ABSTRACT

MOLINA, JONATHAN RUEDA. Estuarine exchange model of the Pamlico and Albemarle Sounds. (Under the direction of Tom Sawyer Hopkins.)

The thermohaline dynamics of the Croatan-Albemarle-Pamlico Estuarine System (CAPES) controls its estuarine circulation and exchange with the Atlantic Ocean. The exchange with the ocean controls the physical flushing of the freshwater input to the estuarine system and thereby has great influence on its biological, chemical, and physical environment. An improved effort in quantifying the exchange will assist in better defining the biological response of the CAPES to its external forcing. The present study demonstrates the utility of a new approach proposed by Hopkins (1999) for determining the exchange based on the internal potential energy difference between the system and the ocean. The method has the advantage of using easily observable data, i.e., the internal water balance and oceanic salinity. A model of the CAPES exchange, or the Albemarle Pamlico Sound Estuarine Exchange (APSEEx) Model, was constructed using simulation modeling software (EXTEND™). Models developed in this fashion are very economical and facilitate duplication, modification and transfer among users since EXTEND™ is cross-platform compatible (i.e., the software runs in both Windows and Macintosh systems). The major assumptions of the model are that the Sounds are laterally well-mixed to the depth of the sill, and that the exchange with the ocean occurs only through a single inlet having a combined cross-sectional area of the three barrier island inlets (i.e., Oregon, Hatteras, and Ocracoke Inlets). For lack of data, two important processes in the inlet, the vertical mixing (based on the Richardson number) and the bottom friction (based on Ekman dynamics), were calibrated by obtaining a best fit between the model
and observed salinity in the Pamlico Sound. The calibrated model (APSEEx 1998-2000) was able to follow the trend of the internal salinity with $R^2=85.1\%$. By applying a mean water balance (1998-1999) and a mean ocean salinity ($=29.5$ ppt) to the year 2000 instead of their in-situ values, the model was able to predict salinity in the Pamlico Sound for a specific period, i.e., on the order of months. Time-dependent flushing times were calculated for the period 1998-2000. Freshwater replacement of the freshwater volume by river discharge takes $\sim9$ months, while the flushing of the PS volume by the inflowing ocean water is $\sim3$ months. To achieve a reliable simulation model, better time series salinity data from the ocean and sound would be needed, together with calibration data in the inlets for the salinity-mixing and bottom friction coefficients. Possible applications of the APSEEx Model to several scientific and management issues related to the CAPES are discussed. Suggested improvements to the model are also described.
ESTUARINE EXCHANGE MODEL OF THE
PAMLICO AND ALBEMARLE SOUNDS

by
JONATHAN R. MOLINA

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

MARINE, EARTH AND ATMOSPHERIC SCIENCES

Raleigh

2002

APPROVED BY:

David J. DeMaster
David B. Eggleston

Leonard J. Pietrafesa

Tom S. Hopkins
Chair of Advisory Committee
DEDICATION

This work is dedicated to my wife, Reverie

For your love, understanding and support
BIOGRAPHY

Jonathan Molina was born on December 11, 1970 in Makati City, Metro Manila, Philippines. Jon and his siblings were raised by their loving parents, Nomy and Josie, in Las Pinas City. Jon graduated high school from De La Salle-Zobel in 1988. It was while playing ‘fútbol’ for La Salle that he got a chance to play for the Philippines in the world youth soccer tournament (Gothia Cup) in Göteborg, Sweden. Jon wanted to become a medical doctor ever since he was a child and pursued an undergraduate degree in zoology at the University of the Philippines at Los Banos (UPLB). While taking courses in marine zoology and taxonomy, Jon's interests shifted to the marine world. In fact, when he first donned his SCUBA gear in Anilao, Batangas, he immediately he fell in love with the magnificent view of lively corals and colorful reef fishes that seemed to entice him to stay longer than his Actual Bottom Time. He wanted to study more about the oceans and decided to skip medical school. After graduating from college in 1992, he entered the Marine Science Institute at the University of the Philippines (UP-MSI) in Diliman, Quezon City. At UP-MSI, he worked as a research assistant and was involved in several zooplankton and water quality studies in Bolinao, Pangasinan, and scientific expeditions in the South China Sea. He was also actively engaged in other non-marine science matters, because it was at UP-MSI where Jon met and fell in love with his wife, Reverie. Then came the opportunity to study at NC State University. When Jon entered the marine science graduate program at the Department of Marine, Earth and Atmospheric Sciences (MEAS) in Fall 1998, Prof. Tom Hopkins introduced Jon to the systems approach of thinking and solving environmental problems. The stabilizing feedback loop established between Jon and his advisor helped Jon appreciate the science behind estuarine dynamics. Tom also introduced him to EXTEND™ simulation modeling, which Jon has mastered and later applied in his thesis. While working on his masters degree, Jon had the opportunity to teach two undergraduate lab courses (Introductory Oceanography and Earth Systems Simulation Modeling). His initiative in improving these courses paid off when he was presented with the Outstanding Teaching Assistant Award in 2000 and 2002.
ACKNOWLEDGEMENTS

The completion of this masters program would not have been possible without the support, patience and generosity of the following:

My Lord and Savior Jesus Christ - I praise You for the wisdom that You have given me all these years. Thanks for making me a good steward of the Father's creation. “How many are your works, O Lord! In wisdom you made them all; the earth is full of your creatures. There is the sea, vast and spacious, teeming with creatures beyond number-living things both large and small.” Psalm 104: 24-25 (NIV). Thank you for the strength to carry on, for “I can do all things through Christ who strengthens me” Philippians 4:13 (NKJV).

My wife, Reverie - I wouldn't have made it through without your sacrificial love, support, patience, good sense of humor, and good old home-cooked food. Thanks for being my best friend, and for reminding me always to have faith in God.

My family - your continued prayers and support for my endeavors in life have made it possible for you to have a scientist in the family. Dad and Mom, thanks for trusting in me and for allowing me to be adventurous in life.

My advisor, Prof. Tom Hopkins - Thanks for believing in my abilities. Your guidance, constant support, patience, constructive criticism, and creativity throughout this process are unmatched. I also extend my appreciation to my committee members, Drs. Dave DeMaster, Dave Eggleston and Len Pietrafesa, for their valuable inputs to the manuscript.

The Marine Science Graduate Program at the Marine, Earth and Atmospheric Sciences department, headed by Dr. Gerald Janowitz - I am grateful to the education and teaching assistantship that was provided to me throughout my program. I am also indebted to the NC Sea Grant, headed by Dr. Ronald Hodson, for the mini-grants provided to Prof. Hopkins during summers 2000-2001.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>ix</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>3</td>
</tr>
<tr>
<td>Site Dimension and Water Balance</td>
<td>3</td>
</tr>
<tr>
<td>Hydrography</td>
<td>4</td>
</tr>
<tr>
<td>Wind Forcing</td>
<td>6</td>
</tr>
<tr>
<td>Tides</td>
<td>7</td>
</tr>
<tr>
<td>ESTUARINE EXCHANGE</td>
<td>8</td>
</tr>
<tr>
<td>Estuarine Circulation</td>
<td>8</td>
</tr>
<tr>
<td>Methods of Determining Exchange</td>
<td>9</td>
</tr>
<tr>
<td>Stabilizing Feedback Loop</td>
<td>15</td>
</tr>
<tr>
<td>INPUT DATA</td>
<td>16</td>
</tr>
<tr>
<td>Discharge</td>
<td>16</td>
</tr>
<tr>
<td>Water Temperature and Calibration Salinity for the PS and AS</td>
<td>18</td>
</tr>
<tr>
<td>Water Temperature and Salinity for the Atlantic Ocean</td>
<td>21</td>
</tr>
<tr>
<td>Meteorology</td>
<td>23</td>
</tr>
<tr>
<td>MODEL APPLICATION</td>
<td>25</td>
</tr>
<tr>
<td>EXTEND™ Formulation</td>
<td>28</td>
</tr>
<tr>
<td>RESULTS</td>
<td>35</td>
</tr>
<tr>
<td>APSEEx 1998-2000 Model (PS H-block)</td>
<td>36</td>
</tr>
<tr>
<td>APSEEx 1998-2000 Model (AS H-block)</td>
<td>42</td>
</tr>
<tr>
<td>APSEEx 1990-1991 Model</td>
<td>43</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>43</td>
</tr>
<tr>
<td>Possible Applications</td>
<td>47</td>
</tr>
<tr>
<td>Concluding Remarks</td>
<td>51</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>52</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1. Major sources of freshwater running into the Pamlico and Albemarle Sounds and mean annual precipitation minus evaporation (P-E) values for each basin ..................................................... 58

Table 2. Summary of thermohaline exchange model input and *in-situ* calibration data ..................................................... 58

Table 3. Names and summary description of thermohaline exchange models ..................................................... 58

Table 4. List of simulations conducted with the thermohaline exchange model ..................................................... 58
LIST OF FIGURES

Figure 1. Map of Pamlico and Albemarle Sounds, NC .......................... 59
Figure 2. Two-way thermohaline exchange through an inlet .................. 60
Figure 3. Stabilizing feedback loop for a positive thermohaline circulation . . 61
Figure 4. Water quality sampling stations established by the US Geological Survey (USGS) in AS during January 1990-September 1991 .... 62
Figure 5. Selected sampling stations established by the Duke University Marine Lab (DUML) in the southwestern basin of Pamlico Sound, NC between Fall 1998 and Spring 2001 ...................... 63
Figure 6. Synoptic view of the model results for PS salinity .................... 64
Figure 7. Comparison between 1998-2000 Duck Pier salinity and the seasonally varying corrected salinity used in the APSEEx Model .... 65
Figure 8. Albemarle-Pamlico Estuarine Exchange (APSEEx) model organization ................................................................. 66
Figure 9a. Precipitation and Runoff for the first year of series, 1998 ........ 67
Figure 9b. As in 9a for the period August 8-September 3, 1998 ............. 67
Figure 10a. Precipitation and Runoff for the second year of series, 1999 .. 68
Figure 10b. As in 10a for the period August to November 1999 .......... 68
Figure 11. Precipitation and Runoff for the third year of series, 2000 .... 69
Figure 12a. Comparison between the Salinity response and Water Balance Transport during 1999 .............................................. 70
Figure 12b. As in 12a for the period August 1999 to April 2000 .............. 70
Figure 13a. Comparison between the Salinity response and Water Balance Transport during 1998 .............................................. 71
Figure 13b. As in 13a for the period January to June 1998 .................. 71
Figure 14. Comparison between the Salinity response and Water Balance Transport during the period January 1-April 15, 1999 .......... 72
Figure 15. Comparison between the total inflowing volume from the ocean and the total outflowing volume from the sound during 1999 . . . . . 73

Figure 16. Linear regression plot between log-transformed model and observed salinity collected by the DUML for the period 1998-2000 . . . . . 74

Figure 17. Simulation plot for PS salinity applying 1998-1999 mean runoff + net precipitation to the year 2000 . . . . . . . . . . . . . . . . . . . . . 75

Figure 18. Simulation plot for PS salinity applying a mean ocean salinity (=29.5 ppt) to the year 2000 . . . . . . . . . . . . . . . . . . . . . 75

Figure 19. Comparison between the model and observed salinity collected by the DUML during the period 1998-2000 . . . . . . . . . . . . . . . . . . . . . 76

Figure 20. Comparison of Runoff into PS and AS during the period 1998-2000. 76

Figure 21. A comparison between the model and observed salinity collected by the USGS during the period January 1990-September 1991 . . . . . 77
LIST OF APPENDICES

Appendix A. List of data sets for the CAPES region gathered from various agencies ........................................... 79

Appendix B. List of data sets for the Atlantic Ocean gathered from various agencies .................................................. 83

Appendix C. Quick reference to commonly used blocks in EXTEND™ ................................................................. 84

Appendix D.1. Hierarchical blocks representing PS and AS .......................................................... 88

Appendix D.2. Input data panel (PS H-block) .......................................................... 89

Appendix D.3. Preliminary equations panel (PS H-block) .......................................................... 90

Appendix D.4. Steric-height and transport equations panel (PS H-block) ...................................................... 91

Appendix D.5. Thermohaline exchange equations panel (PS H-block) ...................................................... 92

Appendix D.6. Salt and freshwater budgets panel (PS H-block) .......................................................... 93

Appendix E. PS salinity generated by the APSEEx Model for different time periods: (1) January 1990-September 1991; (2) 1996; and (3) 1998-2000 .......................................................... 94

Appendix F. Neuse Estuary Oxygen Model .......................................................... 95
INTRODUCTION

Thermohaline circulation develops through changes in water buoyancy between estuarine basins and the external ocean. Buoyancy gradients generate density gradients, or an internal pressure field fundamental to the estuarine circulation and its exchange with the ocean. Estuarine exchange can have considerable influence on the biological (e.g., larval transport), chemical (e.g., water quality: fate of nutrients; BOD) and physical (e.g., water density, salinity) attributes of an estuarine system (e.g., Hopkins 1978, 1999, 2001; Paerl et al. 1998; Epifanio and Garvine 2001). Knowledge of the exchange can aid in understanding how frequently these attributes are introduced into or flushed out of the system.

An example of a complicated estuarine system is the Croatan-Albemarle-Pamlico-Estuarine System (CAPES), located in eastern North Carolina (NC) (Figure 1). The CAPES is the largest barrier island estuary in the United States (US) and is a key nursery area for the US east coast fisheries (Figure 1). The shallow areas and salt marshes along its fringes serve as nurseries and habitats for all or portions of the life cycle of a variety of commercially important marine species that include blue crabs (*Callinectes sapidus*), croakers (*Micropongonias undulates*), and shrimps (family Penaeidae). During the past several decades, signs of environmental stress are manifested in a number of trends: inappropriate land use, poor agricultural practices, hog production, groundwater pollution, beach erosion on the barrier islands, and over-exploitation of fisheries resources. Some of the consequences have involved flooding, declining fisheries, outbreaks of fish and crab diseases, eutrophication, frequent blooms of algae, and

The poor ecological state of the CAPES is even more compounded by the accumulating evidence that increased incidences of hurricanes can affect the ecological recovery of the sound system (Paerl et al. 2001; Eggleston et al., unpubl. data; Ramus et al., unpublished). These authors have reported that the impacts associated with hurricanes were present in the southwestern Pamlico Sound (PS) after three consecutive hurricanes, "Dennis", "Floyd" and "Irene" affected coastal NC in September and October 1999. Using discharge data from US Geological Survey (USGS) and direct rainfall estimates (rain gauge and Doppler radar measurements) on the surface of PS and Albemarle Sound (AS), Paerl et al. (2001) calculated the subsequent freshwater input into PS during September and October 1999 to be approximately $2.0 \times 10^{10}$ m$^3$ or 83% of the volume of PS. From one week before to two weeks after the passage of "Floyd", they reported a drop in salinity from ~19 ppt to 9 ppt in the surface waters of southwestern PS. Moreover, they also reported a 50% minimum increase in the nitrogen loading that induced increased algal blooms in the PS. They suggest that the depressed salinity and elevated nitrogen loading both created harsh conditions for resident fish and invertebrate species in the PS.

Given that the sound system serves as a processing basin for discharged pollution, nutrients, organic matter and the large volumes of water that feed into the system during hurricane events, the CAPES' resiliency thus becomes a significant problem needing further study. For example, the amount of time it takes for normal salinity to be re-established in the system after major flooding is especially important to estuarine-
dependent organisms (e.g., crabs and shrimps) that may be sensitive to low salinity conditions. Better understanding of the estuarine exchange with the ocean thus becomes an important objective in predicting the amount of time it takes for normal salinity to be re-established.

The methods commonly used to measure the exchange between a basin and the ocean have been through direct observations in the inlet (e.g., current meter measurements), application of the steady-state Knudsen relations, and through numerical circulation models. Recently, Hopkins (1999) developed an approach, called the Thermohaline Exchange Method (TEM) for determining estuarine exchange. The TEM depends only on observable data external to the inlet. In this thesis, I investigate the feasibility of adapting the TEM to a positive estuarine situation where daily time-series of meteorological and ocean-salinity data are available. The objectives of this work were to: (1) adapt the TEM for the CAPES, (2) construct a 2-box model of the PS and AS by utilizing EXTEND™ simulation software, and (3) simulate the exchange for the 3-year period (1998-2000) during which adequate time-series data existed.

**BACKGROUND**

*Site dimension and water balance*

The Pamlico Sound (PS) and the adjoining Albemarle Sound (AS) are the two major bodies of water that comprise the CAPES and both serve as holding basins for the major portion of NC’s drainage system (Figure 1). The system is relatively shallow, with its western shore bounded by the mainland and its eastern shore protected from the Atlantic Ocean by a 200-mile stretch of barrier islands known as the "Outer Banks".
The PS, which is the larger of the two sounds, covers an area of approximately 4350 km\(^2\) and has an average depth of approximately 4.5 m. It is characterized by a complex bathymetry, with extensive shoaling around the margins and within the sound. The sound has two sub-basins separated by Bluff Shoal, which runs from Bluff Point on the northwestern mainland shore to Ocracoke Inlet on the opposite southeastern barrier island shore (Figure 1). The northern sub-basin (max. depth approx. 8 m) is generally deeper than the southern sub-basin (max. depth ~7 m). To the north, the PS is coupled with the AS via Croatan (~3 m) and Roanoke Sounds (~3 m). To the south, it is connected to Core Sound (~1 m). Major sources of freshwater into the PS are the Neuse and the Tar-Pamlico rivers and the AS (Table 1) (Giese et al. 1985). Exchange of PS with the ocean occurs via the barrier island inlets that include Oregon, Hatteras and Ocracoke inlets.

The AS covers an area of approximately 1243 km\(^2\) and has an average depth of ~5.5 m, which is comparable to its larger counterpart. The maximum depth is almost 9 m. The Chowan and Roanoke rivers are the major rivers that drain into the AS (Table 1) (Giese et al. 1985). Other lateral tributaries include Perquimans, Little, Pasquotank, North and Alligator Rivers, and Currituck Sound. In contrast to the PS, the AS does not have an open interaction with the Atlantic Ocean.

**Hydrography**

Although the CAPES is ecologically and economically significant, very little work has been done since the early 1950s in studying and describing its water properties and hydrodynamics, most of which derive from studies in the PS (e.g., Marshall 1951;
Water temperature in the PS and AS has a seasonal cycle that is nearly in phase with the air temperature. Surface water temperature data, obtained from the NC USGS website (http://www.nc.usgs.gov), show that maximum temperatures occur during the summer months (June-July) and can reach up to 30°C, while the minimum exists during the winter months (December-January) and can go down to almost freezing temperature. Thermal gradients between the surface and bottom layers are weak (<3°C) and thermal variations across the sound do not exceed 2°C. (Roelofs and Bumpus 1953; Bowden and Hobbie 1977).

Salinity data sampled in the southwestern PS (courtesy of J. Ramus-Duke University Marine Lab (DUML)) for the years 1998-2000 show that in the surface mixed layer (~4 m), maximum salinity (~20 ppt) occurs during the summer months while minimum salinity (~10 ppt) occurs during the late fall and early winter months (also Ramus et al., unpublished). Below the wind-mixed layer, remnants of ocean input salinity accumulate in the deeper portions of the sound and create a halocline of 4-6 ppt.

Spatially, the salinity is fairly uniform except near its end points at the mouths of rivers and at the bottom near inlets. A weak horizontal salinity gradient in the north-to-south and west-to-east orientation exists with the high salinity distributed in the southern and eastern regions of the Sound since these are adjacent to the inlets that connect PS to the ocean (Pietrafesa et al. 1986). The salinity in the southern end near Ocracoke Inlet tends to be higher than in the northern end near Oregon Inlet due to relative differences in the salinity of the source of saltwater. For example, the ocean water that enters through Ocracoke and Hatteras Inlets is a near-shore modification of the Carolina Coastal Water
(CCW), which ranges from 34.5-37 ppt (Pieterafesa et al. 1986). Conversely, the water that enters Oregon Inlet is influenced by Virginia Coastal Water (VCW), which ranges from 31-34 ppt (Pieterafesa et al. 1986).

In contrast to PS, AS is less saline because it does not have a direct connection with the ocean. Salt that enters through Oregon Inlet is diluted in the PS and reaches the AS via Croatan and Roanoke Sounds. The AS has an average salinity ranging from 0-5 ppt. Because the AS is generally shallow, winds also have a significant effect on mixing.

**Wind forcing**

Wind can indirectly impact salinity of ocean water entering PS via the inlets as shown in two examples of hydrographic data collected near Oregon Inlet. In a study during the period 20 June-2 July 1973, southerly winds induced Ekman transport of surface waters away from the coast with a sequential upwelling and replacement of colder bottom waters that moved through the Inlet on a flood tide. During northerly winds, constant warmer temperatures were observed in PS as upwelling was interrupted and warmer downwelled oceanic waters passed through the Inlet on a flood tide (Knowles and Singer 1977). In a similar study for the period 9 February-3 March 1974, southerly winds near Oregon Inlet forced the subtidal frequency to flow out of the Inlet ("ebb"), while the opposite was true ("flood") under northerly winds (Singer and Knowles 1975; Pietrafesa and Janowitz 1988). In fact, the wind control on the salinity is further complicated by the existence of the southern Inlets, Ocracoke and Hatteras. That is, southerly winds, most common in the summer, tend to set up the sea-level on the PS side and set down the ocean sea-level at Oregon Inlet more strongly than they do for the
southern inlets. This situation favors a greater outflow to the north and a greater (compensating) inflow to the south. Conversely, under northeasterly winds, which is predominant in winter, more inflow occurs at Oregon inlet and more outflow occurs at the southern Inlets (Xie and Pietrafesa, 1999). This wind control on the exchange does not affect the volume balance but does affect the salt because the salinity of ocean water to the south is greater.

Wind forcing, in addition to thermohaline exchange and tides, is a principal forcing function controlling water circulation and mixing. Wind roses for Cape Hatteras for the year 1941 (Marshall 1951) show that the mean wind field is generally bimodal with south to southwesterly winds blowing from March to August and north to northeasterly winds from September to February. These prevailing conditions were also observed in PS during 1978-1980 (Pietrafesa et al. 1986). Wind stress vector fields from Cape Hatteras and New Bern were found to be aligned in a northeasterly-southwesterly direction and similar to the major axis of PS. Moreover, winds from a barrier island station at Cape Hatteras tend to have a larger magnitude than winds from a mainland station at Cherry Point (Pietrafesa et al. 1986).

Tides

The tides in the PS are small except near the inlets (Marshall 1951). Tidal effects are rapidly dampened with distance from the inlets due to the small tidal volume. However, the principal lunar semi-diurnal or M2 component (period = 12.42 h), which is the main tidal constituent in both the Mid and South Atlantic bights, dominated in several
sea-level and current measurements made at stations within the Sound including Neuse River (Singer and Knowles 1975; Chao 1981; Pietrafesa et al. 1986).

ESTUARINE EXCHANGE

Estuarine circulation

Several different classification schemes have been used to characterize different estuaries (Stommel 1951; Pritchard 1952, 1955; Cameron and Pritchard 1963; Hansen and Rattray 1966). Initially, Stommel (1951) suggested that classification be based primarily on processes such as tides and winds that contribute most to vertical mixing in the estuary. Pritchard (1952, 1955) and Cameron and Pritchard (1963) next proposed that estuaries be classified based on two schemes. The first scheme was based on the geological or geomorphological processes that formed the estuary (i.e., drowned river valley, fjord type, bar built and tectonic estuaries). The second scheme was based on characteristics of relative salinity stratification in the estuary (salt wedge or highly stratified, partially mixed or moderately stratified, and well-mixed or vertically homogeneous). Pritchard (1952, 1967) also classified estuaries based on dilution: positive (where runoff and precipitation exceeds evaporation), inverse (where evaporation exceeds runoff and precipitation), and neutral (where there is a balance between freshwater supply and evaporation). Subsequently, there were attempts to quantify estuarine classification. Hansen and Rattray (1966) described the vertical stratification and water circulation in the estuary (through the stratification-circulation diagram) by developing a two-parameter system of estuarine classification that required measurements of salinity and velocity. Such an attempt to quantify estuarine
classification is constrained by the amount of salt that enters the estuary and the amount of kinetic energy that cause mixing within the estuary (Pritchard 1989). Hopkins (1978) defined thermohaline circulation in estuaries as positive and negative based on whether dense bottom water originates externally (ocean) or internally (estuary), respectively. Hence, a corresponding criterion would require that bottom densities be lesser internally \((\rho_{\text{external}} - \rho_{\text{internal}} > 0)\) for positive basins and bottom densities be greater internally \((\rho_{\text{external}} - \rho_{\text{internal}} < 0)\) for negative basins. Estuarine circulation can be illustrated by a simple sequence of events in a rectangular-shaped tank that is initially partitioned by a temporary barrier (Pritchard, 1989). On one side of the barrier is freshwater and on the other side is saltwater. When this barrier is eliminated, gravity acts on the density differences between freshwater and saltwater. Saltwater, being more dense than freshwater, flows down and under the freshwater. At the same time, freshwater flows up and above the saltwater. This results in a stratified water column with lighter (fresh) water at the top and heavier (salt) water at the bottom. The net seaward flow through the estuary will be equal to the freshwater discharge. River water will tend to flow seaward as a layer of freshwater and will be separated by a distinct interface above that of the underlying saltwater (Bowden 1967). This type of circulation is initiated when the density or buoyancy of the surface water is changed at some location relative to another.

**Methods of determining exchange**

**A. Direct Observations**

Time-series measurements of fluxes in inlets are complex and insufficient to properly monitor the net volume or salt exchange between semi-enclosed basins
(Hopkins 1999). The research challenge lies not only with the hazards involved in the installation of the instrument in the field but more importantly with the difficulty of integrating point measurements over the inlet's area, both in the vertical and horizontal direction.

B. Knudsen Relations

The Knudsen relations are based on volume and mass (salt) conservation. They assume a steady-state condition in both water volume and salt fluxes. The Knudsen relations have long been used in approximating the annual mean water-exchanges, e.g., in the Hardangerfjord (Norway) by Saelen (1967).

The salt continuity equation in the PS can be expressed as:

\[ \rho_{AO} S_{AO} V_{AO} = \rho_{PS} S_{PS} V_{PS} , \]  

where \( S_{AO} \) and \( S_{PS} \) are the salinities of the inflowing Atlantic Ocean water and outflowing PS water, respectively; \( \rho_{AO} \) and \( \rho_{PS} \) are the respective densities (kg m\(^{-3}\)); and \( V_{AO} \) and \( V_{PS} \) are the respective volume transports (m\(^3\) d\(^{-1}\)). In practice, the \( \rho_{AO} \) and \( \rho_{PS} \) can be canceled since the two densities are the same (3% variation at the most; Pickard and Emery 1990). Therefore Eq. (1) becomes:

\[ S_{AO} V_{AO} = S_{PS} V_{PS} . \]  

The volume continuity, on the other hand, gives the following relationship for the PS:

\[ V_{AO} + R_{PS} + P_{PS} = V_{PS} + E_{PS} , \]  

where \( R_{PS} \), \( P_{PS} \), and \( E_{PS} \) are the river runoff, precipitation, and evaporation in the PS, respectively. If the water balance (\( WB \)) for PS is taken as

\[ (R_{PS} + P_{PS}) - E_{PS} = WB , \]  

10
then the volume transport outflowing from PS is

\[ V_{ps} = V_{ao} + WB. \]  \hspace{1cm} (5)

By combining Eqs. (2) and (5), the Knudsen relations for salt conservation through a cross-section in the inlet is given as the following set of equations:

\[ V_{ao} = \frac{WB \cdot S_{ps}}{S_{ao} - S_{ps}} \]  \hspace{1cm} (6.1)

and

\[ V_{ps} = \frac{WB \cdot S_{ao}}{S_{ao} - S_{ps}}. \]  \hspace{1cm} (6.2)

Assuming steady state for the Knudsen relations in PS is equivalent to neglecting variability in the salinities of PS and the ocean. While steady-state conditions may be a valid approximation over long time-scales, it is not justifiable over shorter time-scales, such as seasonal to weekly. For example, salinity measurements in the CAPES (e.g., Pietrafesa et al. 1986, Garret 1993) demonstrate considerable variability. Thus, the Knudsen relations cannot be applied to monitor the thermohaline exchange in the CAPES relevant to many of the issues cited in the Introduction.

C. Numerical Modeling

An approach that has been applied in investigating ocean circulation and exchange is by solving the modified versions of the Navier-Stokes equations through numerical modeling. Several studies, particularly in the CAPES region, have utilized this approach to investigate estuary-shelf exchange processes (e.g., Pietrafesa et al. 1986; Pietrafesa and Janowitz 1988; Pietrafesa and Janowitz 1991; Xie and Eggleston 1999).
A sophisticated, three-dimensional (3D) shallow water model, the PALPAM, revealed that PS reaches a quasi-steady state condition within 10 hours of the onset of wind forcing. Although the PALPAM model indicated good agreement with sea-level changes on the PS side of the Oregon Inlet, the model was slow in predicting these sea-level response times, i.e., the spin up of sea-level at Oregon Inlet lagged observations by 26 hours (Pietrafesa et al. 1986; Pietrafesa and Janowitz 1991). The PALPAM model also lacked the capacity to simulate the baroclinic flows in areas such as those near the rivers and inlets. Moreover, the model simulated the PS and the AS separately such that the water exchange between the two sounds was prescribed at the model grid boundary linking the two sound basins (Xie and Pietrafesa 1999).

Recognizing the significance that the individual compartments of a system do not function independently, Xie and Pietrafesa (1999) adapted a 3-D Princeton Ocean Model (POM) to the CAPES and used a system-wide modeling approach by dynamically coupling the PS and the AS, and the CAPES and the adjacent continental shelf. The baroclinic, wind-driven model was applied using the passage of a cold front (which caused an abrupt wind shift from southwesterly to northerly) as a test case. An analysis of the model results and observations indicated that the 3-D model was able to reproduce the circulation and salinity distribution within the CAPES and the exchange between the CAPES and coastal ocean over short time-scales (i.e., days). The model was also able to simulate the formation of a low salinity plume on the ocean side of Oregon Inlet, which was verified in a sea surface temperature (SST) AVHRR image observed by a NOAA satellite (16 March 1996).
In a similar modeling experiment, Xie and Eggleston (1999) used the same model to analyze the effect of different wind directions on the exchange between the CAPES and the Atlantic Ocean and to relate the effects with the spatio-temporal variation in larval supply of estuarine-dependent fish and crustaceans in the CAPES. Two different water-exchange modes were identified: a stratified mode and an unstratified or barotropic mode. The stratified mode (where surface and bottom flow are distinctly different in all inlets) was produced during westerly and southwesterly winds, whereas the stronger barotropic mode (surface and bottom flow are in the same direction, with inflow occurring in Oregon Inlet and outflow in Hatteras and Ocracoke Inlets) was produced during northerly and northeasterly winds. With these two modes, several larval recruitment patterns were postulated in each inlet. Thus, spatio-temporal variability in larval recruitment into PS was attributed to the interplay of the wind forcing with the topography of the coastline, as well as the location of the source inlets in which the larvae entered the CAPES (Xie and Eggleston 1999).

The application of numerical models in the CAPES in the previous discussion provides us with a synoptic view of wind-driven water circulation, inlet exchange and spatial distribution of conservative properties (i.e., salinity). However, none of these modeling efforts has attempted to measure the thermohaline exchange in the inlets and to monitor the salinity fluctuations over annual time-scales by coupling the exchange with the freshwater discharged into the system.

D. Thermohaline Exchange Method (TEM)

Hopkins (1999) developed an alternative method for calculating the thermohaline exchange for the case of the Gibraltar Strait in the Mediterranean. This method was
recently applied to the PS (Hopkins 2001), which is an estuary characterized by positive thermohaline circulation. The fundamental hypothesis of the approach is that thermohaline exchange occurring in the inlets is proportional to the internal potential energy difference between the two basins at the depth of the sill. The dynamic sequence for the thermohaline exchange has been described in more detail for a positive estuary in Hopkins (2001). Briefly, when freshwater runoff and rainfall accumulates in the PS, significant positive buoyancy is added to the system. This causes the density of the water columns inside the PS to decrease and to have less weight than the water columns in the ocean (since salinity largely influences density in this case). A landward baroclinic pressure gradient is produced at the depth of the sill, and saltwater from the ocean is forced into the PS. Since the weight of the water increases with depth, the baroclinic force and the resulting baroclinic flow will similarly increase with depth. Contemporaneously, the internal sea-level rises due to the combination of the inflow volume and the increased steric-height caused by the accumulated freshwater inside. This creates a barotropic pressure gradient that generates an outflow to the ocean and is constant with depth. Thus, the combined flow generates a surface outflow and a bottom inflow. Moreover, the inflow is exposed to a frictional force at the bottom that reduces the flow. The frictional force is proportional to the square of the velocity, the roughness of the bottom, and the bottom area of the inlet. This leads to a velocity profile with a maximum PS outflow at the surface and a maximum ocean inflow above the bottom (Figure 2).

The two-way exchange described is self-adjusting to conserve the volume of water such that the net exchange will be equivalent to the internal water balance. With
greater friction, the interface between the inflow and outflow becomes shallower with the two flows still balanced. While the buoyancy is not necessarily conserved at every time step, it converges to a running mean condition over time.

The sea-level gradient can be independently influenced by other factors such as tidal, wind forcing, or atmospheric pressure differences. This causes the sea-level to oscillate about a zero mean level. As a result, an oscillating barotropic flow component that is superimposed on the thermohaline exchange is generated. The water transport that is coupled to this oscillating component integrates to zero over time.

The goal of this study was to assess whether or not the TEM could be used to generate real-time salinity and thermohaline exchange information for the CAPES. In the section below on Model Application, the formulations used in the thermohaline exchange model will be explained with reference to the equations used by Hopkins (1999).

**Stabilizing Feedback Loop (FBL)**

A perturbation in the input ("force"=PS buoyancy) causes a modification in the output ("response"=estuarine exchange) of a system. If the response correspondingly modifies the force, then a negative or stabilizing FBL is established. For example, an increased freshwater input into PS increases the buoyancy of PS waters. The increased buoyancy gradient between the PS and ocean increases the baroclinic pressure gradient that, in turn, increases the estuarine exchange with the ocean through the inlet. This leads to an increased influx of ocean water that provides more salt to PS and gradually decreases the buoyancy of PS waters, and consequently the baroclinic pressure gradient driving the exchange with the ocean. The decrease in ocean salt influx causes the PS to
return to its previous buoyancy condition and a stabilizing FBL is established (Figure 3). Stabilizing FBLs, such as the above example, are necessary in sustaining dynamic equilibrium in the system, and can be classified as non-linear where the response (thermohaline exchange) is proportional to the force (baroclinic pressure gradient) driving it and the force is reduced by the response that it drives (Hopkins 2001).

**INPUT DATA**

The Albemarle Pamlico Estuarine Exchange (APSEEx) Model requires time-series input data: meteorological, runoff and ocean salinity (Table 2). Also, to calibrate the model output, salinity data in both sounds that have reasonable distributions in time and space were needed. An important criterion for the compilation of data sets was the availability of at least a year of continuous, daily-averaged time-series data for both input and *in-situ* calibration data. After reviewing the available data (Appendix A, B), the only time-series that closely matched these criteria were for January 1990-September 1991, and January 1998-December 2000 (Table 3).

*Discharge*

**A. Description**

The daily mean discharge measurements for the major local rivers that discharge into PS and AS were taken from the USGS water database (http://water.usgs.gov/pubs/circ1123/collection.html). The standard methods used in the USGS Stream-Gaging Program will be briefly discussed in this section. Data from a gaging station at a specific river is composed of a continuous record of stage, individual measurements of discharge
throughout a range of stages, and data on various factors that can affect the relationships between the stage and discharge. Discharge measurements are made with current meters. The continuous record of stage is collected by automatic recorders and manual measurements at field installations. These data are gathered by field personnel, or more recently, transmitted at intervals of either 3 or 4 hours to the NC District office in Raleigh through the Geostationary Operations Environmental Satellite (GOES) data-collection system for automatic storage and processing. Daily discharges are then calculated using the gaging data combined with other complementary data including weather records (USGS Water-Resources Data for NC, 1999).

Stage-discharge relationship curves are produced from plots of individual discharge measurements versus the corresponding stages. Daily mean discharges are then estimated by applying the daily mean stages to the stage-discharge curves. These discharge data are updated periodically to ensure accuracy since the stage-discharge relationship may vary due to the following: backwater from ice or debris such as log jams; algal and aquatic growth in the stream; sediment movement; and malfunction of recording equipment.

Both real-time and historical daily mean discharge data are conveniently made available to the public via the USGS website (http://water.usgs.gov/nc/nwis/sw). Each station is considered "PROVISIONAL" until the data are published (within 6 months of the end of the water year) in a water data report on a water-year basis (the 12-month period from October 1 through September 30 of the following year).
B. Data Processing

Daily-averaged discharge data for different periods from the different streams or rivers were obtained from the USGS website. The discharge is given in cubic feet per second (ft³ s⁻¹) and was transformed into cubic meters per day (m³ d⁻¹) to be dimensionally consistent in the model. Despite the availability of discharge data from the USGS water database, there was difficulty in approximating specific-year daily freshwater discharge into the sounds. First, there were incomplete same-year discharge data for most of the available stations. Second, there was an inadequate number of sampling stations near the mouth of the main rivers (i.e., Neuse, Tar-Pamlico, Roanoke and Chowan). Therefore, for both models (APSEEx 1990-1991 and APSEEx 1998-2000), the total freshwater discharge into each sound was estimated by normalizing the year's data to the published annual mean discharge for PS and AS. To do this, the ratio of the annual mean discharge into the sound and the annual mean discharge of the major stations (combined) nearest the river mouth was determined from historical values. This ratio was then multiplied by the daily mean discharge of some of the observed stations to provide a total runoff estimation for both models (APSEEx 1990-1991 and APSEEx 1998-2000).

Water Temperature and Calibration Salinity for the PS and AS

A. Description

i. Water Temperature. The USGS, in cooperation with the NC Department of Environment, Health, and Natural Resources, has collected water-quality data in several stations in PS's major rivers and in AS's waters for several years during the past decade.
One of the main goals is to establish baseline conditions in both Sounds. However, for AS these efforts lasted only for a short period (1989-1991) with the USGS maintaining only the stations in the major rivers in both Sounds (Garret 1993).

Measurements of water-quality data were taken using the USGS mini-monitor, a data-collection system, which is controlled by a fully programmable datalogger and controller that turns the mini-monitor on at 15-minute intervals for approximately one minute. The mini-monitors are powered by an external 12-V battery with solar panels to maintain full charge and are housed in water-tight containers attached to U.S. Coast Guard channel markers. Continuous water-quality data include near-surface and near-bottom specific conductance; near-surface water temperature; and near-surface, mid-depth, and near-bottom dissolved-oxygen concentrations. These data are available to the public as daily averaged data in several USGS water-quality data publications and through the NC USGS website (http://wwwnc.usgs.gov).

**ii. Salinity (Calibration Data).** Salinity data were taken from two different sources. The first set of data (USGS) were available for the waters of AS as near-bottom (one meter above sea floor) salinity. Data were derived and calculated from the specific-conductance data that were collected as described in the preceding section. Data collected in most stations (Figure 4) did not have a complete time series for the period January 1990-September 1991. None of the stations were located in the mixed center of the sound (Figure 4).

The second set of data was obtained from the DUML courtesy of J. Ramus. Between Fall 1998 and Spring 2001, several stations were established in the southwestern basin of the PS (Figure 5). Water column properties (max. ~6m) were collected onboard
the R/V *Susan Hudson* using a Sea-Bird Electronics (SBE) 25-03 Sealogger Conductivity, Temperature and Depth (CTD) equipped with a SeaTech *in-situ* fluorometer, SeaTech transmissometer (0.5m), a Biospherical Instruments QSP-200PD 4π PAR light sensor and Yellow Springs Instruments 5739 DO probe. These fortnightly sampled profiles were part of a study to investigate the response of the water column and phytoplankton biomass of the PS to event scale flooding (Ramus et al., unpublished).

**B. Data Processing**

**i. Water Temperature.** Daily near-surface water temperature data were obtained from the NC USGS website and were relatively complete for the two periods the model was run. Gaps in the data were linearly interpolated when possible. For the APSEEx 1998-2000 model, input water temperature ranged from 0.9 to 30.4 degrees °C for the PS compartment, and 3.1 to 30.4 °C for the AS compartment. For the APSEEx 1990-1991 model, input water temperature ranged from 4 to 30.4 °C for both PS and AS compartments.

**ii. Salinity (Calibration Data).** The first set of salinity data were compiled from USGS water-quality data publications as daily-averaged near-bottom salinity for AS for the period January 1990-September 1991 (Figure 4). As mentioned above, salinity data were not complete for most stations throughout the model period, and stations were not located in the center of the sound. A procedure was taken to get representative time series for the model period. To normalize for the individual stations to their common mean value for the entire sound, salinity data from several stations in AS were weight averaged (Figure 4). Several series of stations within the sound were chosen (i.e., Series 1: Stations 5, 7, 9; Series 2: Stations 3, 7, 9; Series 3: Stations 3, 5, 7; Series 4: Stations 3, 5, 7, 9; and Series
5: Stations 3, 4, 5, 6, 7, 9). Stations at the mouth of the Roanoke and Croatan Sounds (Stations 10 and 11) and inside the rivers (Stations 1, 2 and 8) were excluded since these were considered as oceanic and riverine endmembers, respectively (Figure 4). For each series, daily salinity at each station was multiplied by the weighted area that the station approximately occupies in AS. These were summed and divided by the total weighted area to get the representative salinity in AS. The most complete salinity time-series (Series 5) that best represented the AS salinity was chosen as calibration data for the AS compartment of the APSEEx 1990-1991 model. Mean salinity of Series 5 was 1.4 ± 0.6 ppt.

For the second set of calibration data, the raw CTD data (from J. Ramus, DUML) were processed using SBE's Windows version of SEASOFT that includes the SBE Data Processing Software (version 1.5). Several steps were made to ensure that the calibration salinity data represented a well-mixed PS compartment, which is one of the assumptions used in the model. (1) Stations close to the rivers and inlets were not selected to avoid bias due to freshwater and saltwater influence. (2) Same-day profiles from the selected stations were plotted to analyze the extent of freshwater and saltwater influence, after which the outliers were discarded. The profiles were then depth-integrated and used as calibration data for the PS compartment of the APSEEx 1998-2000 model (Figure 6).

Water Temperature and Salinity for the Atlantic Ocean

A. Description

The lack of complete time-series data for the Atlantic Ocean off any of the Outer Banks Inlets for the periods January 1990-December 1991 and January 1998-December
2000 was a constraining factor. Therefore, daily profiles of water temperature and salinity sampled from the US Army Corps of Engineers-Field Research Facility (USACE-FRF) on the ocean side of Duck, NC (Figure 1) were used to represent the oceanic endmember. Because Duck Pier is located 30 nautical miles north of Oregon Inlet (Figure 1) and is proximal to the heavy discharge of freshwater from Chesapeake Bay, Virginia and Delaware Bay, Delaware, it cannot be assumed that the data completely represent the ocean inflow at Oregon Inlet, and certainly not at the two southern inlets, which are more saline than ocean water that enters Oregon Inlet (Pietrafesa et al. 1986). The daily profile of Conductivity, Temperature and Depth (CTD) data that were collected at the end of the FRF pier using an Ocean Sensor CTD are available at http://www.frf.usace.army.mil along with other high quality field data on bathymetric, oceanographic, and meteorological conditions.

B. Data Processing

Daily profiles of water temperature and salinity data were downloaded from the USACE-FRF website. Linear interpolation was necessary for a few data gaps. Because the CTD data were only available for the period 1994-2000 (Appendix B), the ocean water temperature and salinity data used as input data for the APSEEx 1998-2000 model were applied to the APSEEx 1990-1991 model. Water temperature data used in the APSEEx 1990-1991 model (January 1998-September 1999) ranged from 4 to 34.9 °C, while water temperature data used in the APSEEx 1998-2000 model (January 1998-December 2000) ranged from 1.95 to 34.9 °C.

As mentioned above, the salinity measurements from Duck Pier do not reflect the magnitude of ocean salinity outside the three main barrier island inlets. Using available
data during a 1977-78 MEAS/NCSU cruise (Curtin, 1978) outside the three inlets, CTD
data indicate a seasonal trend for salinity (i.e., low salinity during winter and high salinity
during summer). Therefore, it was necessary to add a seasonally varying correction to
the amplitude of the Duck Pier salinity to simulate ocean salinity reflective of the three
inlets (Figure 7). Mean ocean salinity simulated in the APSEEx 1990-1991 model was
28.9 ± 2.5 ppt, while that in APSEEx 1998-2000 model was 29.5 ± 3.0 ppt.

Meteorology

A. Description

Meteorological data were obtained from the State Climate Office of NC (NC-
SCO) and from the National Climatic Data Center (NCDC) website (http://www.ncdc.
oaa.gov/ol/climate/climatedata.html) and include, air temperature, precipitation,
evaporation, relative humidity, and wind speed. The data encompass stations near the
wetland coast and at Cape Hatteras.

B. Data Processing

Precipitation data were divided into: Southwest Pamlico (Neuse), Southwest
Pamlico (Tar-Pamlico) and Northeast Pamlico for the PS, and West and East Albemarle
for the AS. Precipitation data were then averaged per sound to represent mean
precipitation for each sound.

Because the evaporation data from the NC-SCO were taken from a mainland
station, the data were considered not to represent the evaporative conditions occurring in
the sound. Some of the parameters that affect evaporation on the mainland (i.e., air
temperature and water vapor) may be biased by the fact that the station is surrounded by
land. Therefore, evaporation was estimated using Fick's first law of diffusion, which states that a diffusing substance moves from a region of high concentration to a region of low concentration at a rate that is proportional to the spatial gradient of concentration (Dingman 1994). This can be shown in finite-difference form as

\[ E = K_E \nu_a (e_s - e_a), \quad (7) \]

where \( E \) is the evaporation rate [cm day\(^{-1}\)], \( e_s \) and \( e_a \) is vapor pressure of the evaporating surface and overlying air [millibar, mb], respectively, \( \nu_a \) is the wind speed [km day\(^{-1}\)], and \( K_E \) is the coefficient reflecting the efficiency of vertical transport of water vapor by the turbulent eddies of the wind [cm km\(^{-1}\) mb\(^{-1}\)]. \( K_E \) is a function of the water body's area \((A_L)\) (Harbeck 1962) such that

\[ K_E = (1.69 \times 10^{-4}) A_L^{-0.05}, \quad (8) \]

where \( K_E \) is in cm km\(^{-1}\) mb\(^{-1}\) and \( A_L \) is in km\(^2\). The vapor pressure of the water surface is equal to the saturation vapor pressure at water temperature, \( T_w \), such that

\[ e_s = e_{sat}(T_w), \quad (9) \]

where

\[ e_{sat}(T) = 6.11 \exp \left( \frac{17.3T}{T + 237.3} \right), \quad (10) \]

with vapor pressure in mb and temperature in °C. The vapor pressure in the air is a function of relative humidity, \( W_a \), and air temperature, \( T_a \), such that

\[ e_a = W_a e_{sat}(T_a), \quad (11) \]

where \( W_a \) is expressed as a ratio.
Using this approach, only measurements of air and water temperatures, relative humidity, wind speed, and sound area are necessary to estimate evaporation rate. Since meteorological data (i.e., relative humidity and wind speed) obtained from the NC-SCO and NCDC were only available as hourly measurements (Appendix A), evaporation rate was initially calculated on an hourly basis and then daily-averaged.

**MODEL APPLICATION**

Box models that are heavily based on established physical processes (e.g., changes in water density due to water temperature and salinity fluctuations) are among those models that can reproduce nature effectively (Carlsson 1998). By using a new generation of simulation modeling (e.g., using EXTEND™ Simulation Software), the investigator is able to (1) concentrate more on the correct physics involved in the system rather than spending excessive time in the analysis of the complicated programming codes (Carlsson 1998), and (2) learn and understand more about the relationship between the response being studied and its forcing (Hopkins 1999; Hopkins 2001).

EXTEND™ is a non-linear process modeling software that uses a hierarchical structure of processes connected in series for representing the flux of mass through a sequence of ecosystem compartments. Each of these compartments can also be connected in parallel to represent optional pathways for fluxes that can be switched by threshold values or other internal information. Initially, simple assumptions about the system can be defined and modeled. As the knowledge improves about how a system behaves, more processes can be progressively merged into the model. The software provides the user with excellent flexibility in a system whose local dynamics vary in
space. Moreover, models developed in this fashion are very economical and facilitate duplication, modification and transfer among users. For example, EXTEND™ is cross-platform compatible (i.e., the software can run models under Windows 3.1x, Windows 95 and 98, Windows NT, PowerMacintosh or Macintosh systems) and will allow model sharing between colleagues who use different computer platforms. The only restriction to model size will be the computer resources available to the user (Diamond, et al. 2000).

In the present work, EXTEND™ was utilized in developing the estuarine exchange simulation model of the AS and PS (APSEEx). The present formulation of the model represents both AS and PS as well-mixed boxes (in the vertical and horizontal direction) with the PS connected to the Atlantic Ocean (Figure 8). A preliminary one-box model for the PS was built with the assumption that the contents are well-mixed and that a single inlet (i.e., Oregon Inlet) that has a combined cross-sectional area of the three actual inlets, and a single river exists. For a first-order approximation, using transport values for river runoff and mean salinity values from the PS and the Atlantic Ocean, a mass and salt balance for PS was modeled. The freshwater runoff was the primary forcing function for the estuarine circulation.

The next step was to gather both daily temperature and salinity data taken from the PS and from the Atlantic Ocean to calculate their respective water densities. The water densities were, in turn, used to calculate for the steric-height gradient through the inlet. As the understanding of the system increased, more physical processes were included in the model, and the AS compartment was added and coupled to the PS through another inlet (i.e., Croatan Sound). The boundary between the two compartments was defined based on spatial water property gradients and internal dynamics. Daily river
discharge, precipitation, and evaporation data were added to the coupled AS-PS model to get more representative salinity in both compartments.

The calibration of the salinity-mixing and frictional coefficients (see EXTEND™ Formulations below) was conducted by means of the "sensitivity analyses" routine in EXTEND™. This allows the user to run the model for a sequence of values for a given parameter (Diamond, et al. 2000). Simulations were run typically for up to 4 times, varying the value of the parameter in question with each run until a best fit was obtained. For calibration purposes, salinity data for both AS and PS were gathered to validate model results. However, due to scarcity of same year salinity data for both sounds, these coefficients were calibrated in a two-step process. The model was first run for January 1998-December 2000 to calibrate with the PS salinity (APSEEEx 1998-2000), and then, the model was run for January 1990-September 1991 to validate the AS salinity (APSEEEx 1990-1991) (Table 3).

During the early phases of developing the model, the model was run using a time step (Δt) equal to 1 day. As more processes (e.g., mixing and bottom friction) were included in the model, Δt was reduced to ensure that all calculations in the model were reflected in the model plots, thereby avoiding numerical instability. The primary purpose was to use the largest Δt that will give accurate results that have no significant differences when compared to a smaller Δt, thus permitting the simulation to run at an accelerated rate (Diamond, et al. 2000). In the final model, the Δt used was equal to 0.2 day (=4.8 h).
EXTEND™ Formulation

EXTEND™ models are documents that are systematically organized into different components, more commonly called "blocks". Blocks are usually connected to other blocks using "line connectors" or "name connectors". These blocks conveniently include procedural statements that tell what a block should do (e.g., an "Add block" simply adds 2 or 3 inputs such as the sum of river runoff from two separate discharge stations in the PS), and may contain user-entered data (e.g., a "Constant block" allows the user to input a constant value such as the PS mean salinity). Once a model is constructed, more blocks can be added and data can be replaced as it suits the user. With "Plotters", solutions to model simulations can be easily visualized by the user. (EXTEND™ has a library that contains a broad range of blocks that can be used in science and engineering modeling, see Appendix C for a list of blocks used in the thermohaline exchange model).

The thermohaline exchange model was divided into 2 "Hierarchical blocks" or H-blocks to represent the PS and AS (Appendix D.1). The H-blocks are the main compartments of the model and information generated from each H-block is passed on to the other via line or name connectors. Each of these H-blocks is made up of several panels (or sub-compartments) that contain all the individual blocks needed to run the model. The following are the names of the panels used in the model: (1) Input Data panel, (2) Preliminary Equations panel, (3) Steric-Height and Volume Transport Equations panel, (4) Thermohaline Exchange Equations panel, and (5) Salt Balance and Freshwater Balance Equations panel. The contents and function of each panel is explained briefly in the following text.
A. Input Data Panel

The input data panel (Appendix D.2) contains all the constants and input data blocks needed to introduce the constants and time-series data from each sound in the model. Some of the constants include the surface area and mean depth of the sound, the sill depth and width, the reference ocean salinity, and the mean runoff from the major rivers. The time-series data includes water temperature and salinity from the ocean, and water temperature, river runoff and precipitation data from the sound. This panel also introduces the input data that is either entered or generated from the other H-block (either PS or AS) and includes water temperature and salinity, inflowing mixed water salinity, and steric-height and exchange components. Each of the blocks is connected to a name connector and is used in other parts of the model, e.g., to calculate other state variables.

B. Preliminary Equations Panel

The preliminary equations panel (Appendix D.3) makes the initial calculations or unit conversions for other constants and state variables that will be used in other parts of the model. Examples include the initial sound volume, the volume of runoff and net precipitation entering the sound, and the volume of freshwater exiting the sound. These parameters can be calculated by entering their respective equations in equation blocks, or by simply using the Add, Subtract, Multiply or Divide blocks (see Appendix C).

A Gamma filter is used to delay (i.e., 2-day lag) and skew the freshwater entering the system ($U_{wb}^n$). This was done to simulate the delay and smoothing associated with the river discharge being mixed into the PS and AS. The procedure allows the model to not only account for the net freshwater input but to also allow instantaneous sea-level (as
controlled also by other forces) to drive the fluctuating portion of the barotropic flow $U^{nl}$ (transport due to sea-level fluctuation) in the exchange.

C. Steric-Height and Transport Equations Panel

A hierarchical block was constructed to calculate densities by entering the respective temperature and salinity values in the One Atmosphere International Equation of State of Seawater (Millero and Poisson 1981) (Appendix D.4). The steric-height variable is calculated for both sounds and for the ocean using the respective density values of freshwater, PS and the ocean (Hopkins 1999). If the vertically-averaged density is defined as

$$
\bar{\rho}(z) = \frac{1}{z} \int_0^z \rho(z) dz,
$$

then the steric-height parameter can be defined as

$$
\zeta^{sh}(z) = \frac{1}{\rho_o} \left[ \rho_r - \bar{\rho}(z) \right] z,
$$

where $\rho_r$ is an arbitrary reference density. By subtracting a reference pressure of $P_r = \rho_r g z$ from both sides of Eq. (13), then Eq. (13) can be rewritten as

$$
P(z) - P_r = g \rho_o \left[ \zeta^{ht} + \zeta^{wb} - \zeta^{sh}(z) \right].
$$

To determine the steric-height difference between the ocean and the CAPES, we will refer to Eq. (13) and make the following denotations:

Let $\zeta^{sh}_{(OC)}$ be the Atlantic Ocean steric-height, $\zeta^{sh}_{(PS)}$ the PS steric-height, and $\zeta^{sh}_{(AS)}$ the AS steric-height. Let

$$
\Delta \zeta^{sh}_{(PS)} = \zeta^{sh}_{(PS)} - \zeta^{sh}_{(OC)}
$$

be the steric-height difference between PS and Atlantic Ocean. Furthermore, let
\[ \zeta_{OC}^{sh} = \left( \frac{\rho_r - \bar{\rho}_{OC}}{\rho_{PSA}} \right) D_S \]  

(16)

and

\[ \zeta_{PS}^{sh} = \left( \frac{\rho_r - \rho_{FW}}{\rho_{PSA}} \right) d_{PS} + \left( \frac{\rho_r - \bar{\rho}_{OC}}{\rho_{PSA}} \right) \left( D_S - d_{PS} \right), \]  

(17)

where \( \rho_{FW} \) is the freshwater density, \( \bar{\rho}_{OC} \) is the average density of the Ocean, \( \rho_{PSA} \) is the depth-averaged density of PS, \( D_S \) is the sill depth and \( d_{PS} \) is the equivalent pycnocline depth of PS. The equivalent pycnocline depth was defined by Hopkins (1999) as the equivalent pycnocline for a two-layered water column having the same integrated density at the depth of the sill \( (D_S) \) as the observed water column. The equivalent pycnocline depth for the PS, \( d_{PS} \), can be defined as

\[ d_{PS} = \frac{\rho_{OC} - \rho_{PS}}{\rho_{OC} - \rho_{FW}} \cdot D_S, \]  

(18)

where \( \rho_{PS} \) is the water density for PS. This parameter estimates the 'level of accumulation' of light water in the basin, which is difficult to delimit since the waters above the sill are already a mixture of the inflowing and accumulated waters.

Subtracting Eq. (16) from (17) will yield the steric-height difference between PS and Atlantic Ocean as

\[ \Delta \zeta_{PS-OC}^{sh} = \left( \frac{\rho_{OC} - \rho_{FW}}{\rho_{PSA}} \right) d_{PS}. \]  

(19)

Eq. (19) is calculated in the PS H-block and this information is transferred to the AS H-block via name connections.

In the same approach, if we let
\[ \Delta \zeta_{(AS)}^{sh} = \zeta_{(AS)}^{sh} - \zeta_{(OC)}^{sh} \]  \hspace{1cm} (20)

be the steric-height difference between AS and Atlantic Ocean and assign

\[ \zeta_{OC}^{sh} = \left( \frac{\rho_r - \overline{\rho}_{\text{FW}}}{\rho_{\text{ASA}}} \right) D_s \]  \hspace{1cm} (21)

and

\[ \zeta_{AS}^{sh} = \left( \frac{\rho_r - \rho_{\text{FW}}}{\rho_{\text{ASA}}} \right) d_{AS} + \left( \frac{\rho_r - \overline{\rho}_{\text{OC}}}{\rho_{\text{ASA}}} \right) (D_s - d_{AS}) \]  \hspace{1cm} (22)

where \( \rho_{\text{ASA}} \) is the depth-averaged density of AS and \( d_{AS} \) is its equivalent pycnocline depth.

\[ d_{AS} = \frac{\rho_{\text{OC}} - \rho_{\text{AS}}}{\rho_{\text{OC}} - \rho_{\text{FW}}} \cdot D_s. \]  \hspace{1cm} (23)

Then the steric-height difference between AS and Atlantic Ocean \( (\Delta \zeta_{AS-OC}^{sh}) \) would be

\[ \Delta \zeta_{AS-OC}^{sh} = \left( \frac{\rho_{\text{OC}} - \rho_{\text{FW}}}{\rho_{\text{ASA}}} \right) d_{AS}. \]  \hspace{1cm} (24)

Eq. (24) is calculated in the AS H-block and is used in Eq. (25). Finally, to get the steric-height difference between PS and AS \( (\Delta \zeta_{PS-AS}^{sh}) \) we can then assign

\[ \Delta \zeta_{AS-PS}^{sh} = \Delta \zeta_{AS}^{sh} - \Delta \zeta_{PS}^{sh} = \left( \zeta_{AS}^{sh} - \overline{\zeta}_{OC}^{sh} \right) - \left( \zeta_{PS}^{sh} - \overline{\zeta}_{OC}^{sh} \right) = \Delta \zeta_{AS-OC}^{sh} - \Delta \zeta_{PS-OC}^{sh}. \]  \hspace{1cm} (25)

D. Thermohaline Exchange Equations

This panel (Appendix D.5) includes sound volume calculations, where the sound volume is represented by a holding tank (see Appendix C). The exchange caused by the thermohaline circulation, \( u^{th} \), is defined as the sum of the following

\[ u^{th} = u^{bc} + u^{bt} + u^{bf} + u^{ub}, \]  \hspace{1cm} (26)
where $u^{bc}$ is the baroclinic component of the flow, $u^{bt}$ is the barotropic component, $u^{bf}$ is that due to bottom friction, and $u^{wb}$ is that due to the freshwater exiting the basin. All other forces (winds, tides) affecting the sea-level near the inlet do not result in a net exchange of volume, but do modify the exchange in a time-dependent sense. The net transport of the thermohaline circulation must equal the net water balance (Hopkins 1999)

$$\int u^{th} dA = \int u^{wb} dA,$$  \hspace{1cm} (27)

where $A$ is the cross-sectional area of the inlet. However, Eq. (27) implies that

$$\int u^{bc} + \int u^{bt} + \int u^{bf} = 0.$$  \hspace{1cm} (28)

Of the three components of flow in Eq. (28), the barotropic component is considered the unknown. The bottom frictional transport is taken as 19% of the value of the bottom layer transport without friction, after Hopkins (1999).

In the remaining equations, the thermohaline components are expressed in the form of a surface outflow, $U_{out}$, and a bottom inflow, $U_{in}$, where $d_o$ is the depth at which $u^{th} = 0$, and $U^{bc}$, $U^{bt}$, $U^{bf}$, and $U^{wb}$ are the corresponding volume transports of the flows described above in Eq. (26). The outflow can be expressed as

$$U_{out} = \int_0^{d_o} u^{th} = U^{bc} (d_o) + \frac{d_o}{D} [U^{bt} + U^{wb}],$$  \hspace{1cm} (29)

where

$$U^{bt} = -U^{bc}_{D_o} - U^{bf}.$$  \hspace{1cm} (30)

Substituting Eq. (30) into (29) gives

$$U_{out} = U^{bc}_{d_o} + \frac{d_o}{D} [U^{wb} - U^{bc} - U^{bf}],$$  \hspace{1cm} (31)
Conversely, the inflow can be expressed as

\[ U_{in} = -\int_{D_0}^{D_1} u^{th} = -\left[ U_{D_s}^{bc} - U_{D_a}^{bc} + \frac{D_s}{D_a} \left[ U^{ht} + U^{wh} \right] + U^{bf} \right]. \]  

(32)

By rearranging the terms, we get

\[ U_{in} = U_{(D_s)}^{bc} - U^{wh} + \frac{d_a}{D_s} \left[ U^{wh} - U_{(D_s)}^{bc} - U^{bf} \right]. \]  

(33)

The total water volume in each sound is accounted for by continually keeping track of the inputs and the outputs in a holding tank (see Appendix C).

E. Freshwater and Saltwater Balance Panel

The total salt and freshwater are both budgeted using the holding tanks (see Appendix C). PS Salinity is obtained by dividing the salt content by the time-varying water volume (Appendix D.6)

The amount of salinity-mixing between the surface and bottom layers in the inlet is represented as a fraction, defined as \( S_{mf} \) (see Hopkins 1999). The \( S_{mf} \) fraction is the amount of lower layer water mixed up and the amount of upper layer water mixed down. To formulate this type of mixing, the value for \( S_{mf} \) was taken as proportional to the inverse of the Richardson number, that is

\[ S_{mf} = K_{sm} \left( \frac{\partial U^2}{\partial z} - \frac{\partial S}{\partial z} \right), \]  

(34)
where $K_{sm}$ is a salinity-mixing coefficient, the salinity difference $\left( \frac{\partial S}{\partial z} \right)$, as a proxy for the density, represents the stability, and the vertical derivative of the baroclinic velocity ($u^c_{shear}$ in Appendix D.3) represents the shear.

**RESULTS**

The thermohaline exchange model was applied for two different time periods (January 1990-September 1991 and January 1998-December 2000) (Table 3). These time periods had the most complete daily-averaged time-series data for both input and *in-situ* calibration data (Table 2). However, there were some limitations in the available calibration data sets. First, the APSEEx 1990-1991 model lacked valid ocean and PS salinity data that would correctly calibrate the PS and therefore the AS salinity. Secondly, the APSEEx 1998-2000 model also lacked AS salinity data that would have otherwise calibrated the salinity-mixing and bottom friction in the Croatan and Roanoke Sounds. Since calibration data for both cases were insufficient, this section will mainly present the results from the PS H-block of the APSEEx 1998-2000 model that had relatively adequate (long time-series) calibration data from the PS and the ocean. During this period, the NC coast experienced several hurricanes, including "Bonnie", "Dennis", "Floyd" and "Irene" that either made landfall or approached the NC coastal areas. Next, results of the AS H-block of the APSEEx 1998-2000 model will be described. Lastly, snapshots of the results of the APSEEx 1990-1991 model will be presented briefly.
The runoff pattern for 1998 is a typical seasonal sequence for runoff in the PS (Figure 9a). Maximum runoff generally occurs from January to April followed by a minimum in June, when evaporation rates are greatest (Giese et al. 1979). This is succeeded by hurricane events during the initial fall months from August to October that influence the occurrence of several high runoff events.

The runoff, which is measured at the river mouth, is lagged (~2 days) to allow for mixing into PS water. For example, when hurricane "Bonnie" hit the NC coast on August 25-29 (Figure 9b), rainfall peaked on August 27, and this signal was followed by a peak in runoff after a 2-day lag. In theory, runoff is easily mixed into the estuary during hurricanes since these rain events are accompanied by strong winds. Moreover, hurricanes and storms that generate a large direct precipitation into the estuary act to reduce any lag with respect to runoff.

During 1999 (Figure 10a), the winter runoff was relatively low compared to the same period in 1998. Integrated runoff from January to April 1999 was only ~2.9x10^9 m^3 and was much less compared to the same period in 1998 which had ~8.0x10^9 m^3. During the fall months in 1999, PS was hit by 3 sequential hurricanes, "Dennis", "Floyd" and "Irene" (Figure 10a, 10b). These hurricanes had a combined effect that brought in extremely heavy rainfall and resulted in almost 2 months of flooding throughout most of eastern NC (USGS 2000). The integrated runoff to PS from August 29-November 15
alone was $\sim 8.3 \times 10^9$ m$^3$, which is approximately 66% of the runoff for the whole year of 1999. The buffered runoff response to the peak in rainfall caused by "Dennis" on August 30 and September 3 was lagged by almost 12 days from the first rainfall peak (Figure 10b). The initial runoff response on September 11 was weak since "Dennis" remained off the coast and did not start to make landfall until several days later. After "Dennis" reached central NC on August 30 and after "Floyd" made landfall on the eastern portion of NC on September 16, the runoff response was much stronger between September 18-21. There was a short hiatus before another hurricane ("Irene") approached the coastal areas of NC on October 17-18, and the runoff response from "Irene's" signal was recorded 5 days later.

### iii. 2000 Period

Hurricanes during 2000 were relatively less intense as compared to 1998 and 1999 (Figure 11). The integrated runoff calculated for the months of January to April was $\sim 3.5 \times 10^9$ m$^3$, slightly higher than the same period in 1999. During the fall months, there were several storm events that triggered a response in the runoff but these were not as intense as in the previous two years. Integrated runoff calculated from July to October was only $\sim 2.3 \times 10^9$ m$^3$ and this is only about 28% of what flowed in the PS during the sequential hurricanes of 1999.

### B. Salinity Response

This section will describe the behavior of salinity with respect to runoff especially during large rainfall events (i.e., 1998 and 1999). It is important to note certain factors that were taken into consideration during the construction of the thermohaline exchange model. First, a seasonally varying correction (see Data Processing Section of ocean
inputs) was added to the amplitude of the Duck Pier salinity to simulate ocean salinity reflective of Oregon, Hatteras, and Ocracoke Inlets (Figure 7). Second, the effect of wind set up acting as a control on the ocean input salinity was not included in this version of the model (see Wind Forcing Section). Third, the formulation of the TEM in effect stabilizes the salt variability inside PS and AS through a negative FBL between the force and response (see Stabilizing FBL Section). These factors will be relevant in explaining how salinity responds to different storm signals.

The salinity response to huge storm events can be best explained by examining the effect of the sequential hurricanes of 1999 on the PS salinity (Figure 12a, 12b). When hurricanes "Dennis" and "Floyd" hit NC, PS salinity on September 20, 1999 dropped to 10 ppt (Figure 12b), which was below the 3-year (1998-2000) mean PS salinity (14.7 ± 3.5 ppt) calculated from the model. When hurricane "Irene" approached the coast a month later, salinity continued to decrease on October 16 to ~9 ppt. The resulting depressed salinity was a response to the freshwater runoff (~8.3x10⁹ m³) that flowed into the system after the sequential hurricanes. It was not until the next April (2000) that PS salinity returned to the 3-year mean salinity (Figure 12b).

Another example of the salinity response to huge storm events is during the winter storms of January to April 1998 (Figure 13a, 13b). The integrated amount of freshwater runoff discharged into the PS during this period was ~7.9 x10⁹ m³ or ~95% of the runoff during the sequential hurricanes of 1999. PS salinity would be expected to drop similarly as it did (~10 ppt) during the hurricane event in 1999. However, PS salinity decreased to 7 ppt during the month of February (Figure 13b), and such a response would seem to be erroneous. By examining the initial stages of the simulation
during February 1998, the depressed salinity in the PS was likely caused by the winter runoff peak (Figure 13b) that was in phase with the salinity minimum from the ocean (Figure 7). The mean ocean salinity ($25.0 \pm 3.0$ ppt) during January to February 1998 was relatively lower than the mean ocean salinity ($29.0 \pm 2.0$ ppt) during September to October 1999 (Figure 7). The difference in salinity explains why PS salinity during January to February 1998 was anomalously lower than the PS salinity during September to October 1999 since not enough salt from the ocean was available to ‘salt up’ the PS during early 1998 when the simulation was started. Furthermore, PS salinity after the winter 1998 storm event returned to the 3-year mean salinity in only ~4 months (Figure 13a, 13b). This recovery period was faster compared to the recovery after the Fall 1999 hurricanes, which took more than 6 months (Figure 12b). By examining the simulated ocean salinity, the difference in recovery period between the two events can be explained by the availability of salt to PS during the recovery periods: maximum salinity ($30.0 \pm 3.0$ ppt) during March to June 1998, and minimum salinity ($28.8 \pm 2.0$ ppt) from October 15, 1998-March 31, 1999 (Figure 7).

An example of salinity response to small storm events is during the winter storms of January to February 15, 1999 (Figure 14), where PS salinity dropped below the 3-year (1998-2000) mean value as a response to the $\sim 1.6 \times 10^9$ m$^3$ integrated runoff that flowed into the PS. The winter perturbation was less in amplitude and duration, only ~40% of the 1998 winter storms and ~20% of the 1999 sequential hurricanes. While the two huge storm events were sufficient to hold down the salinity below the 3-year mean PS salinity, the 1999 winter storms barely freshened the sound (minimum of $\sim 14$ ppt) and was not enough to cause a long-term depressed salinity regime for the PS. In fact, the recovery
period, despite being in phase with minimum ocean salinity (28.4 ± 1.0 ppt for the period February 15-March 15, 1999), took about a month for the salinity of the system to return to the 3-year mean condition (Figure 14).

C. Volume Exchange during "Floyd"

The exchange between the PS and the ocean, i.e., the total volume of water coming in from the ocean and the total volume discharged from the PS, was similar during small storm events (Figure 15). This effect could well be explained by a stabilizing FBL that was created due to the buoyancy perturbation introduced into the sound during runoff and precipitation events (Figure 3). However, during large storm events like hurricane "Floyd", large amounts of freshwater dumped into PS cause abnormal ocean inflow such that the amount of outflow was much larger than the inflow (Figure 15).

D. Flushing Time

The flushing time by fresh and salt water were calculated for the PS. Information gathered on the flushing time is important, for example, in predicting how long a pollutant remains in the system. Flushing time can also influence the biological oxygen demand (BOD) of a system.

I estimated that it takes approximately 9 months of freshwater runoff to replace the existing freshwater volume in the PS at a rate equal to the river discharge (i.e., freshwater flushing time). In EXTEND™, this is designated as

$$FT_{fw} = \frac{FWC}{FWC_{in}}$$  (35)
where $FT$ is the flushing time by freshwater ($fw$), $FWC$ is the total freshwater volume of the sound, and $FWC_{in}$ is the total combined freshwater source (Appendix D.3). The salinity recovery time will be different from the freshwater replacement time since the recovery is also affected by other factors such as the salinity of inflowing ocean water and the freshwater volume of the perturbation.

Furthermore, the flushing time of the PS volume by the inflowing ocean water can be calculated as approximately 3 months. This is shown in EXTEND™ as

$$FT_{oc} = \frac{Vol_{Initial}}{TotUin - WB}$$

where $Vol_{Initial}$ is the initial volume of the sound, $TotUin$ is the total water volume entering the sound, and $WB$ is the water balance (Appendix D.3).

E. Calibration of model salinity

Sensitivity analyses were performed to calibrate both the salinity-mixing and frictional coefficients. The values attained for the salinity-mixing coefficients (Eq. 34) were $9.5 \times 10^{-8}$ (PS) and $3.9 \times 10^{-8}$ (AS), and the frictional coefficient was 0.19 for both PS and AS. A least squares linear regression was applied to compare the model and observed salinity data. Raw model and observed data were logarithmically transformed to satisfy regression conditions of normality and equal variance (Neter et al. 1996). Equal variance tests on residuals of log-transformed model and observed salinity data were significant using both Barlett’s and Levene’s test. Results of the regression show very good agreement between predicted salinities and observed values (Figure 16).
F. Simulation Runs

A couple of simulation runs were done to test the robustness of the APSEEx Model. These simulations are explained below and summarized in Table 4.

i. Simulation using mean water balance (runoff + net precipitation)

The PS and AS runoff and net precipitation values for the year 2000 were replaced with constant mean values from the previous two years (1998-1999) in an effort to investigate if the model would track the observed vertically-integrated salinities in the southwestern PS. Model results for the year 2000 show that the time variability in PS salinity qualitatively matched the observed salinities (Figure 17).

ii. Simulation using mean ocean salinity

A constant mean ocean salinity (=29.5 ppt) was applied for the final year 2000, while allowing the model to use the variable ocean salinity for the first two years, 1998-1999. Results show that the time variability of the DUML vertically-integrated salinity was closely matched for the year 2000 (Figure 18).

*APSEEx 1998-2000 Model (AS H-block)*

Better calibration data for the AS would be important in understanding how the PS and AS can be better coupled. It would also give insight into the dynamics (e.g., salinity-mixing and bottom friction) that could be simulated by including a third box to represent the Croatan and Roanoke Sounds. Although it would be intuitive that the PS primarily drives the salinity variability in the AS, the model results show that different watersheds could also generate an additional salinity variability in each sound (Figure 19). The disparity can be attributed to the difference in watershed characteristics (e.g.,
runoff) between the two drainage basins. As Figure 19 shows, the AS salinity follows the trend of PS salinity but not at a constant ratio because of differences in the phasing and amplitude of the runoff into PS and AS (Figure 20).

**APSEEx 1990-1991 Model**

The results for the APSEEx 1990-1991 model show that the AS salinity was within the range of the USGS salinity data (Figure 21), despite the fact that erroneous salinity-mixing and bottom friction coefficients might have been used. Since salinity data for both the PS and the ocean were lacking or insufficient for the model period, these coefficients in both the AS and PS H-blocks could not be calibrated.

**DISCUSSION**

An alternative method (TEM) for determining the non-linear thermohaline exchange through an inlet (Hopkins 1999) was applied to a thermohaline exchange model of the CAPES. Salinities generated by the model for the period January 1998-December 2000 closely followed the trend of depth-averaged salinities measured in the southwestern Pamlico Sound for the same time period (Figure 6). An interesting aspect from the results of the study is the ability of the sound to regulate its salt content when exposed to very large runoff perturbations. I calculated the drop in salinity from ~20 ppt to ~9 ppt during the Fall 1999 hurricane event to be ~55%. Using Paerl et al. (2001)'s average surface salinity measurements in the southwestern PS one week before (~19 ppt) and two weeks after (~9 ppt) the passage of hurricane "Floyd", I similarly calculated the drop in salinity to be ~53%. During this sequence of hurricanes, the runoff forced the
freshening of the sound for about 6 weeks after which the recovery took more than 6 months (Figure 12b). This is what Hopkins (2001) referred to as the hysteresis between the response and the recovery. The response was forced by the freshening event, while the recovery was the consequence of a stabilizing FBL inherent in the thermohaline exchange dynamics (Figure 3).

It is important to note that the positive thermohaline exchange between the PS and the ocean allows both the volume and salt exchange to be self-regulating, as was especially evident during extreme rainfall events which altered mean salinity in the PS (Figure 12a, 12b). This self-regulation occurs because the estuarine exchange is proportional to the force (primarily dictated by the salinity) driving it, and the force is reduced by the net exchange that it drives. Both the baroclinic and barotropic forces that drive the estuarine exchange increase during storms. While the barotropic force that drives the flow out of the basin quickly resolves any volume perturbation, the baroclinic force that results in a two-way flow is much slower to resolve any density perturbation because of the 2-way nature of the exchange. For example, after a runoff event the baroclinic force increases, which causes an increased salt influx and a decreased salt-flux outflow (lower salinities) that results in a net influx of salt into the basin. As this adjustment proceeds the baroclinic force weakens and the net salt flux inward exponentially decreases. This negative FBL is continuously operating in response to the variability in the water balance. As a consequence, previous runoff events are eventually ‘forgotten’ and the system is always converging asymptotically to a running mean value for the salinity appropriate to the half-life of the FBL.
The time-dependent flushing times, expressed as volume divided by inflow, were calculated during the 1998-2000 period. The freshwater replacement of the freshwater volume by river discharge takes \( \sim 9 \) months. Conversely, the flushing of the PS volume by the ocean inflow takes \( \sim 3 \) months. Note that these flushing times would not be appropriate for polluted substances such as particulate organic materials, nutrients and toxins that react with the water and sediments (Hopkins 2001).

Simulation runs were done to demonstrate the usefulness of the thermohaline exchange model. Examples include applying the following mean values to the year 2000 instead of their *in-situ* values: 1) 1998-1999 mean water balance (runoff plus net precipitation), and 2) mean ocean salinity. This exercise is practical since in most cases, only runoff and precipitation time-series data will be readily available from state agencies (e.g., NC-SCO and USGS), and ocean salinity time-series data is difficult to obtain due to lack of observational data. By simply applying either the mean water balance or the mean ocean salinity, time-dependent predictions of PS salinity and thermohaline exchange between PS and the ocean can be obtained for a specific period, however, only on the order of months (Figure 17, 18).

The TEM can be applied to other estuaries (e.g., Chesapeake Bay). It has been applied in the Mediterranean Sea, a negative estuary, to describe the exchange on an annual scale (Hopkins 1999). This is the first time that it has been applied to a positive estuary (Hopkins 2001). When the TEM is applied to the thermohaline exchange model using EXTEND™, the method allows for a time-dependent budget of salt for PS (Appendix E) and AS. Thus, the thermohaline exchange model can keep track of the density, sea-level, and freshwater in each of the sounds and can calculate the respective
exchanges through the inlets on a time-dependent mode. A method that has been applied to measure water-exchange between PS and the ocean is by current meter measurements in the inlets (e.g., Singer and Knowles 1975, Knowles and Singer 1977). Point measurements using current meters make it difficult to integrate over the inlet's area, both in the vertical and horizontal direction. This is especially critical with inlets that have asymmetric flow patterns. Moreover, instrument installation in the field presents a hazard to the instrument. Although current meters provide time-series (daily to monthly) measurements of fluxes, the time-series data are not long enough to provide information on water-exchange over annual time-scales. Another method that has been applied to measure the water-exchange through the inlets is through numerical modeling (e.g., Pietrafesa et al. 1986; Pietrafesa and Janowitz 1988; Pietrafesa and Janowitz 1991; Xie and Eggleston 1999). Although this method is excellent in providing a synoptic view of spatial distributions within the CAPES, the procedure is costly for long time intervals. Furthermore, information on certain parameters such as ocean salinity entering the inlets, and volume of freshwater entering the PS and AS through rivers are estimated and prescribed at the model grid boundaries instead of using observed data.

Some of the major assumptions that were used to represent the CAPES in the thermohaline exchange model include: (1) the one-box representation for each of the homogeneously mixed waters of the PS and AS; (2) the exchange of the PS with the ocean through a single inlet that has a combined cross-sectional area representing the three actual inlets, and (3) the use of ocean salinity based on waters off Duck, NC. The major approximations used in the formulations of the model involved the calculation of the vertical mixing of salinity and bottom friction coefficients in the inlet. The vertical
mixing of salinity was formulated based on the Richardson number where the stability is represented by the salinity differences and the shear is represented by the vertical derivative of the baroclinic velocity. Conversely, the friction at the bottom layer was taken as a proportion of the baroclinic transport at the bottom layer, after Hopkins (1999). Once these coefficients were calibrated, they were not changed throughout the simulation and the model continued to track internal salinity consistently. Note that a non-perfect fit was expected because of the assumptions and lack of more accurate ocean salinity data. This proves that the non-linear relationship between the forcing and the exchange is a valid argument (see Stabilizing FBL Section). However, in-situ observations are needed to better calibrate the salinity-mixing and bottom friction. Once this is done, the model could be used in real-time associated with runoff and meteorological data to predict internal salinity.

Possible Applications

The thermohaline exchange model, or an improved version could be of great utility to answering a number of core scientific and management issues related to the CAPES. Selected examples for PS and AS with possible applications of the APSEEx Model are briefly discussed below.

1. Anoxia/Hypoxia

*Issue:* Anoxic (no detectable DO) or hypoxic (DO<4mg L⁻¹) conditions exist when the rate of oxygen consumption by oxidation of live and dead particulate organic matter exceeds the supply from photosynthesis and the atmosphere. A shift to anoxic conditions in the CAPES can have severe stressful impacts on resident organisms such as

**Application:** The exchange model would provide real-time estimates of *in-situ* oxygen that could be calibrated to USGS oxygen meters (http://www.usgs.gov).

**Simulation Approach:** An existing two-layer model (Neuse Estuary Oxygen Model, NEOM) that can give estimates of oxygen in the Neuse Estuary is currently used for instructional purposes in at NC State University (i.e., MEA 400, Earth Systems Simulation Modeling Lab, Appendix F). Although the NEOM has its limitations, since it still uses the Knudsen Relations in quantifying exchange between the Neuse Estuary and the PS, the model is two-layer and can quantify oxygen levels in the bottom layer. The NEOM could be adapted to the PS and AS and improved at the level of sophistication of the APSEEx Model such as the application of Thermohaline Exchange Method (TEM). Currently, surface and bottom layer nitrogen and oxygen levels can be simulated by the NEOM.

Some of the major sources and sinks of top and bottom layer oxygen in the CAPES that could be simulated in the improved version of the NEOM are listed below. These sources and sinks can be estimated or, if data exists, can be calibrated using literature values.

Sources of top-layer oxygen include 1) atmospheric diffusion into the surface layer (e.g., Officer 1976), 2) primary production (e.g., Rudek et al. 1991; Mallin 1994; Mallin and Paerl 1994), and 3) advection from river runoff (e.g., Neuse River Estuary MODeling and MONitoring (MODMON) program: http://www.marine.unc.edu/neuse/modmon)). Sinks include 1) advection to the tributaries and ocean (e.g., Officer et al.
Sources of bottom-layer oxygen could be simulated by 1) diffusive downward flux (e.g., Officer 1976), 2) vertical mixing (e.g., Officer et al. 1984), and 3) advection from the ocean (e.g., Officer et al. 1984), while loss terms include 1) bottom layer advection and entrainment to the top layer (e.g, Paerl et al. 2001), and 2) respiration (e.g, Paerl et al. 1998).

2. Salinity tolerance problem for primary nursery areas & larval recruitment to nursery areas

Issue: Declines in nursery area salinity due to increased runoff and precipitation may have direct short-term physiological effects on resident organisms and larval recruits in the CAPES (Eby et al. 2000; Lenihan and Peterson 1998).

Application: The model could monitor salinity and thermohaline exchange between the PS and a nursery area.

Simulation Approach: A hypothetical nursery area within the PS could be designated by constructing another box that exchanges with the PS in the APSEEx Model. This nursery area box would have in-situ input data that includes water temperature, salinity, runoff and meteorological data. The box will exchange with the PS, and use the same dynamics involved in the thermohaline exchange between the two sounds and between PS and the ocean. It would be possible to track salinity and determine possible stress for estuarine-dependent organisms in the nursery area that may be sensitive to low salinity conditions. Moreover, water-exchange between the PS and nursery area could be monitored to determine whether water-exchange conditions favor
larval transport (e.g., across the PS from Hatteras Inlet) especially during hurricanes, when floodwaters can disrupt recruitment of early juvenile crabs to the PS (Eggleston, NCSU, pers. comm.).

3. Groundwater

Issue: Groundwater can be a mechanism to transport dissolved pollution (e.g., nitrates) from urban and rural areas to coastal surface waters. Since groundwater flux is very difficult to measure, its omission can create errors in coastal water budgets and estimates of nutrient, salt and contaminant fluxes (Bokuniewicz 2001).

Application: Submarine discharge of groundwater has been estimated to be 40% of the total freshwater flux off the Carolina coast (Moore 1996). Given the accuracy of the APSEEx Model to predict salinity, and assuming it could be well calibrated with respect to the salinity-mixing and bottom friction processes in the inlets, the model could budget the subsurface entry of groundwater into the PS and AS.

Simulation Approach: The salinity-mixing ratio in the APSEEx Model is calibrated based on the existing water balance of the model. When groundwater contribution [PS Groundwater = PS Evaporation + Net Freshwater Inflow from Ocean to PS - PS Runoff - PS Precipitation - Net Freshwater Inflow from AS to PS] is estimated and included in the water balance of the model, then the salinity-mixing ratio has to be re-calibrated. Using the previous PS groundwater equation and the existing APSEEx 1998-2000 Model, the mean annual groundwater input to PS is estimated to be ~22% of the freshwater runoff into PS.
Concluding Remarks

A preliminary thermohaline exchange model was constructed in an attempt to study the exchange between the CAPES and the ocean. This endeavor was also an attempt to evaluate the applicability of the TEM suggested by Hopkins (1999). The thermohaline exchange model appears to be an effective research and management tool. However, to achieve a reliable simulation model for this economically important system, a coordinated effort to gather observational data is critical in the model calibration process. Real-time salinity measurements outside the ocean inlets are needed to replace ocean salinity measured off Duck, NC waters. To demonstrate how the PS and AS can be properly coupled, there is a need for real-time salinity measurements in the Albemarle, Croatan and Roanoke Sounds. Finally, some of the suggested improvements to the thermohaline exchange model include the following: (1) inserting an additional box to the PS to separate the southwestern and northeastern basins at Bluff Shoal, and allowing this southwestern box to communicate with the ocean through an inlet (Hatteras and Ocracoke); 2) inserting an additional box to represent the Croatan and Roanoke Sounds; (3) inserting the effect of wind setup on controlling the distribution of exchange between the northern and southern inlets; and (4) involving the effects of tide. With these improvements, complementary EXTEND™ models of bio-geo-chemical processes could be constructed to address various science and management issues in the CAPES.
REFERENCES


WEBSITES

National Climatic Data Center
(http://www.ncdc.noaa.gov/ol/climate/climatedata.html)

Neuse River Estuary MODeling and MONitoring (MODMON) program
(http://www.marine.unc.edu/neuse/modmon)


USGS Water-Resources Data for NC, 1999 (http://water.usgs.gov/nc/nwis/sw)

US Army Corps of Engineers-Field Research Facility (http://www.frf.usace.army.mil)
Table 1. Major sources of freshwater running into the Pamlico and Albermarle Sounds and mean annual precipitation minus evaporation (P-E) values for each basin estimated from Giese et al. (1985).

<table>
<thead>
<tr>
<th>Basin</th>
<th>P-E (m³ s⁻¹)</th>
<th>Freshwater Source</th>
<th>Freshwater Inflow (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pamlico Sound</td>
<td>79</td>
<td>Neuse River</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tar-Pamlico River</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Albemarle Sound</td>
<td>487</td>
</tr>
<tr>
<td>Albemarle Sound</td>
<td>23</td>
<td>Chowan River</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Roanoke River</td>
<td>252</td>
</tr>
</tbody>
</table>

Table 2. Summary of thermohaline exchange model input and in-situ calibration data.

<table>
<thead>
<tr>
<th>Interval/Model Name</th>
<th>Meteorology</th>
<th>Runoff</th>
<th>Ocean Salinity</th>
<th>Calibration Salinity</th>
</tr>
</thead>
</table>

Table 3. Names and summary description of thermohaline exchange models.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Period Covered by Input and Calibration Data</th>
<th>Source of Calibration Data</th>
</tr>
</thead>
</table>

Table 4. List of simulations conducted with the thermohaline exchange model.

<table>
<thead>
<tr>
<th>Parameter simulated</th>
<th>Description</th>
<th>Period Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean salinity</td>
<td>PS &amp; AS: Mean ocean salinity (34 ppt)</td>
<td>2000</td>
</tr>
</tbody>
</table>
Figure 1. Map of the Pamlico and Albemarle Sounds, North Carolina. The Pamlico Sound exchanges with the Atlantic Ocean through three barrier island inlets, namely Ocracoke, Hatteras, and Oregon. Duck Pier is located 30 nautical miles north of Oregon Inlet.
Figure 2. Two-way thermohaline exchange through an inlet: a) the pressure differences, b) the baroclinic, barotropic, frictional and combined velocity profiles. From Figure 2 of Hopkins (2001).
Figure 3. Stabilizing feedback loop (FBL) for a positive thermohaline circulation. From Figure 3a of Hopkins (2001).
Figure 4. Water quality sampling stations established by the US Geological Survey (USGS) in AS during January 1990-September 1991.
Figure 5. Selected sampling stations established by the Duke University Marine Lab (DUML) in the southwestern basin of Pamlico Sound, NC between Fall 1998 and Spring 2001 (courtesy of J. Ramus and J. Priddy).
Figure 6. Synoptic view of the model results for PS salinity. Note: Salinity (ppt) is on the left y-axis while Water Balance Transport (m$^3$/day) is on the right y-axis.
Figure 7. Comparison between 1998-2000 Duck Pier salinity and the seasonally varying corrected salinity used in the APSEEx Model. Note: Outliers (encircled) may be due to local runoff from large rain events.
Figure 8. Albemarle-Pamlico Estuarine Exchange (APSEEEx) model organization.
Figure 9a. Precipitation (m$^3$ day$^{-1}$) and Runoff (m$^3$ day$^{-1}$) for the first year of series, 1998.

Figure 9b. As in 9a for the period August 8-September 3, 1998. Note: (1) Precipitation is on the left y-axis while the Runoff is on the right y-axis, (2) Change in scale for Runoff.
Figure 10a. Precipitation (m$^3$ day$^{-1}$) and Runoff (m$^3$ day$^{-1}$) for the second year of series, 1999.

Figure 10b. As in 10a for the period August to November 1999.
Figure 11. Precipitation (m$^3$ day$^{-1}$) and Runoff (m$^3$ day$^{-1}$) for the third year of series, 2000.
Figure 12a. Comparison between the Salinity response (ppt) and Water Balance Transport ($m^3$ day$^{-1}$) during 1999. Note: Salinity is on the left y-axis while Water Balance Transport is on the right y-axis.

Figure 12b. As in 12a for the period August 1999 to April 2000.
Figure 13a. Comparison between the Salinity response (ppt) and Water Balance Transport (m$^3$ day$^{-1}$) during 1998. Note: Salinity is on the left y-axis while Water Balance Transport is on the right y-axis.

Figure 13b. As in 13a for the period January to June 1998. Note: Change in scales for Salinity and Water Balance Transport.
Figure 14. Comparison between the Salinity response (ppt) and Water Balance Transport (m$^3$ day$^{-1}$) during the period January 1-April 15, 1999. Note: (1) Salinity is on the left y-axis while Water Balance Transport is on the right y-axis; (2) Change in scales for Salinity and Water Balance Transport.
Figure 15. Comparison between the total inflowing volume from the ocean (m$^3$ day$^{-1}$) and the total outflowing volume from the sound (m$^3$ day$^{-1}$) during 1999. Note: Abnormal inflow during hurricane "Floyd".
Figure 16. Linear regression plot between log-transformed model and observed salinity collected by the DUML for the period 1998-2000.

\[ R^2 = 85.1\% \]
\[ \log Y = 0.245 + 0.778 \log X \]
\[ p < 0.05 \]
Figure 17. Simulation plot for PS salinity (ppt) applying 1998-1999 mean runoff + net precipitation to the year 2000.

Figure 18. Simulation plot for PS salinity (ppt) applying a mean ocean salinity (≈29.5 ppt) to the year 2000.
Figure 19. Comparison between the model and observed salinity collected by the DUML during the period 1998-2000.

Figure 20. Comparison of Runoff into PS and AS during the period 1998-2000.
Figure 21. Comparison between the model and observed salinity collected by the USGS during the period January 1990-September 1991.
Appendix
Appendix A. List of data sets for the CAPES region gathered from various agencies.

<table>
<thead>
<tr>
<th>Basin Name</th>
<th>Stations</th>
<th>Data Description</th>
<th>98-00^</th>
<th>90-91^</th>
<th>Period of record</th>
<th>Duration</th>
<th>Source**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chowan</td>
<td>Ahoskie Creek at Ahoskie</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1950-2000</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Albemarle Sound at light 3 (Site 5)</td>
<td>WT, S&quot;</td>
<td></td>
<td></td>
<td>WY1989-91</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Alligator River at light 8 (Site 7)</td>
<td>WT, S&quot;</td>
<td></td>
<td></td>
<td>WY1989-91</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Blackwell River near Franklin VA</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1941-2000</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Chowan River near Edenhouse (Site 3)</td>
<td>WT, S&quot;</td>
<td></td>
<td></td>
<td>WY1989-91</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Chowan River near Eure</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1974-76</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Currituck Sound at US 158 bridge (Site 9)</td>
<td>WT, S&quot;</td>
<td></td>
<td></td>
<td>WY1989-91</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Nottoway River near Sebrell VA</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1941-2000</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pasquotank River near South Mills</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1995-99</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Potecasi Creek near Union</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1958-2000</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td>Columbia</td>
<td></td>
<td>P&quot;</td>
<td></td>
<td></td>
<td>1975-87;1991-93</td>
<td>daily</td>
<td>2</td>
</tr>
<tr>
<td>Edenton</td>
<td></td>
<td>P&quot;</td>
<td></td>
<td></td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
</tr>
<tr>
<td>Elizabeth City</td>
<td>AMD*</td>
<td>1993-99</td>
<td>hourly</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elizabeth City</td>
<td>P&quot;</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lewiston</td>
<td>P&quot;</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manteo Airport</td>
<td>AMD*</td>
<td>1993-99</td>
<td>hourly</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manteo Airport</td>
<td>P***</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plymouth</td>
<td>P&quot;</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plymouth 5E</td>
<td>P&quot;</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Williamston</td>
<td>P&quot;</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

^ Plus signs (+) indicate the data used in the Pamlico and Albemarle compartments of both APSEEEx 1998-2000 and 1990-1991 Models
" D=Discharge (cu. m/sec); WT=Water Temperature (°C); S=Salinity (ppt); P=Precipitation (m); E=Evaporation (m); CTD=Conductivity, Temperature, Depth
* AMD=Advanced Meteorological Data: Dry Bulb Temp, Relative Humidity, Dew Point Temp, Wind Speed, Wind Direction, Wind Gust, Station Pressure
**1= United States Geological Survey; 2 = NC State Climate Office; 3 = J. Ramus (Duke Marine Lab); 4 = D.Eggleston and N.Reyns (NC State/MEAS)
### Appendix A. (continued)

<table>
<thead>
<tr>
<th>Basin Name</th>
<th>Stations</th>
<th>Data Description</th>
<th>98-00^</th>
<th>90-91^</th>
<th>Period of record</th>
<th>Duration</th>
<th>Source**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roanoke</td>
<td>Cashie River At Sr 1257 Near Windsor</td>
<td>D&quot;</td>
<td>+</td>
<td>+</td>
<td>1987-2000</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Roanoke Jamesville</td>
<td>WT&quot;</td>
<td>+</td>
<td></td>
<td>1998-2000</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Roanoke River At Nc 45 Nr Westover</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1997-98</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Roanoke River Nr Plymouth</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1997-98</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td>Tar Pamlico</td>
<td>Black Swamp Nr Batts Crossroads</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1981-82</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Chicod Cr At Sr 1760 Near Simpson</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1975-87; 1992-99</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Conetoe Creek Near Bethel</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1956-99</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Credle Ditch Nr Rose Bay</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1988-92</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Durham Creek At Edward</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1965-92</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Green Mill Rn At Arlington Blvd At Greenville</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1980-85</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Herring Run Near Washington</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1950-80</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Juniper Branch At Sr 1766 Nr Simpson</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1975-86</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>North Lake Canal above Pungo Lake near Wenon</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1976-80</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Pamlico R At Washington</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1988; 1999</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tar River At Greenville</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1997-99</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tar River At Tarboro</td>
<td>D&quot;</td>
<td>+</td>
<td>+</td>
<td>1931-2000</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Williams Ditch Rose Bay</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1989-92</td>
<td>daily</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Bayboro</td>
<td>P&quot;</td>
<td>+</td>
<td>+</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
</tr>
</tbody>
</table>

^ Plus signs (+) indicate the data used in the Pamlico and Albemarle compartments of both APSEEEx 1998-2000 and 1990-1991 Models

" D=Discharge (cu. m/sec); WT=Water Temperature (°C); S=Salinity (ppt); P=Precipitation (m); E=Evaporation (m); CTD=Conductivity, Temperature, Depth

* AMD=Advanced Meteorological Data: Dry Bulb Temp, Relative Humidity, Dew Point Temp, Wind Speed, Wind Direction, Wind Gust, Station Pressure

**1= United States Geological Survey; 2 = NC State Climate Office; 3 = J. Ramus (Duke Marine Lab); 4 = D.Eggleston and N.Reyns (NC State/MEAS)
<table>
<thead>
<tr>
<th>Basin Name</th>
<th>Stations</th>
<th>Data Description</th>
<th>98-00^</th>
<th>90-91^</th>
<th>Period of record</th>
<th>Duration</th>
<th>Source**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beaufort</td>
<td>Albemarle Canal near Swindell</td>
<td>D&quot;</td>
<td>1977-81</td>
<td>daily</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aurora</td>
<td>P, E&quot;</td>
<td>+</td>
<td>+</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Belhaven</td>
<td>P&quot;</td>
<td>+</td>
<td>+</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>New Holland</td>
<td>P&quot;</td>
<td>+</td>
<td>+</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Washington</td>
<td>P&quot;</td>
<td>+</td>
<td>+</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Neuse</td>
<td>Western Pamlico Sound</td>
<td>CTD&quot;</td>
<td>+</td>
<td>Fall 1998-2000</td>
<td>bimonthly</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Eastern Pamlico Sound</td>
<td>CTD&quot;</td>
<td></td>
<td></td>
<td>Oct &amp; Nov 2000</td>
<td>variable</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Neuse River At Channel Lt. 11</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1997-98</td>
<td>daily</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neuse River At Channel Lt. 9</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1997-98</td>
<td>daily</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neuse River At Channel Lt. 9</td>
<td>WT&quot;</td>
<td>+</td>
<td></td>
<td>1999-2000</td>
<td>daily</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neuse River At Kinston, N. C.</td>
<td>D&quot;</td>
<td>+</td>
<td>+</td>
<td>1930-2000</td>
<td>daily</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neuse River Near Fort Barnwell</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1996-99</td>
<td>daily</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neuse River stations</td>
<td>WT, S&quot;</td>
<td>+</td>
<td></td>
<td>WY 1991-92</td>
<td>hourly</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neuse River stations</td>
<td>WT, S&quot;</td>
<td></td>
<td></td>
<td>WY 1997-98</td>
<td>hourly</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neuse River stations</td>
<td>WT, S&quot;</td>
<td>+</td>
<td></td>
<td>WY 1989-92</td>
<td>daily</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Trent River Near Trenton</td>
<td>D&quot;</td>
<td></td>
<td></td>
<td>1951-99</td>
<td>daily</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Cedar Island</td>
<td>P&quot;</td>
<td>+</td>
<td>+</td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Chapell Hill</td>
<td>P, E&quot;</td>
<td></td>
<td></td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Cherry Point</td>
<td>AMD*</td>
<td></td>
<td></td>
<td>1993-99</td>
<td>hourly</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

^ Plus signs (+) indicate the data used in the Pamlico and Albemarle compartments of both APSEEEx 1998-2000 and 1990-1991 Models
" D=Discharge (cu. m/sec); WT=Water Temperature (°C); S=Salinity (ppt); P=Precipitation (m); E=Evaporation (m); CTD=Conductivity, Temperature, Depth
* AMD=Advanced Meteorological Data: Dry Bulb Temp, Relative Humidity, Dew Point Temp, Wind Speed, Wind Direction, Wind Gust, Station Pressure
**1= United States Geological Survey; 2 = NC State Climate Office; 3 = J. Ramus (Duke Marine Lab); 4 = D. Eggleston and N. Reynolds (NC State/MEAS)
### Appendix A. (continued)

<table>
<thead>
<tr>
<th>Basin Name</th>
<th>Stations</th>
<th>Data Description</th>
<th>98-00^</th>
<th>90-91^</th>
<th>Period of record</th>
<th>Duration</th>
<th>Source**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neuse</td>
<td>Cherry Point P&quot;</td>
<td>+</td>
<td>+</td>
<td></td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
</tr>
<tr>
<td>Columbia</td>
<td>P&quot;</td>
<td></td>
<td></td>
<td></td>
<td>1975-87; 1991-93</td>
<td>daily</td>
<td>2</td>
</tr>
<tr>
<td>Hatteras</td>
<td>AMD*</td>
<td></td>
<td></td>
<td></td>
<td>1975-95</td>
<td>daily</td>
<td>2</td>
</tr>
<tr>
<td>Hatteras</td>
<td>AMD*</td>
<td>+</td>
<td></td>
<td></td>
<td>1993-2000</td>
<td>hourly</td>
<td>2</td>
</tr>
<tr>
<td>Hatteras</td>
<td>P&quot;</td>
<td>+</td>
<td>+</td>
<td></td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
</tr>
<tr>
<td>New Bern</td>
<td>AMD*</td>
<td></td>
<td></td>
<td></td>
<td>1993-99</td>
<td>hourly</td>
<td>2</td>
</tr>
<tr>
<td>New Bern</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td>1975-2000</td>
<td>daily</td>
<td>2</td>
</tr>
<tr>
<td>Ocracoke</td>
<td>P&quot;</td>
<td></td>
<td></td>
<td></td>
<td>1975-76; 1998-2000</td>
<td>daily</td>
<td>2</td>
</tr>
<tr>
<td>Raleigh-Durham Airport (RDU)</td>
<td>AMD*</td>
<td></td>
<td></td>
<td></td>
<td>1993-99</td>
<td>hourly</td>
<td>2</td>
</tr>
<tr>
<td>RDU</td>
<td>AMD*</td>
<td></td>
<td></td>
<td></td>
<td>1975-95</td>
<td>daily</td>
<td>2</td>
</tr>
</tbody>
</table>

^ Plus signs (+) indicate the data used in the Pamlico and Albemarle compartments of both APSEEx 1998-2000 and 1990-1991 Models

" D=Discharge (cu. m/sec); WT=Water Temperature (°C); S=Salinity (ppt); P=Precipitation (m); E=Evaporation (m); CTD=Conductivity, Temperature, Depth

* AMD=Advanced Meteorological Data: Dry Bulb Temp, Relative Humidity, Dew Point Temp, Wind Speed, Wind Direction, Wind Gust, Station Pressure

**1= United States Geological Survey; 2 = NC State Climate Office; 3 = J. Ramus (Duke Marine Lab); 4 = D. Eggleston and N. Reynolds (NC State/MEAS)
Appendix B. List of data sets for the Atlantic Ocean gathered from various agencies.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Data Description</th>
<th>98-00^</th>
<th>90-91^</th>
<th>Period of record</th>
<th>Duration</th>
<th>Source**</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRF Facility at Duck, NC</td>
<td>AOD^</td>
<td>+</td>
<td>+</td>
<td>1994-2000</td>
<td>hourly</td>
<td>5</td>
</tr>
<tr>
<td>USGS Coastal EPIC Stations</td>
<td>WT*, AMD*</td>
<td></td>
<td></td>
<td>various years</td>
<td>daily/hourly</td>
<td>6</td>
</tr>
</tbody>
</table>

1 AOD=Advanced Oceanographic Data: Conductivity, Water Temperature, Pressure, Salinity, SSP, Sigma-t
2 WT=Water Temperature (°C)
3 AMD=Advanced Meteorological Data: Dry Bulb Temp, Relative Humidity, Dew Point Temp, Wind Speed, Wind Direction, Wind Gust, Station Pressure
4 **5 = Field Research Facility of US Army Corps of Engineers; 6 = United States Geological Survey
Appendix C. Quick reference to commonly used blocks in EXTEND™

**External parts of a block:**

- **input connectors**  
- **output connector**

**Blocks used in calculations**

- **Multiply block**
  - multiplies one input by the other

- **Divide block**
  - divides the top input by the bottom input

- **Subtract block**
  - subtracts the bottom input from the top input

- **Add block**
  - adds the three inputs

**Equation block**

- computes an equation you build in the block based on the inputs
- can also include "boolean" statements to evaluate to true or false conditions. Extend's ModL programming is similar to the C programming language. More information is provided in the Extend manual

**Example:**

```
If (CurrentStep == 0)
  Sout = SoutInit;
Else
  Sout = Salt/Volume;
```

**Holding tank block**

- accumulates the total of the input values (e.g. pollution levels in cubic meter)
- allows you to request an amount to be removed via the "want" connector and outputs that requested amount (if it is available) via the "get" connector
- allows you to specify a starting content via the "S" connector
- for our purposes, we integrate (no delay) input values and do not allow the tank to go negative

**Example:**

```
Gain in mass
Present levels in mass
Loss in mass
variables should have the same units
(e.g. water volume in cubic meter)
```

84
Blocks which generate a constant value or data into the model

**Constant block**
- outputs a constant value on each step

**File Input block**
- Reads data from a text file (up to 5 columns) and writes it into the block's table.
  Data can then be used in the model.

**Conversion function block**
- outputs a value that is the input modified by a function
  - some of the functions included are cosine, sine, lognormal, and user-defined

**Conversion table**
- acts as a lookup table
  - It contains a table of values \((x \text{ in and } y \text{ out})\) that are used to calculate what the output value would be for the given input.

**Input function block**
- generates a function over time
  - Some of the functions included are cosine, sine, impulse, ramp, step, and user-defined

**Input data block**
- generates a curve of data over time from a table of values and acts as a lookup table
  - For our purposes, output should be “interpolated”
**Blocks used in writing data to a text file and visualizing data**

**File Output block**
- Writes data to a text file (5 columns) that can be used for another Extend model.
- The file can be referenced by the File Input block or it can be opened in a spreadsheet, like Excel.

**Input/Output Plotter**
- Gives plots and tables of data for up to four value inputs for continuous models

**Multisim Plotter**
- Accumulates the results of up to four runs of a continuous simulation on a single plotter
- Used in sensitivity analyses

**Blocks used in debugging techniques**

**Mean & Variance block**
- Calculates the mean, variance & standard deviation of the input
- Useful in debugging model
- Normally paired with a Readout block

**Integrate block**
- Integrates the input over time
- Also useful in debugging model when paired with a Readout block

**Read Out block**
- Displays the value of the input connector at each time step
- Also useful in debugging model
- Use sparingly or only during debugging because slows down calculation
**Miscellaneous**

**Decision block**
- Makes a decision based on the inputs and internal logic you define.

**Wait time block**
- Delays its inputs for a specified amount of simulation time before passing them to the output.

**System variable block**
- Allows you to regulate some aspect of the model based on the status of the simulation.
- It is usually used in conjunction with a decision-type block, for example, to halt a process after current time reaches a certain value.
- The variables you can use are: current run number, current step, current time, end time, number of runs, number of steps, start time, and time step.

**Example:**

**Gamma block**
- This block converts the input value into a gamma distribution i.e. skewed-gaussian. The "time per step" is incorporated as a system variable "deltatime" or dt to account for changes in the time step of calculation other than unity.

**Sigma-t & Rho block**
- This block calculates for density: sigma-t and rho.
Appendix D.1.

Figure D.1. Hierarchical blocks (or H-blocks) representing Pamlico (PS) and Albemarle AS) Sound. Each of these H-blocks is made up of several panels that contain all the individual blocks needed to run the model. Information that is calculated from each H-block is passed on to the other H-block through line connectors.
Appendix D.2.

Figure D.2. Input data panel (PS H-block). The name connections (with red borders) on the upper left hand side are those variables that are either introduced into the H-block or those that are passed on to the AS H-block.
Appendix D.3.

Figure D.3. Preliminary equations panel (PS H-block) initially calculates or converts constants and variables needed in other parts of the model.
Appendix D.4.

Figure D.4. Steric height and transport equations panel (PS H-block, see text for related equations).
Appendix D.5.

Figure D.5. Thermohaline exchange equations panel (PS H-block, see text for related equations). This is also where the sound volume is budgeted using the Holding tank block.
Appendix D.6.

Figure D.6. Salt and freshwater budgets panel (PS H-block).
Appendix E.

Figure E. PS salinity generated by the APSEEx Model for different time periods: (1) January 1990-September 1991; (2) 1996; and (3) 1998-2000. Note: Seasonal variation in salinity is not constant from year to year.
Appendix F. Neuse Estuary Oxygen Model

NEUSE RIVER ESTUARY

PRELIMINARY EQUATIONS

\[ V_{\text{in}} - V_{\text{out}} + V_{\text{up}} - V_{\text{dn}} \]

\[ 2.5 \text{ Area, } m^2 \]

\[ 0.7 \text{ Surf layer, } m \]

\[ 9 \text{ Sin } \text{Supinit} \]

\[ 6 \text{ Soutinit} \]

\[ 0.6 \text{ Alpha} \]

\[ 28000000 \text{ Area, } m^2 \]

\[ 4,3,5 \text{ for 1-day peak delay & little skewness} \]

\[ \Gamma = 2000 \]

\[ 0.6 \text{ Bot layer, } m \]

\[ \text{Runoff} \]

\[ \text{Entrain} \]

\[ \text{Initial FWC} \]
FRESH WATER

WATER VOLUME

SALT BUDGET

SALT PLOTTERS
Oxygen levels in 2-layer Estuary

- **Top Oxygen**, kg
- **Bot Oxygen**, kg
- **TopO2**, kg/m³
- **BotO2**, kg/m³
- **O2 diffused**, kg
- **TopOxyIn**, kg
- **TopOxyOut**, kg
- **BotOxyIn**, kg
- **BotOxyOut**, kg
- **Photosyn**, kg
- **Respire_O2**, kg
- **Runoff**, kg
- **AtmO2diffuse**, kg
- **AtmO2grad**, kg
- **AdvectIN**, kg
- **AdvectOUT**, kg
- **Entrain up**, kg
- **Entrain down**, kg
- **TopV**, kg/m³
- **BotV**, kg/m³
- **TopO2ini**, kg
- **BotO2ini**, kg
- **O2sat**, kg
- **topvol**, kg
- **botvol**, kg
- **mean dist**, m
- **beta**, kg

Mathematical equations and variables are used to model the oxygen dynamics in the estuary.
Carbon sinking to bottom layer is buried or respired. Holding tank is needed to accumulate the Carbon and respire the carbon from that total instead of respiring it from the sinking carbon at every time step.