPROVEMENT OF HORIZONTAL DIFFUSION COEFFICIENT EQUATION FOR NUMERICAL MODELING OF SALINITY IN A SHALLOW TIDAL RIVER

Introduction

In recent years, numerical modeling is more and more popular in water quality research. Due to its direct correlation to freshwater input, salinity is often used as an indicator in water resources managements and planning for preserving estuarine habitat and aquatic ecosystem. For an example, the study by Livingston et al (2000) indicates that oyster mortality in estuary is directed affected by estuarine salinity. Prediction of salinity intrusion in estuaries and tidal rivers requires adequate estimation of horizontal dispersion coefficient. Numerical modeling and analytical analysis of by Huang and Spaulding (1995) indicate that tidally averaged salinity is proportional to horizontal diffusion coefficient in rivers. For one-dimensional study of streams and rivers, a variety of empirical equations have been proposed by some researchers. Fischer et al. (1979) suggest an equation showing that the dispersion coefficient is proportional to the square of the mean river velocity. Mcquivery and Keefer (1974) evaluated 18 streams and 40 time of travel studies for river flow ranging from 1 to 1000 $m^3/s$, and proposed an dispersion equation that is linearly proportional to the river flow $Q$. More recent empirical equations of longitude dispersion coefficient fro inland rivers have been given by Soe and Cheong (1998), Deng(2001), Kashefipour and Falconer (2002), in which the dispersion coefficient is defined as a function of mean velocity and the river bottom shear velocity. For tidal rivers and estuaries, numerical modeling has become more and more popular in recent year in studying salinity advection-diffusion transport process. The hydrodynamic model (EFDC) developed by Hamrick (2002) is one of the models which have been popularly used by many researchers. The EFDC model has been applied to several estuaries and lakes, for example, Ji et al (2002) for sediment transport, Jin et al (2000, 2002, 2005) for hydrodynamics and sediment transport in Lake Okeechobee, Moustafa and Hamrick (2000) for wetland hydrodynamics and nutrient in Everglade, Wool et al (2003) for Neuse River Estuary, and Shen et al (1999) for James River Estuary. Because of the temporal and spatial variations of velocity, simple empirical equations of horizontal dispersion dependent on river cross-section averaged velocity are not suitable
numerical modeling. The EFDC hydrodynamic model employs Smagoringsky scheme (1963) in determining horizontal eddy viscosity and diffusion. Another horizontal diffusion scheme developed by Overton et al. (1989) has also been used by Huang and Spaulding (1995) in Mt. Hope Bay of Rhode Island.

Effects of horizontal diffusion coefficient on the transport processes of water quality constituents can be examined in a simple test case of salinity intrusion in a one-dimensional open channel with constant depth and river inflow. In the test case, the channel is 14 km long, 2 km wide, and 10 km deep. Salinity $S_0$ is equal to 30 ppt at the seaward boundary. Under steady-state conditions, salinity intrusion is determined from a balance of advection and diffusion. Given the boundary condition at the upstream river inflow zero salinity, and at the downstream seaward salinity equals $S_0$, the solution for salinity along the estuary is given by (Thomann, 1988)

$$S = S_0 \exp \left( - \frac{Ux}{Ah} \right)$$  \hspace{1cm} (1)

Where $U =$ net velocity; $Ah =$ longitudinal diffusion coefficient; $x =$distance from the seaward boundary. Equation (1) shows that increasing horizontal diffusion coefficient leads to the increase of salinity intrusion. For the constant velocity in the open channel at 4.5 cm/s, the horizontal diffusion coefficient is estimated as 300 m2/s, 120 m2/s, 22.5 m2/s, and 0.00 m2/s for the diffusion equation of Kashefipour-Falconer (2002), Koussis-Rodriguez (1998), Overton et al, and Smagoringsky. Comparison of the model predictions for salinity based on those equations are presented in Fig.3-1. Comparing to other approaches, Smargorinsky equation results in unreasonable zero value of horizontal diffusion coefficient and cause no salinity intrusion in the nontidal one dimensional tidal river. Using Overton et al’s coefficient, salinity intrusion occurs only near the river mouth. This simple test case indicates the deficiency of Smargorinsky and Overton et al’ horizontal diffusion equation for modeling diffusion transport in river system.

In this study, the effect of horizontal diffusion coefficient on numerical modeling of salinity in a shallow river has been investigated. The study site, Little Manatee River (LMR), is located in the southwestern of Tampa Bay (Fig.3-2) in Florida, USA. The river system is shallow with the average depth of about 2 meter. The river extends approximately 40 miles from its mouth on the southeast corner of Tampa Bay near Ruskin to its eastward origin in southeastern Hillsborough County. The estuary receives freshwater input from upstream creeks and watershed
runoff. The drainage area is approximately 225 square miles. Tidal effects and salinity intrusions are discernable up to 15 miles from Tampa Bay. Adequate freshwater input is an important factor for preserving the water quality and the aquatic ecosystem in the estuary. In following sections, the horizontal diffusion scheme in the existing EFDC hydrodynamic model (Hamrick, 2002) is described. Enhancement of horizontal diffusion scheme is presented for the improvement of model predictions of salinity in the riverine estuary system.

**Field Observed Data in Little Manatee River**

Field observed data provided by Southwest Florida Water Management District were used in this study. Data include wind speed and directions, water levels, salinity, and temperature in several stations in Little Manatee River. Locations of field measurement stations are given in Fig.3-3. Time series of hourly water levels, temperature, and salinity for the period of 1/1/2005-6/30/2005 are given in Fig.3-4. There are three salinity monitoring stations (S554, S546, and S542) in the river system. Hourly salinity in Station S554 located near the river mouth was used as salinity boundary condition, while salinity in S546 near the mid river and S542 near the upper river was used for the validation of horizontal diffusion coefficient. Water levels as shown in Fig 4 vary between -0.46 ~ 0.91 meters with mixed diurnal and semi-diurnal harmonic tidal components. Water levels obtained from Station S554 were used as tidal boundary, while surface elevations in Station S546 and Station S542 were used in model validation. Freshwater input from upstream at station S500 was obtained from an USGS gage. Other freshwater inputs from drainage sub basins (Fig.3-5) were provided by Southwest Florida Water Management District. As shown in Fig 6, freshwater inputs to the river is generally low, ranging from $0.1 \text{ m}^3/\text{s} - 28 \text{ m}^3/\text{s}$.

**Horizontal Diffusion Scheme in EFDC Hydrodynamic Model**

The Environmental Fluid Dynamics Code (EFDC) developed by Hamrick (1996) was applied to Little Manatee River. The EFDC is capable of simulating flows and transport processes in surface water systems, including rivers, lakes, estuaries, wetlands and coastal areas.
The structure of the EFDC model includes four major modules: (1) a hydrodynamic model, (2) a water quality model, (3) a sediment transport model, and (4) a toxics model. EFDC is capable of simulating both cohesive and noncohesive sediment transport, near-field and far-field discharge dilution from multiple sources, eutrophication processes, and the transport and fate of toxic contaminants in the water and sediment phases (Yang and Hamrick, 2002, 2003; Ji et al 2001, 2002). The physical processes represented in the EFDC model and many aspects of the computational scheme are similar to those in the Blumberg-Mellor model (Blumberg and Mellor, 1987) and the U. S. Army Corps of Engineers' Chesapeake Bay model (Johnson et al., 1993). The EFDC model solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion for a variable density fluid. EFDC uses a sigma vertical coordinate and Cartesian or curvilinear, orthogonal horizontal coordinates. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. 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 formulation of the governing equations for ambient environmental flows characterized by horizontal length scales which are orders of magnitude greater than their vertical length scales begins with the vertically hydrostatic, boundary layer form of the turbulent equations of motion for an incompressible, variable density fluid. To accommodate realistic horizontal boundaries, it is convenient to formulate the equations such that the horizontal coordinates, x and y, are curvilinear and orthogonal. To provide uniform resolution in the vertical direction, aligned with the gravitational vector and bounded by bottom topography and a free surface permitting long wave motion, a time variable mapping or stretching transformation is desirable. The mapping or stretching is given by:

$$\sigma = \left( z^* + h \right) / \left( h + \zeta \right)$$  \hspace{1cm} (2)
Where * denotes the original physical vertical coordinates and -h and $\zeta$ are the physical vertical coordinates of the bottom topography and the free surface respectively. Details of the transformation may be found in Vinokur (1974), Blumberg and Mellor (1987) or Hamrick (1986). Transforming the vertically hydrostatic boundary layer form of the turbulent equations of motion and utilizing the Boussinesq approximation for variable density results in the momentum and continuity equations and the transport equations for salinity and temperature in the following form:

\[
\partial_t (m Hu) + \partial_x (m^2 H u u) + \partial_y (m H v u) + \partial_\sigma (m w u) -(m f + v \partial_x m_y - u \partial_y m_x) H v
\]
\[= -m_x H \partial_x (g \zeta + p) - m_y (\partial_x h - \sigma \partial_y H) \partial_\sigma p + \partial_\sigma (m H^{-1} A_v \partial_\sigma u) + Q_u\]  
(3)

\[
\partial_t (m Hv) + \partial_x (m^2 H u v) + \partial_y (m H v v) + \partial_\sigma (m w v) -(m f + v \partial_x m_y - u \partial_y m_x) H u
\]
\[= -m_x H \partial_y (g \zeta + p) - m_y (\partial_x h - \sigma \partial_y H) \partial_\sigma p + \partial_\sigma (m H^{-1} A_v \partial_\sigma v) + Q_v\]  
(4)

\[
\partial_\sigma p = -g H (\rho - \rho_0) \rho_0^{-1} = -g H b
\]  
(5)

\[
\partial_t (m \zeta) + \partial_x (m H u) + \partial_y (m H v) + \partial_\sigma (m w) = 0
\]  
(6)

\[
\partial_t (m \zeta) + \partial_x (m H \int_0^1 u d\sigma) + \partial_y (m H \int_0^1 v d\sigma) = 0
\]  
(7)

\[
\rho = \rho(p,S,T)
\]  
(8)

\[
\partial_t (m H S) + \partial_x (m H u S) + \partial_y (m H v S) + \partial_\sigma (m w S) = \partial_\sigma (m H^{-1} A_b \partial_\sigma S) + Q_S
\]  
(9)

\[
\partial_t (m H T) + \partial_x (m H u T) + \partial_y (m H v T) + \partial_\sigma (m w T) = \partial_\sigma (m H^{-1} A_b \partial_\sigma T) + Q_T
\]  
(10)

In these equations, u and v are the horizontal velocity components in the curvilinear, orthogonal coordinates x and y, $m_x$ and $m_y$ are the square roots of the diagonal components of the metric tensor, $m = m_x m_y$ is the Jacobian or square root of the metric tensor determinant. The vertical velocity, with physical units, in the stretched, dimensionless vertical coordinate $\sigma$ is $w^*$, and is related to the physical vertical velocity $w$ by:

\[
w = w^* - \sigma (\partial_x \zeta + u m_x^{-1} \partial_x \zeta + v m_y^{-1} \partial_y \zeta) + (1 - \sigma) (u m_x^{-1} \partial_x h + v m_y^{-1} \partial_y h)
\]  
(11)

The total depth, $H = h + \zeta$, is the sum of the depth below and the free surface displacement relative to the undisturbed physical vertical coordinate origin, $\sigma = 0$. The pressure
p is the physical pressure in excess of the reference density hydrostatic pressure, $\rho_0 g H (1 - \sigma)$, divided by the reference density, $\rho_0$. In the momentum equations (4, 5) f is the Coriolis parameter, Av is the vertical turbulent or eddy viscosity, and $Q_a$ and $Q_v$ are momentum source-sink terms which will be later modeled as subgrid scale horizontal diffusion. The density, $\rho$, is in general a function of temperature, T, and salinity, S, respectively and can be a weak function of pressure, consistent with the incompressible continuity equation under the anelastic approximation (Mellor, 1991, Clark and Hall, 1991). The buoyancy, b, is defined in equation (6) as the normalized deviation of density from the reference value. The continuity equation (7) has been integrated with respect to z over the interval (0,1) to produce the depth integrated continuity equation (8) using the vertical boundary conditions, $w = 0$, at $\sigma = (0,1)$, which follows from the kinematic conditions and equation (12). In the transport equations for salinity and temperature (10,11) the source and sink terms, $Q_s$ and $Q_T$ include subgrid scale horizontal diffusion and thermal sources and sinks, while $A_b$ is the vertical turbulent diffusivity. It is noted that constraining the free surface displacement to be time independent and spatially constant yields the equivalent of the rigid lid ocean circulation equations employed by Smetner (1974) and equations similar to the terrain following equations used by Clark (1977) to model mesoscale atmospheric flow. The system of eight equations provides a closed system for the variables u, v, w, $\zeta$, $\rho$, S, and T, provided that the vertical turbulent viscosity and diffusivity and the source and sink terms are specified. To provide the vertical turbulent viscosity and diffusivity, the second moment turbulence closure model developed by Mellor and Yamada (1982) and modified by Galperin et al (1988) has been used.

The EFDC hydrodynamic model employs Smagoringsky scheme (1963) as given in Equation (12) to determine horizontal eddy viscosity and diffusion to account for the temporal and spatial variable in 3D hydrodynamic modeling study.

$$A_M = A_H = c \Delta x \Delta y \left[ \frac{\partial u}{\partial x} \right]^2 + \left( \frac{\partial v}{\partial y} \right)^2 + \frac{1}{2} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2 \right]^{\frac{1}{2}}$$

(12)

Where $A_M$, and $A_H$, represent horizontal diffusion and viscosity coefficient; $c$ is a constant.

**Compare Performance of Horizontal Diffusion Equations in Little Manatee River**
In order to approximate the complex meandering river system, a horizontal orthogonal curvilinear grid system was developed for the Litter Manatee River (Fig.3-3). The model grid system adequately approximates the boundaries and the bayous. In the river main stem, multiple grids were employed to account for the variations of river bathymetry. In the vertical direction, three sigma layers were adopted to resolve vertical mixing in this shallow water system. Field observations of water levels, salinity, and temperature were specified in the river mouth boundary. Wind speeds and directions were applied to surface boundary. Freshwater inputs were specified at locations as shown in Fig.3-5. Model simulations for the period of 2/1/2005-2/15/2005 were used as the spin-up period to set up adequate initial conditions for model calibrations. Observed water levels and salinity for the period of 2/15-2/28 at stations in the river as shown in Fig.3-3 were used in model calibration. Model calibration for surface elevations was satisfactory (Huang and Liu, 2007). However, calibration of salinity was not satisfied until the improvement of the horizontal diffusion scheme was made. Evaluations of the performance of common horizontal diffusion equations for estuarine modeling are described below. Empirical equations for stream horizontal dispersion are not suitable for 3D or 2D numerical modeling, and thus not included in the evaluation discussion.

Smagorinsky’s Horizontal diffusion equation in existing EFDC Model

In the existing EFDC Model, both horizontal diffusive coefficient and eddy viscosity coefficient are calculated according to the Smagorinsky (1963) formulation as shown in Equation 12. Using default \( c=0.05 \), results of salinity at Station 546 and Station 542 are given in Fig.3-7a and Fig.3-7b. In general, model predictions of salinity are lower than observations. Adjusting the value of ‘c’ in Equation 12 shows no improvement on model results. Statistical comparison between model predictions and observations are given in Table 1. In Station 546 located near mid reach of the river, the observed mean salinity is 12.8 ppt for the surface station and 13.95 ppt for bottom station. In comparison, model predictions of mean salinity are 9.44 ppt for the surface station and 10.8 ppt for the bottom station. The errors for predicting mean salinity are approximately 3 ppt at Station 546. In Station 542 near upper portion of the river, observed mean salinity is 5.41 ppt for the top layer and 7.39 ppt for the bottom layer; while the model predictions of mean salinity is 3.69 ppt for the surface layer and 4.61 for the bottom. The
difference of mean salinity is about 1.72 and 2.78 for the surface and bottom in Station 542, respectively. Standard deviations from model predictions are generally about 1.5 ppt lower that those obtained from observations, which indicates underestimations of salinity fluctuations.

Based on the analysis of analytic solutions in the uniform open channel flow for salinity intrusion in the one-dimensional channel as shown in Fig.3-1, increasing horizontal diffusion coefficient would lead to the increase of mean salinity upstream. However, attempts have been unsuccessful by adding a constant value between 10-40 m²/s to the \( A_u \) and \( A_h \) given in Equation 12 in the existing EFDC model. This problem is caused by the coupled horizontal eddy viscosity and diffusion in the existing EFDC hydrodynamic model. Because both horizontal eddy viscosity and diffusion in the existing EFDC hydrodynamic model employ the same equation, simply adding a constant to increase the horizontal eddy viscosity and diffusion is unable to get satisfactory results. Adding a small constant value only made slightly increase of model predictions of salinity, while adding a large constant resulted in the divergence in model simulations.

Overton’s horizontal diffusion equation

Another horizontal diffusion scheme developed by Overton et al (1989) given below has been tested.

\[
A_x = 0.5 \Delta x |u| \\
A_y = 0.5 \Delta y |v| \\
\]

As shown in Equation (13), Overton et al’s horizontal diffusion scheme is proportional to model grid size and stream/river velocity. Overton et al’s equations (Eq 13) have been tested by replacing Smagoringsky’s equation (Eq. 12) in the EFDC model code. Model predictions of salinity are presented in Fig.3-8a, Fig.3-8b against observations. In general, results are similar to those obtained from original Smagoringsky’s horizontal diffusion scheme. Model predictions of salinity underestimate mean salinity in both Station S546 and S542. Model predictions of mean salinity for the surface and bottom layers are 9.45 ppt and 10.8 ppt in Station S546, respectively, which are about 3 ppt lower than the observations of 12.80 ppt and 13.95 ppt for the surface and bottom salinity in Station 546. In Station S542, model predictions of mean salinity of the surface and bottom layers are 3.68 ppt and 4.56 ppt, respectively. Comparing to observations, model
predictions of mean salinity are 1.73 ppt and 2.79 ppt lower in the surface and bottom layers, respectively. Salinity fluctuations from model predictions, as shown in Fig.3-8a and Fig.3-8b, are also lower than observed values. In Station S546, model predictions of standard deviations are 1.05 ppt and 0.87 ppt lower than those from observations for the surface and bottom layers, respectively. In Station S542, model predictions of standard deviations are 1.7 ppt and 1.51 ppt lower than those from observations for the surface and bottom layers, respectively.

Enhanced Smagoringsky Equation

Because comparison of model predicted and observed water levels are good, it is believed that eddy viscosity calculation in solving momentum equations and continuity equations in the hydrodynamic model is reasonable and thus needs no change. However, increase of horizontal diffusion coefficient is needed for the increase model predictions of salinity. In order to allow flexible change of horizontal diffusion to decrease or increase salinity predictions without affecting the stability in hydrodynamic model simulations, horizontal diffusion coefficient and eddy viscosity are decoupled to be separately represented by the different equations.

For horizontal eddy viscosity, Smagorinsky (1963) equation is kept.

\[
A_M = c\Delta x\Delta y\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)^2\right]\]

(14)

For horizontal eddy viscosity, the Smagorinsky equation is modified to

\[
A_H = c\Delta x\Delta y\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \frac{1}{2}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)^2\right] + A_0(x)
\]

(15)

When \(A_0(x)\) is non-tidal stream diffusion coefficient, which allows user to adjust mean salinity by model sensitivity study. In the case of simplified constant flow in a nontidal uniform channel condition, the modified Smagoringsky equation becomes a stream diffusion coefficient. Dependent on model calibrations, \(A_0(x)\) can be calibrated to change the tidally average mean salinity to match observations. Depending on different physical characteristics of different river
reaches or branches, $A_0(x)$ can be specified as different values for different river reaches or branches. Sensitivity studies of the enhanced Smagoringsky horizontal diffusion equation are given below.

**Constant Value A0=20 m2/s for all Model Cells**

According to the concept given in above analytic analysis of salinity intrusion in a uniform channel, increase of horizontal diffusion will cause an increase of salinity intrusion, or the mean salinity a specific river location. With the addition of a constant value of $A_0(x) = 20 \text{m}^2/\text{s}$ to the horizontal diffusion coefficient, the model predicted mean salinity, as expected, increases to reduce the difference between model predictions and observations. In Station S546, model predictions of mean salinity at surface and bottom layers are 11.55 ppt and 12.24 ppt, respectively. In Station S542, the mean surface salinity from model prediction is 6.06 ppt in comparison to the observed 5.41 ppt, while the mean bottom salinity is 6.42 against the observed 7.39 ppt. In addition, salinity fluctuation also increases so that the errors of standard deviation are reduced between model predictions and observations. Because the eddy viscosity employs the original Smagoringsky equation that is decoupled from the horizontal diffusion equation, adding constant to the diffusion coefficient causes no problem in model stabilities.

As shown in Table 1, while adding a constant horizontal diffusion coefficient in the modified horizontal diffusion equations has resulted in some improvement in salinity predictions, further improvement is needed. Considering varies of the salinity difference between model predictions and observations in different river reaches as shown in Station 542 and Station 546, using different horizontal diffusion coefficient for different river branches may be more reasonable.

**Variable A0(x) for Different River Branches with A(x1)=30 m2/s, and A(x2)=5m2/s**

In order to further improve model predictions of salinity based on two salinity observations in Station 546 in mid river and Station in Station S542 in upper portion of the river, two different constants are employed in the enhanced horizontal diffusion equation. After a series of sensitivity studies, optimal constants $A0(x1)= 5 \text{m}^2/\text{s}$ for grid cells in the upper portion of the river and $A0(x2) = 30 \text{m}^2/\text{s}$ for all other river segments were selected that provide better predictions in predicting salinity in the river system. As shown in Fig.3-9a and Fig.3-9b, time
series of model predictions of salinity has been further improved. Especially in Station S542, mean deviation from model predictions matches well with observations. As shown in Table 1, the difference of mean salinity is 0.44 ppt and 0.45 ppt for the surface and bottom of Station S546; and 1.03 ppt and 0.19 for the surface and bottom salinity in Station S542, respectively. Salinity fluctuations as indicating by standard deviations have also been significantly improved as shown in Table 1. The difference of standard deviation is 0.42 ppt and 0.01 ppt for the surface and bottom layers of Station S546, and 0.75 ppt and 0.35 ppt for the surface and bottom layers of Station S542.

**Verification of the Enhanced Horizontal Diffusion Scheme**

The 2nd independent data set for the period of 3/1/2005-6/30/2005 was used for the verification of the enhanced horizontal diffusion equation (Eq. 14) which is decoupled from horizontal eddy viscosity (Eq. 15). Keeping the same model parameters calibrated during model calibration phase for the period of 2/1/2005-2/15/2005, model simulations were conducted for additional four-month period (3/1/2005-6/30/2005). As shown in Fig.3-10a-Fig.3-10b, model predictions of hourly salinity match well with observations in both Station 546 and Station 542. Satisfactory verification indicates that the calibrated model is capable of characterize the hydrodynamic features in the Little Manatee River System. Statistical comparisons with observations are given in Table 2. For water levels, correlation coefficients r between model predictions and observations are 0.99, 0.98, and 0.97 for Station 546, Station 542, and Station 532. For salinity, correlation coefficients r between model predictions and observations are 0.95 and 0.94 for the bottom and surface in Station 546; and 0.93 and 0.88 for the bottom and surface in Station 542, respectively. The root-mean-square errors between model predictions and observed salinity range from 0.89ppt -1.76 ppt, which are commonly considered acceptable in estuarine salinity modeling.

**Spatial Distributions of Salinity and Currents in Little Manatee River**

The EFDC hydrodynamic model with the enhanced horizontal diffusion equation was used to investigate spatial and temporal variations of salinity mixing and transport in the Little
Manatee River system. From model simulations, spatial distributions of salinity and currents at high and low tidal phases were given below to characterize the salinity and currents fields in 2/19/2005. Salinity at high tide Fig.3-11a is about 27 ppt near downstream tidal boundary, about 15 ppt in the area about half the river length from the river mouth, and below 5 ppt near the upper river areas. At the most upstream area near USGS flow gauge, salinity is equal 0 ppt. This shows that the USGS gauge is located outside the tidal and salinity effects area. Salinity in the main stem of the river is in general higher than in the bayous and tributaries due to the saline water intrusion at high tide.

Salinity at low tide is given in Fig.3-11b. Fresh water moves to downstream at low tide. From the most upstream segment to the area halfway between the upstream and downstream boundary, salinity is below 2 ppt and freshwater is dominant. Water with salinity value of 5 ppt reaches the lower portion of the river within about 1/3 of river length from the river mouth. Salinity at the lower river tidal boundary is about 18 ppt. Salinity at bayous is higher than that in the river main stem at low tide because of the weak currents and detention of saltier water.

Currents are given in Fig.3-12a for high tide and in Fig3-12b for low tide for the lower LMR River. For clarity purpose, currents are shown only in the lower portion of the Little Manatee River. It is shown that currents in bayous are much weaker than those in river main stem. As the results, poor flushing occurs in bayous. Current patterns also show that model predictions of currents reasonably follow the curvilinear river boundaries. Near the downstream tidal boundary, ebb tidal currents distribute to branches and flux out of the estuary.

**Conclusion**

Smagorinsky horizontal diffusion scheme is popularly used in estuarine hydrodynamic models (e.g. POM, ECOM3D, EFDC) for estimating horizontal diffusion processes of water quality constituents. In this study, Smagorinsky horizontal diffusion scheme in the 3D EFDC hydrodynamic model has been evaluated in the shallow tidal river system of Little Manatee River. Although the Smagorinsky has been popularly used in estuarine and coastal waters, its performance in the shallow river of Little Manatee River is not satisfactory. Comparing to observations of salinity at surface and bottom layers of two field stations in Little Manatee River, model predictions of salinity resulting from the Smagorinsky horizontal diffusion scheme
considerably underestimate both mean value and the fluctuations of salinity. Because eddy viscosity and diffusivity employ the same Smagoringsky equation in the EFDC model, adjusting diffusion coefficient affects eddy viscosity, which may cause model stability problems. Alternative horizontal scheme by Overton et al produces similar results which also underestimate salinity mean value and fluctuations. In addition to the application to Little Manatee River, a simple test case of analytic solution for salinity intrusion in a uniform open channel flow also shows that Smagoringsky horizontal diffusion scheme results in physically unreasonable zero value of horizontal diffusion coefficient for uniform stream.

The enhanced Smagoringsky diffusion equation has been presented in this paper, in which the horizontal diffusion coefficient is separated from the horizontal eddy viscosity. While the eddy viscosity keeps original Smagoringsky equation, the horizontal diffusivity coefficient has been revised by adding a non-tidal steam diffusion coefficient to the Smagoringsky equation. The steam diffusion coefficient value can be calibrated by sensitivity studies by comparing model predictions with field observations. Because of the decoupling of eddy viscosity and diffusion, increase or decrease of horizontal diffusion coefficient to improve model predictions of salinity will not affect model stability. In the case of Little Manatee River, model predictions by using the enhanced Smagoringsky diffusion equation have shown substantial improvement over the original Smagoringsky scheme and Overton-fisher scheme. Comparing the observed mean salinity of 12.8 ppt at the surface of Station S546, model predictions of mean salinity is 9.44 ppt, 9.45 ppt, and 13.22 ppt for Smagoringsky, Overton-Fisher, and the Enhanced Smagoringsky diffusion scheme, respectively. The mean salinity and standard deviation from model predictions using the enhance diffusion scheme compared well with observations at the bottom of the Station S546 and the surface and bottom of Station S542. Because the horizontal diffusion transport of other water quality constituents are described by the same horizontal diffusion coefficient, the enhanced Smagoringsky diffusion equation decoupled from horizontal eddy viscosity will provide better predictions of the dispersion transport processes for water quality studies in tidal rivers.

Acknowledgements
The authors would like to thank Sid Flannery and Dr. Xinjian Chen from Southwest Florida Water Management District for providing necessary data to support this study.

![Comparison of different dispersion coefficients (m²/s) in an analytic test case of salinity intrusion in a uniform flow channel](image)

Fig. 3-1 Comparison of different dispersion coefficients (m²/s) in an analytic test case of salinity intrusion in a uniform flow channel
Fig. 3-2 Little Manatee River study area.
Fig. 3-3 Field Measurement stations of water levels, temperature, and salinity.
Fig. 3-4 Observations of water levels, water temperature, and salinity from 1/1-6/30/2005.
Fig 3-5 Locations of gauged and un-gauged freshwater inflow
Fig.3-6a Gauged Inflow from USGS station; and ungauged inflow from #1-#2 sub basin
Fig. 3-6b Ungauged inflows from #3-#6 sub basin.
Fig. 3-6c Ungauged inflows from #7-#10 sub basin.
Fig. 3-7a Comparison of observations with model predicted salinity based on Smagorinsky diffusion coefficient equation at station 546 during 2/15-2/28.

Fig. 3-7b Comparison of observations with model predicted salinity based on Smagorinsky diffusion coefficient equation at station 542 during 2/15-2/28.
Fig.3-8a Comparison of observations with model predicted salinity based on Overton’s diffusion coefficient equation at station 546 during 2/15-2/28.

Fig.3-8b Comparison of observations with model predicted salinity based on Overton’ diffusion coefficient equation at station 542 during 2/15-2/28.
Fig.3-9a Comparison of observations with model predicted salinity based on enhanced Smagorinsky diffusion equation variable $A_0(x)$ at station 542 during 2/15-2/28

Fig.3-9b. Comparison of observations with model predicted salinity based on enhanced Smagorinsky diffusion equation with variable $A_0(x)$ at station 546 during 2/15-2/28
Fig.3-10a Model verification: comparison of model predicted and observed salinity in Station 546 during 3/1-6/30.

Fig.3-10b Comparison of model predicted and observed salinity in station 542 in model Verification during 3/1-6/30.
Fig.3-11a. Salinity field at high tide, 2/19/2005

Fig.3-11b. Salinity field at low tide, 2/19/2005
Fig.3-12a  Currents at high tide in the low portion of the river

Fig.3-12b. Currents at low tide in the lower portion of the river
### Tab. 3-1 Statistics of comparison of model predictions of salinity (ppt) with different diffusion equations in Little Manatee River

<table>
<thead>
<tr>
<th></th>
<th>Smagoringsky</th>
<th>Overton</th>
<th>Enhanced Diffusion A0=20 for all cell</th>
<th>Enhanced Diffusion* A0(x1)=30 A0(x2)=5</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Correlation r</strong></td>
<td>0.6786</td>
<td>0.6737</td>
<td>0.6463</td>
<td>0.6802</td>
<td></td>
</tr>
<tr>
<td><strong>RMSE</strong></td>
<td>4.2556</td>
<td>4.257</td>
<td>2.989</td>
<td>2.7374</td>
<td></td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
<td>9.44</td>
<td>9.45</td>
<td>11.55</td>
<td>13.22</td>
<td>12.80</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>2.51</td>
<td>2.51</td>
<td>2.22</td>
<td>3.14</td>
<td>3.56</td>
</tr>
<tr>
<td><strong>S546 (Top layer)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Correlation r</strong></td>
<td>0.6052</td>
<td>0.6018</td>
<td>0.6504</td>
<td>0.7132</td>
<td></td>
</tr>
<tr>
<td><strong>RMSE</strong></td>
<td>3.9913</td>
<td>3.9979</td>
<td>2.8955</td>
<td>2.3714</td>
<td></td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
<td>10.8</td>
<td>10.8</td>
<td>12.24</td>
<td>13.5</td>
<td>13.95</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>2.2</td>
<td>2.2</td>
<td>2.16</td>
<td>3.08</td>
<td>3.07</td>
</tr>
<tr>
<td><strong>S546 (Bottom layer)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>correlation r</strong></td>
<td>0.6729</td>
<td>0.6746</td>
<td>0.6687</td>
<td>0.8757</td>
<td></td>
</tr>
<tr>
<td><strong>RMSE</strong></td>
<td>2.7079</td>
<td>2.7079</td>
<td>2.1626</td>
<td>1.7097</td>
<td></td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
<td>3.69</td>
<td>3.68</td>
<td>6.06</td>
<td>6.44</td>
<td>5.41</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>0.87</td>
<td>0.88</td>
<td>0.97</td>
<td>1.73</td>
<td>2.58</td>
</tr>
<tr>
<td><strong>S542 (Top layer)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Correlation r</strong></td>
<td>0.3599</td>
<td>0.3973</td>
<td>0.5553</td>
<td>0.8464</td>
<td></td>
</tr>
<tr>
<td><strong>error</strong></td>
<td>3.6777</td>
<td>3.686</td>
<td>2.3848</td>
<td>1.3811</td>
<td></td>
</tr>
<tr>
<td><strong>Mean value</strong></td>
<td>4.61</td>
<td>4.56</td>
<td>6.42</td>
<td>7.58</td>
<td>7.39</td>
</tr>
<tr>
<td><strong>Standard deviation</strong></td>
<td>1.07</td>
<td>1.06</td>
<td>0.99</td>
<td>2.22</td>
<td>2.57</td>
</tr>
</tbody>
</table>

Note: RMSE = root-mean-square error.

* Enhanced Diffusion* A0(x1)= 30 m²/s for all bit A0(x2)=5 m²/s for upstream segments in Equation 15
Tab.3-2 Statistical comparison between observations and model predictions of salinity by using the enhanced horizontal diffusion equation for the verification period: 3/1/2005-6/30/2005.

<table>
<thead>
<tr>
<th>Water levels (m)</th>
<th>Station546</th>
<th>Station 542</th>
<th>Station532</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation r</td>
<td>0.99</td>
<td>0.98</td>
<td>0.9687</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.0337</td>
<td>0.0361</td>
<td>0.0607</td>
</tr>
<tr>
<td>Salinity (bottom, ppt)</td>
<td>Station546</td>
<td>Station 542</td>
<td></td>
</tr>
<tr>
<td>Correlation r</td>
<td>0.9468</td>
<td>0.9365</td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>1.6264</td>
<td>0.8357</td>
<td></td>
</tr>
<tr>
<td>Salinity (surface, ppt)</td>
<td>Station546</td>
<td>Station 542</td>
<td></td>
</tr>
<tr>
<td>Correlation r</td>
<td>0.9384</td>
<td>0.8777</td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>1.757</td>
<td>0.8965</td>
<td></td>
</tr>
</tbody>
</table>

Note: RMSE = root mean square error
CHAPTER 4

WIND-INDUCED SEDIMENT RESUSPENSION AND TRANSPORT IN APALACHICOLA BAY

Introduction

Apalachicola bay is located on Florida’s northwest coast and covers an area of about 539 sq. km, and it is a shallow water system with approximate depth of 3.0 meter (Fig.4-1). Apalachicola bay is exceptionally important nursery area for the Gulf of Mexico. Over 95% of all species harvest commercially and 85% of all species harvested recreationally in the open Gulf have to spend a portion of their life in the estuary water. The bay is a highly productive estuarine system supporting an abundant recreational and commercial fishery. About 90% of Florida’s oysters (8-10% of the national crop) and the third highest catch of shrimp occur in the bay (Livingston, 1984). Cat Point and Dry Bar are two most productive oyster beds in Apalachicola bay (Livingston, 1984).

Water quality is closely related with the health of ecosystems. Water quality parameters such as chlorophyll-a, total suspended solids (TSS), turbidity, salinity can be useful indicators of ecosystem health. Sediments in shallow waters can impact the physical and ecological environment of a water column through sediments resuspension and transport. Increased suspended sediment can reduce light availability, which impacts algal and aquatic vegetation growth (Blom et al, 1994). Sediment resuspension also affects the cycling of nutrients through absorption and desorption of the dissolved nutrients from and to the water column, also sediment resuspension can impact the water quality by resuspension of organic pollutants and heavy metals (Jin 2005). Sediment contamination information is a useful indicator of ecosystem health, as sediments play a significant role in influencing the fate and effects of many toxic substances. All metals are occurring naturally in the environment, however, they are also produced by anthropogenic point and non-point sources. Many trace metals and toxic substances become incorporated into sediments as they attach to suspended particles and settle into estuarine ecosystems. Direct contact with or ingestion of such contaminated sediments may affect the health and behavior of benthic organisms. In addition, bioconcentration may occur if the contaminants are consumed by higher organisms such as fish, birds, and humans. As such, the
detection and management of contaminated sediments are critical to maintaining ecosystem health.

The main composition at the estuarine bed is usually cohesive sediment surface erosion processes in sediment, which undergoes periodic resuspension and deposition. The upper portion of the bed, on the order of a few centimeters, is generally referred to as the active layer. Resuspension of bottom sediment from the active layer is one of the major sources for total suspended sediments (TSS) in the water column (Lin and Kuo, 2001). Sediment transport is affected by many natural and anthropogenic factors. For example, in shallow water estuaries of the Gulf of Mexico, tides, wind and river discharge can easily re-suspend surficial sediments causing high turbidity and changes in salinity regimes (McKee and Baskaran, 1999; Livingston, 2006). Sediment has many adverse effects on aquatic life. Excess sediment clouds the water, making it impossible for submerged aquatic vegetation (SAV) rooted on the sound’s bottom to receive enough sunlight to grow. SAV is critical habitat for many aquatic animals including crabs, young fish, and oyster larvae. Sediment also smothers fish eggs and bottom-dwelling oysters, and covers the gravel bottoms where fish spawn and aquatic insects live. In addition, sediment does not break down or dissolve like some pollutants. Instead with each storm or heavy rain it is stirred up again.

Sediment resuspension may result in changes of water quality which may cause adverse impacts on oysters and shellfish in estuaries. Voley and Encomio (2006) investigated biological effects of suspended sediments resulted from dredging activities on shellfish in the Charlotte Harbor. The resuspension of sediments may adversely impact oyster health discounted. Increased levels of suspended sediments could reduce pumping rate in oysters. Increased sedimentation may also reduce oyster recruitment as oyster settlement is higher on shells with less siltation. High levels of suspended silt could also interfere with the feeding apparatus of swimming stages of oyster larvae. In nature contaminants and nutrients associated with excess sedimentation would place an even greater stress on the physiology of oysters and clams. The combination of sediment and polychlorinated biphenyl (PCB) compound exposure reduced glycogen content in the adductor muscle of C. virginica. Exposure to PAH-contaminated sediments increased levels of stress proteins in C. virginica. Contaminated sediments can also depress immunological function in oysters and increase susceptibility to oyster parasites such as Perkinsus marinus. Sediments may also harbor pathogens that can be released into the water column during
resuspension. Pathogens may increase in prevalence and intensity due to decreased host condition, as a result of sedimentation-related stress. Increased sediment concentration and low dissolved oxygen were speculated to be the reasons of increased disease susceptibility. Volety and Encomio (2006)’s study indicate that identifying regions of varying sedimentation and resuspension has important implications on the restoration of oyster reef habitat the estuary.

Modeling sediment transports usually requires a hydrodynamic model to provide information of circulation in the bay. Huang and Jones (2001) and Huang and Spaulding 2002) have conducted hydrodynamic modeling study using the 3D Princeton Ocean Model (POM) by Blumberg and Mellor (1987). Huang et al. (2002)’s modeling study indicates that wind plays a significant role in the transport process of salinity in Apalachicola Bay. For modeling sediment transport, the Environmental Fluid Dynamics Code (EFDC) by Hamrick (1996) has an advantage in its coupled hydrodynamic and sediment transport models. For the hydrodynamic model component, EFDC and POM are quite similar. Both employ orthogonal curvilinear grid system in horizontal and sigma coordinate system in the vertical. Therefore, the model grid system and bathymetry information developed by Huang et al (2002) can be readily adapted to the EFDC model domain for coupled hydrodynamic and sediment transport modeling.

In this study, the 3D EFDC hydrodynamic model was applied to describe circulation and salinity in the bay in response to wind, tides, and freshwater inputs. The coupled sediment transport model was used to investigate wind-induced sediment resuspension and transport in the bay. The sediment transport model solves the transport equation with source and sinks terms to represent sediment deposition and re-suspension. Hourly observations of TSS at two stations in the bay were used to validate the model. The validated model can be used to describe spatial and temporal distributions of sediment transport in the bay. In order to investigate wind effects, data that cover two storm events were selected in this study. In the following sections, the hydrodynamic and sediment transport models are described. Model calibrations and verifications are presented. Temporal and spatial distributions of sediment concentrations resulting from sediment resuspension and transport in response to wind forcing are discussed.

**Observations of Wind-Induced Sediment Resuspension**
High TSS may cause significant mortalities during the earliest phase of larval development and result in decreased oyster filtration rates and larval growth rates (e.g., Dekshenieks et al., 2000). Although oysters require certain levels of concentration of suspended solids to develop and grow, high TSS tends to clog gills and interfere with filtration (decreasing filtration rate) and respiration, thus reducing growth rates (e.g., Stanley and Sellers, 1986; Hofmann et al., 1994). In addition, TSS principally reduces oyster filtration rate rather than to increase food supply (Klinck et al., 2002). On the other hand, some previous studies found that changes in TSS concentrations were not significantly related to live oyster density (Cressman et al., 2003). Lower flow speeds could contribute to removal of particles by increasing the time water is in contact with the oysters and thus increasing their ability to filter particulates; it could also be that particles settled out of the water at these lower speeds (Cressman et al., 2003).

The Apalachicola National Estuarine Research Reserve (ANNER) operates a System-wide Monitoring Program to track short-term variability and long-term changes in estuarine waters. It provides valuable long-term data on water quality and weather at frequent time intervals, which helps researchers and water resources managers to understand how human activities and natural events can change ecosystems that including oysters and shellfish in the bay. The ANNER currently measures physical and chemical water quality indicators, nutrients and the impacts of weather on estuaries. Hourly turbidity data are obtained from two field observation stations, Cat Point and Dry Bar (Fig.4-1), which are operated by Apalachicola National Estuarine Research Reserve (ANNER). Analysis of the observations showed the significant effect of surface wind on the turbidity at both stations during the time (Fig.4-2 and Fig.4-3). During the period of June 1 to July 30, at both stations, both turbidity and wind speed have the very similar pattern that turbidity increases while the wind gets stronger. During the first storm event occurred on June 10, the turbidity appeared to have a pulse increase at both stations, and the turbidity reduced while the wind got weaker. In the 2nd storm even occurred on July 10, turbidity picked up again when the storm event approached and reached a higher value than that in the first storm as the result of stronger wind speed. For the shallow estuary of Apalachicola Bay with average depth around 3.0 m, analyses of these data indicates that wind is the dominant factor on driving flow velocities and therefore transporting suspended solids.

There are correlations between turbidity, suspended sediment, and water clarity (Davies-Colley and Smith, 2001). Values for turbidity and suspended sediment are commonly assumed to
be equivalent since turbidity and suspended sediment concentration are usually highly correlated. Correlation regression between turbidity and TSS concentration (Fig.4-4) has been derived by analysis of data from a field study by personals at Environmental Cooperative Science Center at Florida A&M University.

\[
TSS (\text{Mg} / L) = 1.861 \times Turb(NTU) + 3.383
\]  
(1)

Description of Hydrodynamic and Sediment Transport Model

The Environmental Fluid Dynamics Code (EFDC) is applied in this paper for hydrodynamic and sediment transport modeling. EFDC developed by Hamrick (1992) is a general-purpose modeling package for simulating one- or multi-dimensional flow, transport, and bio-geochemical processes in surface water systems including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions. This model is supported by U.S. Environmental Protection Agency (EPA) and has been used extensively throughout USA. In addition to hydrodynamic, salinity, and temperature transport simulation capabilities, EFDC is capable of simulating cohesive and non-cohesive sediment transport, near field and far field discharge dilution from multiple sources, eutrophication processes, the transport and fate of toxic contaminants in the water and sediment phases, and the transport and fate of various life stages of finfish and shellfish. Special enhancements to the hydrodynamic portion of the code, including vegetation resistance, drying and wetting, hydraulic structure representation, wave-current boundary layer interaction, and wave-induced currents, allow refined modeling of wetland marsh systems, controlled flow systems, and near-shore wave induced currents and sediment transport. The EFDC model has been extensively tested, documented, and applied to environmental studies worldwide by universities, governmental agencies, and environmental consulting firms.

The computational schemes in the EFDC model are equivalent to the widely used Princeton Ocean Model (POM) by Blumberg and Mellor (1987) in many aspects. The EFDC model uses sigma vertical coordinate and curvilinear orthogonal horizontal coordinates. It employs second order accurate spatial finite differencing on a staggered or C grid to solve the equations of momentum, while time integration is implemented using a second order accurate
three-time level, finite difference scheme with an internal-external mode splitting procedure to separate the internal shear or baroclinic mode from the external free surface gravity wave or barotropic mode. The external mode solution is semi-implicit and simultaneously computes the two-dimensional (2-D) surface elevation field by a preconditioned conjugate gradient procedure. The external solution is completed by the calculation of the depth-averaged barotropic velocities using the new surface elevation field. The model's semi-implicit external solution allows large time steps that are constrained only by the stability criteria of the explicit central difference or higher order upwind advection scheme (Smolarkiewicz and Margolin, 1993) used for the nonlinear accelerations. Horizontal boundary conditions for the external mode solution include options for simultaneously specifying the surface elevation only, the characteristics of an incoming wave (Bennett and McIntosh, 1982), free radiation of an outgoing wave (Bennett 1976; Blumberg and Kantha, 1985), or the normal volumetric flux on arbitrary portions of the boundary. The EFDC model's internal momentum equation solution, at the same time step as the external solution, is implicit with respect to vertical diffusion. The internal solution of the momentum equations is in terms of the vertical profile of shear stress and velocity shear, which results in the simplest and most accurate form of the baroclinic pressure gradients and eliminates the over-determined character of alternate internal mode formulations. Time splitting inherent in the three-time-level scheme is controlled by periodic insertion of a second-order accurate two-time-level trapezoidal step.

The EFDC model implements a second-order, accurate in space and time, mass conservation, fractional step solution scheme for the Eulerian transport equations for salinity, temperature, and other constituents. The transport equations are temporally integrated at the same time step or twice the time step of the momentum equation solution. The advective step of the transport solution uses either the central difference scheme used in the Blumberg-Mellor model or a hierarchy of positive definite upwind difference schemes. The highest accuracy upwind scheme, second order accurate in space and time, is based on a flux-corrected transport version of Smolarkiewicz's multidimensional positive-definite advection transport algorithm (Smolarkiewicz and Clark, 1986; Smolarkiewicz and Grabowski, 1990), which is monotonic and minimizes numerical diffusion. The horizontal diffusion step is explicit in time, whereas the vertical diffusion step is implicit.
Under horizontal Cartesian coordinates and the vertical sigma coordinate, the governing continuity, momentum, and transport equations used in the model (Hamrick, 1996) are

\[
\frac{\partial H}{\partial t} + \frac{\partial H u}{\partial x} + \frac{\partial H v}{\partial y} + \frac{\partial \omega}{\partial \sigma} = Q_H
\]

\[
\frac{\partial (H u)}{\partial t} + \frac{\partial (H u u)}{\partial x} + \frac{\partial (H u v)}{\partial y} + \frac{\partial (u \omega)}{\partial \sigma} - f H v
\]

\[
= -H \left( p + p_{atm} + \phi \right) + \left( \frac{\partial^2 z_b}{\partial x^2} + \sigma \right) \frac{\partial p}{\partial x} + \frac{\partial}{\partial \sigma} \left( A_v \frac{\partial u}{\partial \sigma} \right)
\]

\[
\frac{\partial (H v)}{\partial t} + \frac{\partial (H v u)}{\partial x} + \frac{\partial (H v v)}{\partial y} + \frac{\partial (v \omega)}{\partial \sigma} - f H u
\]

\[
= -H \left( p + p_{atm} + \phi \right) + \left( \frac{\partial^2 z_b}{\partial y^2} + \sigma \right) \frac{\partial p}{\partial y} + \frac{\partial}{\partial \sigma} \left( A_v \frac{\partial v}{\partial \sigma} \right)
\]

\[
\frac{\partial p}{\partial \sigma} = g H \left( \frac{\rho_w \rho_0}{\rho_0} \right) = g H b
\]

\[
(\tau_{xz}, \tau_{yz}) = \frac{A_v}{H \partial \sigma} (u, v)
\]

where \( u \) and \( v \) are horizontal velocity components in the Cartesian horizontal coordinates \( x \) and \( y \), respectively; \( b = \) buoyancy; and the vertical velocity in the stretched vertical coordinate \( \sigma \) is \( \omega \). The physical vertical coordinates of the free surface and bottom bed are \( z_s \) and \( z_b \) respectively, and \( g \) represents gravitational acceleration. The total water column depth is \( H \), and \( \phi \) is the free surface potential, which is equal to \( z_s g \). The effective Coriolis acceleration \( f \) incorporates the curvature acceleration terms according to Eqs.(3) and (4). \( Q_H \) represents volume sources and sinks, including rainfall, evaporation, infiltration, and lateral inflows and out-flows from rivers. The kinematic atmospheric pressure referenced to water density is \( p_{atm} \), and the excess hydrostatic pressure in the water column is given by Eq.(5). The vertical turbulent momentum diffusion coefficient \( A_v \) relates the shear stresses to the vertical
shear of the horizontal velocity components in Eq.(6). Actual and reference water densities are represented by $\rho$ and $\rho_0$, respectively. The values $\tau_{xc}$ and $\tau_{yc}$ are the vertical shear stresses in the x- and y-directions.

The sediment transport model is coupled with hydrodynamic model with the same resolution. The governing equation for TSS concentration is

$$
\frac{\partial HC}{\partial t} + \frac{\partial HuC}{\partial x} + \frac{\partial HvC}{\partial y} + \frac{\partial (w\tau_x) - \partial (w\tau_y)}{\partial \sigma} = \frac{\partial}{\partial x} \left( A_H \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( A_H \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial \sigma} \left( \frac{A_v}{H} \frac{\partial C}{\partial \sigma} \right) + Q_s
$$

(7)

where $C$ is suspended sediment concentration; $u, v, w$ are velocity in x, y and z-direction; $w_s$ is settling velocity; $A_H, A_V$ are horizontal diffusivity and vertically eddy diffusivity; $H$ is water depth; and $Q_s$ represents external sources and sinks. Vertical boundary conditions for the sediment transport equation are

At the water surface, $\sigma = 1$, there is no net transport across the free surface and, therefore, diffusion flux always counterbalances the settling flux and the boundary condition is

$$
-\frac{K_H}{H} \frac{\partial C}{\partial \sigma} - w_s C = 0; \quad \sigma \to 1
$$

(8)

At the sediment bed, $\sigma = 0$, the net sediment flux is equal to the summation of sediment erosion flux and sediment deposition flux (Jin and Ji 2005)

$$
-\frac{K_H}{H} \frac{\partial C}{\partial \sigma} - w_s C = J_e - J_d; \quad \sigma \to 0
$$

(9)
Where $J^r_o$ is the mass of sediment eroded from the bed and $J^d_o$ is the mass of sediment deposit to the bed per unit bed area per unit time. Resuspension flux $J^r_o$ is simulated as

$$J^r_o = \begin{cases} w_r \tau \left( \frac{\tau_b - \tau_{ce}}{\tau_{ce}} \right)^\alpha, & \tau_b \geq \tau_{ce} \\ 0, & \tau_b \leq \tau_{ce} \end{cases}$$

(10)

where $\tau_b$ is the stress exerted by the flow on the bed, $\tau_{ce}$ is the surface erosion rate per unit surface area of the bed and $\tau_{ce}$ is the critical stress for surface erosion or resuspension. The critical erosion rate and stress and parameter $\alpha$ are generally determined from laboratory or in field experimental observation.

Water column-sediment bed exchange of cohesive sediment and organic solid is controlled by the near bed flow environment and the geomechanics of the deposited bed. Net deposition to the bed occurs as the flow-induced bed surface stress decreases. The most widely used expression for the deposition flux $J^d_o$ is

$$J^d_o = \begin{cases} -w_d S_d T_d = -w_d S_d \left( \frac{\tau_{cd} - \tau_b}{\tau_{cd}} \right)^\alpha, & \tau_b \leq \tau_{cd} \\ 0, & \tau_b \geq \tau_{cd} \end{cases}$$

(11)

where $\tau_b$ is the stress exerted by the flow on the bed, $\tau_{cd}$ is a critical stress for deposition which depends on sediment material and physiochemical properties(Mehta et al.,1989) and $S_d$ is the near bed deposition sediment concentration. The critical deposition stress is generally determined from laboratory or field observations and values ranging from 0.06 to 1.1 $N/m^2$ have been reported in the literature. Given this wide range of reported values, in the absence of site specific data the deposition stress in this study case and is generally treated as a calibration parameter. The deposition stress is an input parameter in the EFDC model.

Hydrodynamic Model Calibration and Verification
In previous study, the POM hydrodynamic model (Blumberg and Mellor, 1987) has satisfactorily been calibrated and verified for Apalachicola Bay by Huang et al. (2002) and Huang and Spaulding (2002). As described above, POM and EFDC are very similar. Therefore, model setups used in the previously calibrated and verified POM hydrodynamic model were converted to the EFDC hydrodynamic model. The orthogonal curvilinear model grid system contains 954 horizontal grid cells in the horizontal (Fig.4-5). In vertical direction, five layers were employed in the sigma coordinate. The horizontal length $DX$ and longitudinal length $DX$ vary between 160m to 2000 m. The water depth in each grid ranges from 0.5m to 10.7 m and the average depth is 3.0 m.

The EFDC hydrodynamic model was calibrated and verified using the same data set that was used in the model validation of the POM hydrodynamic model (Huang et al, 2002). The EFDC model was calibrated by using the observations taken during the period of June 1 to June 15 of 1993. A 31-days spin-up period in May was used to provide initial salinity, temperature, and water surface elevation. Five boundary conditions were applied to the model domain: river inflows, winds, tides, temperature, and salinity. Ocean boundary openings were located at Indian Pass, West Pass, Sikes Cut, East Pass, and Dog Island. Measurements were taken at the ocean openings for surface and bottom salinity, temperature, and local water level. Model coefficients (bottom drag coefficient, bottom roughness, horizontal diffusion and viscosity, surface wind dragging coefficient, time-step, vertical and horizontal grids) were selected to minimize the difference between model predictions and observations. A summary of the model calibration coefficients is given in Tab.4-1.

The hydrodynamic model was verified for the period of June 16-June 30 of 1993. Comparisons between model simulation and field observations are presented in Fig.4-6 for surface elevations, and in Fig.4-7 for salinity, which show that the model predictions of hourly water level and salinity follow the general variation pattern and reasonably match the observations. Statistic comparison between model predictions and observations are reasonable as given in Tab.4-2. For surface elevation, correlation is 0.99 and the root mean square error is 0.035 m. For salinity, correlation coefficient is 0.94 and 0.84 for Cat Point and Dry Bar, respectively. At Cat Point station, the root-mean-square is 2 ppt, and the mean salinity difference is 0.9 ppt. At Dry Bar station, the root-mean-square is 2.8 ppt, and the mean salinity difference is 0.6 ppt.
Sediment Transport Model Calibration and Verification

Data sets for two storm events for the period of 6/1/2005 – 7/30/2005 as shown in Fig.4-8 were used in sediment model study. The first storm event in June was used for model calibration, and the 2nd storm event in July was used for model verification. The bottom sediments of Apalachicola Bay are silty sand, sandy silt, or silt (Kofoed and Gorsline, 1963). The sediment transport dynamics in estuaries is a complicated process. In the modeling study presented in this paper, only Total Suspended Solid (TSS) was modeled. The sediment transport model was coupled with the calibrated hydrodynamic model to simulate the total suspended sediment (TSS) transport in the bay. Weather data and turbidity data were obtained from NOAA's National Estuarine Research Reserve System (NERRS). Time variation of precipitation, wind speed and direction, and the turbidity were presented in Fig.4-2 and Fig.4-3 for Stations Dry bar and Cat Point. Tidal elevations and river flow shown in Fig.4-8 were used as model boundary conditions. With hourly observations of surface elevation, freshwater inflow/outflow, wind speed and directions specified at the hydrodynamic model boundaries, hydrodynamic model simulations provide necessary data of currents for coupled sediment model for simulating sediment resuspension and transport modeling.

Initial setting for parameters in the sediment transport model was specified based on the review of available literatures. A constant initial cohesive sediment in bed is set as $1 \times 10^4$ $\text{g/m}^2$ and bottom layer of water column has a constant cohesive sediment initial concentration of 50 $(\text{mg/l})$. The critical bottom shear stresses for sediment deposition and resuspension are the most important parameters for sediment transport modeling. A constant settling velocity of $2.0 \times 10^{-6} \text{m/s}$ and resuspension rate of $0.3 \text{g/m}^2\text{s}$ are used for cohesive sediment, and the critical stress of $0.03 \text{N/m}^2$ is applied in this study, and also, basing on the observation value at USGS station, a constant TSS carried by river inflow is chosen as 31 $\text{mg/l}$ (based on the USGS survey data at station near Sumatra, FL). The values of the parameters are selected through the calibration process of the prototype simulations.
Calibration of the sediment transport model was conducted for the period of June 1 to June 30. Initial simulation for the period from May 16, 2005 to May 30, 2005 was used as a spin-up period to provide approximate initial and field conditions. After a series of simulations, optimal model parameters were selected that provide acceptable predictions of sediment concentration in comparing to observations. Then by keeping the same model parameters, model simulations were verified by another independent data set for the period of July 1-July 30. Results from model simulations indicate that model predictions reasonably characterize the pulse increase of sediment concentration during the calibration and verification periods.

Time variation of simulating TSS concentration at both stations of Dry Bar (Fig. 4-9) and Cat point (Fig. 10) were compared with observations. Although locating at the different part of the bay, both plots shows strong correlation between sediment movement and wind speed. The peaks and valleys seen in suspended solids time series data are consistently reflected in the wind time series data. There are two storm events during the time. When the wind speed picks up, the resuspension of the sediments is accelerating, when the first storm appeared on a June 10 with wind speed at 10.7 m/s, the TSS concentration reached at 0.97 g/l at Dry Bar and 0.51 g/l at Cat point; On June 11, wind speed reduced to about 2 m/s, which would cause the sediment settled down, so the TSS concentrations were reduced to 97 mg/l at Dry Bar and 63 mg/l at Cat Point. On July 9, when a strong storm with wind speed at 18 m/s hit the region, the TSS concentration also hit the high values with 2.42 g/l at Dry Bar and 0.5 g/l, and when wind got weak, the sediment also settled down to the bed quickly. The TSS concentration at Dry Bar is higher than at Cat Point because that it is shallower, so the sediments in bed is easier to be suspended by the bottom shear stress created by the strong wind. Statistical comparisons with observations are given in Table 4-3. In Cat Point, correlation coefficients r between model predictions and observations are 0.92 for the model calibration, and 0.73 for the verification; in Dry Bar, correlation coefficients r between model predictions and observations are 0.81 and 0.75 for the model calibration and verification, respectively. The root-mean-square errors between model predictions and observed TSS concentration range from 0.03 g/l to 0.21 g/l, which are commonly considered acceptable in estuarine modeling.
Spatial Distributions of Wind-Induced Sediment Transport

Wind induced fluid velocity has a strong effect on the transport of TSS and its variation throughout not only time by also space. To invest the effect of wind on the distribution of TSS concentration along with other factors, five moments were selected during the simulating time (as shown in Fig.4-10). From those Figures, we can see that the spatial patterns in bay wide TSS are instantly impacted by physical factors such as wind, tides as well as the bathymetry of the bay. In other words, the spatial TSS patterns may change quickly with changes wind and tidal forcing. Fig.4-11 and Fig.4-15 show the TSS distribution in relatively calm period, while Fig.4-12-4.14 show changed sediment distribution in a day during a storm even. From Fig.4-11, we can see that the high TSS appeared in the southwestern part near west pass and east bay; in the early storm day of June 10, When the storm approached (as shown in Fig.4-12), the wind blow the water from southwest to northeast, the sediments in bed was resuspended and transported to northeast, so the high TSS were found at the part near east bay and the northeast corner of the bay (Fig.4-13) as the wind brought the resuspended solids in water column from the south to the east during the time, in the late of the day, when storm pasted, the wind has change direction and flowed from north to south, however, it is important to note that when wind velocities decline abruptly after storms, strong current persistent in the water as residual circulation from previous storm event. The energy created by the storm in the water column wouldn’t dissipate completely right after the storm, even when the wind had become calm, the TSS distribution still kept a similar spatial pattern (as shown in Fig.4-14), and remain the high TSS concentration at east bay and northeast mouth of the bay. The movement of sediments shows how wind can incorporate enough energy into the surface waters that a bulging effect occurs as the surface waters are pushed to one side. The bulging of the surface waters will push the deeper, denser waters to the opposite side of the estuary. While the wind kept calm for several days, high TSS concentrations were found in the southwestern part of St. George Sound and near west pass and in East bay (Fig.4-15), which is similar to Fig.4-11. This is mainly due to the features of the physical settings of the bay, or water depths are shallower in these high TSS areas than in other parts of the bay and sediments can be easily resuspended by tidal forcing when the wind is not strong.
Conclusion

Analysis of field observations indicates that sediment resuspension is highly correlated to wind speed at monitoring stations of Cat Pont and Dry Bar in Apalachicola Bay. In this study, the 3D EFDC hydrodynamic and sediment transport model has been applied to predict wind induced sediment resuspension and transport process in the bay. Employing the similar setup and same dataset from the previously calibrated POM hydrodynamic model (Huang and Jones, 2000; Huang and Spaulding, 2002), the EFDC hydrodynamic model has been satisfactorily calibrated and verified by comparing to observations of surface elevations and salinity. Coupled with the validated hydrodynamic model to obtain temporal and spatial variations of currents, the 3D sediment transport model was applied to predict sediment resuspension and transport for the period of June 1 to July 30 in 2005. The study period covers two storm events, which causes substantial increase of sediment concentrations in the field measurement stations. With field observations of freshwater inputs, wind speed and directions, and tidal elevations specified in model boundaries, the sediment model has been calibrated for the first storm event and verified with the 2nd storm event. Comparing to hourly sediment concentrations observed at Station Cat Point and Station Dry Bar, model predictions reasonably characterize the sudden increase of sediment concentration as the result of sediment resuspension in the storm event during June 10 and another storm event during July 9, 2005. The validated sediment transport model was used to simulate the temporal and spatial transport of sediment in the bay in response to dominant wind forcing together with tidal and freshwater inputs during the storm event of July 9. Spatial sediment concentrations presented at different phases demonstrate sediment resuspension, transport and deposition processes. Near the area of two oyster bars at Cat Point and Dry Bar, sediment clouds appeared as the result of the wind-induced sediment resuspension. Results from this study will provide useful sediment information to support integrated ecological study of the Apalachicola Bay system, especially on the oyster growth and mortality.

This study demonstrates that the coupled hydrodynamic and sediment transport is capable of describing the complex circulation and transport process in the shallow estuary of Apalachicola Bay in response to wind, tides, and freshwater inputs. Both observation data and simulation results indicate that Wind is considered to be a dominant factor driving the movement of suspended sediments and the result shows strong correlation between these two variables both
temporally and spatially, besides the wind, tiding current and bottom bathymetry also can affect the distribution of the suspended solids especially in calm days. Sediment re-suspension affects estuarine water quality because it usually courses releases of nutrients and other water quality constituents to the water columns. In addition, increase of turbidity leads to less light penetration through the water column. Because the EFDC model code is coupled with water quality sub model and has interface with a popular water quality model (WASP, by USEPA), the calibrated model can be used as an effective tool for scientists and resources managers to examine effects of management scenarios or natural stressors on estuarine aquatic ecosystem in Apalachicola Bay.

**Acknowledgement**

This study has been funded by USEPA STAR Grant. Data for deriving correlation regression equation between turbidity and TSS were provided by NOAA Environmental Cooperative Science Center at Florida A&M University.
### Tab.4-1 Calibrated parameters used in the hydrodynamic model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom friction coefficient</td>
<td>0.001</td>
</tr>
<tr>
<td>Winds tress drag coefficient</td>
<td>0.001</td>
</tr>
<tr>
<td>Coefficients for calculating</td>
<td></td>
</tr>
<tr>
<td>Horizontal eddy viscosity</td>
<td></td>
</tr>
<tr>
<td>Horizontal diffusivity</td>
<td>0.05</td>
</tr>
<tr>
<td>Vertical sigma layers</td>
<td>5</td>
</tr>
<tr>
<td>Time step</td>
<td>20 sec</td>
</tr>
</tbody>
</table>

### Tab.4-2 Comparison between observations hydrodynamic model predictions of water levels and salinity.

<table>
<thead>
<tr>
<th></th>
<th>Correlation r</th>
<th>RMSE</th>
<th>Mean (ppt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Observation</td>
<td>Simulation</td>
</tr>
<tr>
<td>Surface Elevation</td>
<td>0.9916</td>
<td>0.0358 (m)</td>
<td></td>
</tr>
<tr>
<td>At Cat Point</td>
<td>0.94</td>
<td>2.18 (ppt)</td>
<td>24.2 (ppt) 23.3 (ppt)</td>
</tr>
<tr>
<td>Salinity</td>
<td>0.84</td>
<td>2.87 (ppt)</td>
<td>23.51 (ppt) 24.1 (ppt)</td>
</tr>
</tbody>
</table>

Note: RMSE = root mean square error

### Tab.4-3 Statistical comparison between observations and model predictions of TSS concentration at Cat Point and Dry Bar

<table>
<thead>
<tr>
<th>TSS (g/l)</th>
<th>Cat Point</th>
<th>Dry Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calibration</td>
<td>Verification</td>
</tr>
<tr>
<td>Correlation r</td>
<td>0.92</td>
<td>0.73</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.03</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Note: RMSE = root mean square error
Fig. 4-1 Apalachicola Bay bathymetry and monitoring stations:

a) Station Cat Point Salinity, water levels, and turbidity

b) Station Dry Bar: salinity and turbidity
Fig. 4-2. Observations at Station Dry Bar from June 1 to July 30: a) Precipitation, b) wind direction, c) wind speed, d) turbidity
Fig. 4-3  Observations at Cat Point from June 1st to July 30th: a) Precipitation, b) wind direction, c) wind speed, d) turbidity
Correlation between turbidity and TSS: r=0.88
Least square fit equation: TSS =1.861 *Turb +3.383

Note: Data were provided by Kevin, Wenrui did the analysis

Fig.4-4 Correlation of TSS concentration versus turbidity in Apalachicola Bay
Fig. 4-5 Hydrodynamic model grid system
Fig. 4-6 Comparison of model prediction of surface elevation with field observation at Station Cat Point

Fig. 4-7 Comparison of model prediction of salinity with observation at monitoring stations of Cat Point and Dry Bar.
Fig. 4-8 Boundary forcing conditions for modeling wind-induced sediment re-suspension and transport during 6/1/2005-7/30/2005
Fig. 4-9 Comparison of observation and simulation of TSS at Station Cat Point during June 1 to July 30.
Fig. 4-10 Comparison of observation and simulation of TSS at Station Dry Bar. Snapshot of spatial distributions of TSS were taken at following time steps: 
A: 12 am, June 8; B: 6 am, June 10; C: 12 pm, June 10; D: 12 am, June 10; E: 12 am, June 15
Fig. 4-11 Model predicted spatial distributions of TSS concentration at 12 AM, June 8 corresponding to time step at ‘A‘ shown in Fig. 10.
Fig.4-12 Model predicted spatial distributions of TSS concentration at 6 am, June 10 corresponding to time step ‘B’ shown in Fig.10
Fig.4-13 Model predicted spatial distributions of TSS concentration at 12 pm, June 10 corresponding to time step ‘C’ shown in Fig.10
Fig.4-14 Model predicted spatial distributions of TSS concentration at 12 am, June 10 corresponding to time step ‘D’ shown in Fig.10
Fig. 4-15 Model predicted spatial distributions of TSS concentration at 12 am, June 15 corresponding to time step ‘E’ shown in Fig. 10
CHAPTER 5

GENERAL CONCLUSION

This study presents the improvements and application of the EFDC (Environmental Fluid Dynamics Code) model. The primary goal is to improve and investigate the capability of the model. In summary, there are three primary benefits associated with the project:

1) This study presents a new algorithm to reduce the numerical errors induced by the calculation of horizontal pressure gradient term near steep topography. The pressure terms in sigma coordinate system was re-organized to avoid the subtractions of two large horizontal pressure terms. The concentration profile was calculated in the convenient sigma grid cells, using the fourth order Lagrangian interpolation method, then, the horizontal concentration difference at sigma grid cell interface was determined instead of calculating horizontal pressure and its gradient, and finally the horizontal pressure gradient in the water column is calculated from the horizontal salinity gradient. The proposed method is easy to program, while it maintains fourth-order accuracy in interpolating variables between sigma and Cartesian coordinate for non-linear vertical stratification structures. The proposed algorithm was applied in EFDC model and successfully reduced the spurious flow caused by truncation errors. Method for EFDC model development can also apply to other sigma-coordinate models (e.g., POM, Delfta3D, ECOM3D, etc) for coastal and estuarine applications.

2) The enhanced Smagoringsky diffusion equation has been presented in this study, in which the horizontal diffusion coefficient is separated from the horizontal eddy viscosity. While the eddy viscosity keeps original Smagoringsky equation, the horizontal diffusivity coefficient has been revised by adding a non-tidal steam diffusion coefficient to the Smagoringsky equation. The steam diffusion coefficient value can be calibrated by sensitivity studies by comparing model predictions with field observations. Because of the decoupling of eddy viscosity and diffusion, increase or decrease of horizontal diffusion coefficient to improve model predictions of salinity will not affect model stability. In the case of Little Manatee River, model predictions by using the enhanced Smagoringsky diffusion equation have shown
substantial improvement over the original Smagoringsky scheme and Overton-fisher scheme. Because the horizontal diffusion transport of other water quality constituents are described by the same horizontal diffusion coefficient, the enhanced Smagoringsky diffusion equation decoupled from horizontal eddy viscosity will provide better predictions of the dispersion transport processes for water quality studies in tidal rivers.

3) This study demonstrates that the coupled hydrodynamic and sediment transport EFDC model is capable of describing the complex circulation and transport process in the shallow estuary of Apalachicola Bay in response to wind, tides, and freshwater inputs. Both observation data and simulation results indicate that Wind is considered to be a dominant factor driving the movement of suspended sediments and the result shows strong correlation between these two variables both temporally and spatially, besides the wind, tiding current and bottom bathymetry also can affect the distribution of the suspended solids especially in calm days. Sediment re-suspension affects estuarine water quality because it usually courses releases of nutrients and other water quality constituents to the water columns. In addition, increase of turbidity leads to less light penetration through the water column. Because the EFDC model code is coupled with water quality sub model and has interface with a popular water quality model (WASP, by USEPA), the calibrated model can be used as an effective tool for scientists and resources managers to examine effects of management scenarios or natural stressors on estuarine aquatic ecosystem in Apalachicola Bay.

Further improvements to the presented study would include applying more case studies for environmental and ecological studies, and more comprehensive study for sediment model calibration and validation. There are some limitations of the sediment modeling in current study that should be considered and improved upon in future study. One class of suspended sediment was simulated in all the model runs. Constant values of critical shear stress for erosion and settling velocity were applied over the entire model domain. Varying bed and suspended sediment size distribution existed in the bay and the critical shear stress and settling velocity may vary with characteristics such as the sediment type, bioturbation of the bottom sediments or the depth of the eroded material (Jin L. and Albert Y., 2003). Although the wind has been proved to be the dominant force of the sediments transport in Apalachicola bay, some other factors such as
the sediment carried by the tide from the Gulf and runoff of the precipitation may still impact the sediments in the bay, which haven’t been counted because of the shortage of available data. For more accurate results, further more complicated study might be considered depending on the availability of the data.
BIBLIOGRAPHY


Department of Mechanical and Environmental Engineering, University of California, Santa Barbara.


Livingston, R.J., 2006, Restoration of Aquatic Systems, CRC Press, Boca Raton, FL.


BIOGRAPHICAL SKETCH

Education

PhD; Civil and Environmental Engineering, Florida State University (successfully defended the dissertation on April 9th, 07)

- Dissertation: Three dimensional Numerical Model of Hydrodynamics and Transport in Estuaries. (Main works include: Improved EFDC model in reducing horizontal pressure gradient and horizontal diffusion induced numerical errors, with model validation, one application in Apalachicola Bay, and another in Little Manatee River).

M.S; Civil Engineering, Dalian University of Technology, July, 2002

- Thesis: 2-D Hydrodynamic and Pollutant Transport Model in Hakata Bay

B.S; Civil Engineering and Computer Engineering, Dalian University of Technology, July, 1999

Professional experience

Florida State University, Civil and Environmental Engineering Tallahassee, FL

Research Assistant 08/03 - current

- Applied efficient methods to reduce numerical errors in sigma coordinate hydrodynamic models (enhanced EFDC code)
- Developed 3-D Apalachicola Bay hydrodynamic and sediment transport model
- Developed 3-D Little Manatee River hydrodynamic model (enhanced EFDC model code)
- Joined the development of coupled physical and ecological models for stress-response simulations of Apalachicola Bay

Teaching Assistant 08/04-05/05

In charge of Hydraulics lab (Required course in our Department for all undergraduate students)

Dalian University of Technology, China

Research Assistant 01/01-01/03

Developed 2-D hydrodynamic and pollutant transport model in Hakata Bay (Japan)

Certificate & Membership

- Engineer-in-Training (E.I.T.)
- American Society of Civil Engineer (A.S.C.E.)
- American Geophysical Union (A.G.U)
Publication

Liu, X and Huang, W. Three dimensional modeling of wind-induced sediment transport in Apalachicola Bay. Submitted

Liu, X and Huang, W. Enhancement of horizontal diffusion calculation in modeling of salinity in a shallow tidal river. Submitted

Liu, X and Huang, W. An effective method to reduce horizontal pressure gradient errors in 3D sigma-coordinate coastal hydrodynamic and transport models. Submitted

Liu, X and Huang, W. Validating A 3-D hydrodynamic and sediment transport model in steep sloping channels. ASME/ASCE/SES mechanics and materials conference at Louisiana State University, Baton Rouge, June 1-3, 2005.


Liu, X and Huang, W. Three dimensional sediment transport model study in Apalachicola Bay. 4th National Oceanic and atmospheric administration education partnership program education and science a forum. Florida A&M University and ECSC(NOAA), Tallahassee, Oct.30-Nov. 1, 2006.